



The effects of public subsidies on emerging industry: An agent-based model of the electric vehicle industry

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ARTICLE INFO

Keywords:

Public subsidy
Emerging industry
Electric vehicles
Simulation
Agent-based modeling

ABSTRACT

Public subsidies are widely used as policy incentives to promote strategic industry development, especially in emerging industries that depend heavily on the use of new technologies. This study explores the differential effects of consumer subsidies and manufacturer subsidies on the development of new technology in the electric vehicle industry. An agent-based simulation model is constructed which fully considers the individual heterogeneity of consumers and manufacturers in decision-making, with the parameter settings derived from the data of the U.S. automobile market in 2010. Based on robustness tests, the findings suggest that consumer subsidy is more effective than manufacturer subsidy in promoting the popularity and technological breakthrough of electric vehicles. Subsidy intensity and duration are indicated to be important factors for policy effectiveness.

1. Introduction

Since the global economic crisis, the sluggish growth that persists in many countries has triggered a widespread revolution of re-industrialization for quicker economic recovery. The development of emerging industries, which is important for re-industrialization in the long term, has received attention from governments and researchers. A proliferation of literature has emerged to investigate the driving factors of the development of emerging industries, and the maturity of new technologies has been considered as one of the key factors (e.g., Hung and Chu, 2006). However, due to insufficient investment by the private sector, many emerging industries were hardly developed in the early stages (Andrews and DeVault, 2009).

Therefore, governments are motivated to intervene in the market, with various kinds of government policies and incentives, among which subsidies are one of the most commonly used financial incentives by governments. Faced with different types of emerging industries, the subsidy method varies. For example, as for the emerging industries rooted in a first-generation technology such as the information technology, manufacturer subsidies are preferred by governments to stimulate new innovation; while, with industries relying on advanced-generation technologies such as electric vehicles (EVs), consumer subsidies are as important as manufacturer subsidies. It is because consumer preferences are usually stuck in established products due to the path dependence (Hoeffler et al., 2006). Advanced-generation technologies will be greatly challenged by traditional technologies when

entering the market.

With regard to the effects of different subsidies, many studies suggest that both consumer subsidies and manufacturer subsidies play an important role in fostering technology development, especially in emerging industries that depend heavily on the use of advanced-generation technologies (Peters et al., 2012; Taylor et al., 2005). However, due to the difficulties in comparison of subsidies with multi-dimensional features like intensity and duration, few researchers have clarified the differential effects of consumer subsidies and manufacturer subsidies on the development of emerging industries. How public policies should be designed to balance the instruments in the policy mix has emerged as a very interesting topic and an inspiration for the conduct of this study.

In seeking a clear understanding of the effects of government subsidies on new technology emergence, in this paper we use electric vehicles' development in the U.S. to examine the subsidy performance from the consumer and manufacturer perspective and adopt an agent-based simulation model to deal with the incomparability of different subsidies. The choice of the EV industry in the U.S. is appropriate for two reasons. First, electric vehicles face a dilemma for popularity due to the advantageous benefits of conventional internal combustion engine vehicles (CVs) in terms of price and performance (Klößner et al., 2013). Development at the industry needs both consumer subsidies and manufacturer subsidies for a long time. Second, to facilitate the commercialization and diffusion of EV technologies, a number of subsidy policies from both the demand and supply sides have been implemented

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<https://doi.org/10.1016/j.techfore.2018.12.013>

Received 4 March 2016; Received in revised form 13 December 2018; Accepted 15 December 2018

Available online 27 December 2018

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in the U.S. over the last decade (Sierzchula et al., 2014). Related data is available to set the parameters of an agent-based simulation model.

The present study aims to contribute to the literature in three aspects. First, this study provides a comparison between the effects of consumer subsidies and manufacturer subsidies on the cultivation of new technologies using a simulation method, and takes into account the factors of subsidy intensity and validity duration, which have been suggested to influence the subsidy effects in existing literature (Murray et al., 2014). It is beneficial to shed light on the government incentive policies in assisting technology advancement. Second, the study differentiates the traditional and new technologies from the perspectives of product price, performance and post-adoption expenditure, and constructs an agent-based model which fully considers the heterogeneity of consumers and manufacturers, thus making a significant improvement to existed simulation research on industry dynamics. Finally, the simulation and parameters settings are based on an elaborate data collection from the U.S. EV market. The results are reliable and have good robustness.

The layout of this paper is proceeded as follows. Section 2 provides a comprehensive review of research on the effects of public subsidies. Section 3 constructs an agent-based model with the assumptions of consumer choices and firm decisions, and describes the parameter setting. Section 4 presents the simulation results of the EV industry in different scenarios. Finally, Section 5 summarizes the main conclusions and policy implications.

2. Literature review

Public subsidy is widely used as one of the most important policy instruments for the support of emerging industries. According to the objective for providing subsidies, public subsidy is conventionally classified into two broad categories: consumer subsidy and manufacturer subsidy (Lin and Jiang, 2011). Comparatively, consumer subsidies are a kind of demand-side instrument aimed at stimulating the market penetration of new products, in the form of direct price control, consumer tax relief, etc. (Cotti and Skidmore, 2010). Manufacturer subsidies are a kind of supply-side instrument aimed at improving product competitiveness through subsidizing production or innovation activities of firms, in the form of direct grant and business loans (Nemet, 2009).

Numerous studies have theoretically analyzed the role of public subsidies in fostering new technologies. Referring to Mowery and Rosenberg (1979), market demand is the dominant influential factor of technological innovation. However, consumer preferences are usually locked in traditional technologies due to path dependence, resulting in limited development space for new technologies (Hoeffler et al., 2006). Hence, consumer subsidy is advocated by governments to relieve this problem. On the one hand, consumer subsidy can be used to create niche markets, which protect new technologies from competition with traditional technologies (Nill and Kemp, 2009). On the other hand, through offering a positive policy signal, consumer subsidy is expected to alleviate the market uncertainty of new technologies and induce innovation investments by firms (García-Quevedo et al., 2016).

In contrast to consumer subsidy, manufacturer subsidy is supposed to resolve market failure, which is associated with social resources allocation in the generation of new technologies (Martin and Scott, 2000). According to existing studies, the development of new technologies needs substantial R&D investment before reaching competitiveness. However, due to the spillover effects of innovation activities and informational asymmetries in the capital market, firms tend to underinvest in the innovation activities of new technologies (Bloom et al., 2013). Subsidies granted to the firms directly ease the financing constraint and reduce the firms' attendant costs, so as to stimulate private R&D investments to achieve an optimal level.

With regard to related empirical research, the effects of consumer subsidies and manufacturer subsidies are now reviewed.

2.1. Effects of consumer subsidies

The empirical studies of consumer subsidies are reviewed based on their effects on technology diffusion and fostering innovation. In relation to technology diffusion, consumer subsidies have been proved in existing studies to be effective in stimulating the early market adoption of energy-saving appliances. For example, Silveira et al. (2013) conducted an economic analysis of the subsidy effects on solar plant installation, highlighting the importance of government subsidy for solar photovoltaic systems to achieve economic viability. Chang et al. (2013) applied system dynamics to explore the causal relationship between government subsidies and solar water heater installation in Taiwan, showing that for every NT\$500/m² increase in the installation subsidies, the 2020 solar water heater installation areas increase by 10,820 m², while government policies for subsidizing R&D costs fail to increase the solar water heater installation significantly.

Furthermore, a large body of literature has investigated the effectiveness of consumer subsidies in fostering innovation (Girod et al., 2017), with extensive discussion on the factors influencing subsidy effects. Referring to Finon and Menanteau (2003), between price-based subsidy and quota-based incentives, the former kind of subsidy method is considered as a good compromise to promote technical progress, especially for the less mature technologies (Costantini et al., 2015), while the effect of the latter still has to be further confirmed. Compared to broad-based policies such as green certificates, targeted subsidies are more likely to induce innovation on some costly energy technologies (Johnstone et al., 2010). Meanwhile, some researchers analyzing the influences on government subsidies point out that the effects of government subsidy depend on factors such as the subsidy amount and the policy stability (Murray et al., 2014).

In the EV industry, vehicle purchase incentives, notably subsidies and tax credits have been adopted in many countries to accelerate the popularization of electric vehicles. The existing studies have sufficiently demonstrated the positive impacts of subsidies in the EV industry (Shafiei et al., 2018). Among different types of subsidy method, the up-front price reduction is supposed to be the most powerful incentive in stimulating EV adoption (Bjerkkan et al., 2016; Diamond, 2009), while the specific subsidy policy considering different levels of consumer income and purchase location would yield higher social benefits (Skerlos and Winebrake, 2010).

2.2. Effects of manufacturer subsidies

As for the effects of manufacturer subsidies, extensive research has demonstrated the positive impacts on technology development. Government direct grant is found to be an important resource for firms' internal R&D funds, and induce firms to increase R&D investment, thus promoting the innovation output (Klaassen et al., 2005), which has been proved by researchers in the field of technology innovation associated with wind energy (Nemet, 2009), solar photovoltaic (Johnstone et al., 2010), as well as sulfur dioxide abatement (Taylor et al., 2005). However, this argument has been challenged by other studies who find that subsidies are costly in terms of the ultimate gains from the development of new technology, and may crowd-out private R&D investment (Marino et al., 2016). The empirical evidence as to whether manufacturer subsidies are effective is still controversial.

Similar to consumer subsidies, specific types of manufacturer subsidies influence the implementation effects. Between the selective subsidies assigned after competitive procedure and automatic subsidies granted without any system of assessment, Colombo et al. (2011) show that selective R&D subsidies have a positive impact on the productivity of a sample of high-tech Italian recipient firms whereas automatic incentives do not. Moreover, these arguments have been further tested by the analysis of Alt et al. (2010). They conducted case studies on tax incentives, suggesting that automatic incentives may induce opportunistic behavior on firms that are not actually able to carry out proper

research programs and make effective use of the subsidies.

In the EV industry, significant fiscal revenues as public subsidies have been invested in EV R&D and production. For instance, the plan of the next generation electric vehicle in U.S. commits to fund \$1.5 billion to manufacturers to produce high efficiency batteries and their components (Zhang et al., 2014). The empirical evidence of the effects of manufacturer subsidies on the development of the EV industry is limited due to a lack of data. According to Wang et al. (2014), manufacturer subsidies are expected to fulfill protective and incentive functions. On the one hand, subsidy funds provided by governments could temporarily protect uncompetitive EV firms from bankruptcy and support the development of new entrants. On the other hand, manufacturer subsidy provides EV incumbents additional funds to speed up the R&D progress and expand production scale, thus improving the quality and production efficiency of new products. The market share of EV firms can be expanded.

2.3. Evaluation of subsidy research

There has been much work conducted on the effects of consumer subsidies and manufacturer subsidies respectively, and it is well recognized that both types of subsidies play an important role in shaping the dynamics of innovation (e.g., Horbach et al., 2012), which is particularly significant in the EV industry. Nevertheless, due to the difficulties in ranking different subsidy instruments, the comparison between the effects of consumer subsidies and manufacturer subsidies has not been systematically investigated.

Alternatively, only relatively limited number of studies are devoted to evaluating the differentiated effects of other demand-pull and technology-push policies. For instance, Peters et al. (2012) conducted a panel analysis to explore the innovation effects of domestic and foreign demand-pull (photovoltaic capabilities) and technology-push (public R & D funding) policies on solar photovoltaic modules, concluding that both domestic demand-pull policies and technology-push trigger innovative output in a country, whereas demand-pull policies create significant country-level innovation spillovers. Costantini et al. (2015) explore the differentiated impacts of demand-pull (environmental regulation) and technology-push policies (technological capabilities) in the biofuel sector, suggesting that technology exploitation activities of mature technologies are found to be mainly driven by demand-pull policies, while innovation in less mature technologies is spurred by both demand-pull and technology-push policies.

Confirming the existence of differential effects between policies, the related studies have stressed the importance of a balance between demand-pull and technology-push measures within the policy mix, especially in emerging industries with advanced-generation technologies that compete with conventional products. The support schemes for emerging industries should explicitly take into account policies targeted at both consumers and manufacturers to promote technology diffusion and innovation activities. Otherwise, the policy mix may impose high costs on the entire community without achieving the expected positive impacts in terms of new technology development and social benefits (Frondel et al., 2010). Therefore, it is of great value and necessity to figure out the effects of each subsidy type and make a comparison, so as to explore and design an optimal targeted public subsidy.

3. Methodology

In this section, we construct a simulation model embedded with a multi-agent environment to simulate the diffusion of EVs under different subsidy scenarios. Fig. 1 introduces the model framework and demonstrates how the model works on a step-wise yearly basis in a programming software like MATLAB. Firstly, the simulation starts with initial configurations that populate a “market” with a set of consumer agents and manufacturer agents. We randomize the income of consumers and the capitals of manufacturers in the first period, so that

their characteristics could be heterogeneous and varied in each replication. Then, simulation proceeds with agents interacting according to the rules we specified in following sub-sections, including how consumers make purchase and how firms make decisions regarding entry and exit, production and sales, R&D activities. After the calculation of market share of EVs, time automatically increases by one year step. If the pre-fixed number of periods is not reached, update agent attributes and repeat above procedures; otherwise, terminate the process, as highlighted in Fig. 1. Finally, results in each period will be recorded and averaged after many times of iteration, which will be reported and discussed in Section 4. Following, we will present the decisions of consumers and firms in more details.

3.1. Model

Before discussing the model in further details, some technological attributes of vehicles are introduced at the first place to facilitate the understanding of the following contents.

According to current research on consumer preferences for vehicles (e.g. Peters and Dütschke, 2014), the evaluation of driving performance, sales price, and post-adoption expenditure are decisive factors in consumers' decisions, which are determined respectively by driving range ($range_m$, measured in miles), production cost ($cost_m$, measured in USD) and energy consumption efficiency (eff_m , measured as miles per gallon for CVs and miles per kWh for EVs). m is used to differentiate two kinds of vehicles. It equals 0 for CVs, and equals 1 for EVs.

During the process of technological development, the production costs of vehicles are expected to decrease through firms' process innovation, while the energy consumption efficiency and driving range of vehicles are inclined to increase through product innovation at firm level, until reaching the technology frontier of each attribute. More precisely, the value of $cost_m$ will decrease with the process innovation until to the minimum level, defined as $Fcost_m$, while the values of eff_m and $range_m$ can be increased with the product innovation until to the maximum level, defined as $Feff_m$ and $Frange_m$ respectively.

According to the technological performance of EVs and CVs, the production cost of EVs is assumed to be higher than that of CVs in the long run, whereas the driving range and energy consumption efficiency are in the opposite. Thus, the technology frontiers of the two kinds of vehicles are described in Fig. 2.

In Fig. 1, the X, Y, and Z-axis stand for the driving range, production cost and energy consumption efficiency (transferred to cost of energy consumption per mile for the comparison) respectively. The value of each attribute increases along the corresponding axes. EV firms are capable to produce an automobile with an attribute portfolio in the rectangular solid OL1'SL2'FX3'DE, and at the E point the new technology has realized its full potential. Similarly, CV firms are able to produce an automobile with an attribute portfolio in the rectangular solid OL1NL2QX3MP, and the P point represents the most perfect conventional vehicle. For each firm, its accumulated R&D expenditure decides the value of the driving range, production cost and energy consumption efficiency, meanwhile a different adopted technology determines the extremes of these three attributes.

3.1.1. The purchase decisions of consumers

In our model, consumers are designed with two important characteristics: heterogeneous preference and bounded rationality. To describe the heterogeneous preferences of consumers, the purchase budgets and driving miles are assumed to be different between two individuals. According to Lieven et al. (2011), consumers with higher purchase budgets and lower annual mileages are more likely to be EV purchasers. With respect to the bounded rationality, consumers are assumed to choose a vehicle randomly, from a top ten satisfactory list for instance, rather than in line with the principle of maximum utility, due to the existence of search cost and information asymmetry.

Eq. (1) presents the utility calculation method for each consumer,

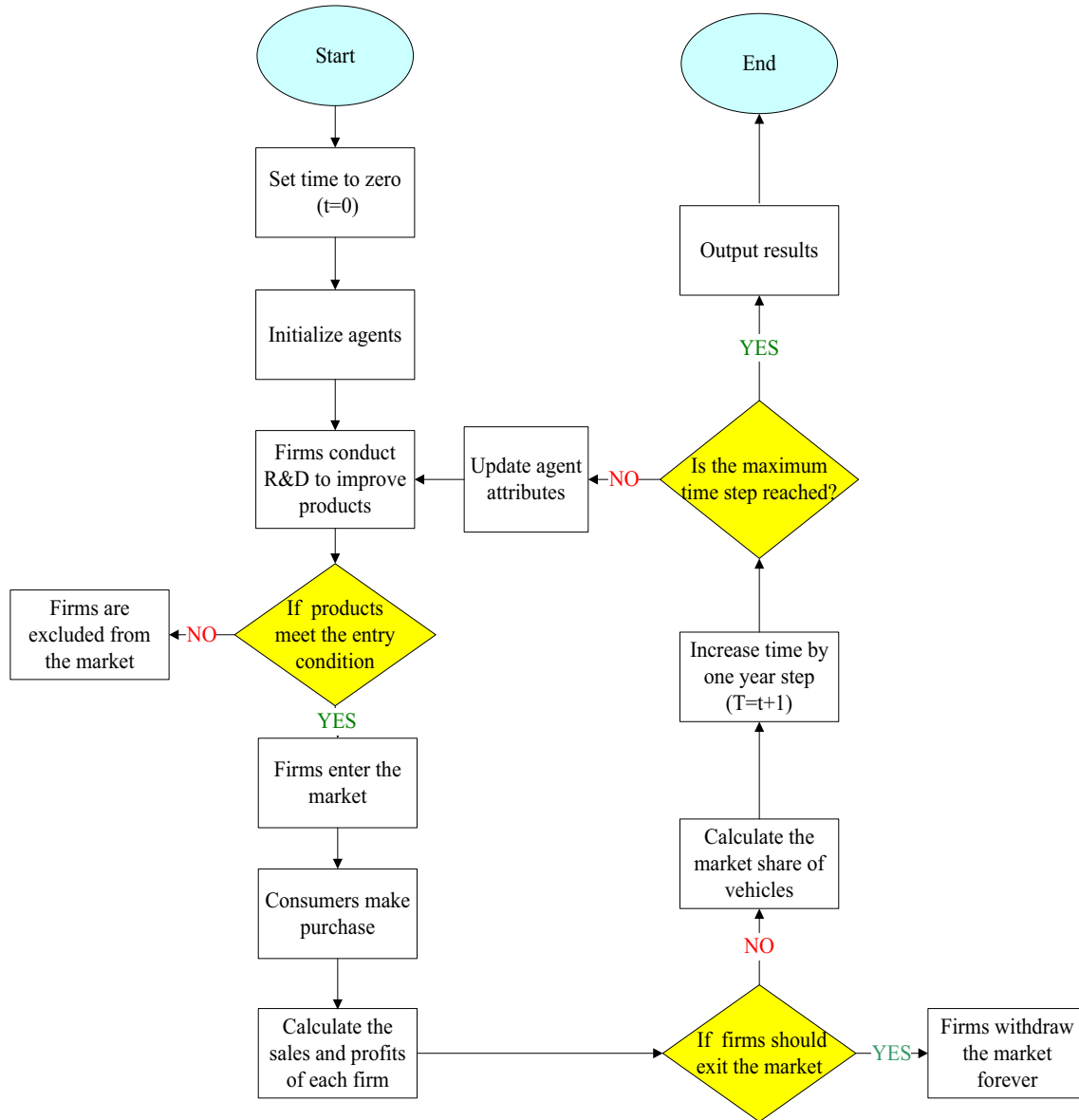


Fig. 1. The flow chart of simulation model.

where i denotes the consumer, and j denotes the vehicle. The utility of purchasing a product $U_{i,j}$ is defined as the remainder that consumer's willingness to pay for a vehicle (WTP) minus the product's total cost of ownership (TCO) referring to existing literature:

$$U_{i,j} = WTP_{i,j} - TCO_{i,j} \quad (1)$$

Consumers' willingness to pay for a vehicle (WTP) is correlated to its driving performance, which is mainly determined by the driving range in our assumption, irrespective of other factors like safety for the sake of model simplification. The value for WTP is positively correlated with the part that the vehicle range surpass the market' minimum requirement $Minrange$, as expressed in Eq. (2), where ω_m and α_m respectively represents consumers' WTP for vehicles with $Minrange$ and a mile of added driving range beyond $Minrange$.

$$WTP_{i,j} = \alpha_m \times (range_j - Minrange_m) + \omega_m \quad (2)$$

The total costs of ownership for a vehicle in a given holding period (TCO) contains three terms: the purchase cost, annual discounted energy expenditure and negative present value of vehicle resale revenue, as shown in Eq. (3), where pc and ec respectively denote the vehicle's

purchase cost and annual energy cost, while $resale$ represents the vehicle's future resale revenue. $A(\rho_0, year)$ is the annuity factor, where ρ_0 is the risk-free interest rate, and $year$ measures the holding period of vehicles.

$$TCO_{i,j} = pc_j + ec_{i,j} \times A(\rho_0, year) - \frac{resale_j}{(1 + \rho_0)^{year}} \quad (3)$$

Purchase cost of vehicles (pc) is simply calculated as the subtraction of consumer subsidy ($subc$) from sales price ($price$), where the subsidy remains zero for CVs throughout all simulation periods. Only products with price lower than the purchase budget are available for consumers to choose.

$$pc_j = price_j - subc_j \quad (4)$$

Annual energy cost, which represents the annual expenditure for vehicles refueling (CVs) or charging (EVs), is calculated in Eq. (5), where VMT represents the annual vehicle miles traveled of consumers, eff represents energy consumption efficiency of vehicles, and pe_m represents the unit price of gasoline or electricity respectively when m equals 1 or 2.

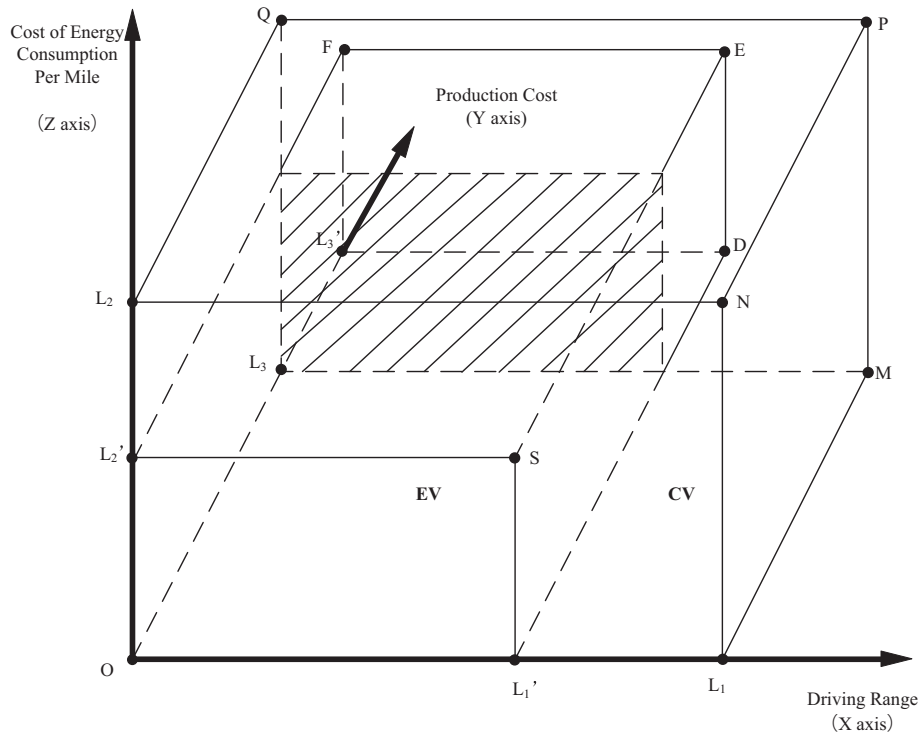


Fig. 2. The technology frontiers of CV and EV.

$$ec_{i,j} = VMT_i \times eff_j \times pe_m \quad (5)$$

Referring to Dexheimer (2003), the future resale revenue of a vehicle (*resale*) is derived as Eq. (6) shows, which considers the vehicle's holding period, depreciation factor (d_m), and sales price.

$$resale_j = (1 - d_m \times year) \times price_j \quad (6)$$

3.1.2. The decisions of firms

It is assumed that there are only two kinds of firms competing in the automobile market. N_{CV} represents the number of CV firms as incumbents, and N_{EV} represents the number of EV firms as potential entrants. Uniform technology frontiers are established within the same type of firms, whereas heterogeneous products result from firms' differentiated R&D efforts. Building on these assumptions, firms' decisions on entry and exit, R&D investment and production investment are further illustrated below.

(1) Decisions on entry and exit

For all start-up EV firms, the driving range and price competitiveness of vehicles are close to zero in the first phase, which can be continuously improved through R&D efforts. When a product meets the following two entry requirements at the same time, it can be allowed to enter the market. First, the vehicle driving range exceeds the minimum requirement of consumers. Second, the product price is lower than the maximum purchasing budget of potential purchasers.

With respect to market incumbents, each firm offers prices based on the mark-up rule. The mark-up is measured as μ_j , thus the relation between a vehicle's sale price (*price*) and production cost (*cost*) can be expressed as:

$$price_j = cost_j \times (1 + \mu_j) \quad (7)$$

where the mark-up is determined as 0.5 multiplied by the ratio of vehicle's driving range to the current maximum level within the similar products as Eq. (8) shows.

$$\mu_j = range_j / \text{Max}(range_j) \times 0.5 \quad (8)$$

Besides, the sales volume of each firm (Q) is assumed to be the sum of all consumers' orders. However, it is worth noting that the actual sales volume may fall short of the order quantity, due to the limitation of production capacity (Q_{max}), which is positively proportional to the capital size of firms (K), denoted as $Q_{max} = \lambda K$.

Given that the interest cost (R) is exclusively incorporated in the administrative expense, a company's sales revenue (Rev), net profit (π) and profit margin (r) can be easily forecast.

In the process of market selection, competitive firms survive and develop while the uncompetitive ones are eliminated. Additionally, if a firm meets any one of the following three situations, it is likely to exit the market and be incapable of reentrance ever again: (a) The capital is below the minimum required level//; (b) the profit margin is negative and the time for firms operating at a loss surpasses the maximum requirement. This assumption ensures that one firm could survive for some time even though in face of a deficit; (c) the profit margin is negative and the asset-liability ratio exceeds a certain proportion. The firm will consequently go bankrupt in this situation.

(2) Decisions on R&D activities

R&D activity is the key factor for firms to improve their competitiveness and profitability. Extensive empirical studies have found evidence of a significant decrease in firms' R&D investments before and after they enter the market. Consequently, we make the following assumptions: given the R&D intensity denoted as ϕ , for those unprofitable potential entrants and new incumbents, R&D expenditure is predicted to be derived from the firm's original capital, expressed as $RD_t = \phi K_t$, while profitable incumbents foster R&D funds from their sales revenue in order to ensure the production capacity unaffected; thus $RD_{t+1} = \phi Re v_t$.

As technology innovation consists of process innovation and product innovation, the R&D expenditure of firms also contains process innovation expenditure RD^{pc} and product innovation expenditure RD^{pd} , of which the former aims to decrease the product's cost while the latter

Table 1
Data of consumers in 2010.

Parameter	Unit	Value	Reference
The number of consumers	Millions	10	U.S. Bureau of Economic Analysis, 2010b
Annual household income	USD	Normally distributed N(74,800,27,300)	Helveston et al., 2015
Vehicle miles traveled	Miles	Normally distributed N(11,836,6377)	Helveston et al., 2015
Vehicle holding period	Years	6	Wu et al., 2015

intends to improve the product's performance.

$$\begin{cases} RD_j^{pc} = q_j RD_j \\ RD_j^{pd} = (1 - q_j) RD_j \end{cases} \quad (9)$$

The coefficient q is randomly assigned with value from $[0, 1]$, the value of which is fixable in the following two situations: first, the driving range meets the threshold of market entry, while the attribute of price fails. To promote products into the market as soon as possible, firms will focus on process innovation to lower the production cost. In this circumstance, the coefficient $q = 1$. Second, on the contrary, the attribute of price meets the minimum requirement of customers, while the range performance fails. Firms will put all the efforts in product innovation to increase driving range. Thus, the coefficient $q = 0$.

In each period, referring to [Malerba et al. \(1999\)](#), the reduction in the production cost and the improvement in the energy consumption efficiency are:

$$\Delta cost_j = a_0 RD_j^{pc} (1 - F \cos t_m / \cos t_j) \quad (10)$$

$$\Delta eff_j = b_0 RD_j^{pd} (1 - eff_j / Feff_m) \quad (11)$$

According to the law of diminishing marginal returns, $(1 - F \cos t_m / \cos t_j)$ and $(1 - eff_j / Feff_m)$ are added, which means when an attribute gets closer to the technology frontier, the rate of technical progress decreases gradually. Based on the variation of $cost$ and eff , we can calculate their new values in the next period.

(3) Decisions on production investment

If the total number of consumers' orders in the current period reaches the maximum production capacity, the firm will seek a capital infusion and expand its scale of production, such as purchasing new equipment and installing another production line. The scale of capital expansion is assumed to be at a given percentage (μ_2) of the current capital. Therefore, the production investment (I) is:

$$I_{j,t+1} = \begin{cases} 0 & (Q_{j,max,t} > Q_{j,t}) \\ \mu_2 K_{j,t} (Q_{j,max,t} - Q_{j,t}) & (Q_{j,max,t} < Q_{j,t}) \end{cases} \quad (12)$$

If there is no manufacturer subsidy granted by governments, the new capital inflow is supposed to be totally supported by bank credit. Otherwise, the added debt (D^B) indicates the part that the production investment exceeds the manufacturer subsidy ($subf$). It is worth noting that the added debt can be negative when the amount of production investment is zero, which implies manufacturer subsidy has been totally transferred as the increase in firms' capital.

$$D_{j,t}^B = I_{j,t} - subf_{j,t} \quad (13)$$

Provided that a firm makes a profit in t period, a certain percentage (σ) of the net profits is assumed to be the repayment of the debt D . The remainder is added to the firm's current capital. If $\sigma\pi_t$ exceeds the current debt D , it is expected that all debt will be paid off, otherwise debt will be remain. Therefore, the debt payment for each period D^R is related to current total debt and profits earned, as Eq. (14) shows.

$$D_{j,t}^R = \begin{cases} \sigma\pi_{j,t} (D_{j,t} > \sigma\pi_{j,t}) \\ D_{j,t} (D_{j,t} < \sigma\pi_{j,t}) \end{cases} \quad (14)$$

Assuming the capital depreciation rate is ρ_2 , after the remaining profit added to the gross capital, the new value for firm capital is:

$$K_t = (1 - \rho_2) K_{t-1} + I_{j,t} + \pi_t - RD_t - D_t^R \quad (15)$$

Then, the gross debt in $(t + 1)$ period is renewed:

$$D_{t+1} = D_t - D_t^R + D_{t+1}^B \quad (16)$$

3.2. Data source of parameters

We simulate the dynamics of the EV industry in the U.S. over 40 years from 2010 to 2050. The base values for our parameter settings refer to the U.S. auto market data in 2010, drawn from a variety of sources including: data published by government departments, findings of the existing literature, and reality-based assumptions. With regard to the reality-based assumptions for parameter settings, a robustness test will be conducted for the exclusion of ad hoc parameter condition (Listed in [Appendix A](#)).

3.2.1. Consumer data

For the number and annual household income of potential consumers, as well as their annual holding period and driving distance of vehicles in 2010, we mainly referred to the data collected from the U.S. Bureau of Economic Analysis and Ford Motor Company ([Helveston et al., 2015](#)), which are summarized in [Table 1](#). Based on the parameter setting for the first period, we further assume that the annual household income of consumers increases at an annual growth rate of 2% ([U.S. Bureau of Economic Analysis, 2010a](#)), while the other parameters remain constant over time. Moreover, a level of 60% of the household income is postulated as the car purchase budget, making a reference to the average expenditure of U.S. residents on vehicles ([U.S. Bureau of Economic Analysis, 2010a](#)).

Concerned with the consumers' willingness to pay for vehicles (WTP), [Hidrué et al. \(2011\)](#) conducted a consumer survey in the U.S. and concluded that the average compensation for a CV supporter to adopt an EV with the driving range of 75 miles was \$22,006, thus $Minrange$ and ω_m for both kinds of vehicles are 75 miles and \$22,006 respectively. Moreover, [Hidrué et al. \(2011\)](#) stated that the individuals' wtp for an added mile varied from \$35 to \$75, decreasing with the longer driving distances. As the driving range of CVs surpasses that of EVs to a large extent, wtp for EVs should be higher than that for CVs, which are respectively assumed as \$50 per mile and \$35 per mile.

3.2.2. Vehicle data

The driving range, production cost and energy consumption efficiency are the three most important technological attributes of vehicles. Regarding the driving range of a vehicle, it depends on two factors: the energy capacity and the energy efficiency. We can use the tank capacity and battery size to respectively utilize the energy capacity of CVs and EVs, denoted as $size_m$. The driving range then can be calculated as $range_m = size_m \times eff_m$.

During the simulation period, we assume that the $size_m$ remains constant over time, whereas the energy efficiency can be continuously improved by firm's R&D efforts in product innovation. Referring to the U.S. CAFE standards on the fuel economy of CVs by the year of 2025 ([Knittel, 2012](#)), we suppose the maximum level of fuel efficiency ($Feff_j$)

Table 2

Data of vehicles in 2010.

	Parameter	Unit	Value	Reference
CV	Tank capacity	Gallons	15	Arsalan et al., 2014; Jo et al., 2016
	Energy efficiency	mpg	22	Knittel, 2012
	Maximum energy efficiency	mpg	54.5	Knittel, 2012
	Maximum driving range	Miles	817.5	Calculation
	Engine cost	USD	2357	Orbach and Fruchter, 2011
	Components cost	USD	8465	Orbach and Fruchter, 2011
	Minimum engine cost	USD	1000	Assumption
	Lifespan	Years	15	Kanari et al., 2003; Aguirre et al., 2012;
	Depreciate rate		6.7%	Calculation
	Gasoline price	USD per gallon	2.7424	U.S. Energy Information Administration, 2012
EV	Battery size	kWh	40	Howell, 2012; Jo et al., 2016
	Energy efficiency	Miles per kWh	0	Assumption
	Maximum energy efficiency	Miles per kWh	15	The performance of Tesla products
	Maximum driving range	miles	600	Calculation
	Battery cost	USD	40,000	Gerssen-Gondelach and Faaij, 2012
	Components cost	USD	9193	Orbach and Fruchter, 2011
	Minimum engine cost	USD	4000	Gerssen-Gondelach and Faaij, 2012
	Lifespan	Years	8	Howell, 2012; Wu et al., 2015
	Depreciate rate		12.5%	Calculation
	Electricity price	USD per kWh	0.1154	U.S. Energy Information Administration, 2012

in the near future is 54.5 miles per gallon (mpg). Meanwhile, based on the performance of Tesla products, the maximum energy efficiency of EVs is assumed to be 15 miles per kWh. Thereby, the maximum driving range of vehicles could be calculated.

With regard to the production cost of vehicles, it is the sum of two parts: cost of power system (*cop*) and cost of other components (*coc*). It is assumed that the cost of power system could be reduced through process innovation while the cost of other components remains constant over time. Due to the lack of reliable data, a conservative estimate of minimum cost of engine is given as \$1000. Meanwhile, referring to the technical target for EVs as being competitive to diesel cars (Gerssen-Gondelach and Faaij, 2012), the minimum battery cost in future is expected to be \$4000. Consequently, the minimum production cost of vehicles could be calculated. The other parameter settings are summarized and presented in Table 2.

3.2.3. Firm data

With reference to the number of vehicle brands worldwide in 2010, 150 conventional firms are assumed as incumbents and 30 EV firms as potential new entrants in the first period. The original capitals of these two kinds of firms are evenly distributed in the interval between 1 billion and 10 billion dollars based on the data pertaining to the listed car companies in NASDAQ. Each firm produces only one type of automotive product.

Due to the differentiation of technology frontiers between EVs and CVs, the improvement of technological attributes through the R&D efforts are not identical. According to Baker et al. (2010), one million dollars in R&D investment results in about \$0.90 reduction in unit battery cost, which implies a \$3.60 decrease of cost in 40 kWh batteries. By virtue of the fixed components costs, a_0 in Eq. (10) that determines the variation in production cost of EVs is 3.6, which works on CVs as well. To the variation in energy consumption efficiency, it is hypothesized that one additional million dollars in R&D investment results in an improvement of about 0.1%. Thus, the parameter b_0 for EVs and CVs are 0.0545 and 0.015, respectively. Other parameter settings for management and production of a firm are summarized in Table 3.

4. Results and discussions

To compare the impact of consumer subsidies and manufacturer subsidies on industry dynamics, we construct three divergent scenarios by taking different intensity and duration of subsidies into consideration.

The first scenario presumes there is no public support and external shock in the auto market, whose simulation results serve as the benchmark to estimate the effect of public subsidies (business-as-usual scenario).

The second scenario introduces a price-based subsidy for EV consumers and supposes three subsidy combinations for the simulation: \$7500 per vehicle for the first 5 years, \$15,000 dollars per vehicle for the first 5 years and \$7500 dollars per vehicle for the first 10 years, based on the maximum fiscal incentive a purchaser of qualified EV could obtain from the U.S. federal and state (Zhang et al., 2014).

The third scenario presents a direct grant for EV manufacturers. Comparatively, the intensity and validity duration stay the same, whereas the subsidy for manufacturers centers on the supply side, rather than the demand side.

4.1. Simulations of business-as-usual scenario

Based on the business-as-usual scenario, the evolutionary dynamics of the EV industry are simulated over 100 distinctly different runs over the period 2010–2050, and the average results of firm R&D investment and technical development are displayed in Fig. 3. Accordingly, the horizontal axis stands for time, and the vertical axis represents the firms' expenditure on process innovation, production innovation, the vehicles' price and driving range, respectively. In order to further display the development process of EV industry along with the technical development, we present some essential features of the incumbent's quantity, average profit margin, market share and Herfindahl index¹ in Fig. 4.

From Fig. 3, it can be seen that in the early stage of industrial development, product and process innovation of EV firms increase sharply to meet the entry threshold of market and, consequently, both the price advantage and driving range of the two kinds of vehicles achieve great improvements, thus the number of EV incumbent firms increases rapidly in the first 5 years (see Fig. 4). However, as internal funds occupied by production and operation after firms enter the market, a large proportion of R&D expenditure are not capable of being maintained as usual. Hence, the product and process innovation of EV firms are lowered to a great extent. As a result, the rate of EV technological progress tends to be decreased.

¹ Herfindahl index is a measure of market concentration, which equals to the quadratic sum of all firms' market share. The higher the index is, the more concentrated the market.

Table 3
Data of firms in 2010.

Parameter	Meaning	Value	Reference
φ	The R&D intensity	5%	Jaruzelski and Dehoff, 2008
λ	The production capacity of one unit of capital	0.01	Assumption
σ	The percentage of profits for repayment	0.15	Malerba et al., 2007
μ_2	The expansion rate of production capacity	0.1	Assumptions
ρ_0	The risk-free interest rate	0.32%	Federal Reserve Board, 2010
ρ_1	The interest rate for bank credits	3.43%	Federal Reserve Board, 2010
ρ_2	The depreciation rate of capital	0.1	Assumption

Due to the inferiority of EVs in aspect of vehicle attributes, customer preferences are locked in the conventional vehicles for a long time and none of the EV manufacturers makes a profit. Continuous unprofitability exerts great pressures on the start-ups, and some are forced to exit the market. The situation is not reversed until some early adopters emerge in 2020, bringing the increase in the sales and profits of EV manufacturers afterwards. As the number of early adopters increase to a certain scale, the market share of EVs starts to expand at a faster growth rate. By 2050, the automobile market is composed of 140 CV firms and 20 EV firms, with a market share of 70.04% and 28.96% respectively.

The simulation results indicate that after a long period of development, EV manufacturers can obtain a certain level of market share as later comers even without government support. The S-shape market share is in accordance with the innovation diffusion theory of Rogers (2003). Nevertheless, the low growth of accumulated profits in the early stage is unable to provide sufficient financing for R&D activities, which play an important role in technological development. In consequence, unfortunately, EVs fail to outperform and break the dominance of CVs by 2050.

4.2. Simulations of subsidy scenario

In this section, the evolutionary dynamics of automobile industry

are simulated by the incentives of consumer and manufacturer subsidies, respectively. To avoid meaningless repeated expression, only the results of the incumbent's expenditure on process innovation and product innovation, market share, and profitability are reported in comparison with those in the business-as-usual scenario.

4.2.1. The consumer subsidy policy

The effects of a consumer subsidy with three subsidy schemes on the EV industry are compared in Fig. 5. As discussed before, by virtue of the inferiority of EVs in vehicle attributes, it is difficult for EV manufacturers to snatch market share from the early incumbents when entering the market. However, with the help of consumer subsidies, the appeal of electric vehicles could be enhanced artificially and encourages reluctant consumers to be early adopters, which has been proved many times in related consumer surveys (e.g. Kwon et al., 2018). In our simulation, an expansion of market share is anticipated in the period of subsidy validity, along with an acceleration in the diffusion of EV technology. Although the market share immediately declines with the removal of consumer subsidy, EV sales gradually return to growth over several periods, providing supports to the positive incentivizing effect of consumer subsidy.

Moreover, compared to results with no subsidies, both the market share and profitability of EV firms outperform in the long term, which

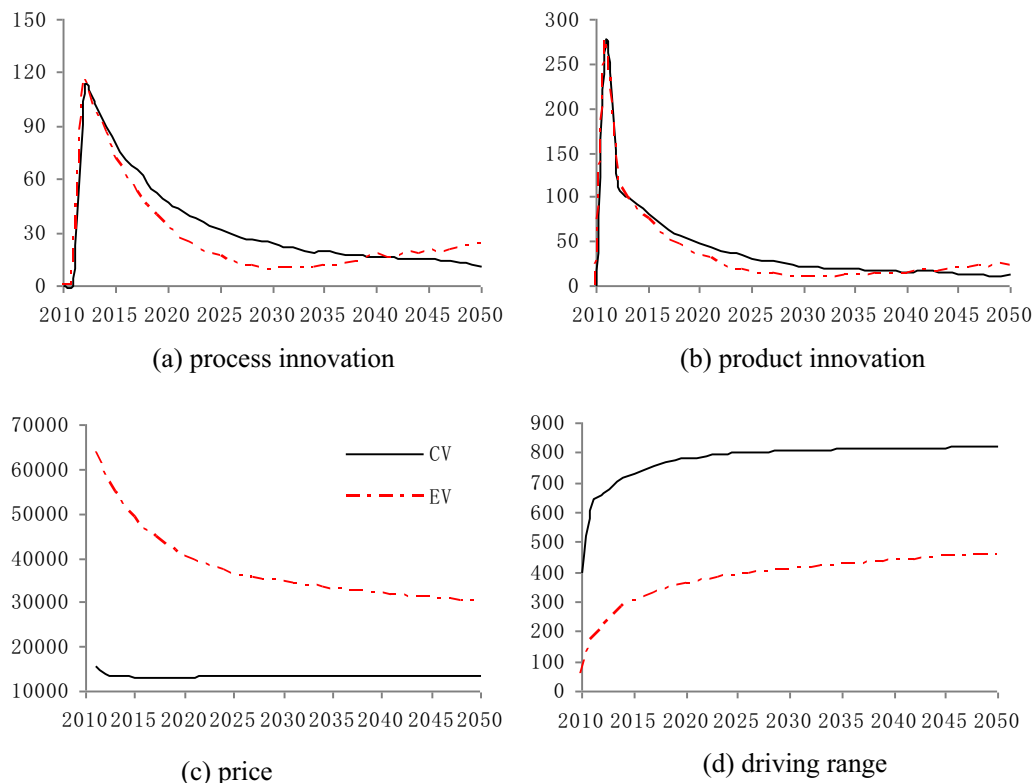


Fig. 3. R&D investment and its effect.

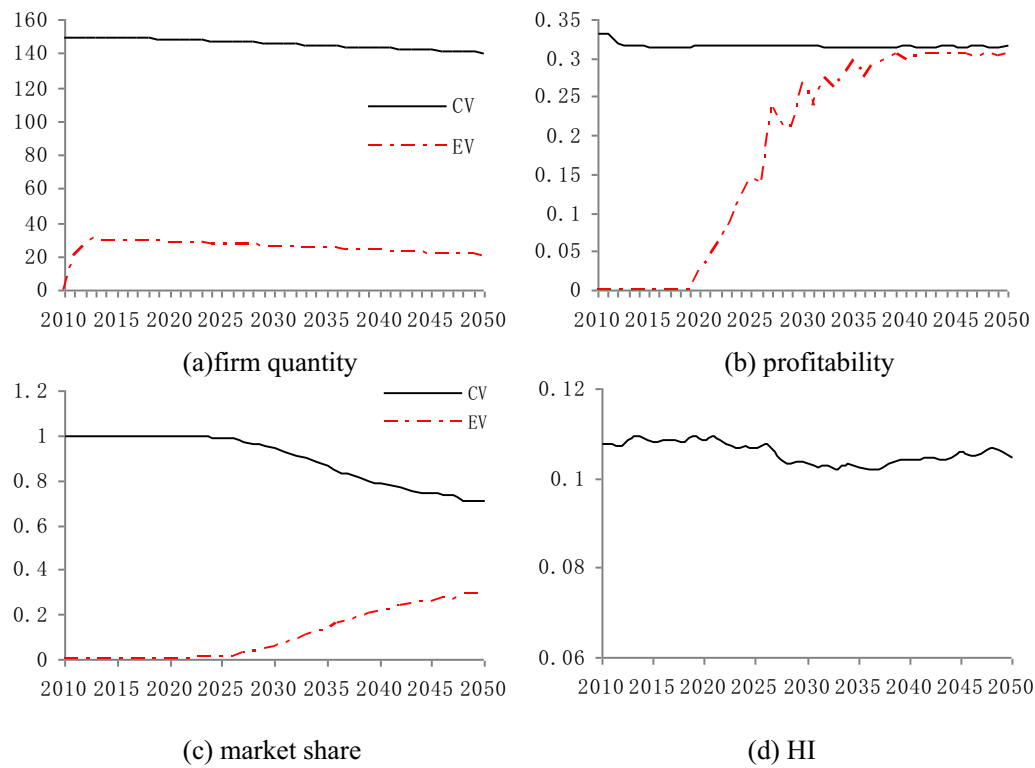


Fig. 4. The evolution of the automobile industry.

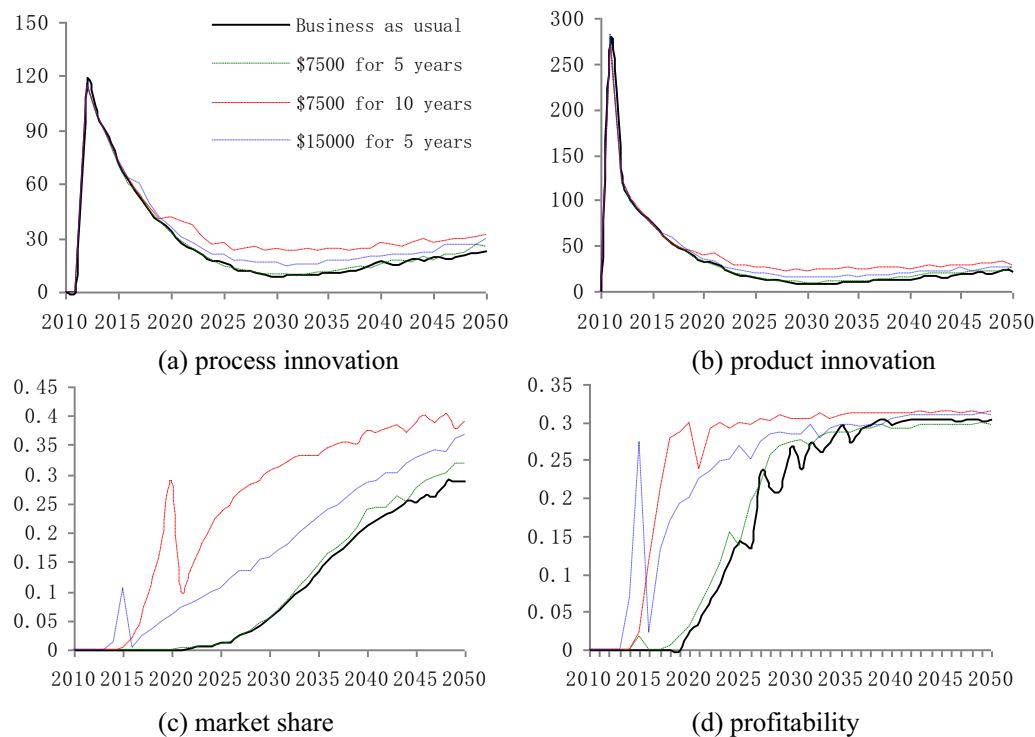


Fig. 5. Simulations under the consumer subsidy scenario.

eliminates the concern that the effect of consumer subsidy may only be temporary. The results are somehow different from [Shepherd et al. \(2012\)](#), in which it states although the impact of subsidies is significant in terms of extra EV sales in the short term, subsidies have little long term impact on share of the fleet. However, this conclusion is reached at a scenario where the operating costs per mile of EVs remain constant

over time while the improvements in EV performance or range are treated as a sensitivity test. In this paper, we assume firms' innovation activities are endogenous to industrial evolution, and the high level of sales revenue accumulated in the subsidy duration would induce firms increase both the investments in product innovation and process innovation, which leads to the further enhancement of vehicle

competitiveness. Furthermore, through consumers' selection, advantageous products show more promise for subsidization, thus competitive EV manufacturers who can develop well without subsidies are capable of more R&D efforts funded from profits, tipping the market into a successful trajectory.

Consumer subsidy looks to be effective in both the short and long term, and the varying effect across intensity and validity duration is further explained. To begin with, the impact is not positive when the consumer subsidy scheme is \$7500 per vehicle for the first 5 years. The market share of EVs over 40 years is only 2.92% higher than that of business-as-usual scenario with a total amount of \$90 million expenditure. In this respect, the effects on EV firms are limited and costly. In contrast, when the consumer subsidy is increased to \$15,000 per vehicle for the first 5 years, an obvious improvement of 6% on market shares is obtained by EV firms in 2050, which indicates that if consumer subsidies were applied too early before the EV technology is fully competitive, subsidy intensity is required to be high enough for the successful adoption of electric vehicles. Similar conclusions have been drawn by [Driscoll et al. \(2013\)](#).

Meanwhile, if the validity duration of subsidy is prolonged from 5 years to 10 years with \$7500 per vehicle, the effect is the most significant among the three schemes. Specifically, the market share of EVs over 40 years is 10% higher than that in the business-as-usual scenario, stressing the significant role that long duration played for the boom of EVs. Our results are consistent with the finding of [Struben and Sterman \(2008\)](#) that consumer subsidies for alternatives must remain in place for long periods for diffusion to become self-sustaining. Moreover, in accordance with the study of [Noori and Tatari \(2016\)](#) which focuses on the market penetration of electric vehicles in the United States, if the government is destined to reach the target of a 20% EV market share by 2030, subsidies lasting for a period of at least ten years are mandated.

In summary, compared to the business-as-usual scenario, which shows great difficulty for EV firms to develop in the first 10 years after entering the market, consumer subsidy is proved to be effective in our study for promoting the EV diffusion and technology development. Higher intensity in the first 5 years brings the emergence of EV adoptions in advance, while prolonging the duration from 5 years to 10 years can result in more additional sales revenue, which leads to profit-R&D accumulation in turn. In this way, the disadvantages of product cost and performance that are significant concerns for consumers, such as high price and low driving range, are hopeful to be overcome. If EV firms can keep increasing their advantages, there is a possibility for EV firms to dominate the market.

4.2.2. The manufacturer subsidy policy

To compare the effects of consumer subsidy and manufacturer subsidy on the same basis, the intensity of manufacturer subsidy is deduced from the total government expenditure in consumer subsidies while the subsidy duration remains the same. As most of the firms in an emerging industry are start-ups that lack information disclosure, the evaluation of the potential outcome of a specific project might be particularly difficult to assess for public agencies. Therefore, referring to the practical experience in policy making, subsidies are set available for all EV firms with production qualification. In line with the above method using proportional allocation, the three schemes of equivalent manufacturer subsidy are to subsidize each EV firm 0.6 million dollars for the first 5 years, 171.1 million dollars for the first 10 years, and 106 million dollars for the first 5 years. After 100 distinctly different simulations, the results pertaining to the process innovation, product innovation, market share and average profit margin of EV firms are shown in [Fig. 6](#).

In the business-as-usual scenario, EV firms as new entrants are short of capital for sustainable R&D investment, and thereby fail to be competitive in the short time. To solve this problem, manufacturer subsidies are granted to all EV firms for supporting their innovation activities. The simulation results show that the average expenditure of EV firms on

both process and product innovation have not significantly increased in the period of subsidy duration compared to the business-as-usual scenario. As a result, the market share and profitability of EV firms remain unchanged. Until 2018, after a long period of accumulation in innovation, the effect of subsidy could be observed. For instance, when each EV firm is subsidized 171.1 million dollars for the first 10 years, the market share of EV firms over 40 years is 7.12% higher than those without subsidies.

From the simulations, it can be seen that the impact of manufacturer subsidy in inducing innovation is limited, and only if the subsidies are provided on a high intensity there appears to be a significant acceleration in the expansion of EV market share, which cast some doubts on the effectiveness of the commonly used policy instrument. The possible reasons for explaining the subsidy inefficiency are as follows. On the one hand, it is the difficulties of qualification judgment that prevent governments from conducting prior assessment, thus some unqualified and inefficient firms that should exit under the base scenario benefit from subsidies. Consequently, those potential manufacturers who desire public support for R&D investments the most are still short of funds, implying the allocation inefficacy of automatic schemes. On the other hand, as [Alt et al. \(2010\)](#) suggest, it is almost impossible for authorities to take effective control of the use of R&D supports. Hence, subsidies may be spent on other business activities not directly related to research.

Overall, as manufacturer subsidies prevent the high-tech start-ups from premature bankruptcy, they are good policies in maintaining the scale and stability of industry, in line with the conclusions of [Wang et al. \(2014\)](#). However, even though the manufacturer subsidy represents a fair allocation and do support the long-term development of new technology to some extent, it is not guaranteed that the subsidized firms are necessarily the best and most desirable for R&D supports, thus it appears not to be the most efficient. According to the comparison study of [Colombo et al. \(2011\)](#), selective schemes are likely to be more beneficial to new technology-based firms than automatic ones, which could be further tested in the future analysis of EV subsidies.

4.2.3. Comparison between differential subsidy effects

To display the differentiated effects of consumer subsidy and manufacturer subsidy more clearly and directly, the simulated results with different subsidy intensity in the first 5 years are assembled simultaneously in [Fig. 7](#). We can see that when the subsidy intensity is less generous, the effects of both kinds of subsidies on the firms' innovation activities and market performance are limited, which, however, can be improved with the increase of subsidy amount. Based on the relationship between subsidy intensity and effect, the first finding can be concluded as follows: both consumer subsidy and manufacturer subsidy have a positive effect on the technology development and diffusion, with a premise that the subsidy intensity is strong enough.

The second finding is related to the differential effects of the two types of subsidies. In view of the consumer subsidy, the market share and profitability of EV firms are believed to significantly increase. Conversely, no improvement is observed with the incentive of manufacturer subsidy until a later stage. It is suggested that consumer subsidy has an immediate and instant effect on the market adoption of new technologies, while the effect of manufacturer subsidy has a time lag. It can be easily understood, as the consumer subsidy provides a direct price reduction in products, whereas the improvement in price through R&D efforts needs a longer period of accumulation.

Finally, the finding is with regard to the subsidy effect in the long term: the consumer subsidy outperforms manufacturer subsidy in supporting the development of EVs, which can be easily found in [Fig. 7](#). As mentioned above, although consumer subsidy is available for all EV products, it has been transferred to the advantageous manufacturers as a form of increased profits in the selection of products by consumers. Meanwhile, although manufacturer subsidy is available for all EV manufacturers in the market, public funds may be occupied by some

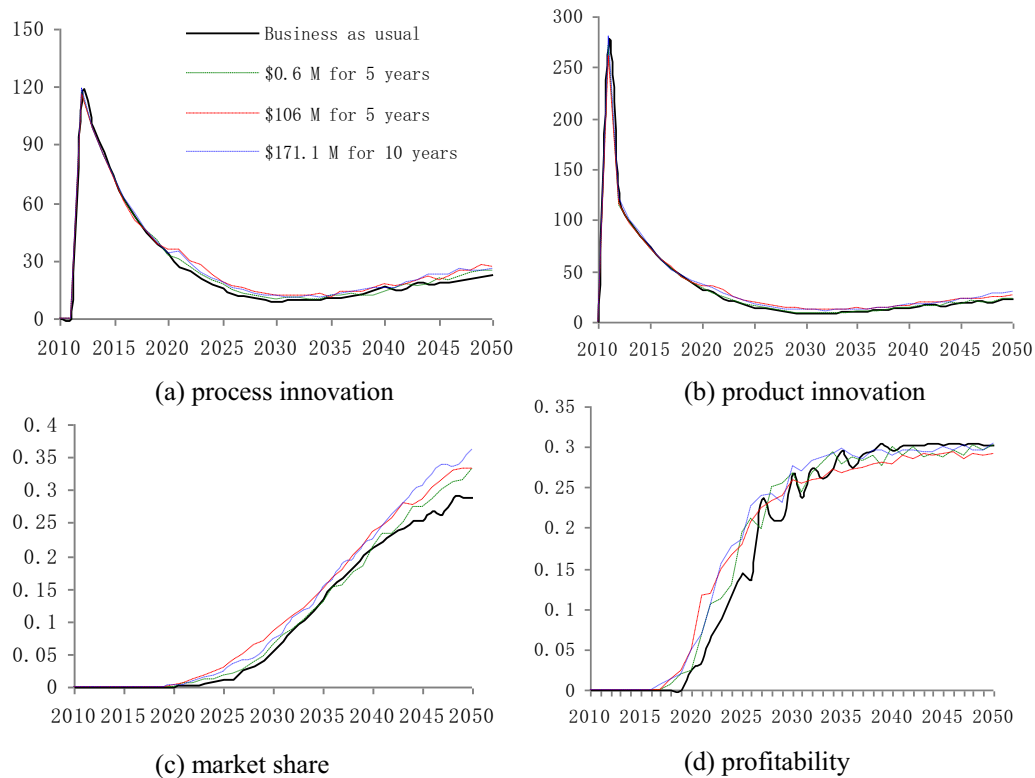


Fig. 6. Simulations under the manufacturer subsidy scenario.

inefficient recipients due to the lack of selection. Even if the manufacturer subsidy is allocated with competitive procedures based upon the assessment for potential EV firms, consumer subsidy tends to be more advantageous in reducing the public expenditure as well as

corruption associated with the selective assignment.

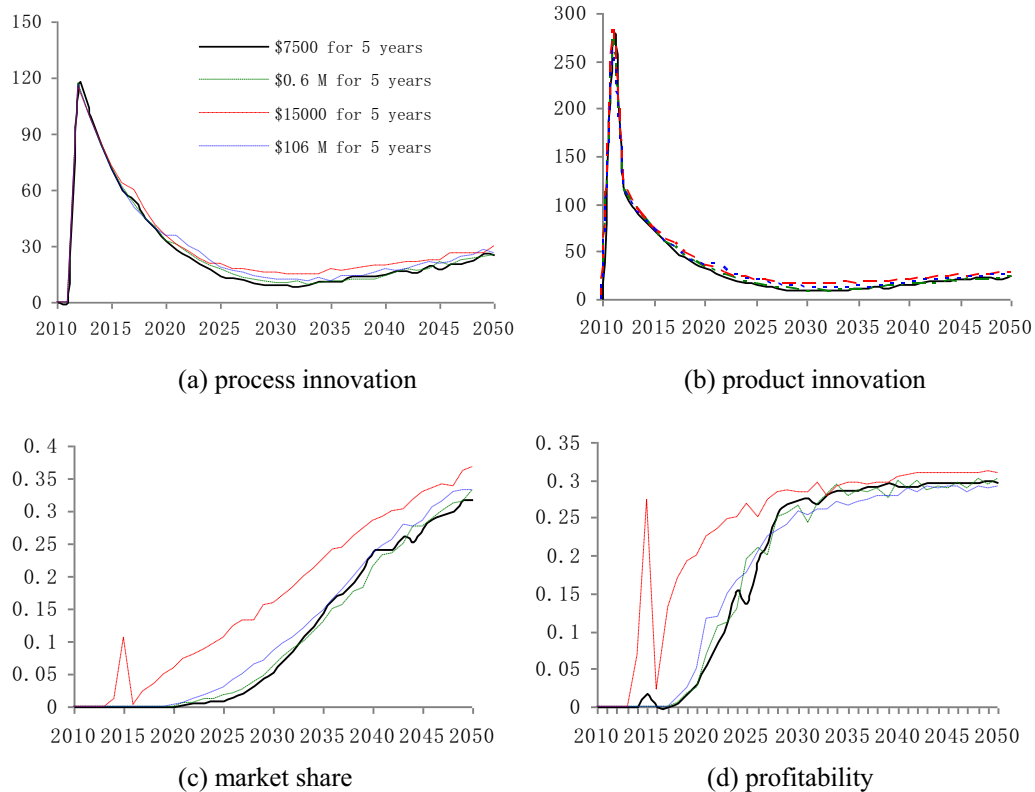


Fig. 7. Comparison between consumer subsidy and manufacturer subsidy.

5. Conclusions and implications

5.1. Conclusions

Public subsidy plays a key role in supporting the cultivation of emerging industries. A variety of empirical studies have evaluated the effects of different subsidy incentives. However, due to the difficulties in comparing policy instruments with multi-dimensional features, the differential effects between consumer subsidy and manufacturer subsidy have not been clarified.

This paper particularly explores the effects of consumer subsidies and manufacturer subsidies respectively on the development of new technology. The EV industry was chosen as a case of emerging industries, and an agent-based model was constructed considering the heterogeneous decisions of consumers and firms. The model parameters are derived from the data of U.S. auto market in 2010. The dynamics of EV diffusion over the period from 2010 to 2050 are simulated under three scenarios: business-as-usual scenario, consumer subsidy scenario and manufacturer subsidy scenario, by taking into account different subsidy intensity and validity duration. The results are concluded as follows:

First, in the business-as-usual scenario where there is no government support, it takes nearly ten years before early adopters of electric vehicles emerge after the EV firms enter the market. Nevertheless, along with the technological progress, the diffusion rate of EVs increases and sales of EVs presents an S-shape, in compliance with the theory of innovation diffusion (Rogers, 2003). Over 40 years of development, EV manufacturers can obtain a certain level of market share as late comers, such as the 28.96% by 2050 in our simulation, but unfortunately it is hard for EVs to outperform conventional vehicles, as the firms' internal funds are insufficient to finance R&D activities.

Second, in the consumer subsidy scenario, early adopters emerge early with the help of consumer subsidies, and the scale keeps increasing after the subsidy expiration, which suggests an positive and long term effect of consumer subsidies on the popularity of electric vehicles. Subsidy intensity and validity duration are important factors for subsidy effectiveness. Higher subsidy intensity advances the emergence of EV adopters, and prolonging the duration results in more EV sales.

Third, in the manufacturer subsidy scenario, even the firms' R&D investment increases with the incentive of manufacturer subsidy, the emergence of early adopters are moderate compared with the business-as-usual scenario, due to lag effects of converting R&D efforts into EV productivity. After ten years of the subsidy implementation, the market share of EVs presents a significant rise compared to the business-as-usual scenario, which implies that manufacturer subsidies affect EV diffusion with a time lag. Moreover, from the perspective of sales volume, the effects of manufacturer subsidy are not as good as consumer subsidy given the equivalent amount of subsidies.

Overall, both consumer subsidy and manufacturer subsidy have a positive effect on the development and diffusion of new technologies, when subsidy intensity is strong enough. However, consumer subsidy performs better than manufacturer subsidy in promoting the development of EV industry. The simulation results indicate the consumer subsidy induces earlier adoption of EVs in the short term and more EV

sales in the long term.

5.2. Policy implications

The conclusions of this paper provide a further explanation for the difficulties encountered in the cultivation of the EV industries, and also provide several important implications for policy makers and regulators to foster new technologies as follows.

On the one hand, some new technologies would develop well without any government support, given enough time and funds. Thus, the government could reduce administrative intervention in the development of technology. On the other hand, if the development of new technology is crucial for keeping national competitiveness, appropriate scheme of public subsidies is in need to accelerate the maturity of new technologies and then promote their deployment and commercialization.

In the early stages of the development of new technologies, a key point in subsidy implementation is to stimulate firms' investment in innovation activities. In this context, a manufacturer subsidy is suggested to be adopted but not by way of equal distribution in the firms without pre-assessment. Specifically, it is suggested a new scheme based on project-mode for manufacturer subsidy, which provides better assurance that sufficient funds are allocated and minimize inefficient use of those funds. It is recommended that each firm applies for subsidies based on the needs of their R&D project. A third-party should be authorized by governments to evaluate the projects comprehensively. After government approval, firms should be granted subsidies in phases. Follow-up subsidies should be dynamically adjusted according to the project progress. If the periodic targets are fulfilled on schedule, firms are able to acquire the planned funds in the next stage. Otherwise, government support should be suspended and the projects remain to be further evaluated.

In the phase of technology diffusion, the path dependence of consumer preferences put new technologies in an inferior position, even the performance of new technologies is almost the same or even better compared to the traditional technologies. Hence, consumer subsidy is suggested to be introduced in addition with the manufacturer subsidy. If consumer subsidy is aimed to induce the emergence of early adopters, a higher subsidy intensity of new product is required, since a low intensity of consumer subsidy at the initial stage cannot take effect. Otherwise, the subsidy implemented after the emergence of early adopters is more preferred than the time of just entering the market, as this kind of subsidy scheme could induce more sales with the same equivalent expenditure. When the new technologies tend to outperform the traditional technologies, public subsidies could be gradually decreased in time. Please note this study is based on the reality of the EV industry in the U.S. only, and more work is needed to investigate whether similar results could apply to other emerging industries in the U.S. and other countries.

Acknowledgements

We are grateful for the financial support from the National Social Science Fund of China (No. 18BGL016).

Appendix A. Sensitivity and robustness analysis

(1) Sensitivity to the parameters assumed by authors

We carry out a sensitivity and robustness analysis on the model referring to Malerba et al. (2007) and Dawid and Reimann (2011). 100 different profiles are generated randomly under the business-as-usual scenario, with part of parameters drawn from a uniform distribution, to test whether the parameters assumed by authors rather than obtained from the empirical facts would significantly influence the simulation results. Table A1 lists the initial value of tested parameters, with their respective ranges given by upper and lower bounds of 10%. For each of the 100 profiles, the simulation results will be recorded and averaged respectively. Over 100 runs, summarized statistics of EV variables in the last simulation period are reported in Table A2.

To verify the stability of the results, we first calculate the 95% confidence interval of these EV variables according to the simulation results under the business-as-usual scenario and examine that whether the mean value of each variable under the settings we discussed above falls into the confidence interval. The comparison results are presented in the sixth and seventh rows of Table A2. As the answer is positive for all variables, our simulation results are suggested to be robust.

Table A1

Parameters drawn from a uniform distribution.

Source: Authors.

Parameters	Meaning	Initial set	Lower bound	Upper bound
$wtp1$	The willingness to pay for a mile of added range of CVs	\$50	\$45	\$55
$wtp2$	The willingness to pay for a mile of added range of EVs	\$35	\$31.5	\$38.5
a_0	Parameter in the process innovation function of CVs	3.6	3.24	3.96
b_0	Parameter in the product innovation function of EVs	0.055	0.0495	0.0605
b_0	Parameter in the product innovation function of CVs	0.015	0.0135	0.0165
σ	Debt payment fraction	0.15	0.135	0.165
μ_2	The expansion rate of production capacity	0.1	0.09	0.11
ρ_2	The depreciation rate of capital	0.1	0.09	0.11
$Lcop1$	Minimum cost of vehicle engine	\$1000	900	1100
$Leff_2$	Maximum electricity consumption efficiency	15	13.5	16.5

Table A2

Statistics of EV variables.

Source: Simulation results.

Variables	Mean	Std	Max	Min	Confidence interval (95%)	Whether the mean value falls into the interval
Company	20.08	0.9286	22	18	[19.74, 20.18]	Yes
Profitability	0.2820	0.1293	0.3333	0	[0.2787, 0.3138]	Yes
Tmarket	0.2919	0.2890	1	0	[0.2384, 0.3300]	Yes
HHI	0.1014	0.0080	0.1212	0.0786	[0.0995, 0.1033]	Yes
Price	29,729	2252	35,920	24,942	[29,218, 30,718]	Yes
Range	466.1	30.94	529.2	373.1	[451.20, 468.25]	Yes
RD^{pc}	25.48	24.49	89.81	0.1745	[18.255, 25.930]	Yes
RD^{pd}	28.27	26.30	100.8	0.1784	[17.693, 26.381]	Yes

(2) Sensitivity to the fuel price

It is proved that the price of fuel has a significant impact on the consumer preference for vehicles (Gallagher and Muehlegger, 2011). We perform a sensitivity analysis to the fuel price, which remains constant as \$2.7424 per gallons under the business-as-usual scenario. Given a steady growth rate, three assumptions of the final fuel price in 2050 are defined: \$2.1939 with a decrease of 20%, \$3.2909 with an increase of 20%, \$3.8394 with an increase of 40%. Over 100 runs for each assumption, results of market share and profitability of EV firms are shown in Fig. A1.

An increase in the fuel price will raise the cost of using conventional vehicles, which will stimulate the purchase of alternative fuel vehicle in turn. While with the increase of the final fuel price to \$3.2909 and \$3.8394, the market share of EV firms in 2050 is respectively 39.68% and 47.42%, increasing by 10.72% and 18.46%. Compared to the business-as-usual scenario, both results surpass the largest market share of 39.16% obtained under a consumer subsidy. On the contrary, if the fuel price steadily decrease to \$2.1939, the final share is expected to decline to 16.96%, just over half of the original level.

These results prove that changes in the fuel price will have a great influence on the EV adoption. In face of resource scarcity, the consumption cost of fuels is anticipated to increase in the future, which implies that the estimation of future demand for EVs under the business-as-usual scenario is underestimated. However, it should be noted that in some countries where the retail prices of gasoline and diesel are regulated to maintain market stability, the shock of oil price variation on the EV adoption would be mitigated.

(3) Sensitivity to the minimum battery cost

At last, we identify the sensitivity of the results to the minimum battery cost in future, which assumed to be \$100 per kWh in 2050 under the business-as-usual scenario. The battery technology is one of the major obstacles faced by EV firms and there exists great uncertainty in the technology innovation activities. We assume three different targets in 2050, including \$120 per kWh, \$80 per kWh, and \$60 per kWh. Over 100 runs for each assumption, results of market shares and profitability of EV firms are shown in Fig. A2.

It is obvious that technology innovation plays a pivotal role in the development of EV industry. If the technical targets are accomplished beyond expectation, which means the minimum unit battery cost over 40 years decreases to \$80 and \$60 per kWh respectively, the market share of EV firms is anticipated to rise to 50.44% and 59.6%, implying the dominance of EV in the market. In contrast, if the future unit battery cost is poorly able to reach \$120 per kWh, EV firms is expected to merely obtain 10.88% of the market share in 2050.

Technology progress seems to be a quite effective approach to enhance the market competitiveness and further establish the superiority of later entrants. In our simulation, because the technology improvements acts as an optimistic case without considering the possibility of failures in R&D investment in each period, the simulation results under the business-as-usual scenario may overestimate the estimation of the EV sales to a certain extent. Therefore, to break through the dominance of conventional vehicles, EV firms need to put more efforts into R&D.

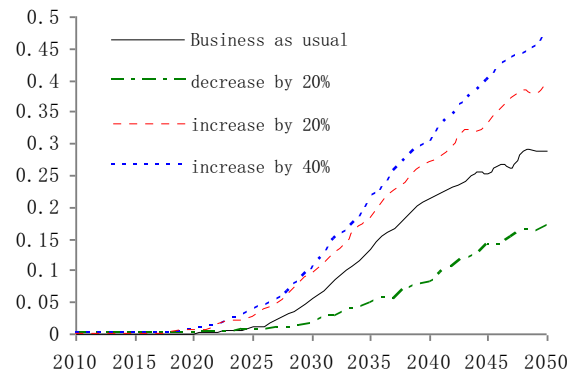


Fig. A1. Sensitivity analysis of the fuel price.

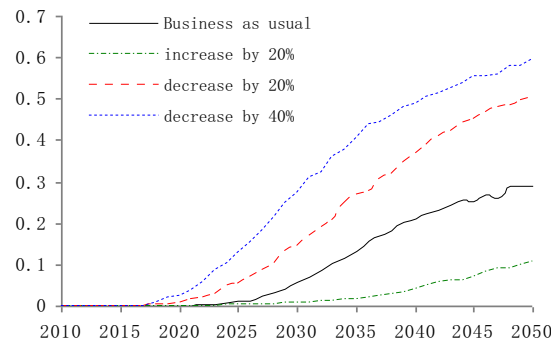


Fig. A2. Sensitivity analysis of the minimum battery cost.

References

- Aguirre, K., Eisenhardt, L., Lim, C., Nelson, B., Norring, A., Slowik, P., Tu, N., 2012. Lifecycle analysis comparison of a battery electric vehicle and a conventional gasoline vehicle. *Front. Energy* 6, 107–111.
- Alt, J., Preston, I., Sibiet, L., 2010. The political economy of tax policy. In: *Institute of Fiscal Studies (Hrsg.). Dimensions of Tax Design The Mirrlees Review*, Oxford (im Erscheinen).
- Andrews, C., DeVault, D., 2009. Green niche market development. *J. Ind. Ecol.* 13 (2), 326–345.
- Arslan, O., Yildiz, B., Karaşan, O.E., 2014. Impacts of battery characteristics, driver preferences and road network features on travel costs of a plug-in hybrid electric vehicle (PHEV) for long-distance trips. *Energy Policy* 74, 168–178.
- Baker, E., Chon, H., Keisler, J., 2010. Battery technology for electric and hybrid vehicles: expert views about prospects for advancement. *Technol. Forecast. Soc. Change* 77 (7), 1139–1146.
- Bjerkan, K.Y., Nørbech, T.E., Nordtømme, M.E., 2016. Incentives for promoting battery electric vehicle (BEV) adoption in Norway. *Transp. Res. D Transp. Environ.* 43, 169–180.
- Bloom, N., Schankerman, M., Van Reenen, J., 2013. Identifying technology spillovers and product market rivalry. *Econometrica* 81 (4), 1347–1393.
- Chang, P.L., Ho, S.P., Hsu, C.W., 2013. Dynamic simulation of government subsidy policy effects on solar water heaters installation in Taiwan. *Renew. Sust. Energy Rev.* 20, 385–396.
- Colombo, M.G., Grilli, L., Murtinu, S., 2011. R&D subsidies and the performance of high-tech start-ups. *Econ. Lett.* 112 (1), 97–99.
- Costantini, V., Crespi, F., Martini, C., Pennacchio, L., 2015. Demand-pull and technology-push public support for eco-innovation: the case of the biofuels sector. *Res. Policy* 44 (3), 577–595.
- Cotti, C., Skidmore, M., 2010. The impact of state government subsidies and tax credits in an emerging industry: ethanol production 1980–2007. *South. Econ. J.* 76 (4), 1076–1093.
- Dawid, H., Reimann, M., 2011. Diversification: a road to inefficiency in product innovations? *J. Evol. Econ.* 21 (2), 191–229.
- Dexheimer, V., 2003. Hedonic methods of price measurement for used cars. In: *Statistisches Bundesamt (Destatis), zuletzt abgerufen am 10.*
- Diamond, D., 2009. The impact of government incentives for hybrid-electric vehicles: evidence from US states. *Energy Policy* 37 (3), 972–983.
- Driscoll, A., Lyons, S., Mariuzzo, F., Tol, R.S., 2013. Simulating demand for electric vehicles using revealed preference data. *Energy Policy* 62, 686–696.
- Federal Reserve Board, 2010. Data Download Program. Available at: <https://www.federalreserve.gov/datadownload/Choose.aspx?rel=H15>.
- Finon, D., Menanteau, P., 2003. The static and dynamic efficiency of instruments of promotion of renewables. *Energy Stud. Rev.* 12 (1), 53–82.
- Fronzel, M., Ritter, N., Schmidt, C.M., Vance, C., 2010. Economic impacts from the promotion of renewable energy technologies: the German experience. *Energy Policy* 38 (8), 4048–4056.
- Gallagher, K.S., Muehlegger, E., 2011. Giving green to get green? Incentives and consumer adoption of hybrid vehicle technology. *J. Environ. Econ. Manag.* 61 (1), 1–15.
- García-Quevedo, J., Pellegrino, G., Savona, M., 2016. Reviving demand-pull perspectives: the effect of demand uncertainty and stagnancy on R&D strategy. *Camb. J. Econ.* 41 (4), 1087–1122.
- Gerssen-Gondelach, S.J., Faaij, A.P.C., 2012. Performance of batteries for electric vehicles on short and longer term. *J. Power Sources* 212, 111–129.
- Girod, B., Stucki, T., Woerter, M., 2017. How do policies for efficient energy use in the household sector induce energy-efficiency innovation? An evaluation of European countries. *Energy Policy* 103, 223–237.
- Helveston, J.P., Liu, Y., Feit, E.M.D., Fuchs, E., Klampfl, E., Michalek, J.J., 2015. Will subsidies drive electric vehicle adoption? Measuring consumer preferences in the US and China. *Transp. Res. A Policy Pract.* 73, 96–112.
- Hidru, M.K., Parsons, G.R., Kempton, W., et al., 2011. Willingness to pay for electric vehicles and their attributes. *Resour. Energy Econ.* 33 (3), 686–705.
- Hoeffler, S., Arieli, D., West, P., 2006. Path dependent preferences: the role of early experience and biased search in preference development. *Organ. Behav. Hum. Decis. Process.* 101 (2), 215–229.
- Horbach, J., Rammer, C., Rennings, K., 2012. Determinants of eco-innovations by type of environmental impact—the role of regulatory push/pull, technology push and market pull. *Ecol. Econ.* 78, 112–122.
- Howell, D., 2012. Overview of Battery R&D Activities. U.S. Department of Energy Vehicle Technologies Program, Washington, DC.
- Hung, S.C., Chu, Y.Y., 2006. Stimulating new industries from emerging technologies: challenges for the public sector. *Technovation* 26 (1), 104–110.
- Jaruzelski, B., Dehoff, K., 2008. Beyond borders: the global innovation 1000. *Strategy Bus.* 53 (Winter), 52–69.
- Jo, Y.S., Bromberg, L., Heywood, J., 2016. Optimal use of ethanol in dual fuel applications: effects of engine downsizing, spark retard, and compression ratio on fuel economy. *SAE Int. J. Engines* 9 (2016-01-0786), 1087–1101.
- Johnstone, N., Haščić, I., Popp, D., 2010. Renewable energy policies and technological innovation: evidence based on patent counts. *Environ. Resour. Econ.* 45 (1), 133–155.
- Kanari, N., Pineau, J.L., Shallari, S., 2003. End-of-life vehicle recycling in the European union. *J. Min. Met. S.* 55 (8), 15–19.
- Klaassen, G., Miketa, A., Larsen, K., Sundqvist, T., 2005. The impact of R&D on innovation for wind energy in Denmark, Germany and the United Kingdom. *Ecol. Econ.* 54 (2–3), 227–240.
- Klößner, C.A., Nayum, A., Mehmetoglu, M., 2013. Positive and negative spillover effects from electric car purchase to car use. *Transp. Res. D Transp. Environ.* 21, 32–38.

- Knittel, C.R., 2012. Reducing petroleum consumption from transportation. *J. Econ. Perspect.* 26 (1), 93–118.
- Kwon, Y., Son, S., Jang, K., 2018. Evaluation of incentive policies for electric vehicles: an experimental study on Jeju Island. *Transp. Res. Part A: Policy Pract.* 116, 404–412.
- Lieven, T., Mühlmeier, S., Henkel, S., Waller, J.F., 2011. Who will buy electric cars? An empirical study in Germany. *Transp. Res. Part D: Transp. Environ.* 16 (3), 236–243.
- Lin, B., Jiang, Z., 2011. Estimates of energy subsidies in China and impact of energy subsidy reform. *Energy Econ.* 33 (2), 273–283.
- Malerba, F., Nelson, R., Orsenigo, L., Winter, S., 1999. ‘History-friendly’ models of industry evolution, the computer industry. *Ind. Corp. Chang.* 8 (1), 3–40.
- Malerba, F., Nelson, R., Orsenigo, L., Winter, S., 2007. Demand, innovation, and the dynamics of market structure: the role of experimental users and diverse preferences. *J. Evol. Econ.* 17 (4), 371–399.
- Marino, M., Lhuillery, S., Parrotta, P., Sala, D., 2016. Additionality or crowding-out? An overall evaluation of public R&D subsidy on private R&D expenditure. *Res. Policy* 45 (9), 1715–1730.
- Martin, S., Scott, J.T., 2000. The nature of innovation market failure and the design of public support for private innovation. *Res. Policy* 29 (4–5), 437–447.
- Mowery, D., Rosenberg, N., 1979. The influence of market demand upon innovation: a critical review of some recent empirical studies. *Res. Policy* 8 (2), 102–153.
- Murray, B.C., Cropper, M.L., de la Chesnaye, F.C., Reilly, J.M., 2014. How effective are US renewable energy subsidies in cutting greenhouse gases? *Am. Econ. Rev.* 104 (5), 569–574.
- Nemet, G.F., 2009. Demand-pull, technology-push, and government-led incentives for non-incremental technical change. *Res. Policy* 38 (5), 700–709.
- Nill, J., Kemp, R., 2009. Evolutionary approaches for sustainable innovation policies from niche to paradigm? *Res. Policy* 38, 668–680.
- Noori, M., Tatari, O., 2016. Development of an agent-based model for regional market penetration projections of electric vehicles in the United States. *Energy* 96, 215–230.
- Orbach, Y., Fruchter, G.E., 2011. Forecasting sales and product evolution: the case of the hybrid/electric car. *Technol. Forecast. Soc. Change* 78 (7), 1210–1226.
- Peters, A., Düttschke, E., 2014. How do consumers perceive electric vehicles? A comparison of German consumer groups. *J. Environ. Policy Plan.* 16 (3), 359–377.
- Peters, M., Schneider, M., Griesshaber, T., Hoffmann, V.H., 2012. The impact of technology-push and demand-pull policies on technical change—does the locus of policies matter? *Res. Policy* 41 (8), 1296–1308.
- Rogers, E.M., 2003. *Diffusion of Innovations*, fifth ed. Free Press, New York, NY.
- Shafiei, E., Davidsdottir, B., Fazeli, R., et al., 2018. Macroeconomic effects of fiscal incentives to promote electric vehicles in Iceland: implications for government and consumer costs. *Energy Policy* 114, 431–443.
- Shepherd, S., Bonsall, P., Harrison, G., 2012. Factors affecting future demand for electric vehicles: a model based study. *Transp. Policy* 20, 62–74.
- Sierzchula, W., Bakker, S., Maat, K., van Wee, B., 2014. The influence of financial incentives and other socio-economic factors on electric vehicle adoption. *Energy Policy* 68, 183–194.
- Silveira, J.L., Tuna, C.E., de Queiroz Lamas, W., 2013. The need of subsidy for the implementation of photovoltaic solar energy as supporting of decentralized electrical power generation in Brazil. *Renew. Sust. Energ. Rev.* 20, 133–141.
- Skerlos, S.J., Winebrake, J.J., 2010. Targeting plug-in hybrid electric vehicle policies to increase social benefits. *Energy Policy* 38 (2), 705–708.
- Struben, J., Sterman, J.D., 2008. Transition challenges for alternative fuel vehicle and transportation systems. *Environ. Plan. B: Plan. Design* 35 (6), 1070–1097.
- Taylor, M.R., Rubin, E.S., Hounshell, D.A., 2005. Control of SO₂ emissions from power plants: a case of induced technological innovation in the US. *Technol. Forecast. Soc. Change* 72 (6), 697–718.
- U.S. Bureau of Economic Analysis, 2010a. National Data-Personal Income and Outlays. Available at: <https://apps.bea.gov/iTable/iTable.cfm?ReqID=19&step=4&isuri=1&1921=flatfile>.
- U.S. Bureau of Economic Analysis, 2010b. Motor Vehicle Data. Available at: https://www.bea.gov/national/xls/gap_hist.xlsx.
- U.S. Energy Information Administration, 2012. Annual energy review 2011. Government Printing Office.
- Wang, Y., Chang, X., Chen, Z., Zhong, Y., Fan, T., 2014. Impact of subsidy policies on recycling and remanufacturing using system dynamics methodology: a case of auto parts in China. *J. Clean. Prod.* 74, 161–171.
- Wu, G., Inderbitzin, A., Bening, C., 2015. Total cost of ownership of electric vehicles compared to conventional vehicles: a probabilistic analysis and projection across market segments. *Energy Policy* 80, 196–214.
- Zhang, X., Xie, J., Rao, R., Liang, Y., 2014. Policy incentives for the adoption of electric vehicles across countries. *Sustainability* 6 (11), 8056–8078.
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