Evolutionary dynamics of promoting electric vehicle-charging infrastructure based on public–private partnership cooperation

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Abstract

Low profit margins have become a significant barrier to investment in and the operation of electric vehicle-charging infrastructure, leading to an urgent need for new business models. Notwithstanding, nonmandatory policies and unclear responsibilities create a social dilemma in which it is difficult to promote charging facilities in urban residential areas. This study examines the feasibility of overcoming this dilemma by examining possible incentive mechanisms involving government, charging infrastructure operators, real estate agencies, and electric vehicle users. Leveraging evolutionary game theory, this study designs a theoretical model based on strategic interactions among different agents in promoting charging facilities in urban residential areas. Our results indicate that (1) the optimal scenario in one in which all participants work closely together to popularize charging facilities, and this scenario has theoretical possibilities in the real world; (2) government subsidies are necessary but not sufficient for promoting charging facilities in urban residential areas; (3) electric vehicle user participation in promotion is critical; and (4) the operation model in this study is more economically efficient than prevalent industrial operation models, and the role of real estate agencies cannot be ignored.

Keywords: charging infrastructure, real estate, public–private partnership cooperation, evolutionary dynamics, incentive mechanisms, China

1. Introduction

Environmental change and the fulfillment of carbon neutrality goals require the widespread uptake of electric vehicles (EVs) by the consumer market [1, 2]. According to a recent report by the International Energy Agency, total global vehicle sales fell 16% against the backdrop of the 2020 global epidemic, but sales of EVs grew 41%, relative to the previous year [3]. The world's preference for EVs is accelerating, but EV development remains nascent. In 2020, over 3 million EVs were sold worldwide, accounting for 4.6% of the new-car market; China, as the largest producer and seller of EVs, has a total of 4.92 million EVs, accounting for only 1.75% of the total car ownership there [3, 4]. While the growing electrification of road vehicles remains a priority for the future, with the growth of EV use, meeting the growing demand for charging infrastructure has become another important issue [5-7].

Currently, there is still a huge demand for charging facilities, owing to the large EV market; the gap between demand and supply will continue to grow if no attention is paid to their availability. Fig. 1 presents the number of EVs and charging facilities in China, where the blue dotted line indicates the ratio of total EV sales to total charging-facility ownership. To encourage charging infrastructure development, China has enacted two important policies—namely, the *Development Guide for Electric Vehicle Charging Facilities (2015–2020)* and the *Guidelines on Accelerating the Construction of Charging Facilities for Electric Vehicles* [8, 9]. These guides promise construction and operation subsidies and encourage related agents to explore sustainable business models. Note that China's EV subsidies are decreasing year by year while charging-facility subsidies are gradually increasing: indeed, subsidies are shifting from vehicle subsidies to facility subsidies at the national level [10]. The program driven by the *New Energy Automobile Industry Development Plan (2021–2035)* emphasizes the coordination of multiple agents (e.g., power grids, property management, and urban parking for facilitating charging facilities) [11]. However, such policies are not mandatory, and it is unclear what responsibilities each relevant agent should assume in promoting charging facilities. To the best of our knowledge, the literature contains no theoretical analysis of these issues.

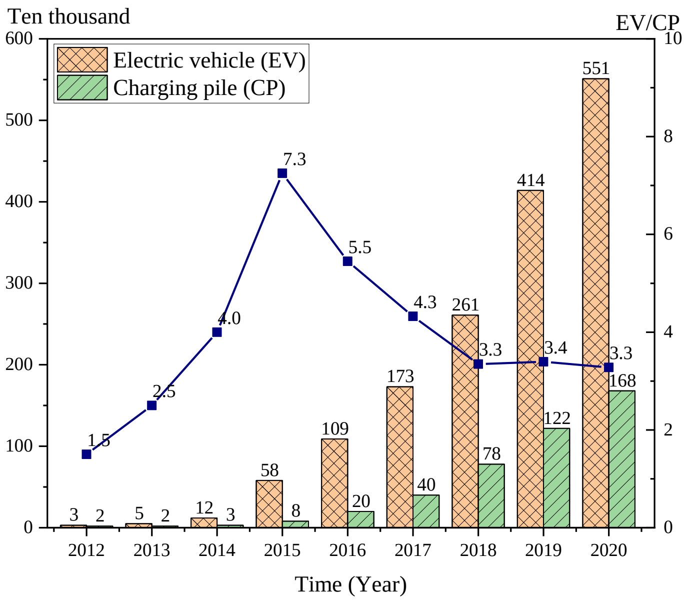

Fig. 1. Number of EVs and charging piles in China.

This study aims to design a mechanism called “electric vehicle-charging infrastructure/public–private partnership” (EVCI–PPP) with regard to the operation of charging facilities; this study also looks to clarify the responsibilities of the agents involved, analyze their willingness to cooperate, and examine the economics of the mechanism’s design. Specifically, real estate agencies (REAs) have been introduced as new agent partners in promoting urban residential charging facilities. The role of REAs is to invest in charging facilities to improve the travel service environment in residential areas. There are two reasons for considering REAs as potential agents in the rollout of EV charging facilities. First, REAs control the majority of city residential and commercial properties [12], and investing in infrastructure helps increase property values by reducing the price (in time, comfort, and monetary terms) of residential travel [13, 14]. Second, to qualify for construction, the installation of both public and private charging facilities requires consultation with REAs. The promotion of charging facilities in urban residential areas inherently provides REAs with a new role; however, REAs are not good at operating charging facilities, and so the risk of potentially inefficient service operations persists. Given these circumstances, we consider the PPP mode in constructing multiagent dynamics vis-à-vis investment in charging facilities in urban residential areas while involving REAs. The PPP model is also an important tool for the government in advocating the exploration of sustainable business models in the charging facilities sector [9]: its use can not only reduce the financial pressure of the government by using solid capital, but also leverage the advanced management experience of private enterprises to improve charging performance and service [15].

This study is interested in answering the following questions. (1) Are REAs an effective force in promoting EV charging infrastructure? If so, how can this force be managed? (2) Is this model economically viable compared to real-world industrial applications? (3) How can government policies assist in model development? We developed an evolutionary game model to address these questions. Since evolutionary game models can be used to analyze factors that influence social customs, norms, or systems [16], we leverage this approach to analyze evolutionary stabilization strategies regarding the behavior of multiple agents in urban residential EVCI–PPP; we also explain why and how these agents achieve an equilibrium state. The study yields the following findings and management insights for policy and firm-level strategy-makers.

(1) The optimal scenario—in which all participants work closely together to promote charging facilities in urban residential areas—has theoretical possibilities in the real world. We obtain the threshold conditions for multiagent cooperation, and these are detailed in Section 4.2. Therefore, the government, REAs, and charging infrastructure operators (CIOs) could help promote charging-facility construction projects in urban residential areas.

(2) By comparing it to the popular industry operating model, this study demonstrates the superiority of the EVCI–PPP operating model; in so doing, it speaks to the importance of REAs in rolling out charging facilities in urban residential areas.

(3) By undertaking a comparison of the three policy environments, this study finds that the Shanghai subsidy policy environment (S1) is more favorable to the development of an EVCI–PPP project, and has the strongest incentive effect (see Figs. 3, 4, 5, and 6). This finding also demonstrates the importance of a third category of consumer subsidies, in addition to construction and operation subsidies.

(4) Mainstream 7 kw power is still the best choice for charging facilities in urban residential areas, as there is not much difference in revenue compared to those featuring higher power levels. However, as the demand for charging facilities increases, more advanced, intelligent, and higher-power charging-facility updates will become feasible and desirable.

The remainder is organized as follows. Section 2 reviews the related literature. The problem description and model formulation are introduced in Section 3. In Section 4, replicator dynamic equations and stability analysis of the equilibriums are analyzed. Section 5 conducts a case study. Discussions are analyzed in Section 6. Finally, conclusions and policy implications are concluded in Section 7.

2. Literature review

The demand-supply imbalance of charging facilities is still one of the biggest obstacles for the uptake of EVs [17, 18]. The literature related to this study can be divided into three categories, including PPP model design of charging facilities, government subsidies and evolutionary game theory.

First, this study is related to the PPP model design of charging infrastructure. Zhang et al. [19] reviewed the literature investigating public charging infrastructure economics and concluded that the main obstacle to accelerating the development of charging facilities is the lack of an effective business model. As an important public infrastructure, the most common design approach in the existing literature for charging facilities is the PPP. The importance of the PPP model has led to its widespread use in other areas, such as new energy power construction [20] and mega-engineering projects in the construction industry (i.e., air project [21] and highway infrastructure project [22]). However, despite the importance of PPP mode, their application in China's charging facility sector is rare and still in the early stage [23]. Existing studies on PPP projects for charging facilities mainly focus on the public sector, but neglect to explore the application in urban residential areas. For example, Fang et al. [24] constructed a synergistic development system of solar panels, charging facilities and electric vehicles based on the PPP model, and analyzed the theoretical feasibility of the model. Wang and Ke [23] analyzed the PPP projects of public charging facilities in Anqing, China, and sorted out the project structure and the responsibilities of the relevant subjects. Yang et al. [10] also analyzed the PPP charging facilities promotion project for urban shopping malls with multi-subject cooperation, and analyzed the pricing issues of different charging models.

In addition to the aforementioned charging facility PPP studies, existing studies also analyze the management of charging facility PPP projects, including risk identification and evaluation [18], tax impact [25], private-partner selection [26]. Unlike these studies, this study aims to conduct a theoretical investigation into the application of the PPP model for charging facilities in urban residential areas, clarify the responsibilities of relevant subjects, and analyze the evolution of their strategies. In addition, REAs may become a new driving force for the development of charging facilities, but existing studies do not design PPP models for charging facilities in urban residential areas that consider REA participation, nor do they theoretically confirm the possibility of their realistic application. To this end, this study contributes to the literature by designing a PPP model for the promotion of charging facilities in urban residential areas that considers the cooperation of multiple agents: government, REAs, CIOs, and EV users.

Second, this study is related to the growing operation literature that examines government subsidies in various contexts. Government subsidies has played an important role in promoting green technologies or pro-environmental product [27-30]. In the charging sector, government subsidies have a similar role, but a new concern has been raised: how government subsidies can adapt to the development of the charging facility market to improve the utilization of subsidies [10, 19]. To this end, existing research is also exploring the application scenarios where subsidies are more appropriate and the impact of subsidies on the specific operation of charging facilities. For example, Yang et al. [10] analyzed the impact of different charging facility subsidy policies on the economics of charging model choices, and found land lease fees are an important barrier limiting the development of charging facilities, and a 7 kW slow charging mode is more appropriate in the current subsidy. Zhang et al. [31] analyzed the impact of government subsidies on the pricing of charging service fees, and found government subsidies can help reduce the high investment cost of charging facilities and facilitate multi-party cooperation to reduce charging service fees. Fang et al. [5] analyzed how government subsidies affect the competition between charging stations and gas stations, and found government subsidies help avoid market fluctuations in charging facilities. However, these studies emphasize more on the role of construction subsidies and ignore operational subsidies. The role of subsidy policies in the promotion of charging facilities in urban residential areas and their optimal form of utilization are also lacking. To this end, this study contributes to the literature by dividing subsidies into construction and operation subsidies and analyzing their role in the promotion of charging facilities in urban residential areas.

The third literature stream is related to the evolutionary game theory and its applications. Evolutionary games originated in the field of population biology and were proposed by Smith and Price [32] to provide a new analytical paradigm for studying multi-round dynamic game problems. Methodologically, it emphasizes dynamic equilibrium rather than static equilibrium and is widely used by economics to analyze the influences of social habits, norms and institutions and to explain their formation processes [16, 33]. The common forms of evolutionary game models are divided into two-party [34-41] and three-party [24, 42-45]. Evolutionary game theory has facilitated the study of co-evolutionary behavior in socio-economic systems and is widely used in a number of areas: EV and EV charging infrastructure adoption [17, 24, 30, 44], e-waste recycling [33, 42], supply chain management [38, 40, 41, 43, 46], facility location of hazardous materials logistics [45], e-collaboration [36], coal mine safety supervision [39], urban heat supply system [34] and audit [35].

Compared to the classical game theory that participants are assumed to be perfectly rational and enjoy perfect information, evolutionary game theory is based on "limited rationality" and do not require participants perfect information and complete rationality [20]. It believes that participants usually achieve game equilibrium through trial and error, and emphasizes the dynamic process of "change-adjustment-convergence" of behavioral decisions [47, 48]. In this study, we propose an EVCI-PPP model for the rollout of charging facilities in urban residential areas, which is a typical nonlinear system with relevant agents including government, REAs, CIOs, and EV users. Each stakeholder makes different strategic choices based on their costs and benefits, and they are all limited rational. This study aims to analyze the evolution of game strategies of the stakeholders of this EVCI-PPP, the relevant influencing factors and their formation process. Therefore, it is very suitable to use evolutionary game theory to model and analyze needs of this study than the traditional game.

3. Modelling framework

3.1 Model description and assumption

In the urban residential EVCI-PPP project, main participants include the government, CIOs, REAs and EV users (EVUs), given in Fig. 2. REAs are responsible for investing in charging facilities and their installation sites, and CIOs are responsible for operating and managing charging facilities. Together they set up a special purpose vehicle (SPV) company responsible for the construction and operation of charging facilities in the community, a setup that is consistent with the real operation of PPP projects in China [23]. EVUs choose SPV-operated charging facilities to charge their vehicles. The government supervise firms and organize EVUs to participate in the EVCI-PPP program by subsidizing all participants. Note that the government acts only as a market regulator and not as a player, a setting that is consistent with reality and with the role of government as defined in existing research, such as Yang et al. [10] and Fang et al. [24].

Players in each population has two strategies to choose from: for the EVCI-PPP, labeled as cooperators (C), or stay with the status quo, labeled as defectors (D). The payoff of each player in the game depends on the strategic choices of individuals in other populations. An encounter occurs between three players, each from a different population, with the corresponding benefit matrix shown in Table 1. During this process, two basic scenario M1 and M2 are derived from the cooperation model (M3) in Figure 2. Among them, M1 refers to the mode in which REAs invest and operate charging facilities in urban residential areas alone; M2 is the mode in which CIOs invest and operate charging facilities in urban residential areas. Both

M1 and M2 are the most likely models for investing in charging facilities in real-world urban residential areas.

Based on the analysis of the above dynamics, the following assumptions are listed.

Assumption 1. The probability of REAs actively investing in charging facilities is x. If REAs choose to participate in the EVCI-PPP project, they will receive a construction subsidy from the government G_1. The annual investment and maintaining costs of charging facilities are C_1 and C_2, and the annual residual value of the charging facility is RV_{ci}. Note that the REAs enjoy a return of (k) and the CIOs enjoy a return of ($1-k$) if REAs and CIOs jointly invest in an SPV. The cost and income of the charging facilities are counted using the life cycle method [5, 24] and shown in (1) and (2).

$$C_1 = C_{ci} * \frac{\gamma(1+\gamma)^{L_{ci}}}{(1+\gamma)^{L_{ci}} - 1} \tag{1}$$

where C_1 refers to the annual investment in EV charging infrastructure. C_{ci} is the initial investment value of an EV charging facility. L_{ci} is the assigned service life of the charging facility. γ is the discount rate.

$$RV_{ci} = RV_{ci0} * \frac{\gamma(1+\gamma)^{L_{ci}}}{(\gamma+\gamma)^{L_{ci}} - 1} \tag{2}$$

where RV_{ci} is the annual residual value on the EV charging infrastructure, RV_{ci0} is the final residual value of an EV charging pile.

Assumption 2. The probability of CIOs actively participating in the project is y. CIOs participating in the project will receive government operating subsidies G_2, and will incur operating and information service costs C_3. Notably, if REAs do not participate in the cooperative CIOs participate, then the CIOs will pay all costs of the charging facility, including facility investment costs ($C_1 + C_2$) and land lease fees C_4.

Assumption 3. The probability of EV users actively participating in the project is z. If EV users choose to use the project's charging facilities, they will receive a government consumption subsidy G_3. EV users have two options: charging at the EVCI-PPP project's charging facilities, or charging at public charging stations.

Assumption 4. There are three types of electricity prices $i_1 < i_2 < i_3$, where i_1 represents the commercial supply tariff from the national grid, i_2 is the service tariff for charging facilities in community EVCI-PPP projects and i_3 is the charging price for public charging stations (non-EVCI-PPP project). It is assumed that electricity for charging facilities in community EVCI-PPP projects belongs to a customized negotiated tariff, between ordinary residential and commercial tariffs; and electricity for public charging facilities in the third scenario belongs entirely to commercial tariffs. Revenue sharing brought by electricity price difference makes cooperative behaviors possible.

Assumption 5. In this game system, all participants are finitely rational. All participants find the optimal choice through trial and error based on their costs and benefits, and finally reach the system equilibrium.

The relevant parameters symbols and meanings is shown in Table 1.

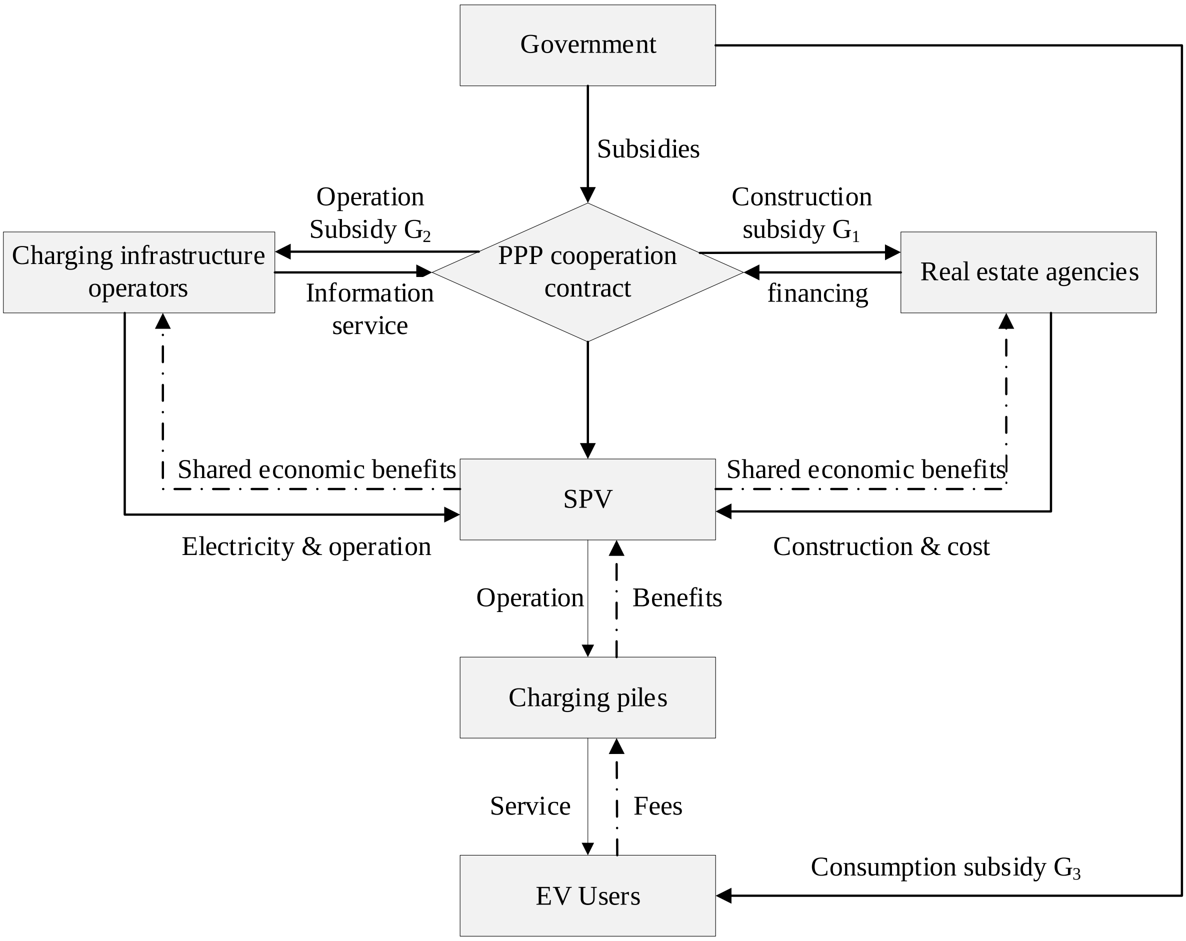

Fig. 2. The dynamic interaction of all participants based on EVCI-PPP mode.

Table 1

Parameter symbols and meanings.

Parameter symbols	Meaning	Parameter symbols	Meaning
G_1	Subsidies for the construction of charging facilities	k	Percentage of EVCI-PPP operating income available to

			REAs
G_2	Subsidies for the operations of charging facilities	RV_{ci}	Annual residual value of charging facilities
G_3	Subsidies for the consumption of charging facilities	RV_{ci0}	Residual value at the end of life of the charging facility
C_1	Annual investment cost of charging facilities	i_1	Commercial electricity prices from National Grid
C_2	Annual maintenance costs for charging facilities	i_2	Service tariff for charging facilities in EVCI-PPP
C_3	Charging facility operation and information service costs by CIOs	i_3	Service tariff of public charging facilities (non-EVCI-PPP)
C_4	Unit charging facility site rental costs	P_e	Rated power of charging facilities
C_5	Charging facility operation and information service costs by REAs	B_{ad}	Advertising revenue from charging facilities
C_{ci}	Initial investment cost per unit of charging facility	T	Annual effective operating hours of charging facilities
γ	The discount rate	R_{ci}	Risk cost of using charging facilities
L_{ci}	Rated life of charging facilities		

3.2 Payoff matrix and population dynamics

The individual payoff matrix reflects the interdependencies within and between populations. The individual payoffs corresponding to the 8 strategy combinations and the 3 cooperation models (M1, M2 and M3) are shown in Table 2. The general expression for the replicator dynamic equation is:

$$\frac{dx_i}{dt} = x_i[u(x_i, x) - u(x, x)] \tag{3}$$

where x_i refers to the selection probability of the pure strategy, $u(x_i, x)$ refers to the expected utility when using a pure strategy, and $u(x, x)$ refers to the average expected utility. Based on this, we can obtain the expected payoff of the REAs, shown in (4). Note that E_{REA1} is the expected payoff of REAs choosing to positively invest in charging facilities, and vice versa for E_{REA0}. $\overline{E_{REA}}$ is the averaged expected payoff of REAs. Similarly, the expected payoffs of CIOs and EVUs are shown in (5) and (6), respectively.

$$\begin{cases} E_{REA1} = -\left(\left(i_1 - i_2\right)P_e - B_{ad}\right)z\left(1+\left(k-1\right)y\right)T + C_3 y + RV_{ci} - C_1 - C_2 - C_5 + G_1; \\ E_{REA0} = yC_4; \\ \overline{E_{REA}} = \begin{pmatrix} -\left(\left(i_1 - i_2\right)P_e - B_{ad}\right)z\left(1+\left(k-1\right)y\right)T + \\ \left(-C_4 + C_5\right)y + G_1 + RV_{ci} - C_1 - C_2 - C_5 \end{pmatrix} x + yC_4; \end{cases} \tag{4}$$

$$\begin{cases} E_{CIO1} = \left(\left(\left(i_1 - i_2\right)P_e - B_{ad}\right)kzT - RV_{ci} + C_1 + C_2 + C_4\right)x - \left(\left(i_1 - i_2\right)P_e - B_{ad}\right)zT \\ \quad + RV_{ci} - C_1 - C_2 - C_3 - C_4 + G_2; \\ E_{CIO0} = 0; \\ \overline{E_{CIO}} = \begin{pmatrix} \left(\left(\left(i_1 - i_2\right)P_e - B_{ad}\right)kzT - RV_{ci} + C_1 + C_2 + C_4\right)x - \left(\left(i_1 - i_2\right)P_e - B_{ad}\right)zT \\ + RV_{ci} - C_1 - C_2 - C_3 - C_4 + G_2 \end{pmatrix} y; \end{cases} \tag{5}$$

$$\begin{cases} E_{EVU1} = \left(\left(i_2 - i_3\right)\left(-1+y\right)x + \left(-i_2 + i_3\right)y - i_3\right)TP_e + R_{ci}\left(-1+y\right)x - R_{ci}y + G_3; \\ E_{EVU0} = -P_e T i_3; \\ \overline{E_{EVU}} = \left(\left(\left(-1+y\right)x - y\right)\left(i_2 - i_3\right)TP_e + R_{ci}\left(-1+y\right)x - R_{ci}y + G_3\right)z - P_e T i_3; \end{cases} \tag{6}$$

According to Equations (4) and (5), the net present value (NPV) of the project can be calculated as shown in (7). NPV measures the net value of a project, i.e., current and future revenues minus current and future costs.

$$\begin{aligned} \mathrm{NPV} &= \overline{E_{REA}} + \overline{E_{CIO}} \\ &= \begin{pmatrix} \left(\left(P_e\left(-i_2 + i_1\right) - B_{ad}\right)zT + C_5 + 2C_6 - RV_{ci} + C_1 + C_2\right)y - \\ \left(P_e\left(-i_2 + i_1\right) - B_{ad}\right)zT - C_5 - C_6 + G_1 + RV_{ci} - C_1 - C_2 \end{pmatrix} x \\ &\quad - y\left(\left(P_e\left(-i_2 + i_1\right) - B_{ad}\right)zT + C_6 - G_2 - RV_{ci} + C_1 + C_2 + C_3\right) \end{aligned} \tag{7}$$

Further, according to Friedman [47], the replicator dynamic equation by REAs, CIOs and EVUs are listed in (8), (9) and (10). For simplicity, let $\alpha_1 = \left[P_e\left(i_2 - i_1\right) + B_{ad}\right]T$ and $\alpha_2 = C_1 + C_2 - RV_{ci}$, where α_1 refers to the income from operating the EV charging infrastructures, α_2 is the construction investment cost of EV charging infrastructures.

$$\begin{aligned} f_{REA}(x) &= \frac{dx}{dt} = x(E_{REA1} - \overline{E_{REA}}) \\ &= x\left(1-x\right)\left\{\left[z\left(-1+k\right)\alpha_1 - C_4 + C_5\right]y + \alpha_1 z - C_5 + G_1 - \alpha_2\right\} \end{aligned} \tag{8}$$

$$f_{CIO}(y)=\frac{dy}{dt}=y(E_{CIO1}-\overline{E_{CIO}})$$
$$=y(1-y)\{[C_4+\alpha_2-kz\alpha_1]x+\alpha_1 z-C_3-C_4+G_2-\alpha_2\} \tag{9}$$

$$f_{EVU}(z)=\frac{dz}{dt}=z(E_{EVU1}-\overline{E_{EVU}})$$
$$=z(1-z)\{[(-1+y)x-y]T(i_2-i_3)P_e+R_{ci}(-1+y)x-R_{ci}y+G_3\} \tag{10}$$

Similarly, the expected payoffs and replicated dynamic equations can be obtained for both M1 and M2, see Appendix.

Table 2

Payoff matrix, where 1 indicates a cooperator and 0 a defector.

Strategies			Scenario			Profit matrix
REAs	CIOs	EVUs	M1	M2	M3	
0	0	0	√	√	√	$\{0,0,-P_e i_3 T\}$
0	0	1	√	√	√	$\{0,0,-P_e i_3 T+G_3\}$
0	1	0		√	√	$\{C_4,-C_1+RV_{ci}+G_2-C_2-C_3-C_4,-P_e i_3 T\}$
0	1	1		√	√	$\left\{\begin{matrix}C_4,[P_e(i_2-i_1)+B_{ad}]T-C_1+RV_{ci}+G_2-C_2-C_3-C_4,\\-P_e i_2 T-R_{ci}+G_3\end{matrix}\right\}$
1	0	0	√		√	$\{-C_1+RV_{ci}+G_1-C_2-C_5,0,-P_e i_3 T\}$
1	0	1	√		√	$\left\{\begin{matrix}[P_e(i_2-i_1)+B_{ad}]T-C_1+RV_{ci}+G_1-C_2-C_5,0,\\-P_e i_2 T-R_{ci}+G_3\end{matrix}\right\}$
1	1	0			√	$\{-C_1+RV_{ci}+G_1-C_2,G_2-C_3,-P_e i_3 T\}$
1	1	1			√	$\left\{\begin{matrix}[P_e(i_2-i_1)+B_{ad}]Tk-C_1+RV_{ci}+G_1-C_2,\\ [P_e(i_2-i_1)+B_{ad}]T(1-k)+G_2-C_3,\\-P_e i_2 T-R_{ci}+G_3\end{matrix}\right\}$

Notes: M1 refers to the EVCI-PPP model without the participation of CIOs; M2 refers to the EVCI-PPP model without the participation of REAs; M3 is the complete EVCI-PPP model.

3.3 Asymptotic stability analysis of the equilibriums

In order to analyze the asymptotic stability of the equilibrium point, the Lemma 1 [43, 49] and Lemma 2 [24, 43, 50] are needed.

Lemma 1. *On the asymmetric games, if the evolutionary equilibrium point E is asymptotically stable, then the equilibrium E must be a strict Nash equilibrium. Since the strict Nash equilibrium is a pure strategic equilibrium, the equilibrium E is also a pure strategic equilibrium.*

Lemma 2. *(Lyapunov stability theorem) when eigenvalues (λ) of the Jacobian matrix meet $\lambda < 0$, the equilibrium point is asymptotically stable (or evolutionary stable strategy, ESS) and vice versa; if it is mixed (eigenvalues are partly positive and partly negative), it is called the saddle point and is unstable.*

Lemma 1 implies that the ESS only appears in the pure strategy, without focusing on the mixed strategy. In addition, literature [42] also demonstrates that the mixed strategy is not an evolutionary equilibrium strategy because it does not guarantee that all eigenvalues have negative real parts at the same time. In this regard, we only need to analyze the pure strategy. According to Eq. (8) – Eq. (10), the pure strategic equilibrium points include (1,1,1), (1,1,0), (1,0,1), (1,0,0), (0,1,1), (0,1,0), (0,0,1) and (0,0,0). The standard Jacobian matrix *J* is denoted in (9).

$$J = \begin{bmatrix} \frac{\partial f_{REA}(x)}{\partial x} & \frac{\partial f_{REA}(x)}{\partial y} & \frac{\partial f_{REA}(x)}{\partial z} \\ \frac{\partial f_{CIO}(y)}{\partial x} & \frac{\partial f_{CIO}(y)}{\partial y} & \frac{\partial f_{CIO}(y)}{\partial z} \\ \frac{\partial f_{EV}(z)}{\partial x} & \frac{\partial f_{EV}(z)}{\partial y} & \frac{\partial f_{EV}(z)}{\partial z} \end{bmatrix} \tag{9}$$

Next, the above eight equilibrium points (pure strategy) are sequentially substituted into the Jacobian matrix and their corresponding eigenvalues are obtained. We use Maple's Jacobi function to implement this process. In accordance with Theorem 2, we analyzed asymptotic stability, including whether the eight equilibria are ESS and the conditions for the formation of ESS. (see Table 3).

Table 3

The equilibrium stability of the pure strategy.

Equilibrium	Eigenvalue	Stability
$E_1(0,0,0)$	$\begin{cases} \lambda_1^1 = -C_5 + G_1 - \alpha_2 \\ \lambda_2^1 = -C_3 - C_4 + G_2 - \alpha_2 \\ \lambda_3^1 = G_3 > 0 \end{cases}$	Saddle point
$E_2(0,0,1)$	$\begin{cases} \lambda_1^2 = \alpha_1 - C_5 + G_1 - \alpha_2 \\ \lambda_2^2 = \alpha_1 - C_3 - C_4 + G_2 - \alpha_2 \\ \lambda_3^2 = -G_3 < 0 \end{cases}$	If $\alpha_1 + G_1 < C_5 + \alpha_2$ and $C_3 + C_4 + \alpha_2 > G_2 + \alpha_1$, $E_2(0,0,1)$ is asymptotically stable, otherwise it is the saddle point.
$E_3(0,1,0)$	$\begin{cases} \lambda_1^3 = -C_4 + G_1 - \alpha_2 \\ \lambda_2^3 = C_3 + C_4 - G_2 + \alpha_2 \\ \lambda_3^3 = -(i_2 - i_3)TP_e + G_3 - R_{ci} \end{cases}$	If $G_1 - \alpha_2 < C_4$, $G_2 > C_3 + C_4 + \alpha_2$ and $G_3 + (i_3 - i_2)TP_e < R_{ci}$, $E_3(0,1,0)$ is asymptotically stable, otherwise it is the saddle point.

$E_4(0,1,1)$	$\begin{cases}\lambda_1^4 = -C_4 + k\alpha_1 + G_1 - \alpha_2 \\ \lambda_2^4 = -\alpha_1 + C_3 + C_4 - G_2 + \alpha_2 \\ \lambda_3^4 = (i_2 - i_3)TP_e - G_3 + R_{ci}\end{cases}$	If $k\alpha_1 + G_1 - \alpha_2 < C_4$, $C_3 + C_4 + \alpha_2 < G_2 + \alpha_1$ and $G_3 + (i_3 - i_2)TP_e > R_{ci}$, $E_4(0,1,1)$ is asymptotically stable, otherwise it is the saddle point.
$E_5(1,0,0)$	$\begin{cases}\lambda_1^5 = C_5 - G_1 + \alpha_2 \\ \lambda_2^5 = -C_3 + G_2 \\ \lambda_3^5 = -(i_2 - i_3)TP_e + G_3 - R_{ci}\end{cases}$	If $G_1 > C_5 + \alpha_2$, $G_2 < C_3$ and $G_3 + (i_3 - i_2)TP_e < R_{ci}$, $E_5(1,0,0)$ is asymptotically stable, otherwise it is the saddle point.
$E_6(1,0,1)$	$\begin{cases}\lambda_1^6 = -\alpha_1 + C_5 - G_1 + \alpha_2 \\ \lambda_2^6 = -C_3 + G_2 + (1-k)\alpha_1 \\ \lambda_3^6 = (i_2 - i_3)TP_e - G_3 + R_{ci}\end{cases}$	If $\alpha_1 + G_1 > C_5 + \alpha_2$, $(1-k)\alpha_1 + G_2 < C_3$ and $G_3 + (i_3 - i_2)TP_e > R_{ci}$, $E_6(1,0,1)$ is asymptotically stable, otherwise it is the saddle point.
$E_7(1,1,0)$	$\begin{cases}\lambda_1^7 = C_4 - G_1 + \alpha_2 \\ \lambda_2^7 = C_3 - G_2 \\ \lambda_3^7 = -(i_2 - i_3)TP_e + G_3 - R_{ci}\end{cases}$	If $G_1 - \alpha_2 > C_4$, $G_2 > C_3$ and $G_3 + (i_3 - i_2)TP_e < R_{ci}$, $E_7(1,1,0)$ is asymptotically stable, otherwise it is the saddle point.
$E_8(1,1,1)$	$\begin{cases}\lambda_1^8 = C_4 - k\alpha_1 - G_1 + \alpha_2 \\ \lambda_2^8 = C_3 - G_2 - (1-k)\alpha_1 \\ \lambda_3^8 = (i_2 - i_3)TP_e - G_3 + R_{ci}\end{cases}$	If $k\alpha_1 + G_1 - \alpha_2 > C_4$, $G_2 + (1-k)\alpha_1 > C_3$ and $G_3 + (i_3 - i_2)TP_e > R_{ci}$, $E_8(1,1,1)$ is asymptotically stable, otherwise it is the saddle point.

In this study, optimal equilibrium is expected to be obtained to maximize social welfare. That is, all three participants are involved in the EVCI-PPP project and only the equilibrium $E_8(1,1,1)$ is expected to occur. According to Table 3, the following proposition can be confirmed.

Proposition: When $k\alpha_1 + G_1 - \alpha_2 > C_4$, $G_2 + (1-k)\alpha_1 > C_3$ and $G_3 + (i_3 - i_2)TP_e > R_{ci}$ are satisfied and either $\alpha_1 + G_1 < C_5 + \alpha_2$ and $C_3 + C_4 + \alpha_2 > G_2 + \alpha_1$ are satisfied, only the optimal equilibrium $E_8(1,1,1)$ emerges and is an ESS.

Proof. According to Table 2, $\lambda_1^8 = -\lambda_1^4$, $\lambda_2^8 = -\lambda_2^6$ and $\lambda_3^8 = -\lambda_3^7 = -\lambda_3^5 = -\lambda_3^3$ mean that $E_4(0,1,1)$, $E_6(1,0,1)$, $E_7(1,1,0)$, $E_5(1,0,0)$ and $E_3(0,1,0)$ cannot be the ESS if $E_8(1,1,1)$ is an ESS. Here, $E_8(1,1,1)$ is the ESS implying $\lambda_1^8 = C_4 - k\alpha_1 - G_1 + \alpha_2 < 0$, $\lambda_2^8 = C_3 - G_2 - (1-k)\alpha_1 < 0$ and $\lambda_3^8 = (i_2 - i_3)TP_e - G_3 + R_{ci} < 0$. Moreover, $E_1(0,0,0)$ is a saddle point because of $\lambda_3^1 = G_3 > 0$. Based on this, the uniqueness of the equilibrium $E_8(1,1,1)$ is guaranteed as long as $E_2(0,0,1)$ does not occur. This means $\lambda_1^2 = \alpha_1 - C_5 + G_1 - \alpha_2 > 0$ or $\lambda_1^2 = \alpha_1 - C_3 - C_4 + G_2 - \alpha_2 > 0$. The proposition is proved.

4. Case study

4.1 Context and parameter setting

The top three cities in China in 2020 in terms of new energy vehicle ownership are Shanghai, Beijing and Shenzhen, which have also been chosen by existing studies as case studies for charging modes of charging facilities [10]. For this reason, we select these cities as case contexts of this study. Specifically, subsidies for charging facility are divided into construction subsidies, operation subsidies and consumption subsidies. Charging facility types are divided into 7-kW alternating current (AC) slow charging, 120-kW direct current (DC) fast charging and 350-kW DC ultra-fast charging. Note that the residual value rate of used equipment in China is 5% and that according to the literature [5], the maintenance and operation costs of charging facilities are set at 2% and 7.3% of the total investment cost, respectively. Given the fact that REAs are not good at operating charging facilities, assume that REAs cost 20% more to operate than CIOs. The parameters of charging facility policies in different cities and different types of charging facilities are summarized in Tables 4 and 5, respectively. For simplicity, according to Table 4, the subsidy policies in Shanghai, Beijing and Shenzhen are set as modes S1, S2 and S3 respectively.

In China, the utilization rate of charging facilities is less than 15% in 2018, so this study assumes a 20% utilization rate of charging facilities in 2020. The effective operating hours of charging facilities in a year is 1752 hours. Considering that the proportion of EVs in Shanghai, Beijing and Shenzhen in 2020 is 10.14%: 9.75%: 8.57%, the effective operating hours of charging facilities in the three cities are set at 1752 hours, 1684.62 hours and 1480.73 hours respectively. In addition, assuming an advertising benefit of $200 per unit of charging facility and a potential usage risk cost of $100. As for the charging cost, the commercial electricity price and the public charging facility charging price (non-EVCI-PPP) are set at 0.1 USD/kWh and 0.3 USD/kWh, and the charging price for the EVCI-PPP project is in between, set at 0.2 USD/kWh. This setting is consistent with existing research and real-world applications [24]. Because REAs bear more investment costs in partnership with CIOs, this study assumes a 7:3 distribution of benefits between the two. To expand revenue sources, assume USD 350 per charging post per year of advertising revenue. Finally, the original values of x, y and z are set to be 0.1. The remaining parameters are listed in Table 6. The simulation experiments were performed by MATLAB 2015b.

Table 4

Policy parameter related to charging facility in Shanghai, Beijing and Shenzhen (references from literature

[10]).

Parameters	Symbols	Values		
		Shanghai (S1)	Beijing (S2)	Shenzhen (S3)
Construction subsidy of charging facilities	G_1	30% of total investment cost	30% of total investment cost	AC 15.48 USD/kW; DC 61.92 USD/kW
Operation subsidy of charging facilities	G_2	0.03096 USD/kWh	0.06192 USD/W for 7 kWh and below, and 0.0774 USD/W for above 7 kWh	-
Consumer charging subsidies	G_3	774 USD/vehicle	-	-

Notes: 1 USD = 6.46 RMB

Table 5

Parameters related to charging facility (references from literature [5], [10] and [24]).

Parameters	Symbols	Values		
		Slow charger	Fast charger	Ultra-fast charger
Power of charging pile /kW	P_e	7	120	350
Service life /year	L_{ci}	15	15	15
Equipment initial investment cost /(USD/pile)	C_{ci}	32577.6	53065.2	80774.4
Equipment Purchase cost /(USD/pile)		619.2	13003.2	30960
Distribution facility cost /(USD/pile)		30000	30000	30000
Construction cost /(USD/pile)		1555.92	7740	15480
Other cost /(USD/pile)		402.48	2322	4334.4
Residual value of wasted equipment /(USD/pile)	RV_{ci0}	252.15	410.72	625.19
Equipment maintenance cost /(USD/pile)	C_2	1628.88	2653.26	4038.72
Equipment operation cost by CIOs /(USD/pile)	C_3	2378.16	3873.76	5896.53
Equipment operation cost by REAs /(USD/pile)	C_5	8893.68	14486.8	22051.41
Land lease cost /(USD/pile)	C_4	59443.20	59443.20	59443.20

Notes: 1 USD = 6.46 RMB

Table 6

The remaining parameters of the case (references from [24]).

Parameters	Symbols	Values
Commercial electricity prices from National Grid	i_1	0.1
Service tariff for charging facilities in EVCI-PPP	i_2	0.2
Service tariff of public charging facilities (non-EVCI-PPP)	i_3	0.3
Percentage of EVCI-PPP operating income available to REA	k	0.7
Annual advertising revenue from unit charging pile	B_{ad}	350
Annual usage risk cost of charging facilities	R_{ci}	100

4.2 Analysis of willingness to cooperate and net benefits

In China, the residential charging infrastructure is mainly slow charging at 7-kW, so this section focuses on the impact of multiple subsidy policies on the willingness to participate and NPV of project agents at this charging power. The setting of comparison models is described below.

Prevalent operations models: M1 refers to the EVCI-PPP model without the participation of CIOs; M2 refers to the EVCI-PPP model without the participation of REAs; M3 is the complete EVCI-PPP model.

Subsidy policies from different cities: S1 refers to Shanghai's subsidy policy (with subsidies for charging facility construction, operation and consumption), while S2 and S3 refer to Beijing (with subsidies for charging facility construction and operation) and Shenzhen (with subsidies for charging facility construction only).

4.2.1 Comparison with prevalent operations models

As mentioned in 3.2, this section focuses on the two patterns, i.e. M1 and M2, as they are most likely to be applied in practice. Fig. 3 shows that all three models have better NPV in the S1 policy environment, with the model M3 in this paper being better than the two operations models used in industry (M1 and M2). Under the S2 and S3 policy environments, the M3 model is still the one with the best economic returns, but the industrial operation model M1 is significantly better than M2. In these scenarios, the NPV of M2 is almost zero, indicating that CIOs are not willing to invest and operate charging facilities in urban residential areas alone. This is consistent with the reality of slow proliferation of charging facilities in urban residential areas, especially in contexts where the real estate is not yet planning to invest and charging facility operators are reluctant to invest in charging facilities. In addition, Figure 3 also shows that S1 has the best policy effect under the three subsidy policy environments, followed closely by S2 and S3.

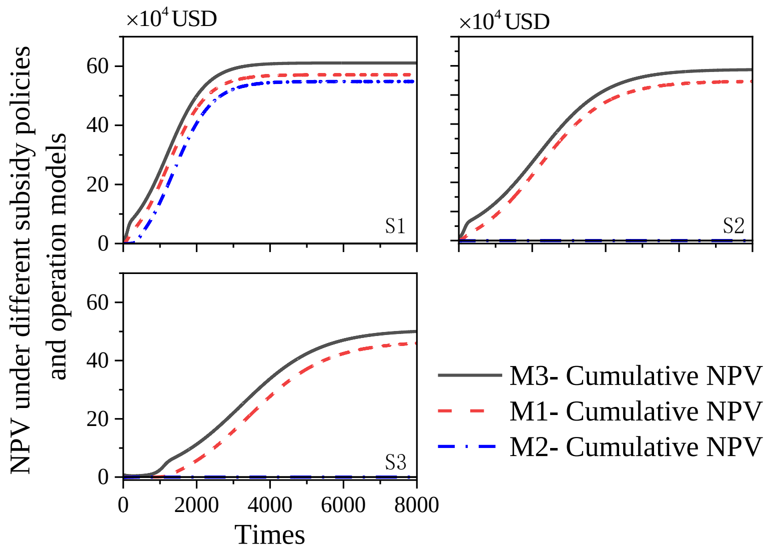

Fig. 3. Cumulative NPV of 7-kw charging piles under different subsidy policies and operations models.

4.2.2 Comparison under different subsidy policies and charging powers

Because M3 is the highest NPV among the three operations models and the 7-kw charging facility is the mainstream charging mode, this section analyzes the willingness of project-related agents to participate under this charging power and M3 model. Fig. 4 shows that the charging facility policies in S1, S2 and S3 can all lead to an equilibrium of (1, 1, 1). In other words, regardless of which subsidy policy is chosen, the project moves toward an equilibrium of (1,1,1). However, compared to S1 and S2, EVUs have a lower willingness to participate under S3 policy environment, which makes it difficult for CIOs to benefit from the cooperation between REAs and CIOs, and their willingness to participate decreases significantly; as EVUs' willingness to participate increases, CIOs' willingness to participate also increases rapidly. The evolution of CIOs' willingness to cooperate in S3 is also consistent with the fact that M1 is more dominant than M2 in Fig. 3.

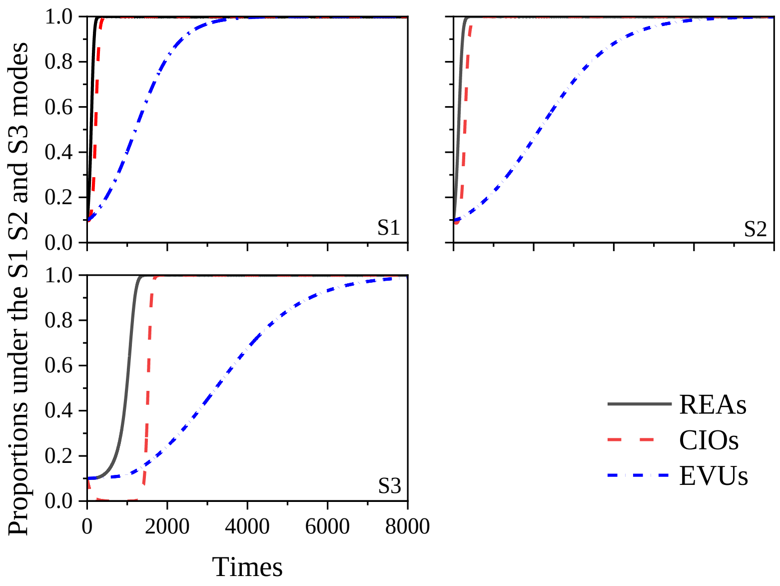

Fig. 4. Evolutionary proportions of players under the S1 S2 and S3 modes.

As for the NPV, Fig. 5 shows that the NPV of the project under policy S1 is significantly better than that of S2 and S3 under the base charging mode of 7-kw. To assess the impact of charging power (120-kW and 350-kW) on the choice of charging mode and policy for the project, a comparative analysis is shown in Fig. 6. The results show that the increase in charging facility power rapidly increases the NPV of the project and reduces the NPV differences of the two policies (S1 and S2). However, the increase in NPV for the 120-kW and 350-kW compared to the 7-kW charging model is not significant and only increases the efficiency of the benefits obtained; this also indicates that the 7 kW charging model is still the most cost effective option in the current environment.

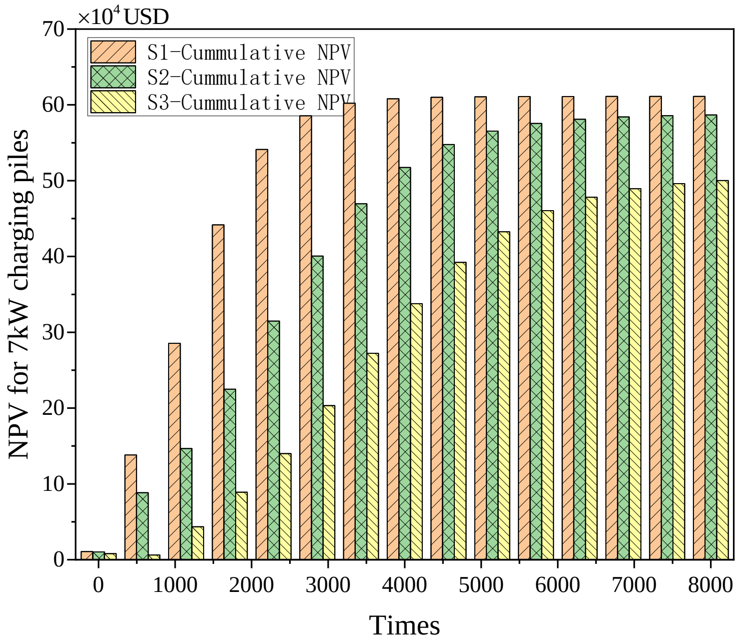

Fig. 5. NPVs of EVCI-PPP considering multiple subsidy models in the 7-kW scenario.

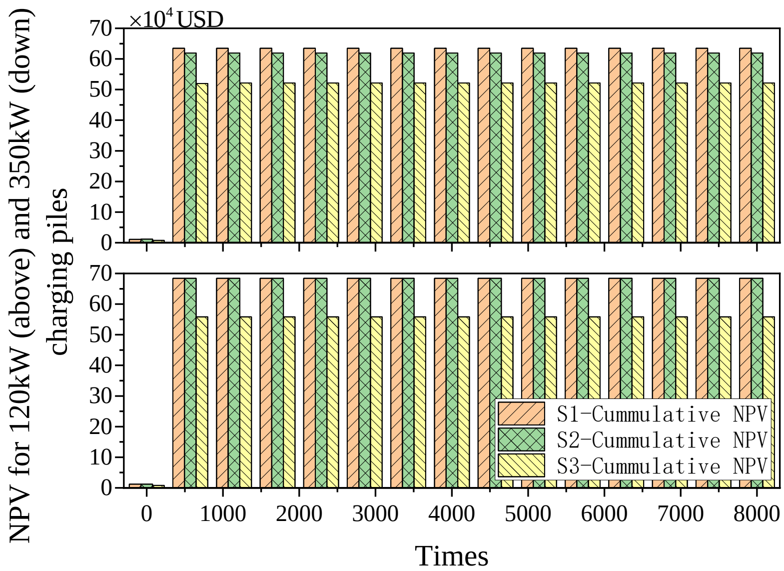

Fig. 6. NPVs of EVCI-PPP considering multiple subsidy models in the 120-kW and 350-kW scenarios.

4.3 Sensitivity analysis

Given that Shenzhen has the worst policy effect, using Shenzhen as a base case can provide theoretical support for the development of charging facilities in more cities in reality. In addition, according to Fig. 4, CIOs are less willing to participate compared to REAs, and the willingness of EVUs to cooperate significantly affects the overall net income of the project and the willingness of CIOs to cooperate. Therefore, this section aims to identify the core factors that enhance the willingness of EVUs and CIOs to participate, as well as enhance the NPV of the project. According to Table 2, it can be seen that the endogenous factors of the project include G_2, G_3, T, i_2, k and B_{ad}. A sensitivity analysis of these factors is shown below.

4.3.1 Impact of factors related to EVUs

EVUs are the primary recipients of program services, and their participation is critical to program benefits. Fig. 7 illustrates the impact of i_2, T and G_3 on EVUs' choice of collaboration strategy. Among them, the government's consumption subsidy can significantly enhance the speed of EVUs' participation in cooperation; EVUs are more sensitive to the service tariff of project charging facilities, and their willingness to participate decreases significantly above 20% of the current tariff and drops to 0 above 40%. As for the effective operating hours of charging facilities, effectively improving the service hours of facilities can significantly increase the willingness of EVUs to participate. However, if the number of effective service hours per year is reduced by a further 20%, their willingness to participate will drop to zero.

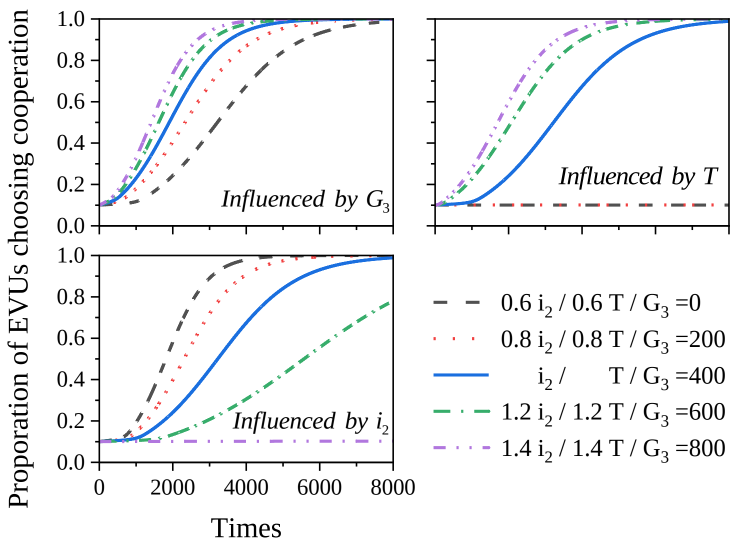

Fig. 7. Proportion of EVUs choosing cooperation influenced by i_2, T and G_3.

4.3.2 Impact of factors related to CIOs

Fig. 8 illustrates the impact of G_2, T, i_2, k and B_{ad} on CIOs' choice of collaboration strategy. The impact of subsidies on the evolutionary trajectory of CIOs is shown in the upper left panel in Fig. 8. The larger is G_2, the sooner the evolutionary trajectories of CIOs reach 1. However, compared to the consumer-oriented incentives in Fig. 7, CIOs need more incentives to significantly increase their willingness to cooperate. The impact of advertising revenue on the evolutionary trajectory of CIOs is shown in Figure 8, middle and upper. The higher the annual advertising revenue, the faster the evolutionary trajectory of CIOs grows. When annual advertising revenue drops to 300 and below, the evolutionary trajectory of CIOs will be 0. The effect of the revenue distribution ratio is shown in the first right-hand side of Fig. 7. The impact of annual effective operating hours on the evolutionary trajectory of CIOs is shown in Figure 7, bottom left. The larger is T, the higher the willingness of CIOs to collaborate. CIOs are reluctant to collaborate when the T-value will be 80% and below. The last panel (bottom middle) shows the impact of the project service tariff. The lower the price of electricity, the higher the willingness of CIOs to participate. This may be because lower service charges lead to more demand for charging, especially if the demand for charging is low.

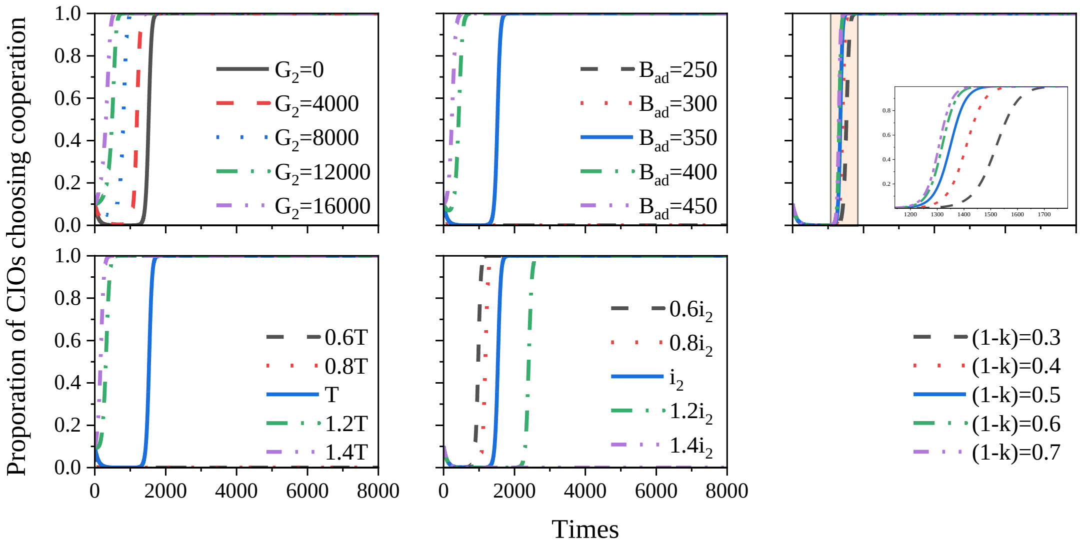

Fig. 8. Proportion of CIOs choosing cooperation influenced by G_2, B_{ad}, k, T and i_2.

4.3.3 Impact of factors related to NPV of the project

Fig. 9 illustrates the impact of relevant factors on the project NPV. Three of these factors (G_2, G_3 and i_2) significantly affect the rate of obtaining net project revenue, and two factors (B_{ad} and T) significantly increase the total project revenue. In terms of net revenue growth rate, subsidies for the consumer side are significantly higher than those for CIOs, and the amount of subsidy is relatively much smaller. In addition, lower annual effective operating hours and advertising revenue for charging facilities, and higher charging prices for project facilities would bankrupt the project with a net gain of 0.

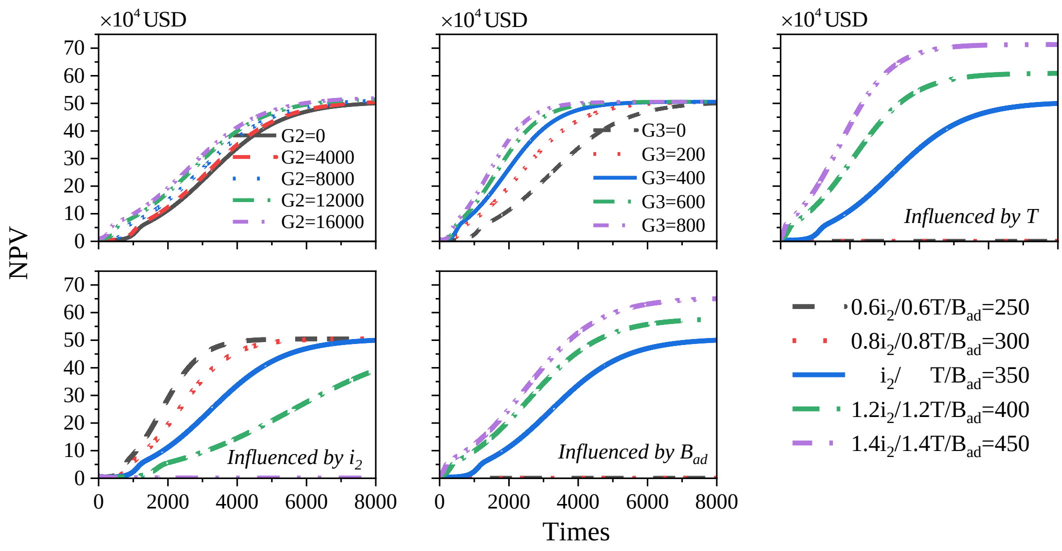

Fig. 9. NPV of the EVCI-PPP influenced by G_2, G_3, T, i_2 and B_{ad}.

5. Discussion

5.1 Theoretical contributions

This study contributes to the literature by proposing a new operation model and the conditions for its application in promoting charging facilities in urban residential areas. It also highlights the importance and unique role of REAs (as a new class of agents) in the rollout of urban charging facilities. However, to the best of our knowledge, the importance of REAs has not been identified, and the responsibilities of the agents involved in promoting urban charging facilities remain unclear; in any case, an effective operation model is urgently needed [19]. To prove the effectiveness of our proposed operation model (M3), this study compares it to current and prevalent operation models (M1 and M2) in the industry; it finds that among the three models, the operation model proposed herein promises the highest economic return (Fig. 3). This advantage holds true in all three policy environments (S1, S2, and S3). Another important contribution is that it finds that charging-facility rollouts by REAs (M1) illustrate better economic performance than those by CIOs (M2), thus demonstrating the importance of REAs. This performance advantage holds true in all three policy environments, and one possible reason for this is that REAs have core resources in the construction of charging infrastructure and its installation points. Without the participation of REAs, high land lease fees will inhibit CIOs' willingness to invest. Therefore, a central takeaway from this study is that governments should actively promote the participation of REAs in the construction of charging facilities.

5.2 Managerial implications

So that the proposed model might better guide practice, this study discusses three specific managerial implications—namely, subsidy policies, operation benefits, and charging demand, which we examine in turn below.

5.2.1 Analysis of subsidy policies

We obtain some key findings concerning subsidy policies, as follows. (1) In considering the three subsidy models (S1, S2, and S3), we find that Shanghai's subsidy policy (S1) is more likely to stimulate investor willingness to invest; it also promises the highest net return. (2) Compared to subsidizing CIOs, subsidizing EV users will be more effective in promoting infrastructure rollout.

These findings provide policy-makers with some clues from multiple perspectives. First, government subsidies are thought to promote the willingness of all three players to cooperate, but especially EV users. In the current early stages of the EV charging infrastructure industry, firms associated with EV charging facilities have only weak profitability [19]; however, EV users remain an important subsidy target because they represent a source of EVCI–PPP project profitability. From an information economics perspective, the granting of government subsidies for charging infrastructure constitutes an important message to consumers, and in this sense they will promote flow-backs of more social capital into the market and support the development of the charging infrastructure industry [5]. This study shows that policy S1 with consumption subsidies offers better program returns than S2 without consumption subsidies, thus supporting the above view. Second, in China, charging facilities are most commonly subsidized for construction, which means that the EVCI–PPP model has a basis for real-world existence. However, although operational subsidies remain important, they are more expensive and less effective than consumer subsidies (Fig. 9). Therefore, when designing subsidy policies, the government should prioritize consumer subsidies over operational ones.

5.2.2 Analysis of operating benefits and charging demand

Some conclusions can also be drawn in terms of operating benefits, as follows.

(1) The mainstream 7-kw service is still the first choice in promoting charging facilities in urban residential areas.

(2) Increased advertising income can lead to a faster evolutionary trajectory for an advantageous strategy, so that it more quickly approaches 1.

(3) An appropriate income distribution ratio can significantly increase the willingness of SPV participants to cooperate.

(4) The annual effective service time of the charging infrastructure is critical to the success of an EVCI–PPP project.

(5) When the electricity price of the charging infrastructure is halved, the user's charging demand increases significantly.

First, the promotion of 7-kw-based slow charging in urban residential areas remains the best option: although Fig. 6 shows that higher-power charging facilities promise better returns, they are not overly larger than those with 7 kw facilities. The main reason for this is that the current charging demand is still not sufficient to match the higher charging power, and that while the higher-power facilities scale back individual charging time, no additional demand is yet arriving. Second, advertising revenue is an additional benefit. EVCI–PPP companies should make full use of their existing equipment, data, and operational experience to create more value-added services and reduce operational costs, including those related to information consulting, advertising, and marketing. Zhang et al. [17] also report this finding. Third, REAs and CIOs should negotiate the income distribution ratio to solidify long-term cooperation and maximize total benefits. In the current state of urban residential charging-facility development, CIOs are significantly less willing to participate than REAs, given the high land lease fees involved. Therefore, enacting an appropriate revenue allocation ratio is crucial to CIO buy-in. CIOs have advanced management experience in charging infrastructure—something that REAs do not have—and REAs have a natural geographic advantage in terms of capital investment and facility installation. We confirmed that cooperation between these two sets of agents would constitute a win–win situation (Fig. 3).

Fourth, in China, the annual effective service time of charging infrastructure is very low, with an average utilization rate of less than 15% [17]. This figure is the most direct evidence of charging-facility mismanagement, and there is considerable room for improvement in the profitability of charging facilities through improved management. EVCI–PPP should devote itself to the management and maintenance of charging facilities, and learn from relevant experiences to prevent problems such as charging and parking difficulties—especially those wrought by the occupation of space by fuel-powered vehicles. Additionally, it is also possible to replace charging facilities with smarter and higher-power facilities to enhance the efficiency of facility services. However, our findings indicate that while higher charging power will result in higher revenue, the difference in revenue is not significant compared to that derived from mainstream 7 kw power. Finally, the charging price is also an important factor of charging demand. The effect of lower charging prices on increased user demand is evident. In China's current state of power system adjustment, charging facilities have long-term and stable charging needs that make them an important user of power systems [17]. This means that charging-facility companies have the opportunity to negotiate with power companies to achieve lower charging prices while achieving a win–win situation.

6. Conclusion and policy implications

The use of electric vehicles (EVs) has flourished in recent years, in response to the growth of sustainable transport and a drive toward an environmentally clean society; nonetheless, the inadequacy of charging facilities has started to hamper the growth of EV use. To solve this problem, we suggest a novel electric vehicle-charging infrastructure/public–private partnership (EVCI–PPP) operation model by which to improve the construction and operation of EV charging facilities in urban residential areas. We provide a theoretical explanation for the application of this model by building a three-dimensional evolutionary game model involving real estate agencies (REAs), charging infrastructure operators (CIOs), and EV end-users, and by analyzing the stable equilibrium conditions of eight cases. We also analyzed a final case study to provide insights into management practices by which to develop China's charging-facility industry.

Compared to previous studies, this study is novel in the following respects. First, this study adds a new agent, REAs, to capture the complex behavior of their investment decisions and incorporate them into the dynamics of charging-facility rollout. Previous studies have ignored the role of REAs in charging-facility rollouts, and their dynamics are relatively absent from their discussions. Furthermore, by designing an EVCI–PPP operation model, this study proposes a new mechanism for dividing responsibilities. Second, we compare this model to prevalent operation models within the industry, through the use of case studies; in the process we demonstrate its superiority and the importance of REAs in the rollout of charging facilities in urban residential areas.

We propose several practical suggestions for increasing charging infrastructure proliferation, charging demand, and operating benefits, and reducing charging price, so as to achieve win–win benefits. First, while government subsidies are an effective strategy by which to enhance the willingness of all players to cooperate, from the perspective of financial pressure, the government should encourage the application of the REA-driven EVCI–PPP model. Second, companies subscribing to the EVCI–PPP model should broaden their revenue channels and take full advantage of existing equipment, data, and operational experience to develop value-added services and reduce operating costs. REAs and CIOs should also make full use of their strengths to negotiate the income distribution ratio of long-term cooperation and achieve a win–win business situation. Moreover, they should pay attention to the management and maintenance of charging facilities so as to prevent management issues—such as charging and parking difficulties—while considering charging infrastructure's low utilization rate (i.e., 15%). Finally, SPV in EVCI–PPP projects should seize the opportunity to work with power companies to negotiate lower electricity prices and capture more charging demand.

This study has some limitations that should be addressed. First, while subsidy policies serve as an incentive mechanism by which to improve the willingness of participants to cooperate, government incentives can take many forms, such as indirect and direct subsidies. Thus, future research could look more deeply at incentive strategies and their forms, and explore their impact on the cooperation model. Second, as the current government strategy is analyzed based on static scenarios, it behooves the government to analyze the influence of dynamic strategies on EVCI–PPP projects. These considerations are left to future research.

Appendix

M1: Charging infrastructure service system consisting of REAs and EVUs. The expected payoffs of REAs and EVUs are shown in (A1) and (A2), respectively.

$$\begin{cases} E_{REA1} = \left(P_e\left(i_2 - i_1\right) + B_{ad}\right)zT + RV_{ci} - C_1 - C_2 - C_5 - C_6 + G_1; \\ E_{REA0} = 0; \\ \overline{E_{REA}} = -x\left(z\left(P_e\left(-i_2 + i_1\right) - B_{ad}\right)T - RV_{ci} + C_1 + C_2 + C_5 + C_6 - G_1\right); \end{cases} \quad \text{(A1)}$$

$$\begin{cases} E_{EVU1} = -\left(\left(i_2 - i_3\right)x + i_3\right)TP_e - R_{ci}x + G_3; \\ E_{EVU0} = -P_e T i_3; \\ \overline{E_{EVU}} = \left(-Tx\left(i_2 - i_3\right)P_e - R_{ci}x + G_3\right)z - P_e T i_3; \end{cases} \quad \text{(A2)}$$

The replicator equation dynamics of M1 are listed in (A3) and (A4).

$$f_{REA}(x) = \frac{dx}{dt} = x(E_{REA1} - \overline{E_{REA}}) = x\left(-1 + x\right)\left(-z\alpha_1 + C_5 + C_6 - G_1 + \alpha_2\right) \quad \text{(A3)}$$

$$f_{EVU}(z) = \frac{dz}{dt} = z(E_{EVU1} - \overline{E_{EVU}}) = \left(-1 + z\right)z\left(\left(T\left(i_2 - i_3\right)P_e + R_{ci}\right)x - G_3\right) \quad \text{(A4)}$$

M2: Charging infrastructure service system consisting of CIOs and EVUs. The expected payoffs of CIOs and EVUs are shown in (A5) and (A6), respectively.

$$
\begin{cases}
E_{REA1} = \left(P_e\left(i_2 - i_1\right) + B_{ad}\right) zT + RV_{ci} - C_1 - C_2 - C_3 - C_4 + G_2; \\
E_{REA0} = 0; \\
\overline{E_{REA}} = -y\left(z\left(P_e\left(-i_2 + i_1\right) - B_{ad}\right)T - RV_{ci} + C_1 + C_2 + C_3 + C_4 - G_2\right);
\end{cases} \tag{A5}
$$

$$
\begin{cases}
E_{EVU1} = -\left(\left(i_2 - i_3\right) y + i_3\right) TP_e - R_{ci} y + G_3; \\
E_{EVU0} = -P_e T i_3; \\
\overline{E_{EVU}} = \left(-Ty\left(i_2 - i_3\right) P_e - R_{ci} y + G_3\right) z - P_e T i_3;
\end{cases} \tag{A6}
$$

The replicator equation dynamics of M1 are listed in (A7) and (A8).

$$
f_{CIO}(y) = \frac{dy}{dt} = y(E_{CIO1} - \overline{E_{CIO}}) = y\left(-1 + y\right)\left(-z\alpha_1 + C_3 + C_4 - G_2 + \alpha_2\right) \tag{A7}
$$

$$
f_{EVU}(z) = \frac{dz}{dt} = z(E_{EVU1} - \overline{E_{EVU}}) = \left(-1 + z\right) z\left(\left(T\left(i_2 - i_3\right) P_e + R_{ci}\right) y - G_3\right) \tag{A8}
$$

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