Energy Proceedings
Vol 37, 2023
ISSN 2004-2965

# Network-integrated evolutionary analysis for electric vehicle charging infrastructure deployment in the UK

Jie Sun[1], Boli Chen[2], Yukun Hu[1*]

1 Department of Civil, Environmental and Geomatic Engineering, University College London, WC1E 6BT, UK

2 Department of Electronic and Electrical Engineering, University College London, WC1E 6BT, UK
(*Corresponding Author: yukun.hu@ucl.ac.uk)

## ABSTRACT

Due to the current booming growth of electric vehicles (EVs), the insufficiency of charging infrastructure (CI) distributions has become one of the key obstacles to the potential expansion of the EV market. To further upgrade the Electric vehicles Charging infrastructure (EVCI) in the UK, governments have launched multiple incentives to encourage EVCI deployment and investment from the industry. In order to measure the effectiveness and feasibility of the current policies and seek other potential measurements, this paper applies an evolutionary game analysis integrated with complex network topologies, which aims to probe into the interactions and competitiveness between stakeholders. It contributes to practitioners and academia in the following aspects: (1) thorough insights into EVCI markets by modelling the evolution of EVCI distribution under heterogeneous incentives. (2) an equilibrium of EVCI deployment in the evolution process and elucidates the different impacts of incentives. (3) a whole network involving the main stakeholders, governments, EVCI investors, and end-users, facilitating an effective policy framework.

**Keywords:** Electric Vehicles, Charging stations, Policy incentives, complex networks, Evolutionary game theory

## NONMENCLATURE

| | |
|---|---|
| *Abbreviations* | |
| EV | Electric vehicles |
| CI | Charging infrastructure |
| CV | Conventional Vehicles |
| GHG | Greenhouse gases |

## 1. INTRODUCTION

The transportation sector is recognized as one of the primary contributors to greenhouse gas (GHG) emissions, promoting governments all over the world to actively engage in endeavors to mitigate carbonization [1]. The transformation from Conventional Vehicles (CVs) to Electric Vehicles (EVs) and the deployment of the charging infrastructure is widely acknowledged as the most promising way to support the decarbonization process [2]. This progress is further accelerated by advancements in vehicular technologies and the implementation of supportive measures and incentives by national governments [3]. To address the challenge of the growing demand for EV charging and the current limitations in infrastructure, the UK government has set ambitious goals of installing 300,000 public charging stations by 2030, aiming to overcome the current count of 34,637 electric vehicle charging points across the country [4]. Despite these initiatives, the disparity between charging demand and the existing infrastructure presents an obstacle to the further development of EVs. In response, the UK government has introduced various policy incentives to promote the installation of charging infrastructure (CI).

Finding the appropriate ratio of EVCI to traditional gas stations requires consideration of the perspectives of three key stakeholders: governments, EVCI investors, and EV-users [3]. In the real market scenario, the construction of CI was significantly influenced by the income of EVCI investors [5]. Subsidies and taxation policies on energy stations, released by governments, directly impact the profit of EVCI and gas stations. Simultaneously, consumer preferences for EVs or CVs, which lead to the demand for EV charging and Gas refilling, would shape the utilization patterns and connection between different energy stations [6]. The

# This is a paper for the international conference on energy, ecology and environment 2023 (ICEEE2023), Aug. 14-18, 2023, London, UK.

following questions are proposed in this paper: (1) How do consumer preferences affect the diffusion of ECVI? (2) How to accelerate and promote the investment in EVCI market? (3) How do the policies influence the distribution of CI and the ratio of energy stations?

The existing literature highlights the significance of heterogeneous incentives. Helmus et al. evaluated the economic performance of CI based on demand-driven and supply-driven strategies, with the Netherlands as the case study [7]. Fang et al. defined EVCI deployment as the process of EVCI investment strategy and investigated the dynamic impacts of policy incentives [5]. Meanwhile, consumer preferences play a crucial role in shaping the adoption of EVCI by influencing vehicle choices. Tan and Lin surveyed the attitudes of EV users in the major cities in China, but there is a need to consider and evaluate the opinions of users from various cities to avoid potential biases in the findings [8]. Li et al., as one of the earliest researchers brought up the idea of applying dynamic evaluation to the diffusion of EVCI, constructed a multi-sectorial stochastic evolutionary game model, aiming to strike a balance between the supply and demand of EV charging and CI [9]. Huang et al. also applied the evolutionary game model to explore the interactions under static and dynamic policies released by governments, to promote public–private partnership cooperation in EVCI planning [10].

Recently, the UK government published aggressive emission targets, aiming to halt the sale of new petrol and diesel CVs by 2030 and achieve zero tailpipe emissions goals from new energy vehicles by 2035[11]. To encourage EVCI deployment, the government is offering grants for over £80 million, aiming to cover 75% of the installation cost for EV chargepoints, with the focus on workplaces and residential areas [12]. These incentives provide plain guidelines for EVCI operators and underscore the significance of forming a robust EVCI market and a sustainable infrastructure network.

This paper commences by introducing the prevailing incentive policies pertaining to EVCI in the UK, utilizing construction subsidies as a representative example. Subsequently, a network-based evolutionary game analysis is employed to assess the competitive dynamics among diverse energy stations, encompassing their integration into the network and an exploration of how incentives impact both individual stations and the relationships between neighboring entities. Furthermore, this paper simulates the impacts of the market under various scenario depths, thus furnishing precise and actionable recommendations for governmental authorities.

## 2. METHODS

Currently, the amount of EVCI is not sufficient in the UK. To promote the construction of charging infrastructure, the network based evolutionary game model was applied to assess the future demand for EV charging and to strategize the appropriate allocation of EVCI resources. The primary objective of this research is to invigorate the market and attract increased investment from stakeholders interested in the domain of EV charging, whose determination would be greatly influenced by the income of projects and the profits. Consequently, the revenue generated by an EVCI is contingent upon factors such as the initial investment, government subsidies and taxation policies, energy prices during construction, usage, and upgrades, as well as the income derived from nearby residents. By analyzing and optimizing these variables, this study endeavors to contribute to the advancement of the EV charging sector in the UK.

The network based evolutionary game analysis is proposed in this paper. There are N stations concerned in the game and every station is affected by other stations around it, which creates competition with its neighbors. For the investors, they have two strategies in the energy stations, CI or GS. The decision from investors would be determined by the profit of stations for their profit-driven determination which needs the incentives from the government. In each round of the simulation, on a given station i, if its neighbors are the same type as i, the station i and its neighbors would share the net profit of the local area. If the neighbors are not the same as station i, and the neighbors get lower profit than i, they would have a certain probability to copy the strategy of station i and turn to the same type as i and vice versa. Based on this completive mechanism of each station, they would need to be considered in the network system, wherein the network topology was applied. In this paper, the small world complex network is applied, and the connections of stakeholders are viewed in this network. Fig.1 shows the temporal snapshots of the characteristics of energy stations in the complex network. The results of the simulation were the average

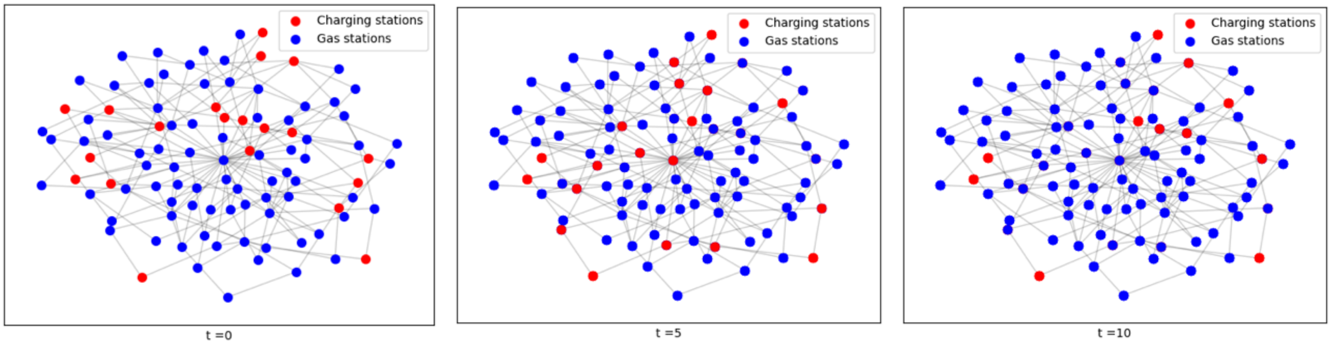


Fig.1 Temporal snapshots of the characteristics of energy stations in the complex network

number of 10 iterations which aim to avoid the exaggerated randomness of the network.

## 3. RESULTS AND DISCUSSION

### 3.1 The influence of balanced and unbalanced policies

In accordance with the policies released by the UK government, a notable observation reveals that the majority of these policies can be categorized as static, falling into two distinct classes: balanced policies and unbalanced policies. The notion of "unbalanced policy" refers to governmental measures exclusively targeting EVCI. Specifically, this paper focuses on the subsidies disbursed by the UK government in support of EVCI. The concept of "balanced policy" encompasses measures aimed at both EVCI and GS, encompassing subsidies and taxation. In this study, these policies were assumed to be equivalently applied for simplicity. The data used in this paper was collected from the UK government [4] [11] [12]. The outcomes of these two policy types are visually represented in Figure 2 and Figure 3. G and F in the figures refer to the amount of subsidies and taxation.

Figure 2 illustrates the dynamics of EVCI occurrence within the network, under various instances of unbalanced policies. Specifically, the proportion of EVCI exhibits considerable fluctuations, particularly when the subsidy is lower than 4000 USD, and diminishes further when the subsidy reaches its minimal amount, effectively reaching zero. Notably, marginal differences are evident between scenarios where the subsidy stands at zero or 2000 USD, as indicated by the orange and blue lines. However, when the subsidy reaches 4000 USD, the proportion of EVCI is maintained at a level close to its initial value. In contrast, a substantial surge in the proportion of EVCI is witnessed within fewer than 20 rounds, as the subsidy surpasses 5000 USD. At this point, the proportion of EVCI reaches 60% and maintains a steady level. In order to attain an additional 20% increase in the proportion of EVCI, the subsidy would need to be doubled, rising to 10,000 USD.

Based on the findings depicted in Figure 2, it can be deduced that a subsidy of 10,000 USD represents a reasonable amount, given that even with an additional 5000 USD increase in the subsidy, the proportion of EVCI does not demonstrate a significant disparity. Consequently, from a fiscal budget perspective, it is evident that 10,000 USD is the most suitable amount for the static subsidy policy.

The market's stability may be compromised if governments solely focus on implementing subsidy policies, given the relatively limited degree of self-accommodation exhibited by the free market [5]. In such circumstances, it becomes necessary to consider implementing complementary policies, particularly those directed towards GS, and taxation emerges as a common approach. This study adopts a perspective that accounts for balanced policies, involving the simultaneous application of subsidies and taxation. As depicted in Figure 3, when both subsidies and taxation remain below 2000 USD, the proportion of EVCI experiences fluctuations before stabilizing at approximately 20%. However, a significant and rapid surge in the proportion of EVCI occurs when balanced policies reach 3000 USD for both EVCI and GSs, leading to a stable proportion of 80% for EVCI. However, as the balanced policies continue to increase, there is no substantial impact on the EVCI market share, as evident from the representation of the green, red, and purple lines.

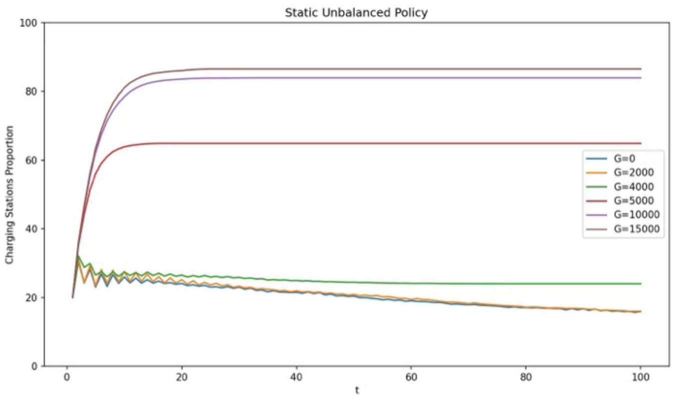


Fig.2 The percentage of EVCI market share under unbalanced policy

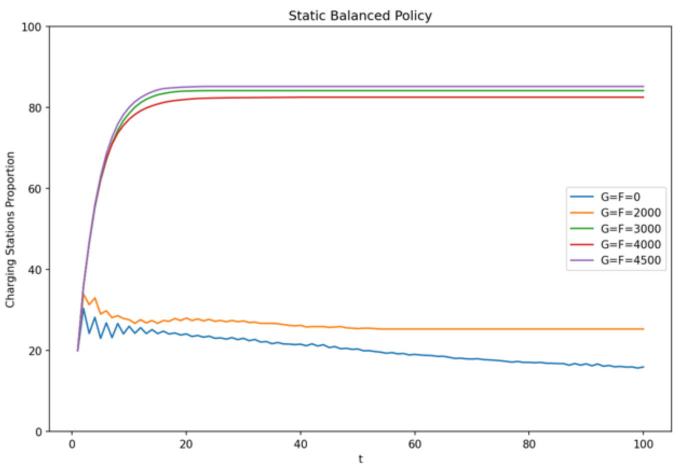


Fig.3 The percentage of EVCI market share under balanced policy

Based on the findings presented in Figure 2 and Figure 3, it becomes evident that balanced policies exhibit notable advantages over unbalanced policies on the aspect of the promotion of EVCI. Achieving an 80% market share of EVCI necessitates only one-third of the resources consumed by unbalanced policies. This disparity in resource consumption demonstrates the greater efficiency and cost-effectiveness of balanced policies in promoting EVCI.

### 3.2 The influence of consumer preferences

The inclination of consumers towards different types of vehicles plays a crucial role in the promotion of EVCI. This correlation is elaborated in Figure 4, which showcases the relationship between consumer choices and the percentage of EVCI. This picture demonstrates a clear trend wherein an increase in the proportion of EV users leads to a corresponding rise in the percentage of EVCI. When only 20% of consumers opt for EVs, the market share of EVCI experiences fluctuations, resulting in a decrease. However, with a rise in the percentage of EV users to 30%, the market share of EVCI stabilizes around its original status. When the proportion of EV users reaches 40% in the market, there is a substantial and sustained surge in the market share of EVCI, stabilizing at approximately 80%.

This picture reveals the significance of early-stage consumer preference for EVs in fostering the growth of the EVCI market. Accordingly, it becomes imperative for the government to implement policies aimed at encouraging consumers to choose EVs during the decision-making process. By ensuring that the proportion of EV-preferred users attains 40%, a substantial market share of EVCI can be achieved, also at around 80%.

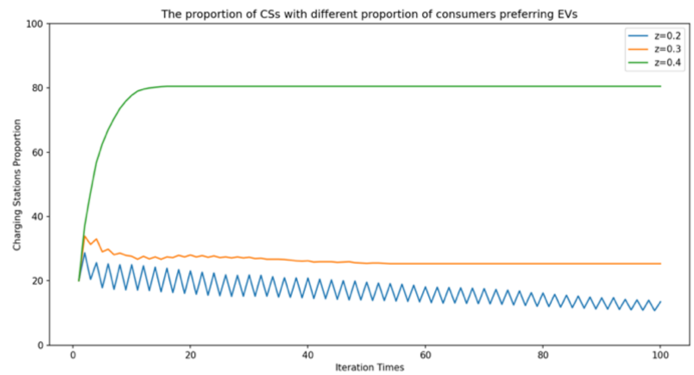


Fig. 4 The percentage of EVCI market share under different consumer preference

## 4. CONCLUSIONS

The increasing consumer interest in EVs underscores the pressing need for an adequate amount of EVCI. Presently, the UK's EVCI remains relatively low compared to other countries, but its market potential is substantial. To address this concern, this paper proposes a network-based evolutionary game model to gain insights into the role of government influence and identify suitable measures.

Based on the simulation results, several key conclusions can be drawn. First, both balanced and unbalanced policies exert significant influence on the market share of EVCI. Second, when compared to unbalanced policies, balanced policies prove more advantageous for fiscal budget management and efficiency enhancement. Balanced policies could stimulate the market and mitigate investor sluggishness effectively. Third, government intervention in the EV selling market is necessary to encourage greater development of EVCI. By promoting EV users to constitute 40% of the market, substantial progress in EVCI can be achieved. Last, the simulation reveals an upper limit to the increase in EVCI market share, approximately reaching 80%.

The insights from this study offer valuable guidance to governments when designing policies to boost the

EVCI market share. Financial support and effective promotional strategies are pivotal, as demonstrated by the initial stagnation of market share in the absence of government intervention. Additionally, the energy station market is expected to persistently include both EVCI and GS due to varying consumer preferences. This study identifies the upper limit of EVCI market share, which encompasses approximately 80% of all energy station types.

Nonetheless, certain limitations must be acknowledged. On the one hand, the consideration of hybrid EV necessitates further attention. In this paper, hybrid EVs demands are simplified into ordinary EVs, which needs future investigations into more specific vehicle categories. On the other hand, as the EVCI proportion grows, subsidy adjustments could alleviate the fiscal budget burden. Hence, dynamic policy changes catering to shifts in the CI and GS market shares over an extended period should be considered in future research endeavors.

**ACKNOWLEDGEMENT**
The work received financial supported from Civil, Environmental and Geomatic Engineering, University College London.

**DECLARATION OF INTEREST STATEMENT**
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

**REFERENCE**
[1] C. Zhang, L. Lv, and Z. Wang, “Evolutionary Game Analysis for Key Participants’ Behavior in Digital Transformation of the Chinese Construction Industry,” Buildings 2023, Vol. 13, Page 922, vol. 13, no. 4, p. 922, Mar. 2023, doi: 10.3390/BUILDINGS13040922.
[2] B. Mawhood, H. Edwards, I. Stewart, P. Bolton, and R. Tyers, “Electric vehicles and infrastructure.” Accessed: Jul. 07, 2023. [Online]. Available: https://commonslibrary.parliament.uk/research-briefings/cbp-7480/
[3] R. Chen, R. Fan, D. Wang, and Q. Yao, “Effects of multiple incentives on electric vehicle charging infrastructure deployment in China: An evolutionary analysis in complex network,” Energy, vol. 264, p. 125747, Feb. 2023, doi: 10.1016/J.ENERGY.2022.125747.
[4] “Electric vehicle charging device statistics: October 2022 - GOV.UK.” https://www.gov.uk/government/statistics/electric-vehicle-charging-device-statistics-october-2022/electric-vehicle-charging-device-statistics-october-2022#experimental-statistics (accessed Jun. 14, 2023).
[5] Y. Fang, W. Wei, S. Mei, L. Chen, X. Zhang, and S. Huang, “Promoting electric vehicle charging infrastructure considering policy incentives and user preferences: An evolutionary game model in a small-world network,” J Clean Prod, vol. 258, p. 120753, Jun. 2020, doi: 10.1016/J.JCLEPRO.2020.120753.
[6] A. U. Rehman, Z. Ullah, A. Shafiq, H. M. Hasanien, P. Luo, and F. Badshah, “Load management, energy economics, and environmental protection nexus considering PV-based EV charging stations,” Energy, p. 128332, Jul. 2023, doi: 10.1016/J.ENERGY.2023.128332.
[7] J. R. Helmus, J. C. Spoelstra, N. Refa, M. Lees, and R. van den Hoed, “Assessment of public charging infrastructure push and pull rollout strategies: The case of the Netherlands,” Energy Policy, vol. 121, pp. 35–47, Oct. 2018, doi: 10.1016/J.ENPOL.2018.06.011.
[8] R. Tan and B. Lin, “Are people willing to support the construction of charging facilities in China?,” Energy Policy, vol. 143, p. 111604, Aug. 2020, doi: 10.1016/J.ENPOL.2020.111604.
[9] J. Li, H. Ren, and M. Wang, “How to escape the dilemma of charging infrastructure construction? A multi-sectorial stochastic evolutionary game model,” Energy, vol. 231, p. 120807, Sep. 2021, doi: 10.1016/J.ENERGY.2021.120807.
[10] X. Huang, Y. Lin, M. K. Lim, F. Zhou, R. Ding, and Z. Zhang, “Evolutionary dynamics of promoting electric vehicle-charging infrastructure based on public–private partnership cooperation,” Energy, vol. 239, p. 122281, Jan. 2022, doi: 10.1016/J.ENERGY.2021.122281.
[11] “UK electric vehicle infrastructure strategy - GOV.UK.” https://www.gov.uk/government/publications/uk-electric-vehicle-infrastructure-strategy (accessed Jul. 07, 2023).
[12] “Grant schemes for electric vehicle charging infrastructure - GOV.UK.” https://www.gov.uk/government/collections/government-grants-for-low-emission-vehicles (accessed Jul. 07, 2023).