

Charging change: Analysing the UK's electric vehicle infrastructure policies and market dynamics

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ABSTRACT

Over the past decades, there has been a rapid adoption of electric vehicles (EVs) and a gradual reduction in the number of Gas Stations, aligning with carbon neutrality objectives. Major oil companies, like Shell, are transferring Gas Stations to Charging Stations, supported by UK government incentives to stimulate the charging infrastructure. This paper systematically investigates three key stakeholders: government, investors, and end-users, examining their interactions and the transition of stations, and evaluating the economic intrinsic competition relationships. Integrating the complex networks, it spatially represents the relative positions of stations and designates Gas Stations as potential future locations for Charging Stations. Meanwhile, this paper comprehensively analyses various policies targeting the UK market, applies dual market analysis to compare the simple and complex market structures among policy scenarios, emphasising the necessity for applying complex interactive markets in industrial evaluation. The findings reveal that direct policies targeting Charging Stations exert immediate and positive effects, while indirect policies targeting Gas Stations and consumers demonstrate marginal diminishing effects. Furthermore, subsidies on the EV prices are less effective compared with other policies, like construction subsidies, operation subsidies, etc., highlighting the need for targeted policy designs, to maximise the expansion and efficacy of EVs and Charging infrastructure.

1. Introduction

With the current development of technology, the growing problem of pollution and the urgency for energy conservation have become demanding and need to be addressed. Carbon emissions caused by Transportation are severe and account for one-fifth of global carbon emissions (Shoman et al., 2023). Compared to internal combustion engine (ICE) vehicles, electric vehicles (EVs) have been shown to reduce greenhouse gas emissions, which are approximately 17%–30% lower than those of ICE vehicles (Li and Wang, 2023; Schwab et al., 2022). However, the current inadequacy of Charging Stations in the UK has generated significant anxiety among residents regarding the choice between EV and ICE vehicles (Beijing et al., 2017).

To meet the necessity of Charging Station development, policies and directives from the government have been released among regions, which aim to impact the revenue of Charging Station operators and attract more investors (Liu et al., 2023). Regions such as Norway, China, the US, the EU, and the UK can be seen as notable leaders in EV and

Charging Station deployment (Chen et al., 2020). Norway, with 80% of new car sales being electric in 2022, benefits from comprehensive incentives, including tax exemptions and non-monetary benefits (Yang et al., 2023). The approach in China involves strong government support and significant investments in Charging stations, achieving a 22% EV market share, whereas the European Union and the United States show more moderate but growing adoption rates (Esmaili et al., 2024; Neshat et al., 2023; Yang et al., 2020). This suggests that combining financial incentives and regulatory support, as seen in Norway and China, could be critical for the UK to enhance its EV adoption rate. Concurrently, the UK promotes EV development through financial incentives such as grants and subsidies for charging infrastructure, alongside a legislative ban on new petrol and diesel cars by 2030 (GOV.UK, 2020). Meanwhile, the sales of EVs in most regions in Europe will experience robust growth in 2022, especially in the UK, which shows great potential development in the future Charging Station market (Schwab et al., 2022). Additionally, there is a disparity in systematic academic research focus on Charging Station policies, with less attention on the UK compared to Norway and China (Peng et al., 2024).

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Nomenclature		USD	
Abbreviations		P_4	EV selling subsidy, USD
CS	Charging stations	P_5	Electricity selling subsidy, USD
EGT	Evolutionary game theory	R	Expectation of revenue of given energy station, USD
EV	Electric vehicle	U	Perceived utility of users choosing a certain type of vehicle, -
GS	Gas stations	e	Annual energy consumption of per EV, kWh
ICE	Internal combustion engines	f	Annual energy consumption of per ICE vehicle, Litre
Parameters		r	Revenue of the given energy station, USD
A	The average profit for each node, USD	k	Noise factor, -
C	Cost of new vehicles, USD	n	Number of stations
D	Demand of current market, -	r	Revenue of the given energy station, USD
E_p	Electricity purchasing price from upper-tier distributors, USD	u	User convenience to the stations,-
E_s	Electricity selling price, USD	x	Percentage of Charging Stations in the network,-
F_p	Gas purchasing price from upper-tier distributors, USD	z	Probability of consumers selecting a certain vehicle,-
F_s	Gas selling price, USD	α_1	Consumers' sensitivity to charging or refuelling utilities,-
I	Investment, USD	α_2	Consumers' sensitivity to the cost of buying a new vehicle,-
L	Service life of devices, years	α_3	Consumers' sensitivity to non-monetary incentives,-
M	Non-monetary incentives from the government, -	β	Consumers' random choice for vehicles,-
N	Number of nodes of the network, -	ε	Discount rate
P_1	Annual operation subsidy for Charging Stations, USD	δ	Number of vehicles around the given energy station,-
P_2	Annual taxation for Gas Stations, USD	η	Percentage of group 3 consumers, which need to purchase or change new vehicles,-
P_3	Subsidy for devices and installation of Charging Stations,	γ	Perceived utility coefficient of energy infrastructures

Therefore, this paper aims to measure the development of Charging Stations in the UK by considering market forces and governmental promotion. Presently, Shell has embarked upon a significant transition by initiating the conversion of select petrol stations into rapid charging stations, notably observed in London during 2022 (Shell, 2022). Motor Fuel Group, an independent forecourt operator within the UK, has undertaken the acquisition of 337 petrol stations from Morrisons, outlining strategic plans for the installation of charging infrastructure (FleetNews, 2024). Meanwhile, an increasing number of researchers are considering Gas Stations as potential locations for constructing Charging Stations (El Hafdaoui et al., 2023). Philipsen designed a survey and concluded that Gas Stations could be viable choices for future fast Charging Stations because the locations of Gas Stations are mostly well-positioned and have a high existing demand for vehicles (Philipsen et al., 2016).

In practical applications, safety is crucial, particularly when installing Charging Stations at locations that were or are Gas Stations. It is necessary to conduct comprehensive risk assessments to ensure safe distances from potentially hazardous areas (Ma and Huang, 2019). For instance, petrol pumps are categorised under Zone 2 hazardous areas, and a minimum distance of 30 feet is recommended to prevent any risks associated with flammable fumes (HSE, 2002). Specific standards, such as the Australian Standard AS 1940–2017, dictate the minimum separation required between fuelling areas and public spaces to prevent fire hazards, such as maintaining at least a 3-m distance from public buildings (Standard Australian, 2017). Furthermore, the International Fire Code in the U.S. mandates that fuel pumps be located at least 20 feet from buildings unrelated to the fuelling operation (IFC, 2020). It is essential to consult local building authorities or fire departments to align with the specific safety regulations applicable to the installation of electric vehicle charging infrastructure at these sites. These measures are vital for ensuring safety and are potential areas for future research to update and refine safety protocols for charging station installations.

These endeavours underscore a discernible transition from traditional energy facilities to electric charging infrastructure, which has garnered considerable attention and acknowledgement within energy enterprises (Feng and Khan, 2024). Therefore, this study simulates the transition from Gas Stations to Charging Stations by exploring their

inner connections, referred to as Energy Stations in the following. Simultaneously, given that Energy Stations are inherently driven by self-interest in the market, investors make decisions based on the profitability of their investment goals. This paper adopts the concept of the profit of energy for the energy station market by applying utility functions to measure the decision-making processes of stakeholders quantitatively (Liu et al., 2024). Moreover, the profit of each energy station would be influenced by its neighbours, which would affect the evolution progress. To capture the interaction between energy stations and determine the strategy of nodes, this paper applied the Complex Networks to simulate the location and relationship of stations. The Small-World network, one of the most applied complex networks in evaluating the Charging Station market, first proposed by Watts and Strogatz (Watts and Strogatz, 1998), is used as topology in this research. Some researchers hold the opinion that the Charging Station market is a perfectly competitive market that matches the characteristics of the Small-World complex network, which is the reason for its application in this context (Atkinson et al., 2021; Fang et al., 2020). For the Decision-Making Mechanisms on Complex Networks, this paper applied the Evolutionary Game Theory (EGT) method to capture the update mechanism of the network and capture the strategies among stakeholders according to evolving policies, as well as market dynamics within the energy station market.

This paper aims to address the following research questions. Firstly, within the energy station market, what are the intrinsic competitive or associative dynamics between Gas Stations and Charging Stations, and how to determine the transition rules from Gas Stations to Charging Stations? Secondly, how do vehicle users influence the distribution and development of energy stations in the market, and how does the performance of a market considering the interactive connections between end-users and energy stations differ from a simple market model? Thirdly, what impact will policy incentives have on the energy station market, and on what level and on what objects should the government apply the policies? The contribution can be summarised in the following content:

First, this study investigates the Charging Station market in the UK, which is experiencing significant change and is relatively under-

researched, especially concerning Charging Station policy. To address the suitability and potential impact of diverse policies within the UK context, the study simulates the effects of these policies on different targeted stakeholders.

Second, this research focuses on the industrial application of energy station evolution, with an emphasis on the transformation of Gas Stations to Charging Stations, which is critical given the increasing need for upgrading traditional energy enterprises. To model this energy station transformation, a combined Complex Networks and Evolutionary Game Theory (EGT) method is employed to capture the dynamic interactions between energy stations, integrating consumer behaviour with infrastructure dynamics.

Third, this paper also applies the innovative dual-market analysis for policy evaluation, comparing simple and complex market structures in this context. This provides an in-depth understanding of how changes within one domain affect another, aiming to maximise benefits for all stakeholders, compared with existing literatures. The study emphasises the necessity of simulating complex markets within the actual industrial environment and highlights the influence of the interplay between stakeholders, which ensures theoretical and practical feasibility while addressing potential adoption barriers that may not be apparent from a purely technical perspective.

This paper is organised as follows. Section 2 reviews the work regarding current incentives and evolutionary game approaches in sustainable systems. Section 3 describes the research problem and explains how the evolutionary game model works. Section 4 shows the results of the simulation, compares the simplified market and complex interactive market, and emphasises the importance of integrating more complicated conditions into the simulation. Sections 5 and 6 discuss and explain the main conclusion.

2. Literature review

The layout of Charging Stations is pivotal for the growth of EVs, especially in the current shift from ICE vehicles to EVs within the vehicle market (Kchaou-Boujelben, 2021). This transition necessitates a focused evaluation of the balance and distribution between Gas stations and Charging Stations (Feng and Khan, 2024). To address these challenges, the section focuses on towards these multifaceted goals. In one aspect, technological advancements are essential for the Charging Station deployment problem. In the meantime, the market dynamic and supportive policy frameworks cannot be underestimated in fostering the development of EVs (Yang et al., 2023). This paper concentrates on the evolution and balance of vehicular infrastructure, probing into the policy environment that facilitates the shift from Gas stations to Charging Stations. It utilises complex networks, integrating the evolutionary game framework to simulate realistic scenarios, alongside conducting comprehensive economic evaluations and behavioural analyses of users. This chapter aims to synthesise findings across three main areas: the current research landscape for Charging Stations, the policy implications, and the methodological application of complex networks to review and expand upon existing research.

2.1. State of the art of EVCI deployment research

Current research on Charging Stations encompasses a diverse array of focal areas, including site selection modelling for charging stations, grid stability and safety, and the dynamics of competition within the vehicle market (Kchaou-Boujelben, 2021). Regarding the site selection for charging facilities, some researchers have employed Points of Interest as a basis for evaluation, constructing models to address the demands for charging and the capacity for coverage (K. et al., 2024). These models include the flow capture model, refuelling flow model, arc coverage model, path partitioning model, and State of Charge tracking model (Keramati et al., 2024; Lai and Li, 2024; Park and Lee, 2024; Pinter et al., 2024; Tahir et al., 2024). Moreover, simulations of traffic

conditions and driving behaviours are integral to the current research, utilising tools such as MATSim to model traffic scenarios, which is valuable given the challenges in obtaining empirical State of Charge data during actual traffic conditions (Zapotecas-Martínez et al., 2024).

Meanwhile, the development of Charging Stations poses significant impacts on distribution networks, including increased electrical losses, alterations in voltage profiles, and potential congestion in power lines (Yousuf et al., 2024). Research on grid safety focuses on optimisation of charging scheduling, strategic placement of CS to minimise grid losses, forecasting and analysing the accessibility and equity of CS deployment, etc. (Esmaili et al., 2024; Keramati et al., 2024; Zhao et al., 2024). Other research proposed a two-level hierarchical charging scheduling method for charging points that accounts for heterogeneous demand and a nonlinear charging profile, aiming to enhance safety and efficiency in power supply (Zhao et al., 2024). Similarly, Fatemeh Keramati developed a mixed-integer linear programming model to determine the optimal location and size of PEV fast-charging stations, seeking to minimise power grid losses and alleviate traffic congestion (Keramati et al., 2024). Research focuses on the equitable distribution of charging facilities, emphasising the spatial equity of charging facilities in Washington (Esmaili et al., 2024).

In the economic aspect of the development of EVs and Charging Stations, many researchers choose to apply game theory as a methodological approach, which involves modelling multiple decision-makers who operate under specific rules, with predefined reward mechanisms for each stakeholders' decisions (Kchaou-Boujelben, 2021). The main decision-makers in these studies include both government agencies and private companies, who are involved in the placement and planning of CS, as well as the end users of the infrastructure (Huang et al., 2022). As game theory becomes increasingly popular for planning CS, quantifying certain types of rewards remains challenging. Researchers frequently employ utility functions to simulate these dynamics, offering a way to measure outcomes that are not easily quantifiable (Liu et al., 2024). Accordingly, this paper utilises utility functions to assess the convenience of vehicle use from the consumers' perspective, highlighting a sophisticated approach to understanding and optimising the deployment of EV charging infrastructure.

Despite numerous studies focusing on the technical aspects of the placement and layout of Charging Stations, there is a general deficiency in the research concerning the actual industrial market and scenarios based on different regions according to the condition. This gap in the literature highlights a need for more insightful approaches that incorporate economic and policy dimensions targeting each scenario. Concurrently, the UK government has implemented specific policies for EV promotion, implying the unique characteristics and substantial potential for development within its market. This paper will focus on the UK as a case study to explore the trends and strategies for industrial conduction, and transition from Gas Stations to Charging Stations, aiming to provide insights into how policy, market dynamics, and cost-efficiency can collectively influence the deployment and evolution of charging infrastructures, thereby facilitating a more sustainable and economically viable transition.

2.2. Deployment policies

Since 2010, the accelerated adoption of EVs has catalysed a focused surge in research regarding the planning of public charging infrastructure (Liu and Wei, 2018). Currently, the advancement of EVs could be greatly noticed in regions such as Norway, the EU, the US, China, and the UK. Norway leads globally with approximately 80% of new car sales being electric, positioning it as one of the best in EV adoption, it implements extensive and aggressive governmental incentives such as significant tax breaks and enhanced accessibility options, which have substantially decreased the ownership costs and expanded infrastructure (Berhorst et al., 2024). Both China and the US, with the largest demands for EVs globally, also represent the most significant markets for charging

infrastructure (Chen et al., 2023a; Esmaili et al., 2024). The US exhibits a more decentralised approach, with policies varying significantly across states and less uniformity in governmental support (Esmaili et al., 2024). China's approach combines state-led directives and substantial investments in charging infrastructure, aiming to lead in both the production and adoption of EVs globally (Chen et al., 2023a).

The UK and the EU are recognised for their substantial potential in EV market expansion (Hopkins et al., 2023). In the UK, despite London and Scotland having the highest density of Charging Stations, with 145 and 72 units per 100,000 individuals, respectively, the overall growth has been deemed inadequate, hindering EV adoption significantly (Department for Transport, 2023a). As of October 2022, the UK had 34,637 public EV charging devices, which can support approximately 850,000 fully electric vehicles and 530,000 plug-in hybrids (Zapmap, 2023). The current charging infrastructure supports a sizeable number of EVs, as noted in the AFID EU/2014/94 directive, stating that countries should reach the aim of a 1:10 ratio of Charging Station to EV (EUR-Lex, 2014). Researchers highlight the necessity for targeted investments and policy measures aimed at enhancing infrastructure efficacy and economic feasibility, underscoring the crucial role of policy in shaping the landscape of EV charging networks (Helmus et al., 2018; Neelam, 2021). Therefore, to enhance the growth of public charging networks, it is crucial for the government to carefully consider strategies for encouraging targeted investments that support the establishment of essential infrastructure. This endeavour should also involve an awareness of how to attain profitability, along with an understanding of the obstacles that may affect this profitability (LaMonaca and Ryan, 2022).

2.3. Evolutionary games and complex network approaches

This paper advances research on Charging Stations by proposing a practical framework for transforming from Gas Stations, utilising complex network and evolutionary game theory (EGT) to simulate spatial and market dynamics. The EGT was initially utilised within biological contexts (Smith and Price, 1973; Taylor and Jonker, 1978). With the advent of artificial intelligence, the application scope of EGT has expanded dramatically across various disciplines, facilitating interdisciplinary methods to discern influential development factors and forecast trends within enterprises (Arlt and Astier, 2023; Wang et al., 2022). Recent applications of EGT have addressed pressing global challenges, including environmental degradation, greenhouse gas mitigation, and energy systems development, showcasing its growing utility in formulating policies and guiding new energy technology strategies (Liu et al., 2023a; Neubauer and Wood, 2014). Yang et al. implemented a tripartite EGT model among regulators, energy enterprises, and whistle-blowers, enhancing regulatory efficiency and reducing costs, whereas Liu emphasised how initial conditions in EGT simulations could affect outcomes in energy regulation (Liu et al., 2015; Yang et al., 2020).

Evolutionary Game Theory (EGT) often operates on the principle of population evolution, where the methodology for uniting individuals to form relationships is a key consideration (Smith and Price, 1973). In real-world social systems, individuals exhibit both topological and statistical characteristics, which profoundly influence the outcomes of EGT simulations (Takiddin et al., 2024). The structure of the network chosen for such simulations is crucial, as demonstrated by researchers who have analysed the impact of different network structures on the diffusion models for EVs and Charging Stations (Fang et al., 2022; Sun et al., 2023; Wang et al., 2023). They demonstrate that the Small-World network is an optimally complex network suited for the EVs and Charging Station markets due to its ability to realistically mimic real-world connectivity (Fang et al., 2022; Li et al., 2019; Wang et al., 2023a; Yuvaraj et al., 2024; Zhu et al., 2019).

This paper utilises the integration of complex networks and EGT as an effective tool to explore the development of Charging Stations. By employing the complex network intergrades with EGT, this research captures the dynamic interplay between Gas Stations and Charging

Stations, including the interactions among users, government, and businesses. This section discusses the significance of case studies, particularly highlighting the UK as a research subject, while also focusing on less commonly addressed, practical research areas, the transition from Gas Stations to Charging Stations and policy-driven changes. Innovatively, this study conducts a Dual Market Analysis comparing simple and complex market structures to underscore the interplay of variables within the study, identifying a diminishing marginal utility effect among indirect policies, and showing the importance of the tailored policy according to regional characteristics. This comprehensive approach, which combines complex network modelling with user behaviour and infrastructure dynamics, offers deeper insights into how changes in one area can impact another. Such an integrated evaluation is uncommon in existing literature but significantly enhances understanding of market dynamics.

3. Methodology

The purpose of this paper is to examine the decision-making mechanisms of key stakeholders in the deployment of Charging Infrastructure, focusing on how the distribution and economic implications of transitioning from gas stations to charging stations affect these processes. Utilising complex network-based simulations, this study explores how interconnected energy stations influence one another and impact market dynamics. The analysis seeks to offer practical recommendations for government and energy investors, facilitating informed decisions that support sustainable market evolution while ensuring that it is financially viable and aligned with the long-term goals of market stability and growth. In the market context, the key stakeholders are the government, investors, and consumers, interacting in complex ways. Consumers are driven by direct incentives such as subsidies, which shape their adoption choices, while investors' returns are influenced by these consumer preferences and governmental policies. By critically examining the government interventions in the form of subsidies or tax policies, the investors' returns and investments can be triggered according to the policy scenarios.

3.1. Problem description

This paper first defines the interactive relationship between consumer and investor choices, which is used to analyse the mutual impact between the proportion of consumers and the evolution of Charging Station distribution. Next, regarding policy design, the paper targets the two main types of energy stations in the market - Charging Stations and Gas Stations. It applies tailored subsidies and taxation measures to assess their respective impacts, comparing the evolution under stationary and interactive scenarios. Furthermore, the competitive relationship between energy stations also affects operators' revenue, which impacts the development of Charging Stations. Therefore, the study of energy stations must be analysed in conjunction with network relationships. In the network, each participant's decision is determined by profit, while the network also captures the strategic interactions and competitive relationships between linked sites. Hence, this paper utilises it as a fundamental framework to explore the deployment and diffusion of Charging Stations, as Fig. 1 shows.

3.2. Assumptions

To examine the theoretical outcomes, several assumptions have been imposed as follows.

- (1) In the network, each player has two strategies, and they can choose to invest in Charging Stations or Gas Stations based on the profit of each station. The size of the nodes in the network is N , which is set as 100, which is the number of energy stations in the

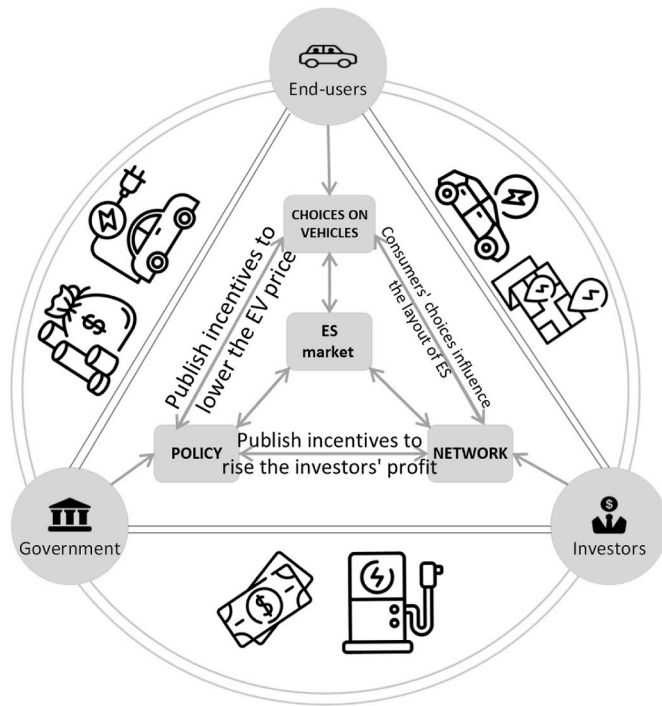


Fig. 1. The network-based evolutionary game framework based on stakeholders and inner interactions.

given network. The percentage of Charging Stations is x and the Gas Stations is $1 - x$.

- (2) The profit of each node is based on energy-selling income and policy incentives, and the competition of neighbouring energy stations would influence the energy-selling revenue. The nodes could share limited information with their neighbours, and all the players are rational. If the given node got a lower payoff than its neighbour nodes, this node would have a certain probability of imitating the strategy of the highest payoff neighbour. In the simulation, all the expenses and earnings are calculated in the energy stations' whole life cycle.
- (3) The same type of strategy of nodes in the neighbours would share the earnings of the corresponding consumers. For example, if the station i is Charging Station, and all its neighbours are Charging Stations, nodes in a given area would share earnings from EV users. If i is a Charging Station and all its neighbours are Gas Stations, i would get all the earnings from EV users, and neighbours would share earnings from ICE vehicle users, and vice versa.
- (4) Assume all the vehicles are distributed evenly across the network and will refuel and recharge at public energy stations.
- (5) The policies incentives target all three stakeholders in the markets, and the specific policies are shown in Table 1.

3.3. Decision Making Mechanisms on Complex Networks

This paper conducts the simulation using a complex network (Watts and Strogatz, 1998). Researchers believe that the complex network is suitable for the representation of the Charging Station market, due to the inside perfectly competition in the market (Fang et al., 2020; Wang et al., 2021). The nodes in the network describe the energy stations in the real market, and edges describe the connections between the nodes, the information could only transfer through the edges. The network structure can be described as an undirected graph $G = (V, E)$, from where V is the collection of nodes in the network and E is the collection of undirected edges between nodes.

During the simulation process, the nodes will get their payoffs in each iteration and make a comparison with their neighbours. Then the strategy replication procedure of each node probabilistically designates the point exhibiting the highest anticipated return for replication and updates the payoff in the next round. The probability was calculated following the Fermi rule (Allen and Nowak, 2014),

$$P(N_i \rightarrow N_j) = \frac{1}{1 + \exp\left(\frac{A_i - A_j}{k}\right)} \quad (1)$$

where node N_i will compare the profit of every neighbour in the area around it and find node N_j who gets the highest payoff. N_i will follow the strategy of N_j with the probability $P(N_i \rightarrow N_j)$. A_i and A_j is the profit of node i and node j , respectively. k refers to the noise factor, which describes the uncertainty of the decision-making process of the evolution in complex networks. The uncertainty comes from the strategy following process, that when the profit of N_i is higher than N_j , there is still a weak probability that N_i will follow the decision of N_j . In this paper, k is set as 0.1, as in the previous research (Allen and Nowak, 2014). In this instance, Fig. 2 depicts the temporal evolution of energy station characteristics within the complex network, illustrating the update mechanism of network nodes, showing the inner competition and interaction of energy stations and the transition of Gas Stations to Charging Stations. Nodes refer to real energy stations, the white one refers to the Gas Stations and red ones refers to the Charging Stations, which could be seen that the increase proportion of Charging Stations. Policy interventions introduce variability in energy station profits across iterations. Initially, the nodes within the network are initialised, and as energy stations evolve, their individual profits mutually affect one another. These profits are contingent upon the policies and strategies implemented by the respective nodes. As iterations progress, the profitability of specific nodes undergoes alterations; some experience increases, while others witness decreases. These interactions among energy stations are facilitated through the interconnected edges that traverse the network.

3.4. Life cycle assessment of energy stations

The payoff of every energy station is equal to the gross income of stations minus the expense, which includes the initial construction costs, annual expenditure of maintenance, servicing, warranties, data services and insurance, and purchasing energy. The way of allocating the annual investment costs of procuring Charging Station and Gas Station equipment establishing and with annual maintenance and operation costs is shown below in Table 2.

The initial investment is about the cost of energy station devices and the cost of installation. For the Charging Station, the initial investment is I_{CS} , and I_{CS}^L is the apportioned annual investment, including the expenses of the devices and the initial installation cost; L_{CS} is the service life of the Charging Stations equipment, which is generally set to 6 years. The general service life for a tank is around 10 years, which leads to the service life of a Gas Station being 10 years. The value of L_{GS} is 10 years (Fang et al., 2020). ϵ is the discount rate, which is 5%.

After station construction, the ongoing daily maintenance and operation of the equipment constitute annual fixed expenditures. The annual investment of the Charging Station and Gas Station can be described as I_{CS}^m and I_{GS}^m . I_{CS}^m and I_{GS}^m are the summation of the Charging Station and Gas Station expenses per year, respectively. Simultaneously, the annual expenditures of energy stations encompass the costs incurred from purchasing energy from upper-tier energy suppliers. For Gas Stations, to meet the local demand for ICE vehicles, it is imperative for them to procure gas from upper-tier gas suppliers. Likewise, Charging Stations need to acquire electrical power from higher-level electricity distributors to cater to the needs of local users of EVs. Generally speaking, ICE vehicles replenish their energy through Gas Stations. In this scenario, the

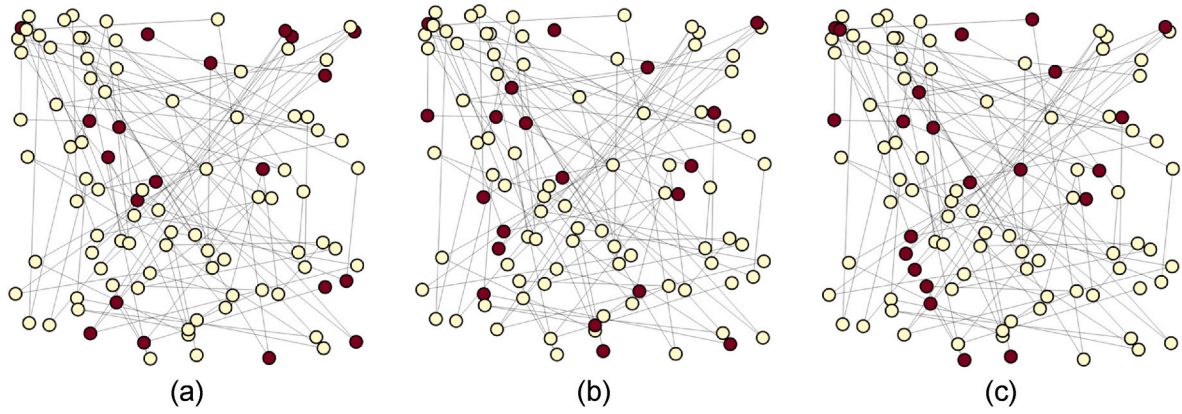


Fig. 2. The temporal snapshots of characteristics of energy stations on the Complex Networks at iteration 0 (a), 10 (b), and 25 (c), in which the white nodes represent Gas Stations and the red nodes represent Charging Stations. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1

The policy incentives applied in the UK.

Parameters	Targets	Introduction
P1	Energy stations	Annual operation subsidy for Charging Stations
P2		Annual taxation for Gas Stations
P3		Initial Expense of devices and the expense of installation for Charging Stations
P4	End users	EV selling subsidy
P5		Electricity selling subsidy

Table 2

Annual cost of initial investment in Charging Stations and Gas Stations based on life cycle assessment.

Energy stations	Type of cost	Equation
Charging Stations	Annual investment	$I_{CS}^l = (I_{CS} - P_3) \times \frac{\varepsilon(1+\varepsilon)^{L_{CS}}}{(1+\varepsilon)^{L_{CS}} - 1}$ (2)
Gas Stations		$I_{GS}^l = I_{GS} \times \frac{\varepsilon(1+\varepsilon)^{L_{GS}}}{(1+\varepsilon)^{L_{GS}} - 1}$ (3)
Charging Stations	With annual maintenance and operation	$I_{CS}^m = (I_{CS} - P_3) \times \frac{\varepsilon(1+\varepsilon)^{L_{CS}}}{(1+\varepsilon)^{L_{CS}} - 1} + I_{CS}^m$ (4)
Gas Stations		$I_{GS}^m = I_{GS} \times \frac{\varepsilon(1+\varepsilon)^{L_{GS}}}{(1+\varepsilon)^{L_{GS}} - 1} + I_{GS}^m$ (5)

fundamental revenue source of energy stations primarily derives from the daily energy needs of end-users, and the energy requirements for each type of vehicle must be calculated based on local charging or refuelling demands.

3.5. The interactive structure between consumer choice and energy stations

To ascertain the energy requirements of each type of vehicle user, understanding their preferences is crucial. Additionally, it is essential to have a breakdown of the current percentage of the types of vehicles in operation. Thus, users are categorised into three groups to determine their energy needs. The first group consists of determined EV users who exclusively utilise Charging Stations. The second group comprises determined ICE vehicle users who solely opt for refuelling at Gas Stations. The third group includes users intending to purchase a vehicle,

Table 3

The revenue of energy stations in different scenarios.

Energy stations	Neighbours	Vehicles	Equation
Charging Stations	Charging Stations	EV	$r_1 = (E_s + P_5 - E_p)D_{EV} + P_1 - I_{CS}^m$ (16)
	Gas Stations	EV	$r_2 = (E_s + P_5 - E_p) \frac{D_{EV}}{x} + P_1 - I_{CS}^m$ (17)
	Charging Stations	ICE	$r_3 = (E_s + P_5 - E_p) \frac{D'_{EV}}{x} + P_1 - I_{CS}^m$ (18)
	Gas Stations	ICE	$r_4 = (E_s + P_5 - E_p) \frac{D'_{EV}}{x} + P_1 - I_{CS}^m$ (19)
Gas Stations	Charging Stations	EV	$r_5 = (F_s - F_p) \frac{D'_{ICE}}{1-x} - P_2 - I_{GS}^m$ (20)
	Gas Stations	ICE	$r_6 = (F_s - F_p)D_{ICE} - P_2 - I_{GS}^m$ (21)
	Gas Stations	EV	$r_7 = (F_s - F_p) \frac{D'_{ICE}}{1-x} - P_2 - I_{GS}^m$ (22)
	Charging Stations	ICE	$r_8 = (F_s - F_p) \frac{D_{ICE}}{1-x} - P_2 - I_{GS}^m$ (23)

including first-time buyers and people with a demand for upgrading vehicles, and they have two choices for EV or ICE vehicles. The choices made by this third group will impact the proportion of existing vehicle types in the market, subsequently influencing the profit margins of different energy stations and, consequently, further affecting their distribution. Contrarily, this group will be influenced by the current EV market too. The prevalence of diverse types of energy stations will affect the choices of the third group of consumers. Therefore, it can be asserted that the development of energy stations and EV are mutually interactive. In this paper, the following methodology is employed to evaluate the choices of the third group of consumers.

Firstly, this paper applies Random Utility Theory with Discrete Choice Model to evaluate the choices that the users made (Jang and Choi, 2021), which is usually employed to elucidate or forecast selections made from a collection of two or more discrete options that are mutually exclusive, which are the EV users and ICE vehicle users in this problem (David and Hensher, 2018). The choices for vehicle consumers are determined by the perceived utility of each type of behaviour, including vehicle cost and subsidies, energy-using utility, and non-monetary incentives (Chen et al., 2023a; Ji and Huang, 2018). Thus, this paper describes the utility function as a combination of related attributes with assigned weights, as follows:

$$U_{EV} = \alpha_1 u_c - \alpha_2 (C_{EV} - P_4) + \alpha_3 M_{EV} + \beta_{EV} \quad (6)$$

$$U_{ICE} = \alpha_1 u_f - \alpha_2 C_{ICE} + \beta_{ICE} \quad (7)$$

where, U_{EV} and U_{ICE} are the perceived utility obtained from users choosing to purchase a new EV or an ICE vehicle, respectively. α_1 measures the consumers' sensitivity to charging or refuelling utilities, which is consumers' response to the convenience and availability of different infrastructures. α_2 refers to the consumers' sensitivity to the cost of buying a new vehicle. α_3 measures the consumers' sensitivity to non-monetary incentives if they choose an EV as their new vehicle. The parameters are set as 0.31, 0.000094 and 0.05 (Zhu et al., 2019). C_{EV} and C_{ICE} are the cost of new EV or ICE vehicles for consumers. M_{EV} refers to the non-monetary incentives from the government for EV purchases, which is set as 10 ; Ji and Huang, 2018). β_{EV} ($0 \leq \beta_{EV} \leq 1$) and β_{ICE} ($0 \leq \beta_{ICE} \leq 1$) refer to the consumers' random choice for EV or ICE vehicle. u_c and u_f refer to the perceived utility that consumers choose to access Charging Stations or Gas Stations, which are determined by the user convenience to the stations and are positively correlated with the number of Charging Station and Gas Stations (Zhu et al., 2019). The utility of charging and refuelling can be expressed as follows:

$$u_c = \gamma \times n \times x \quad (8)$$

$$u_f = \gamma \times n \times (1 - x) \quad (9)$$

where, γ refers to the perceived utility coefficient of energy infrastructures, which is set as 0.017 (Zhu et al., 2019). n refers to the number of nodes in the network, the total number of energy stations. x refers to the percentage of Charging Station in the network. The probability of consumers selecting EV and ICE vehicles can be described as follows (Jang and Choi, 2021):

$$z_{EV} = \frac{\exp(U_{EV})}{\exp(U_{EV}) + \exp(U_{ICE})} \quad (10)$$

$$z_{ICE} = 1 - z_{EV} = \frac{\exp(U_{ICE})}{\exp(U_{EV}) + \exp(U_{ICE})} \quad (11)$$

3.6. Evolutionary decision-making mechanisms of stakeholders

To generate the payoff function, it is necessary to get the logic of the competition relationship between station nodes. The nodes in the network could share limited information with each other in a given period, including the strategy of each node and the net revenue. For the concept of each node, the annual net profit equals total income minus the expense. In the context of station interaction, income sharing would occur among stations based on their respective consumers through the edges of nodes. This implies that the revenue generated by these stations would be significantly influenced by the distribution ratio of each consumer type. For example, if node i is designated as Charging Station, and all neighbouring nodes in the vicinity are also Charging Stations, they will jointly derive revenue from EV users and share evenly, yet they will not generate any profit from ICE vehicle users. If node i serves as a Charging Station and all neighbouring nodes in the vicinity are Gas Stations, node i will get all the income from EV users and other nodes will share the profits from ICE vehicle users. Vice versa, when node i is designated as a Gas Station, a similar revenue equation can be deduced.

3.7. Payoff functions in the game configuration

The revenue of each node is determined by the pure income of each station and the annual expenses. Income is derived from the quantity of energy sold by the stations, which is related to the energy demands of the vehicles. As all the vehicles are distributed evenly in the network, the number of vehicles around the given station node is constant, denoted by δ . The energy demand of each node is related to the type of consumers. If the consumers around the given node all belong to Groups 1

and 2, which are pure EV consumers and ICE vehicle consumers, the demand for vehicles of the current market can be described as follows:

$$D_{EV} = \delta \times e \quad (12)$$

$$D_{ICE} = \delta \times f \quad (13)$$

where, e and f are the annual energy consumption of per EV or ICE vehicle. Meanwhile, if there exist consumers around the stations belonging to Group 3, and the percentage is denoted by η , which need to purchase new vehicles, the demand can be described as follows:

$$D'_{EV} = \delta \times e \times \eta \times z_{EV} \quad (14)$$

$$D'_{ICE} = \delta \times f \times \eta \times z_{ICE} \quad (15)$$

Therefore, this paper defines the revenue of each station in different scenarios. The revenue r_i of station i is listed in Table 3.

E_s and E_p refers to the electricity selling price of Charging Stations and the purchase price of upper-tier electricity distributors, the difference between which represents the profit from energy sales. Likewise, F_s and F_p refers to the gas selling price of Gas Stations and the purchase price of upper-tier gas distributors. If all the stations are Charging Stations in the given area and vehicles around them are EV, the revenue would be evenly distributed among nodes. If all the stations are Charging Stations in the given area and vehicles around them are ICE vehicle, the vehicles that might choose to access Charging Stations are group 3 consumers because of the convenience of using EV, and vice versa, for the Gas Stations.

Thus, the expectation of Charging Stations and Gas Stations revenue can be described as follows. In the context, y refers the percentage of Charging Station and z refers to the percentage of EV in the network.

$$R_{CS} = (y \quad 1 - y) \times \begin{pmatrix} r_1 & r_2 \\ r_3 & r_4 \end{pmatrix} \times \begin{pmatrix} z \\ 1 - z \end{pmatrix} \quad (24)$$

$$R_{GS} = (y \quad 1 - y) \times \begin{pmatrix} r_5 & r_6 \\ r_7 & r_8 \end{pmatrix} \times \begin{pmatrix} z \\ 1 - z \end{pmatrix} \quad (25)$$

In conclusion, Table 4 shows the game matrix of the revenue for Gas Stations and Charging Stations, where i, j refer to the relative position of energy stations in the complex network, $i, j \in N$.

The expectation of station i can be described as follows:

$$R = xR_{CI} + (1 - x)R_{GS} \quad (26)$$

4. Case study

The advancement of the Charging Station market in the UK is a critical component of the strategic initiatives aimed at diminishing carbon emissions and bolstering sustainable transport infrastructure (Liu et al., 2023b). Since the intervention in the early 2010s, policy-driven deployment of Charging Stations has been undertaken, with the collaborative engagement between government and private capital (GOV.UK, 2021; Department for Transport, 2023b). Policy interventions are instrumental in enhancing the utility and accessibility of residential and public Charging Stations (Zhu et al., 2019). However, there exists an absence of systematic evaluation regarding the efficacy of these policy interventions within the UK (Liu et al., 2024). The present study seeks to appraise the feasibility of transitioning from Gas Stations to Charging Stations, capturing the complex interplay among the market's stakeholders, by establishing a robust policy framework among scenarios.

4.1. Dataset description

The initial input value of parameters is listed in Table 5.

Currently, the average electricity fee in the UK in 2023 is 0.21 USD/

Table 4
Game matrix of Revenue for Energy Stations.

Station j		Station i	
Charging Station	Gas Station	Charging Station	Gas Station
		(R_{CS}^i, R_{CS}^j)	(R_{CS}^i, R_{GS}^j)
Charging Station	Gas Station	(R_{CS}^i, R_{CS}^j)	(R_{GS}^i, R_{GS}^j)

Table 5
The revenue of energy stations in different scenarios.

Parameters	Value	Reference
Average electricity selling fee, E_s	0.42 USD/kWh	DESNZ (2023)
Average electricity purchase price, E_p	0.21 USD/kWh	Pod Point (2023)
Average gas selling fee, F_s	1.91 USD/Litre	Trading Economics (2023)
Average gas purchase price, F_p	1.84 USD/Litre	GlobalPetrolPrices (2023)
Annual gas consumption, f	630 L	Trading Economics (2023)
Annual electricity consumption, e	1100 kWh	IEA (2023)
Average EV price, C_{EV}	40,000 USD	NimbleFins (2023)
Average ICE price, C_{ICE}	25,000 USD	NimbleFins (2024)
Charging Stations installation cost, I_{CS}	450,000 USD/CS	carwow (2023)
Charging Stations operation cost, I_{CS}^m	40,000 USD/CS	(Department for Transport, 2023a)
Gas Stations installation cost, I_{GS}^m	300,000 USD/GS	BusinessesForSale (2023)
Gas Stations operation cost, I_{GS}^m	30,000 USD/GS	(Department for Transport, 2023a)

kWh, according to the Energy Price Guarantee report from the UK Government (DESNZ, 2023), and the electricity price for charging EV users is 0.42 USD/kWh (Pod Point, 2023), which means E_s is 0.42 USD/kWh and E_p is 0.21 USD/kWh. On the other hand, the cost of gas is 1.84 USD/Litre in the UK according to Trade Economics (Trading Economics, 2023), and the retail price is 1.91 USD/Litre from the Global Petrol Prices (GlobalPetrolPrices, 2023), and F_s is 1.84 USD/Litre and F_p is 1.91 USD/Litre. Generally, The UK Department of Transport reported that the average driver in England travels 4334 miles (about 6974.9 km) a year (Department for Transport, 2023a). According to the report from the RAC Foundation, the average gas consumption of an ICE vehicle is 9 L per 100 km (RAC Foundation, 2023) and the electricity consumption of an EV is 15 kWh per 100 km (IEA, 2023). In that case, the annual gas consumption for an ICE vehicle is 630 L, and the annual electricity consumption of an EV is 1100 kWh, f is 630 L, and e is 1100 kWh. The percentage of customers that need a vehicle upgrade is around 30% (statista, 2023).

For the initial investment in a Charging Station, it contains the basic equipment costs and daily operation costs. In the UK, three-phase power needed to be installed or upgraded when installing the new fast chargers, which might cost from 4000 USD to 20,000 USD (carwow, 2023). According to a report from Trading Depot, the price of a Charging Station in the UK is 25,000 USD (Trading Depot, 2023). A charging station in the city usually contains 10 chargers. Thus, the value of I_{CS} is around 450,000 USD. According to the report, the operation cost of a Charging Station, including the labour cost, maintenance cost, etc, is around 40,000 USD per Charging Station (Department for Transport, 2023a),

which means the value of I_{CS}^m is 40,000 USD. On the contrary, the investment for installing a Gas Station, including the 10 stations regarding tankers, tanks, etc, is around 300,000 USD, and the operation cost is about 30,000 USD per year (BusinessesForSale, 2023). For the policy part, the UK Gov, as business owners, can get up to 10,000 USD¹ when installing a charging point, the value of P_1 (Road infrastructure, 2022).

4.2. Influence of EV market share on charging station deployment

This study has developed an interactive evolutionary game model constructed specifically for the transition from Gas Stations to Charging Stations within the complex network. The model effectively captures the interactive evolution mechanism, showcasing the mutual influence between Charging Station deployment and the development of EVs within the infrastructure network. This section visually illustrates the impact of varying proportions of EVs on the diffusion of Charging Stations. Meanwhile, this paper also elucidates how consumer preferences for different vehicle types, as well as the proportion of EVs in the charging market, affect the proliferation of Charging Stations. Fig. 3 rigorously examines the influence caused by consumers with different proportions of EV adoption in the market, shown in the following curves. The shaded area in the following figures indicates the 95% confidence interval around the median of the 100 numerical simulations, as is the case in Figs. 3–8.

This figure clearly illustrates a pronounced trend: an increase in the proportion of EV users leads to a corresponding rise in the percentage of Charging Stations. Particularly in the early stages of the Charging Station market, as these consumers are likely to be among the first adopters of EVs, an increase in consumer preference results in a sharp increase in the proportion of Charging Stations (Tan and Lin, 2020). A higher percentage of EVs leads to a more rapid and higher stabilisation of CS proportion, suggesting a strong adoption of Charging Stations due to a higher percentage of EVs.

When comparing these results to cases in other studies, it is important to consider the context of the market and policies that could affect the adoption of EVs and the subsequent need for Charging Stations (Kazemtarghi et al., 2024). For instance, markets with more aggressive EV adoption policies might display trends like the $Z = 0.9$ scenario, where the saturation of Charging Stations happens rapidly and reaches a

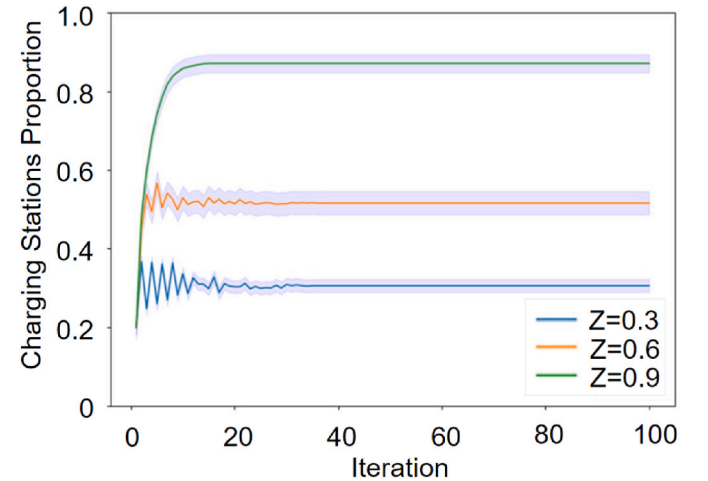


Fig. 3. The influence of EV market share on Charging Stations deployment.

¹ From the UK Gov, a business owner can get up to 850 pounds subsidy when installing a charging point, including 350 pounds for a socket and 500 pounds for space-occupying.

high proportion. It can also help policymakers and businesses evaluate the growth of CS based on current or projected EV adoption rates. The trends observed here underscore the importance of considering consumer behaviour, technology adoption rates, and policy effects when planning for infrastructure to support EVs (Tan and Lin, 2020).

4.3. Influence of EV selling subsidy on charging station deployment

Considering the different impacts that varying proportions of EVs can have on the Charging Station market from Fig. 3, this part intends to exert influence on the sales market of EVs by applying different subsidies to the price of EVs to stimulate demand-side consumers' desire to purchase EV by leveraging their sensitivity to price. The study will affect EV sales prices ranging from 0 to 3000 USD, as the curves show. The response of the EV market, with the application of different subsidies, is shown in Fig. 4.

The reduction of upfront costs for consumers through EV selling subsidies might have a positive impact on the adoption rates of EVs. As more individuals acquire EVs, the demand for Charging Stations naturally increases. The data depicted in the figure illustrates the relationship between the level of EV selling subsidies and the market proportion of Charging Stations over several iterations, revealing a positive correlation where higher subsidies are associated with an increased proportion of Charging Stations. Notably, the difference in the proportion of charging stations between a subsidy of 2000 USD and 3000 USD is less distinct compared to the difference observed between a 1000 USD subsidy and no subsidy, which shows a similar trend with other studies (Chen et al., 2023a). This indicates that beyond a certain threshold, increases in subsidy amounts lead to diminishing effects on the proportion of charging stations. This finding suggests that while subsidies do foster the growth of Charging Stations, policymakers need to periodically reassess the subsidy amounts to maintain efficiency and avoid fiscal overreach. Additionally, an increase in the Charging Station proportion is observed even in the absence of subsidies, suggesting that other factors are also influencing the expansion of the network. According to some research, inherent growth in Charging Stations could also stem from supportive policies beyond direct subsidies, driven by consumer behaviour, investor confidence, and other supportive mechanisms (Liu et al., 2024).

4.4. Influence of operation subsidy on charging station deployment

To promote the deployment of Charging Stations, the UK government incentive policies encompass subsidies targeting the market share of Charging Stations, which are the operation subsidy and initial investment subsidies. This section investigates the evolution of Charging

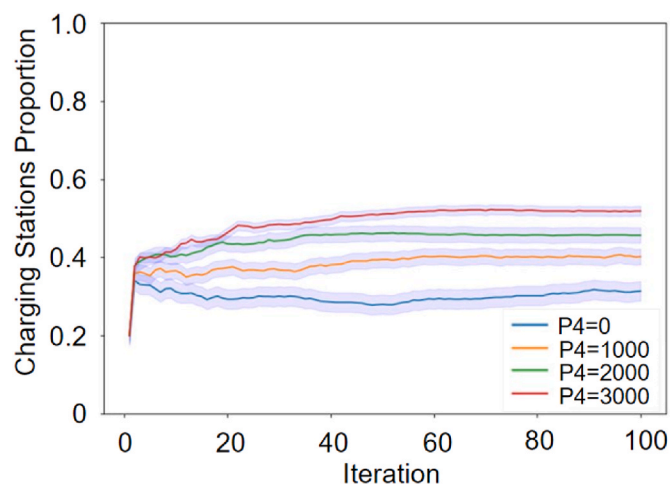


Fig. 4. The influence of EV sale subsidy on EV market share.

Station deployment under operation subsidy incentive ranging from 0 to 60,000 USD under both simple stable market conditions and mutual inter-market interactions, as shown in Fig. 5 (a)(b).

Fig. 5 illustrates a positive correlation between subsidies and the proportion of Charging Stations. Fig. 5(a) illustrates a simplified response of the Charging Station market, indicating that the market exhibits a pronounced reaction to policies with substantial incentives, while its response to policies with smaller incentives is comparatively modest. Observing the reactions of interactive markets provides a more complex representation and shows greater sensitivity to the impact of policies, as Fig. 5(b) shows. It reveals that even without government subsidies, the Charging Station market experiences slight growth. This is due to the charging demands of the initial number of EV owners, enabling initial growth in the Charging Station market according to another research (Liu et al., 2023). This further validates the theory proposed in this paper, underscoring the necessity of considering the interplay between markets in the simulation process.

4.5. Influence of taxation of gas stations on charging stations deployment

The annual policy impact can also be directed towards existing Gas Stations. Reducing Gas Stations can, to a certain extent, incentivise and accelerate the development of Charging Stations. Similarly, the effects of such policies on the market are simulated and analysed in two scenarios: a simple stable market and a complex interactive market, as illustrated in Fig. 6a and b.

In both markets, the impact of taxation on the proportion of Charging Stations exhibits similarities. When the tax amount is below 20,000 USD, the future steady-state trend of Charging Stations reflects a similar equilibrium and does not exhibit a directly positive correlation. This is attributed to the fact that tax policies indirectly influence the Charging Station market share by affecting the revenue of Gas Stations and the percentage of Gas Stations, thereby demonstrating a lagged and relatively weak correlation. When taxation reaches 40,000 USD, the proportion of Charging Stations will surge to 80%, and it is not expected to increase significantly with further increments in taxation. It could also be seen that the similar diminishing effect of charging stations' percentage to the EV selling subsidy might indicate that the indirect policy has a delayed influence on charging stations. Other research applied a general balanced policy, that the subsidies for Charging Stations equal to taxes for Gas Stations (Fang et al., 2020). It could release the fiscal burden to some extent but might miss capturing the detailed dynamic of different types of policies.

4.6. Influence of construction subsidy on charging stations deployment

To promote the diffusion of Charging Stations, the incentive policies encompass subsidies for the initial construction process, which involves equipment acquisition and installation expenses. The effects of such policies on the market were analysed in a stable state market and a complex interactive market, ranging from 0 to 120,000 USD, as illustrated in Fig. 7 (a) and (b).

Both markets demonstrate similar responses to construction subsidies, eventually stabilising at relatively proportional levels. It is evident that construction subsidies can have a relatively direct and prompt impact on the proportion distribution of Charging Stations. This phenomenon is likely attributed to the fact that construction costs represent a substantial expense, and in the early stage of the process of Charging Station construction, directly influencing the payback period and short-term profits. Thus, it is observable that construction subsidies are crucial in promoting the establishment of Charging Stations. However, given that substantial construction subsidies impose significant fiscal pressure on the government, it is advisable to implement this subsidy in conjunction with others to alleviate the fiscal burden on the government. Other research also shows that the subsidy has a diminishing effect but unlike the conclusion here they are targeted research in

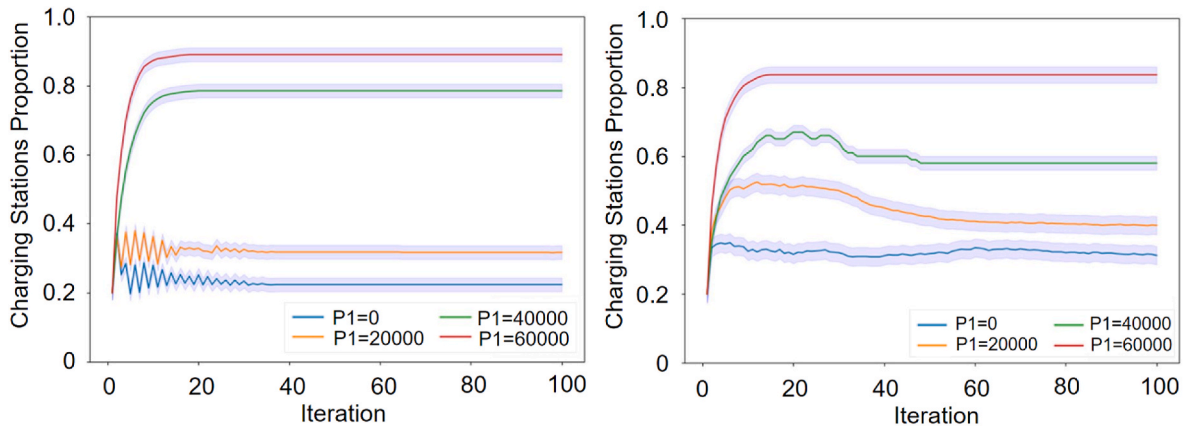


Fig. 5. The response of Charging Station market share of operation subsidy under stable market and interactive market. (a) simple stable market, (b) mutual inter-market interactions.

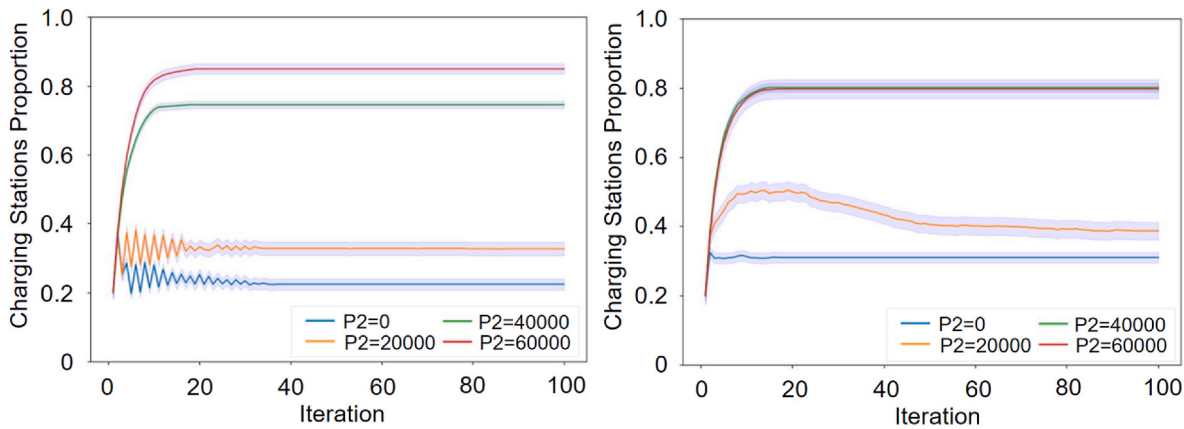


Fig. 6. The response of Charging Station market share of Gas Station taxation under stable market and interactive market. (a) simple stable market, (b) mutual inter-market interactions.

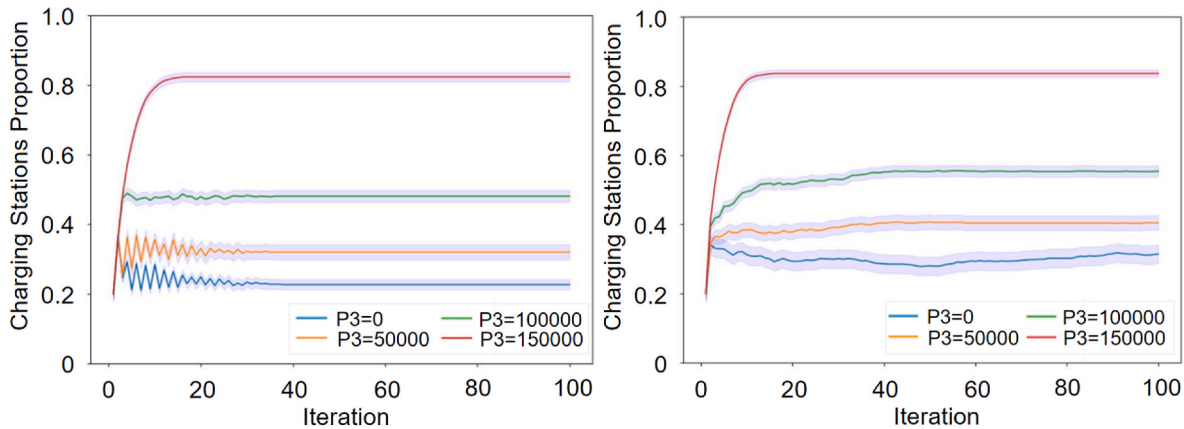


Fig. 7. The response of Charging Station market share of construction subsidy under stable market and interactive market. (a) simple stable market, (b) mutual inter-market interactions.

specific regions (Chen et al., 2023a; Liu et al., 2023a).

4.7. Influence of electricity subsidy on charging station deployment

This part illustrates the subsidies for electricity prices, which are directly related to end users' preferences. Energy sales constitute the primary revenue source for energy stations, which indicates subsidizing

electricity prices will directly enhance the daily income of Charging Stations and play a promotional role in its market share, as demonstrated in Fig. 8.

The development of Charging Stations is intimately linked with revenue generation, which elucidates that they are highly responsive to profitability. As the subsidy for unit energy increases, the proportion of Charging Stations will grow proportionally. It is evident that complex

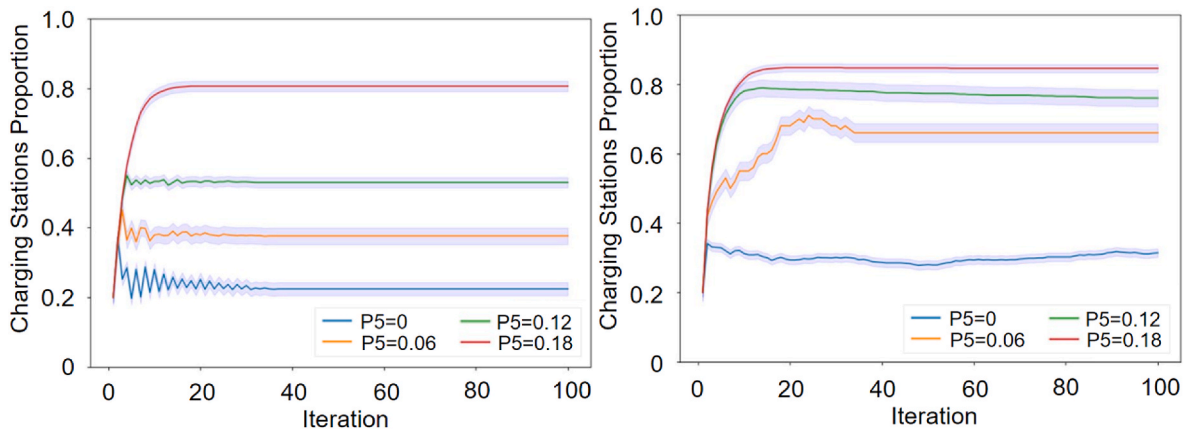


Fig. 8. (a)(b). The response of Charging Station market share of electricity subsidy under stable market and interactive market.

markets are more sensitive to subsidies on energy prices, leading to a rapid surge in the proportion of Charging Stations within a relatively short period. Therefore, measuring the impact of such subsidies necessitates the use of complex market models to ensure the thorough consideration of market sensitivity to user choices. However, subsidizing unit energy incurs substantial government expenditure. Hence, it is recommended that a unit energy subsidy of 0.06 USD/kWh be opted for to balance the promotion of Charging Stations with the government's fiscal considerations. A similar diminishing effect can be seen in this case, showing the obvious trend for indirect policies (Liu et al., 2023a).

5. Discussion

Consistent with previous research, our study reaffirms the pivotal role of governmental incentives in fostering EV development and the expansion of charging infrastructure. Distinctively, our research diverges slightly in its selection of policies from other studies by comprehensively evaluating incentives aimed at both consumers and businesses. Some existing research has not fully considered how consumer-targeted policies can propel the development of charging stations. This study examines the indirect effects of policies, including subsidies for EV purchase prices and electricity costs, and tax for Gas Stations, providing a contrast to some current studies. As the number of subsidies increases, there is a significant enhancement in the proportion of Charging Stations due to a certain subsidy level. Similarly, the findings from the case study show the diminishing marginal effects of the indirect policies, and the need for strategic calibration of subsidies to optimise their effectiveness in expanding charging infrastructure (Chen et al., 2023a).

Additionally, in the context of the ongoing shift from ICE vehicles to EVs within the market, this research focuses on the strategic layout and balance between gas and charging facilities. It delves deeply into the policy environment supporting the transition from Gas Stations to Charging Stations. Furthermore, the Dual Market Analysis used in the present paper, comparing simple and complex market structures, emphasises the importance of simulating complex markets in practical applications, offering insights for real-world implementation. This approach ensures the feasibility of this research both theoretically and practically, aiming to address potential adoption barriers that might not be evident from a purely technical perspective. Meanwhile, when installing charging points at gas stations, stringent adherence to safety regulations set forth by local authorities is crucial (Ma and Huang, 2019). For governments, it is also a key component when accelerating the Gas Station transition. This aspect is worth a comprehensive analysis in future research, but it has no influence on the results of this paper.

The simulation results illustrate a positive correlation between consumer preferences for EVs, the level of investment by stakeholders in

Charging Stations, and the market share of Charging Stations. Notably, in the early stages of the Charging Station market, early consumers of EVs provide the initial increase for the Charging Station market share, a 10% sales growth of EVs in the absence of subsidies. This is attributed to early adopters providing an initial source of profit for the charging company through the initial setup phase (Tan and Lin, 2020). As the number of subsidies increases, there is a significant enhancement in the proportion of Charging Stations due to a certain subsidy level. However, subsequent increases face diminishing marginal utility, a phenomenon that aligns with findings from various studies (Wang et al., 2024). Similar to this observation, several researchers have noted that with intensified policy intervention, there is a varying degree of reduction in marginal utility (Chen et al., 2023a,b; Liu et al., 2023). This pattern underscores the need for strategic calibration of subsidies to optimise their effectiveness in expanding charging infrastructure.

It is noteworthy that the initial emergence of the Charging Station market also stimulated the advancement of the EV market, providing the initial probability for EV operation (Fang et al., 2022). Given these interactions, introducing simulations involving complex interactive markets becomes a necessary research tool. This paper assessed four aspects of subsidy policies and one tax policy targeting Gas Stations based on the complex network, targeting both businesses and consumers, showing the relative positions of energy stations. For the iteration, the model illustrates the transition of Charging Stations replacing Gas Stations. It is applicable to exert influence over the daily operations of energy stations, owing to the comparable market fluctuation that underpins policy responses for both types of energy stations.

This paper reveals that the fiscal impacts of executing these policy measures individually would exhibit similar outcomes for markets. For instance, construction subsidies for Charging Stations have a proportionate impact on their market share. When subsidies increase to 150,000 USD, the market share can rapidly stabilise at 80%. This could be attributed to the substantial influence these subsidies have during the initial stages of energy station construction, significantly enhancing investor confidence. In contrast, tax policies for Gas Stations exhibit a lagged effect on the market. If taxation is below 20,000 USD, the impact on the market is minimal, maintaining 40%. However, excessively high taxation, while achieving a rapid 80% market distribution, may concurrently influence market vitality and investor confidence. Therefore, simultaneous implementation of policies for both Charging Stations and taxation on Gas Stations may sustain a higher level of market dynamism. These findings offer several recommendations to policy-makers. Firstly, policy interventions should be employed to promote the expansion of Charging Stations. However, markets that rely solely on subsidies also face their own developmental constraints. Therefore, the government should customise subsidy amounts based on demand to alleviate fiscal burdens. Secondly, the government should prioritise the

synergistic development between EV and Charging Station markets, as policy interventions targeting EVs are equally pivotal for the development of Charging Stations. Thirdly, it is recommended that the government implement combined policies, intervening not only with Charging Stations but also with Gas Stations. This approach can efficiently facilitate market transformation while mitigating fiscal burden (Marion and Muehlegger, 2018).

Due to the unique characteristics of the UK market and national conditions, while the types of policies implemented in the UK could be inspired by those used in other countries, the specific amounts and effects must be simulated based on the UK's unique context. Compared to studies that use normalised policy impact, this paper employs absolute amounts for policy scenario simulation (Murugan and Marisamynathan, 2024). Each approach to policy evaluation has its merits and limitations. The normalised policy evaluation could enhance transferability across different markets while utilising absolute amounts. Although potentially limiting transferability, it provides a more accurate reflection of the market's specific traits and dynamics. Additionally, while existing research often focuses on one type of market, this paper extends its analysis and compare both simple and complex market models. By applying dual market analysis, the study highlights market fluidity and provides a clearer comparison of policy impacts. This approach not only maintains transferability but also necessitates detailed case-specific analysis, thereby balancing the need for generalisability with the specificity required to address unique market characteristics effectively.

Furthermore, in the future, both enterprises and governments should take measures to bolster consumer confidence in the development of EVs, which encompasses initiatives such as improvements in EV battery technology, comprehensive after-sales services for EV battery replacement and second-life applications, and the implementation of solar-powered smart charging. These measures not only serve to convey positive messages to consumers but also contribute to advancing the utilisation of renewable energy sources, promoting the recycling and reuse of EVs and batteries, and reducing pollution emissions, thereby achieving a state of clean and sustainable development. Enterprises are advised to provide consumers with more opportunities to engage with EVs through practical experiences, thereby attracting consumer preferences for EVs. Various policies related to Charging Stations should maintain sufficient policy momentum over an extended period to ensure their effectiveness. It is necessary to adopt a multifaceted approach to policy implementation, creating well-considered policy combinations to avoid inefficient resource allocation. Incentive policies should be customised to different market conditions and analysed in the context of interactive and complex markets to enhance efficiency. Governments are encouraged to implement policies related to vehicle ownership, such as the enforcement of license plate usage restrictions, aimed at fostering a proclivity towards EV adoption among users, which is an effective way of foresting the UK Charging Station market (Tan and Lin, 2020).

6. Conclusion and policy implications

The development of EVs is closely intertwined with the deployment of Charging Stations, and the latter's expansion relies on EV users as a beneficiary base. Designating Gas Stations as a potential Charging Station location in the near term not only reduces construction costs, such as minimising considerations for land usage rights, but also allows current energy companies like Shell to diversify revenue streams, significantly enhancing the involvement of traditional energy companies in the new energy sector. Simultaneously, the UK government has introduced a series of supportive incentive policies to facilitate the deployment of Charging Stations. However, a comprehensive evaluation and in-depth analysis of the policy effectiveness and varying outcomes of these policies are still lacking. Additionally, existing research falls short in evaluating the complex interactive market of different subsidy policies. Addressing these research gaps, this paper establishes an evolutionary game model integrated into a complex network to

investigate the transition of energy stations and the deployment of Charging Stations. Through an analysis of various factors influencing deployment and incentive policies, the study aims to investigate the impact of multiple incentive policies on Charging Station deployment from a dynamic evolutionary perspective, including operational subsidies, construction subsidies, EV purchase price subsidies, and charging subsidies. Simultaneously, this paper provides recommended policy intensity to be implemented based on different market distribution objectives. Simulation results lead to the following conclusions. (1) Relying solely on market-driven mechanisms is insufficient to propel the rapid development of Charging Stations. According to simulation results, naturally growing markets exhibit an upper limit for Charging Station diffusion. Robust incentive measures have the potential to rapidly stabilise the market while maintaining a high proportion of the Charging Station market share. (2) The government should appropriately intervene in multi-faceted influences in the overall energy station market. Results demonstrate that real-world markets are more sensitive to policy impacts, and consequently, it is more challenging to attain absolute market stability swiftly. Therefore, it is advisable for the government to propose tailored measures for different expected development objectives, acknowledging the dynamic nature of the market in advance and emphasising the need for comprehensive coordination in market development.

This study makes several contributions to existing research in the following aspects. Firstly, it considers Gas Stations as potential locations for Charging Stations and abstracts the relative positions of energy stations using complex networks, providing a foundation for assessing the mutual relationships between stations. Secondly, it establishes a network-based evolutionary game framework for Charging Station deployment, integrating deployment costs, revenue, and incentive policies. This framework covers cost and sales analysis across the entire industry chain from upstream to downstream, offering practical guidance for modelling infrastructure deployment practices. Thirdly, it comprehensively analyses and compares various policies targeting the UK market. The study depicts the varied implementation effects of heterogeneous policies and compares them between the traditional simplified market and the more realistic, complex interactive market. This dynamic perspective captures the intricate interactions within the infrastructure network, providing governments with more practical simulation references. This expands theoretical understanding of Charging Station related policies and offers insights for governments to balance policy combinations and adjust policy priorities. Simultaneously, this study provides insights into the transformation of traditional energy companies, accelerating the transition into a sustainable market.

Due to the complexity and variability in the development of energy station markets, this study still has some limitations. On the one hand, numerous factors influence the actual market, and it is not possible for this paper to enumerate all possible scenarios. The evolutionary game tool used in this study focuses on the interactive impact of government, investors and end users. Additionally, the extent of the future connection between the market and the government needs to be predicted. Future research can conduct targeted analysis on Charging Stations based on the varying degrees of connection between investors and the government. This is because different regions may have varying levels of government influence on the market, and investors may have different sensitivities to policies.

CRediT authorship contribution statement

Jie Sun: Writing – review & editing, Writing – original draft, Methodology, Data curation, Conceptualization. **Siying Sun:** Methodology, Formal analysis, Conceptualization. **Boli Chen:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Yukun Hu:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of competing interest

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.

Data availability

Data will be made available on request.

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