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Optimizing Electric Vehicle Charging Station Locations: A Study on a Small Outlying Island in Hong Kong

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Abstract: Electric vehicles (EVs) have been widely considered an essential element to contribute to green and smart transportation, which will further enhance the development of smart cities. Hong Kong, as one of the largest metropolises in the world, has promoted the deployment of EVs for both the private and public transportation sectors over the past decade, with substantial financial subsidies and encouraging policy incentives. With the rapid penetration of EVs, especially in the market of private passenger cars, Hong Kong may face the challenge of insufficient charging facilities in the next few years. As such, the research study aims to develop a mathematical model using a topological method to map out feasible locations for new EV charging facilities on Ap Lei Chau Island, to construct a small Python program to optimize the mapping process of these feasible locations, and to estimate energy consumption and associated economic analysis to foster the spatial planning of EV charging facility networks. In conclusion, optimal locations for new charging facilities for EVs have been revealed to match the rapid growth of EV usage and facilitate the emergence of green and smart transportation.

Keywords: electric vehicle; charging facilities; topological network; island development; optimization model

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1. Introduction

Climate refers to the long-term pattern of weather conditions in a specific place. Whether the climate is dynamic or stable, it influences all living organisms. An unchanging climate provides quality living environments for animals, plants, and people [1]. According to Ng et al. (2018) [2], the climate influences our ways of life. As such, climate change will likely impact people's way of life as it evolves. Rising reliance on fuels, growing exhaust emissions, and the increased use of fossil fuels accelerate the adverse effects of climate change. The transportation sector generates around 25% of worldwide greenhouse gas emissions, most of which can be attributed to road transportation. Road transport is Hong Kong's second-largest source of air pollution, producing almost 50,000 tons of air pollutants, which is merely marginally lower than that of marine transport emissions. Traffic-generated air pollution poses rising threats to the well-being of Hong Kong citizens.

Consequently, it has received wide attention from policymakers, industrial practitioners, researchers, environmentalists, and the community. Hong Kong is a densely populated modern city requiring an eco-friendly transportation system to reduce or even eliminate air pollution for sustainable urban development. Thus, vehicle emissions should be decreased and monitored by employing cleaner technologies [3].

Nevertheless, the insufficient number of public charging stations is the major psychological barrier to the mass acceptance of EVs. As such, the only useful method to deal with this issue is to construct sufficient public charging stations. Exploring feasible locations for new EV charging stations plays a critical role in advancing the use of EVs and shaping the landscape of sustainable transportation. Optimizing EV charging station locations is critical to support a wider acceptance of EVs, address the challenge of range anxiety, and improve user convenience. This valuable insight ensures that charging stations are strategically aligned with areas of high demand, fosters the integration of EV infrastructure into city development plans, and addresses urban planning. Apart from user convenience, the strategic positioning of charging stations facilitates the economic sustainability of private charging networks [4]. Indeed, the study of optimizing EV charging station locations is vital to promoting wider acceptance of a more sustainable mode of transportation.

In past research studies, researchers have focused on the preferences and perceptions of EV charging stations. Ref. [5] carried out a user-centered assessment of fast-charging stations to investigate user preferences and preferred locations for charging stations. Subsequently, Ref. [6] used statistical approaches and identified gas stations, workplaces, and motorway service stations as the most preferred locations for EV charging. Ref. [7] criticized such past research studies as rather outdated. In addition, Ref. [8] summarized that various researchers mainly concentrated on the key topics of EV charging stations, including the heuristic EV charging placement, the coverage problem, the traffic network equilibrium problem, and the flow-capturing method.

Ref. [9] noted that most previous research studies addressed various dimensions of EV adoption, including business models, segmented features of the EV market, incentives and policies, EV operations management challenges or problems, and charging infrastructure design and engineering. Also, the past literature generally concentrated on secondary data forecasting and analysis or survey-based studies to investigate EV adoption, which may pose limited policy implications. Ref. [10] pointed out that most studies mainly focused on stated-preference survey data or choice experiments to explore the possible role of infrastructure. Recent studies are increasingly employing consumer survey data or aggregate car registration data to examine the impact of financial incentives and access to public charging stations on EV sales. In addition, various research studies have adopted different approaches to examine the preferences for charging infrastructure. Ref. [11] employed discrete choice models to investigate the impact of factors such as charger location, time of travel, detour location, and remaining charge on the selection of charging stations. Ref. [12] explored appropriate locations for community EV charging points using a geographic information system-based method. Ref. [13] adopted a mixed method involving a systematic literature review, the analytical hierarchy process, and stakeholder interviews to construct a methodological framework for investigating appropriate locations for EV charging points.

To the best of the authors' knowledge, various countries have carried out research on sustainable improvements and clean energy on islands [14]. Nevertheless, research related to the investigation of optimizing locations of new charging stations for EVs on small outlying islands, notably in Hong Kong, is scarce. To address the research gap, the main purpose of this research is to develop a mathematical model using a topological method to map out feasible locations for new EV charging facilities on Ap Lei Chau Island, to construct a small Python program to optimize the mapping process of the identified locations and to foster the spatial planning of EV charging facility networks. This study is the first to base its analysis on 'sufficient size of the place', 'easy to find', 'residential/commercial/industrial areas', and 'weather conditions'. It categorizes these into different clusters based on geographical locations and conducts a simulation analysis of the charging station layout based on the clustering results. It may create a diversified charging scenario for Hong Kong's small outlying islands. Also, it is one of the first adoptions of machine learning in the area of optimal location selection of EV charging facilities, which may make topographic maps easily useable. In addition, the study promotes research on the use of energy on small outlying islands related to EV promotion. Indeed, the research study is significant for energy substitution for transport on small outlying islands with large populations [14].

This paper is divided into five main sections. Section 1 provides the research background, setting, and objectives. Then, Section 2 describes an overview of electric vehicles in Hong Kong, including public charging facilities, progress, challenges, and opportunities. After that, Section 3 identifies the geographical context and characteristics of the small outlying island, Ap Lei Chau. In Section 4, the research methodology and robust mathematical modeling are given. This section mainly explores appropriate locations and the feasibility of installing more charging stations on Ap Lei Chau Island. Section 5 provides the academic and managerial implications, research limitations, and future research directions.

2. An Overview of Electric Vehicles in Hong Kong

Public Charging Facilities

EV charging infrastructure is essential to facilitate the market uptake of EVs. In Hong Kong, public chargers are offered by both private and public sectors for charging EVs, mostly light goods vehicles and private cars. By the end of 2020, over 3300 chargers from the public and private sectors were available for public usage, among which over 1100 were provided by the government and the remaining were offered by the private sector. In the future, the HKSAR government plans to have a minimum of 5000 public chargers by 2025. The government will likely continue identifying various methods and installing public charging facilities to fulfill the goal. This includes assessing the possibility of offering roadside charging facilities. In addition to the rising demand, the marketization of charging services will motivate the supply of extra public charging facilities [15]. The existing distribution of public charging facilities is shown in Table 1.

Table 1. The existing distribution of public charging facilities in Hong Kong as of December 2022.

Point	Standard	Medium	Fast	Total
Islands	16	162	46	224
North	169	136	31	336
Yuen Long	54	114	60	228
Tai Po	30	20	17	67
Shatin	118	314	94	526
Tuen Mun	14	52	30	96
Tsuen Wan	20	201	25	246
Kwai Tsing	9	129	53	191
Wong Tai Sin	23	59	25	107
Sai Kung	121	83	71	275
Sham Shui Po	29	182	97	308
Kwun Tong	561	322	108	991
Yau Tsim Mong	54	180	100	334
Kowloon City	95	45	36	176
Eastern	21	227	69	317
Southern	6	192	42	240

Table 1. *Cont.*

Point	Standard	Medium	Fast	Total
Wan Chai	67	266	47	380
Central & Western	46	299	47	392
Total	1453	2983	998	5434

Source: [15].

In general, natural gas dominates about 48% of the fuel mix in Hong Kong, followed by nuclear energy and renewable energy contributed to about 28% and coal about 24%) [16]. In other words, fuel is still the main source of electricity generation in Hong Kong. Hereto, government departments (including the Environmental Protection Department) intend to manage and operate 2550 public electric vehicle chargers. The Environmental Protection Department has continuously carried out fee-paying electric vehicle charging services for its more than 1600 medium charges of seven kilowatts (i.e., 74 government car parks) until the end of 2023. Later, fee-paying electric vehicle charging services were conducted in 54 government car parks, covering more than 1000 chargers. As expected, HKSAR plans to expand electric vehicle charging services in the outstanding 20 government car parks before the middle of 2024 [17].

3. EV and Charging Infrastructure Planning on the High-Density Outlying Island of Ap Lei Chau

In the Ming dynasty, there were archives of people settling on Ap Lei Chau Main Street. Due to insufficient land transport, Ap Lei Chau was identified as a no-man's land. In the 1980s, the building of the Ap Lei Chau Bridge significantly changed the ecology and demographics of Ap Lei Chau. Also, the construction of private and public housing attracted incoming residents to the island, generating a new wave of urbanization [18].

Ap Lei Chau Island is a small and densely populated outlying island where almost 80,000 people live in an area measuring 1.3 km^2 (about half a square mile) in Hong Kong, geographically belonging to the Aberdeen area in the southern administrative district of Hong Kong [19]. The sea between Ap Lei Chau and Aberdeen is the typhoon shelter area for ships and yachts. This geographical advantage has led to a high concentration of fishery activity, creating a fishing village in the Ap Lei Chau-Aberdeen area [20]. A bridge connects Ap Lei Chau Island to Aberdeen and provides access to the nearby commercial and industrial area named Wong Chuk Hang. The geographical shape of Ap Lei Chau resembles a smaller version of Hong Kong Island. The southern and middle areas of Ap Lei Chau are hills. The entire island is mainly for residential use, concentrated in the western and northern areas. A small industrial area on the island's southwest corner also provides furniture outlet sales and information technology services such as data centers. The geographical location of Ap Lei Chau Island is shown in Figure 1.

Currently, most of Ap Lei Chau Island residents must commute to other districts for their daily work or schooling. The local government has provided bus routes from the island to downtown areas. There are also small-scale ferry services from the island to nearby Aberdeen. With the operation of the new mass transit railway (MTR) South Island Line in October 2016, Ap Lei Chau Island is now connected to the whole subway system in Hong Kong. There are two stations on the small island, South Horizons Station and Lei Tung Station, located at the west corner and east end of the island. Thanks to the rapid penetration of electric vehicles in Hong Kong, Ap Lei Chau Island has also established an EV fast-charging station close to the residential area on the west corner of the island.

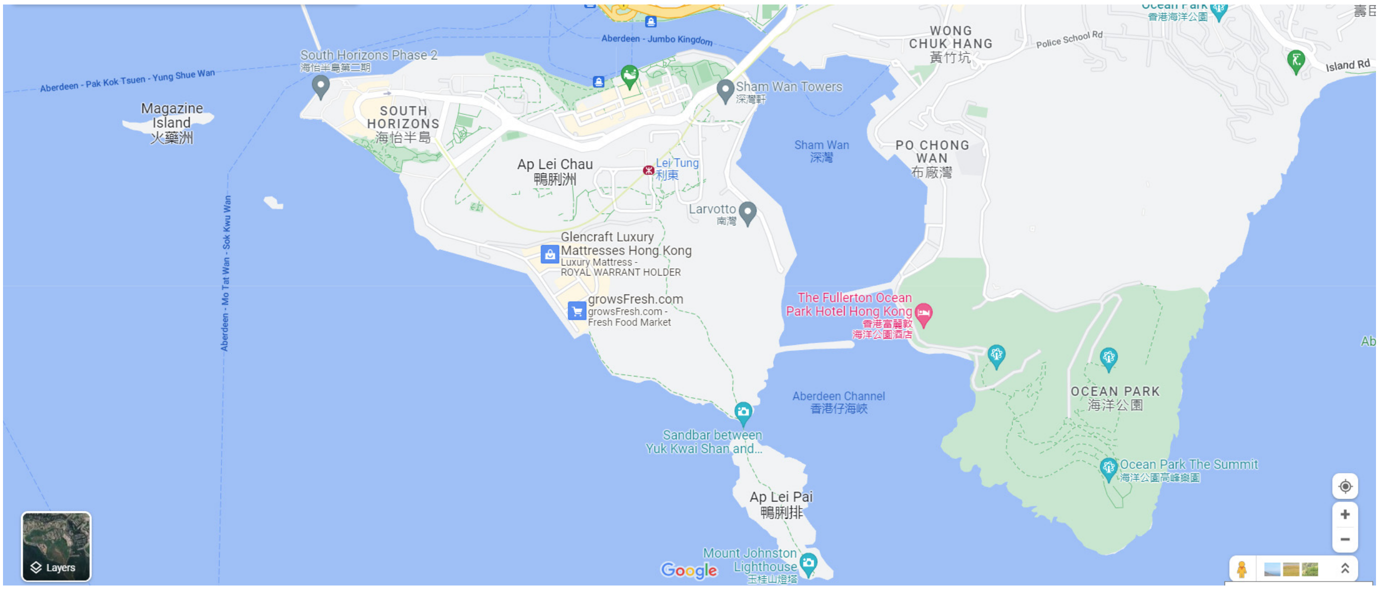

Figure 1. Map of Ap Lei Chau Island. Source: [21].

4. Research Methodology and Mathematical Modeling for Optimal EV Charging Infrastructure Planning

A feasibility study with decision-making criteria has been conducted to identify optimal locations to install EV charging stations on Ap Lei Chau Island, a feasibility study with decision-making criteria has been conducted. Decision criteria were first identified through the literature review and policy analysis, then combined with field visits and map data analysis to assess the applicability of different sites, including (1) sufficient size of the place, an area that is large enough to install several charging stations; (2) close to the road, which is easy for drivers to find; (3) close to residential/commercial/industrial areas or any place that is convenient to access. By following the three decision criteria, the installed charging stations can enhance the convenience for drivers. In the meantime, this can ensure the usage rate of the newly installed charging stations. They can charge their electric vehicles during working or leisure time and use them when needed. (4) Weather conditions must be considered. Since the climate of Hong Kong is subtropical, there may be some extreme weather during the summer (around June to October), such as typhoons (i.e., tropical cyclones); typhoons may lead to other problems, including rainstorms, large waves, flooding, landslides, etc. [1]. Furthermore, the safety issues of the charging stations need to be considered, even under extreme weather conditions. A flowchart of the decision process for identifying optimal locations is provided in Figure 2.

After the decision criteria were processed via the above flowchart, three clusters were identified by clustering analysis according to the geographical situation of Ap Lei Chau Island. Cluster analysis refers to the process of dividing potential charging station locations on Lei Chau Island into different groups or clusters based on geographical location, accessibility, and proximity to residential, commercial, and industrial areas. This method helps identify areas where charging stations would be most beneficial and convenient for users. The clusters include Cluster A, near private housing estates; Cluster B, an industrial and commercial area; and Cluster C, an area near a home ownership scheme housing estate. After that, the topological network from the traffic map is generated, with the necessary driving point (the white dots), as shown in Figure 3. Lastly, the driving nodes of each cluster have been identified, and the associated mean point has been calculated.

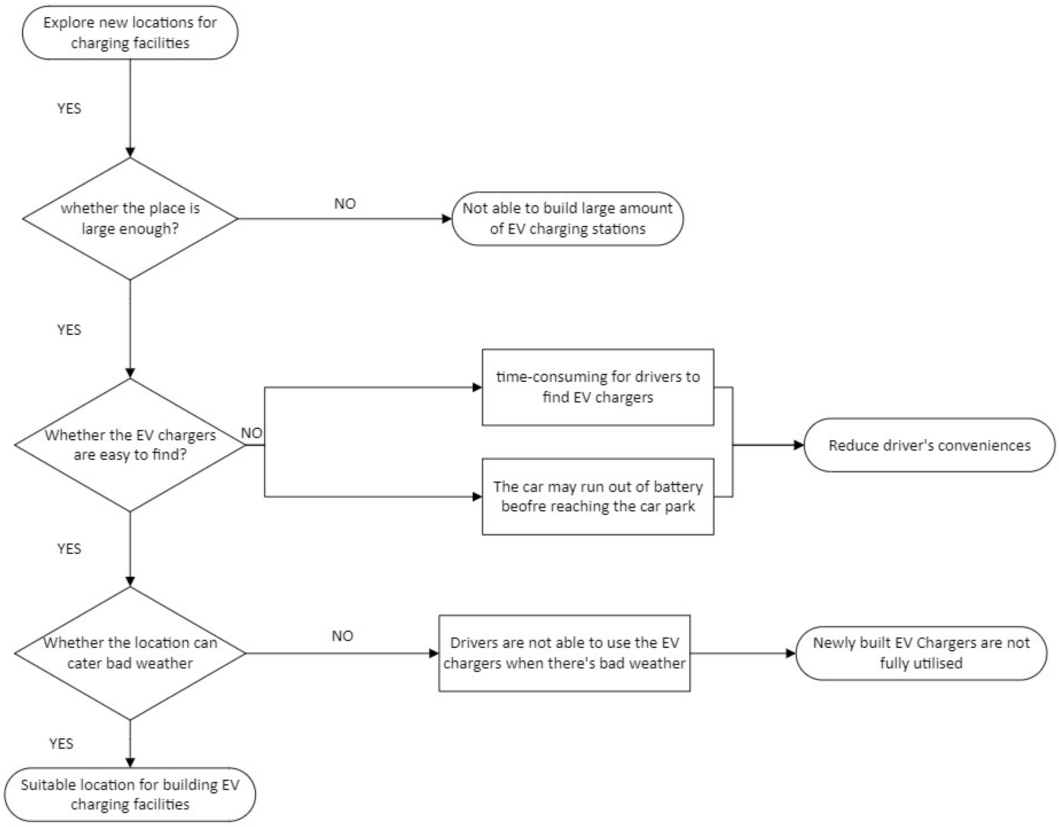

Figure 2. Flowchart of the decision process for electric vehicle charging station locations.

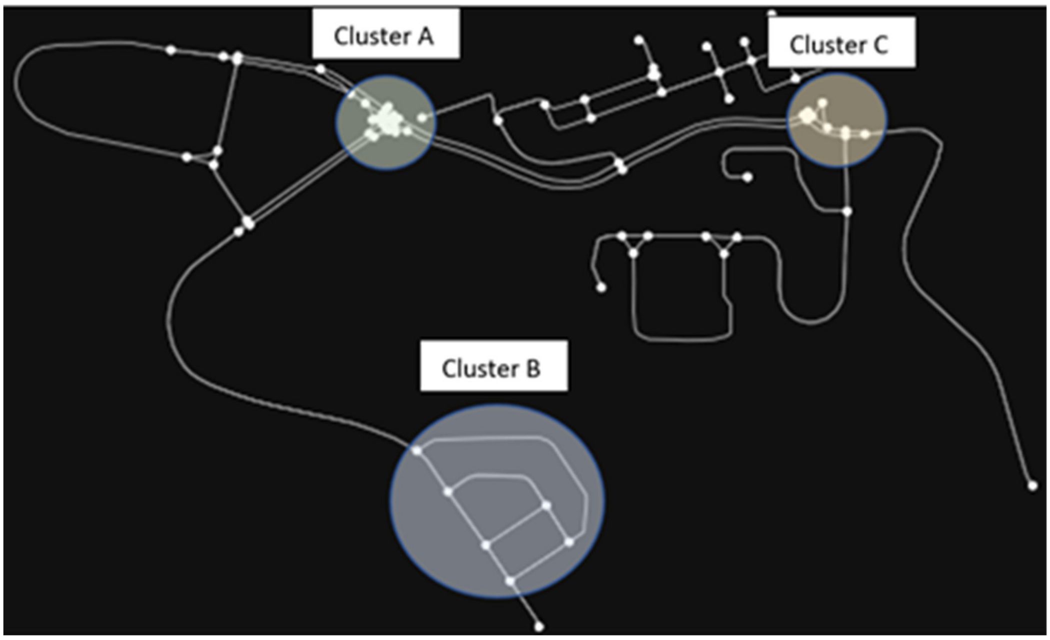

Figure 3. Trimmed road network of Ap Lei Chau Island.

To ensure that the selected nodes effectively serve their designated areas, we have adjusted starting points and routes for each cluster to reflect real-world road conditions and enhance accessibility to the charging stations. For instance, in Cluster A, we relocated the starting point to a car park near private residential areas so that residents have convenient access to charge their vehicles during work or leisure hours. The starting point for Cluster

B was slightly shifted towards inland areas to mitigate potential damage from extreme weather conditions, such as typhoons. In Cluster C, an open, small area was chosen as the starting point because it presented the most ideal implementation plan. These adjustments aim to optimize the distribution and functionality of charging stations across Ap Lei Chau Island.

To further illustrate the clusters' details in the above topological network, Google Maps's API has been employed to demonstrate the following analysis. Firstly, the distance and the average time between each cluster have been estimated to identify the ideal area to install extra charging stations. An extension API of Distance Matrix has been employed to collect the data needed. Mean points are set as the starting points of each cluster.

The following map has been generated with three corresponding routes as shown in Figures 4–6: (i) from Cluster A to Cluster B; (ii) from Cluster A to C; (iii) from Cluster B to C.

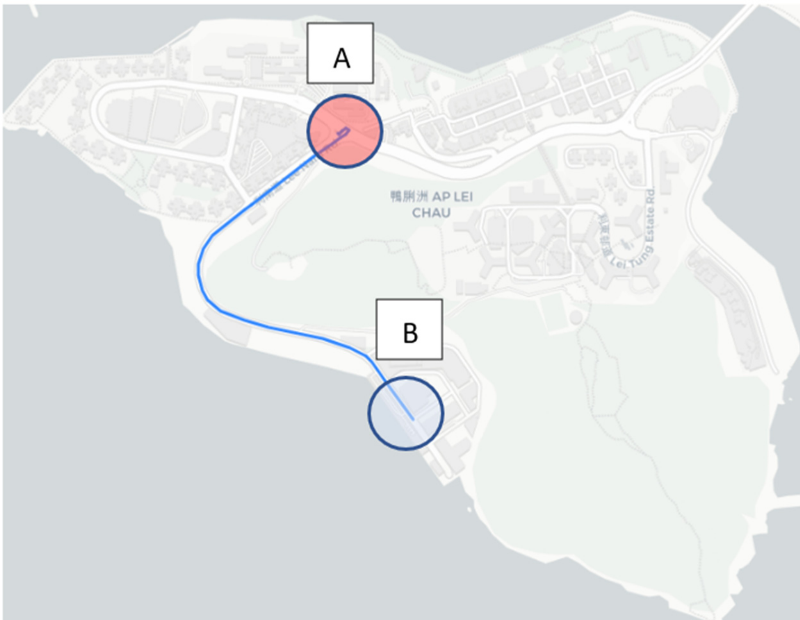

Figure 4. Route from Cluster A to Cluster B on Ap Lei Chau Island.

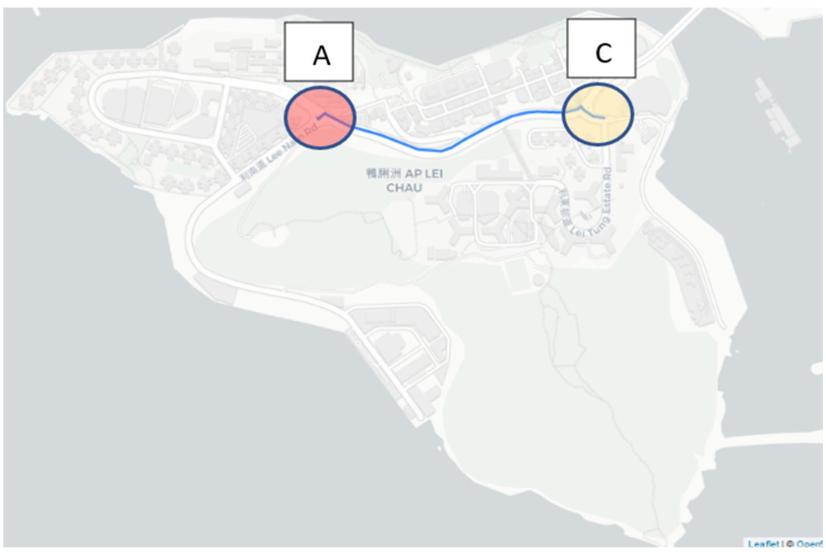

Figure 5. Route from Cluster A to Cluster C on Ap Lei Chau Island.

Figure 6. Route from Cluster B to Cluster C on Ap Lei Chau Island.

Notably, the distance from Cluster A to Cluster B is 1.8 km, and drivers need an average of 6 min to drive from Cluster A to B. The route from Cluster A to C is the shortest path among the 3 routes, which only takes 3 min and covers 0.7 km. The distance between Cluster B and C is 2.6 km, and the detour time is 7 min, as shown in Table 2.

Table 2. Distance and travel time of routes.

Cluster	Origin	Destination	Distance (km)	Time (min)	Speed (km/min)
	A	**B**	**1.8**	**6**	**0.30**
	A	C	0.7	3	0.23

5. Simulation and Discussion

After generating the routes and the detour time, the feasibility of installing the charging stations in each cluster has been discussed. According to the geographical situation of Ap Lei Chau Island and the decision criteria discussed above, each cluster's starting points and routes have been adjusted. The reasons are elaborated as follows. For Cluster A, since the area is very close to the private housing estate (South Horizons Phase 4), it is intended to find the car park they provide and install extra charging stations inside it. Therefore, the starting point of Cluster A has been adjusted to Yi Nam Road instead of Li Nam Road (which is slightly to the West; please refer to Figure 7). Similarly, minor adjustments to the optimal route at Cluster B have also been made. The original starting point of Cluster B is fine, but the concern is that the charging stations may be affected by extreme weather, such as typhoons and heavy rain. Therefore, the starting point has been slightly moved to the inner part of Cluster B to avoid the possibility of damage under extreme typhoon weather. Due to the terrain of Cluster C, several feasible options have been compared for the adjusted starting point: option 1 is a small empty space, which is the ideal plan for implementation; option 2 is to locate EV charging stations at Lei Tung Estate Road, however, with insufficient space to build and install charging facilities; and option 3 is to locate and install EV charging stations on a slope, which could provide a large empty space for us to build charging stations but with a high construction and installation cost, which is not economically effective. Therefore, we have chosen option 1 as our adjusted starting point for Cluster C. Last but not least, based on the practical situation of the road network, the starting nodes of the above three clusters have been slightly adjusted to reflect the real-life situation on the road, as shown in Figures 7–10.

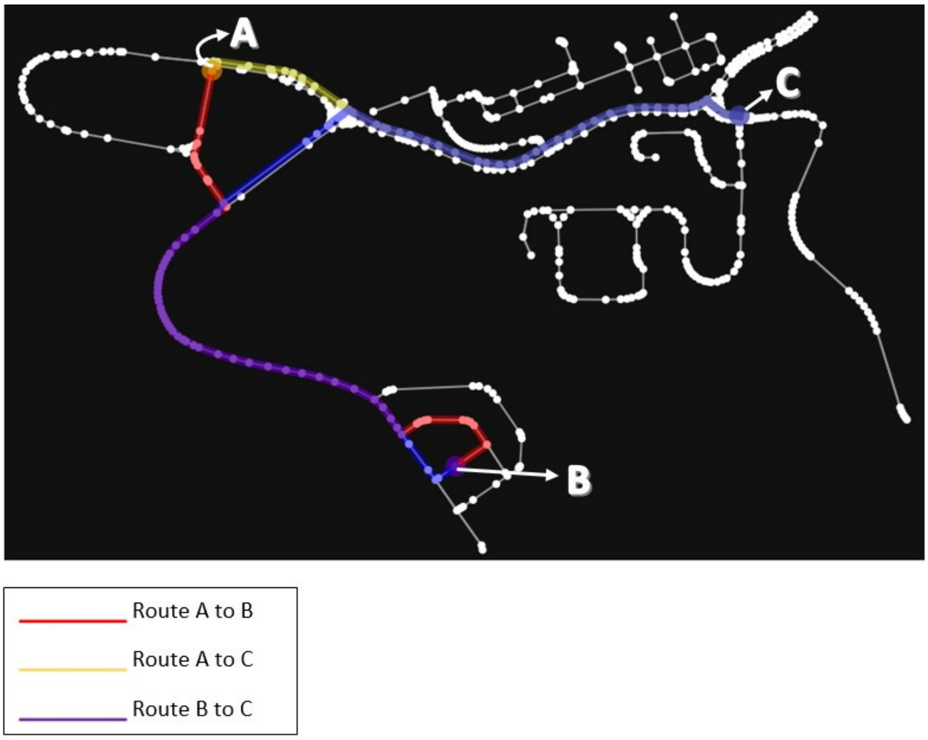

Figure 7. Adjusted nodes for routes of Ap Lei Chau Island.

Figure 8. Adjusted nodes for routes from Cluster A to Cluster B.

After adjusting the routes and starting points, the distance and the average travel time between Cluster A and B became shorter, from 2.6 km to 1.5 km, and the average travel time was shortened from 7 min to 4 min. For Cluster A to Cluster C, the difference between the old and new paths is minimal, increasing by only 300 m, from 0.7 km to 1 km, and the average travel time increased from 3 min to 4 min. For Cluster B to Cluster C, the situation is the same as the path from Cluster A to Cluster C, which is slightly different from the old route. The distance from Cluster B to Cluster C increased from 1.8 km to 1.9 km, with the difference being only 100 m, but the average travel time is the same, only taking 6 min. Details are shown in Table 3.

Figure 9. Adjusted nodes for routes from Cluster A to Cluster C.

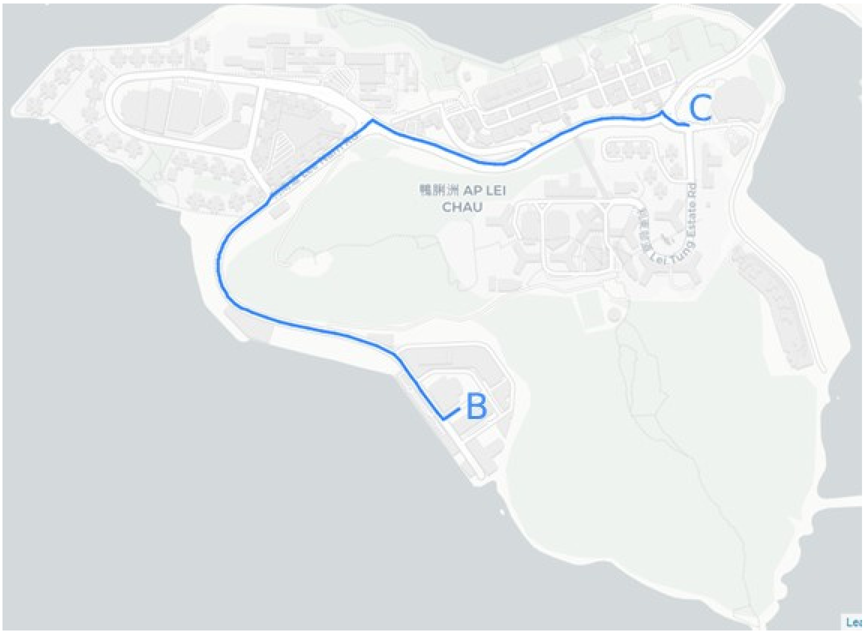

Figure 10. Adjusted nodes for routes from Cluster B to Cluster C.

Table 3. Optimized Distance and Travel Time of Routes.

Cluster	Origin	Destination	Distance (km)	Time (min)	Speed (km/min)
	A	**B**	**1.5**	**4**	**0.375**
	A	C	1	4	0.250

Therefore, the distance and the average travel time between Cluster A and Cluster B have been significantly shortened after the starting points and optimized routes of each cluster were adjusted, whereas the paths between Cluster A and Cluster C, Cluster B, and Cluster C do not show a significant difference in distance and average travel time.

6. Conclusions

The research study has been divided into three main cluster areas. In general, the key findings can be summarized as below:

- The car park needs to be enlarged in capacity by installing additional charging stations near the private housing estate. The rationale behind this is that many users and public transport operators may use the EV charging stations simultaneously, notably during peak hours. Otherwise, it fails to support people's daily lives, including going to work, studying, and maintaining social ties in the community.

- Extreme weather, such as heavy rain and typhoons, may cause serious damage to EV charging stations. Indeed, EV charging stations are vulnerable when located near coastal areas. As such, critical infrastructure management is crucial to the development of EVs.
- The establishment of EV charging stations may require consideration of future expansion factors such as flat areas and empty space. This will help electric vehicles achieve sustainable development in the coming years.

Due to the active involvement of local authorities and the transport industry, fast charging has become a recent technical progression that specialists have made in EV charging infrastructures. In response, our study may provide some possible policy recommendations. EV developers seek to advance EV charging infrastructures to improve the dissemination of EVs. The recent development of battery technologies enables fast charging because they have elevated energy densities and power densities. This has become an ongoing technical trend for EV charging facilities in Hong Kong, known as smart charging, in the next few years. In response, the government may provide research funding (e.g., Innovation and Technology Fund, Research Matching Grant Scheme, etc.). Some strict proclamations from the government authorities that own new residential apartments could consider the construction of new charging facilities aligned with urban development. The government may form a working group with various professionals, policymakers, associations, local communities, and researchers to design how the new charging facilities integrate with the urban landscape. Nevertheless, related policies and regulatory guidelines have also shown efforts to phase out conventional vehicles. In doing so, administrations have further utilized incentives to attract more consumers and manufacturers to increase charging facilities and stations. As expected, it may foster extensive usage of EVs, decrease range anxiety, and increase customer satisfaction. Various incentives have also been offered to private buildings, in terms of direct and indirect subsidies, so that existing charging docks can be renovated in their buildings. Some non-monetary subsidies, such as reserved parking slots with charging ports, could also contribute to the upward trend. As such, the government may develop supporting business and value-added service sectors to create an integrated smart city. Investors and business developers may be motivated to upgrade their existing EV charging facilities and enlarge the EV charging stations. Strong yet sustainable policy incentives will contribute to the increasing number of newly planned charging facilities in the next few years, which will further enhance immensely the rapid development of EVs in Hong Kong as a hub for green and smart transport. The government may proactively design a comprehensive educational campaign to address the importance of smart and green transport to higher education institutions, business enterprises, and the local community. Green transport hubs may alleviate the adverse impact of climate change by minimizing damage to infrastructure and interruptions of transport operations. Nevertheless, electric vehicles generate no tail-pipe emissions; GHGs are produced at the source of generation, which means there is a questionable transition to net zero emissions from road transport. Indeed, the government may need to improve the electricity supply, enrich the design of electric vehicles, and upgrade the charging facilities of the outlying islands to promote the common use of EVs and increase connectivity with the community in the future. In the long term, this may increase people's mobility and help them achieve sustainable development goals (i.e., sustainable development goals 8—decent work and economic growth and 11—sustainable cities and communities).

In conclusion, our paper provides valuable insight into the EV research study and addresses future research directions. Firstly, this study only used Ap Lei Chau Island as a case study to investigate optimizing locations of new charging facilities for EVs. As such, our future research will further examine the optimization of mapping both newly planned charging stations and renovation of existing charging facilities in car parks and residential and commercial buildings on a broader scope, considering additional constraints such as peak hour traffic congestion. The EV routing problem will also be identified in the next research. To what extent and how can we design and implement optimization strategies for EV routing and charging stations in Hong Kong? How can the number of EV charging stations and the best sites be strategically set up in Hong Kong to serve the rising demand for EVs? Secondly, this study used a mathematical model and a small Python program to generate the EV charging facilities study. In doing so, we may carry out semi-structured, in-depth interviews with various stakeholders, including EV firms, associations, policymakers, researchers, and environmentalists, to give constructive feedback on the policy aspects. As such, what are the policy implications and future trends of EV charging stations in the forthcoming years? Thirdly, the study provides foundational work to contribute to a bibliographical review of the spatial localization of new charging facilities for EVs in the next research. What are the key contributions that the research community has generated to the EV industry and regional and global economies? What can the EV research community understand from the trends and development of EV research to continue to contribute to the well-being of the regional and global economies?

Furthermore, the main findings from this research address the significance of using a mathematical model via a topological method to map out feasible locations for new EV charging facilities in Hong Kong's unique contexts, to create a small Python program to optimize the mapping process of these feasible locations, and to forecast energy consumption and associated economic analysis to foster the spatial planning of charging facilities network of EVs. The current study contributes to providing feasible solutions to fulfill the increasing demand for EVs in Hong Kong, as well as the continuous conversation about sustainable transportation. Since EV usage keeps increasing, the suggested strategies aim to foster extensive usage of EVs, improve customer satisfaction, and reduce range anxiety. Optimal planning and construction of EV charging facilities are of great importance in contributing to green and smart urban development, especially for outlying islands with residential and commercial buildings, such as Ap Lei Chau Island, in this research paper. Appropriate planning and development of an electric power system will provide essential support for consumers and residents. Our future research will expand the analysis and discussion on related policy incentives and associated impacts, which will contribute to policy-making relevant to Hong Kong Climate Action 2030+ and carbon neutrality by 2050.

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Conflicts of Interest: Author Christine Yip was employed by the company CAFEA Smart City Limited. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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