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OPTIMIZATION OF CURRENT AND PROPOSED EV CHARGING INFRASTRUCTURE IN SHAH ALAM USING MAXIMUM FLOW ANALYSIS AND MILP

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Abstract:

The rapid growth of electric vehicles (EVs) in Malaysia has intensified the need for effective and spatially efficient planning of charging infrastructure. This study proposes two approaches to evaluate existing electric vehicle charging stations (EVCS) and to identify optimal expansion strategies within Shah Alam, Selangor, focusing on Sections 1 to 24. In the first phase, a maximum flow-based model is employed to assess how much charging demand can be satisfied by the current network of fast charging stations (CS)s. The results reveal a substantial imbalance between demand and available capacity, with only 1.42% of total charging demand being satisfied, thereby exposing significant spatial coverage gaps across the study area. Building upon these findings, the second phase applies a mixed-integer linear programming (MILP) model to determine optimal locations and capacity allocations for new EVCS under realistic budget constraints, with the objective of maximizing satisfied demand. The optimization outcomes provide a targeted expansion strategy that improves demand coverage, station utilization, and cost efficiency. The resulting station configuration is also examined alongside the locations proposed through national planning initiatives to illustrate differences in spatial emphasis and coverage outcomes. Overall, the study demonstrates that integrating maximum flow analysis with MILP offers a systematic and data-driven approach for EVCS planning. The optimization models provide practical insights for urban planners and policymakers seeking to support sustainable EV adoption through efficient and demand-responsive charging infrastructure deployment.

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Keyword:

Charging Stations, Electric Vehicle, Maximum Flow, MILP, Optimization

Introduction

The transition toward electric vehicles (EVs) has intensified globally in recent years, supported by increasing environmental awareness 0, rapid technological progress, and strong policy initiatives across multiple regions 0. This global momentum is increasingly evident in Malaysia, where EV adoption has expanded at an unprecedented rate 0. As reported by Tham and Neo 0, national EV sales rose from 278 units in 2022 to 2,631 units in 2023, before escalating sharply to 28,055 units in 2024. This sustained growth trajectory indicates that Malaysia is entering a decisive stage of EV market development, where infrastructure readiness and strategic planning are essential to support continued adoption 0. Despite the increasing number of EVs on the road, the deployment of EV charging station (EVCS) infrastructure has not progressed at a comparable pace 0, particularly in the provision of fast-charging facilities. Since fast charging plays a crucial role in reducing dwell time and supporting efficient urban travel 0, this study concentrates exclusively on Level 3 or DC charging infrastructure to address existing network limitations and accommodate future demand growth.

As of March 2025, Selangor recorded the highest number of charging stations nationwide, with 1,276 installations reported through the MEVnet platform. However, the spatial distribution and capacity of these stations remain insufficient to serve a rapidly expanding user base 0. Although EV affordability is often perceived as the primary barrier to adoption, previous studies indicate that limited charging availability represents a more significant constraint 0. EV users continue to experience range anxiety and uncertainty in locating nearby charging facilities, particularly during peak periods and within high-density urban environments 00. The concentration of EVs at a limited number of fast-charging stations further exacerbates congestion, leading to extended waiting times and reduced service efficiency 0. These challenges emphasize the need for systematic, data-driven planning approaches that ensure charging infrastructure is strategically positioned and adequately scaled to meet urban demand patterns.

Within this context, Shah Alam represents an appropriate urban case study for examining EVCS deployment strategies. As the administrative capital of Selangor, Shah Alam is characterized by a planned urban structure that supports a diverse range of activities, including administrative, educational, commercial, and residential functions 0,0. This study focuses on the central zone of Shah Alam, encompassing Sections 1 to 24, as this area contains key land-use elements such as government complexes, major university campuses, dense residential neighbourhoods, and designated low-carbon development zones 0,0. MEVnet has identified

Shah Alam as one of the urban areas in Selangor with substantial charging infrastructure requirements. Figure 1 illustrates the spatial distribution of the 29 existing EVCS locations within Sections 1–24 based on verified coordinates, while Table 1 summarizes the availability of AC and DC chargers at each site.

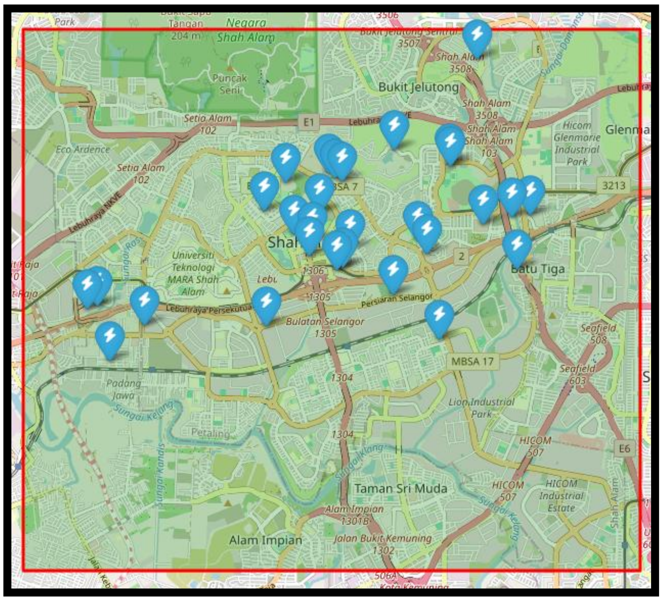


Figure 1: Existing EVCS Location From MEVnet Within Section 1-24 in Shah Alam

Table 1: Filtered List of Existing EVCS Locations

No.	Locations	AC	DC	Section
1	Aeon Shah Alam	2	5	13
2	Alam Sanjung	4	0	22
3	Burger King Shah Alam Extreme Park S13	2	0	13
4	Central I-City	4	0	7
5	Concorde Shah Alam	4	0	9
6	C-Zero	0	0	15
7	Decathlon Shah Alam	1	0	14
8	Dewan MBSA S4	1	0	4
9	Exicom	1	1	15
10	Ken Rimba Condo	6	0	16
11	KPJ Selangor Specialist Hospital	5	0	20
12	Laman PKNS	2	0	14
13	Lotus Shah Alam	0	1	13
14	Mazda Padang Jawa	0	0	16
15	Mercu Maybank	4	4	7
16	MSU	2	0	13
17	Pejabat Pos Besar Shah Alam	0	2	12
18	Plaza Shah Alam	3	0	9
19	Prima U1	3	0	13
20	Pusat Akuatik Darul Ehsan	1	0	13
21	Pusat Perdagangan UMNO	2	0	14
22	Raja Tun Uda Library	1	0	13

23	SACC	2	0	14
24	Shah Alam City Council	1	0	14
25	Shah Alam Extreme Park S13	2	0	13

Following the delineation of the study boundary, an initial dataset comprising 78 CS coordinates was refined to ensure spatial relevance within the selected central zone. This screening process resulted in 29 stations located within or immediately adjacent to Sections 1–24, as presented in Figure 1. Although the presence of 29 stations may suggest reasonable infrastructure coverage, a closer examination of charger composition reveals a notable imbalance. Based on Table 1, only 18 of these locations are equipped with DC fast chargers, a proportion that is insufficient for a dense and rapidly developing urban area with high traffic intensity and mixed land-use characteristics. The limited availability of fast chargers concentrates charging demand at a small number of sites, resulting in operational inefficiencies such as queue formation, increased idle time, and reduced charging convenience 00. Consequently, many users are forced to rely on slower AC chargers, which are less compatible with the rapid turnaround requirements typical of urban charging behaviour. This imbalance highlights the necessity of optimizing the spatial distribution of DC chargers to achieve more resilient, efficient, and equitable access across Shah Alam's central zone.

Strategic planning of EV charging infrastructure is therefore essential to accommodate the anticipated growth in EV ownership in Malaysia 0,0. Identifying optimal locations for EVCS deployment helps avoid redundant installations 0 while ensuring that areas with genuine demand shortages are prioritized. Such an approach also supports effective cost management, given the substantial capital and operational expenditures associated with EVCS development. Optimization techniques provide a systematic framework for maximizing infrastructure performance while minimizing unnecessary investment and have become increasingly central to EV infrastructure planning at both international and national levels 0. However, many local studies continue to rely heavily on forecasting-based approaches, which may lead to inflated demand estimates when not grounded in observed user behaviour and actual charger utilization. As noted by 0, demand projections that are disconnected from real-world conditions risk producing impractical planning outcomes. Consequently, EVCS planning in Malaysia must emphasize optimization strategies that integrate current demand patterns with anticipated growth, ensuring scalability, realism, and alignment with user needs 0.

In response to these challenges, this study develops a structured, data-driven approaches to strengthen EVCS planning in Shah Alam. The research is guided by two primary objectives. The first objective is to evaluate the performance of existing EVCS locations within the central zone using two approaches, beginning with a maximum flow-based model to assess the ability of the current network to satisfy spatially distributed charging demand. The second objective is to formulate a Mixed Integer Linear Programming (MILP) model, implemented using IBM CPLEX, to determine the number and placement of new EVCS installations required to reduce unmet demand and enhance overall network coverage. Together, these objectives provide a comprehensive assessment of current infrastructure performance and support informed, cost-effective decision-making for future EVCS expansion in Shah Alam.

Methodology

This study adopts two approaches consisting of a maximum flow approach followed by a MILP approach. The first approach applies a maximum flow model to evaluate how effectively the existing CS within Shah Alam's central zone satisfies current EV charging demand. This focuses on identifying spatial demand–capacity mismatches, flow distribution patterns, and potential bottlenecks over a three-month demand period. The second approach extends the analysis by formulating a MILP model using IBM CPLEX to determine the optimal number of new EVCS locations and capacity expansions required to reduce unmet demand. Figures 2 and 3 present schematic overviews of the optimization models employed in each phase of the methodology.

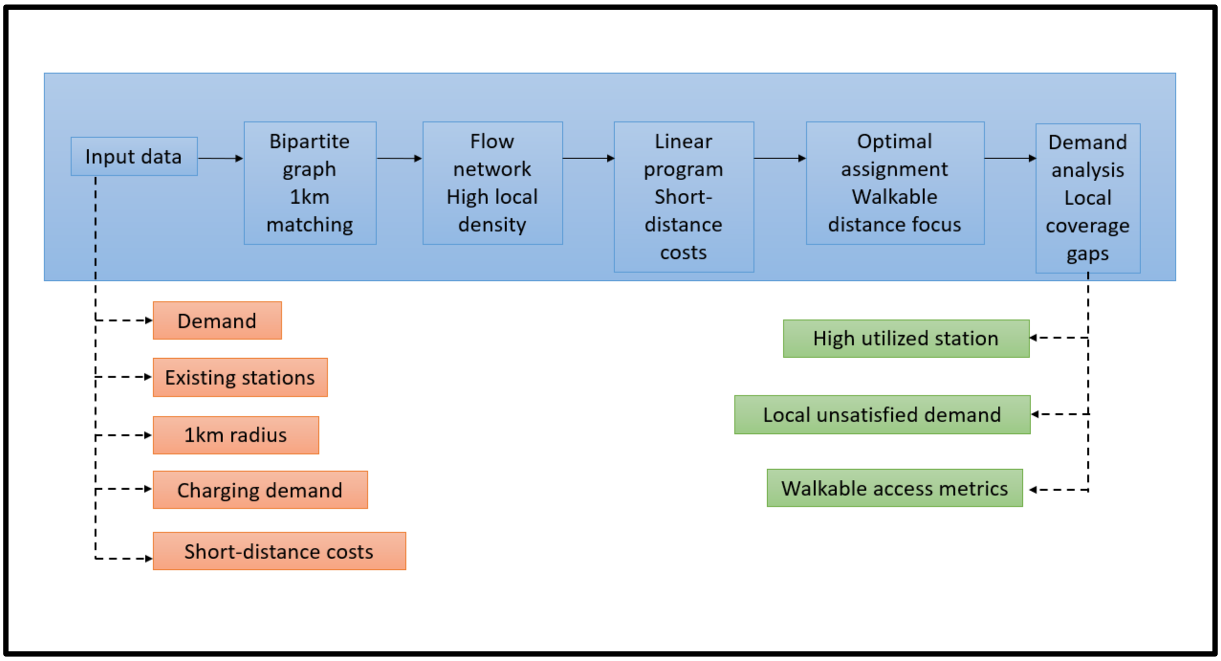


Figure 2: Maximum Flow Approach

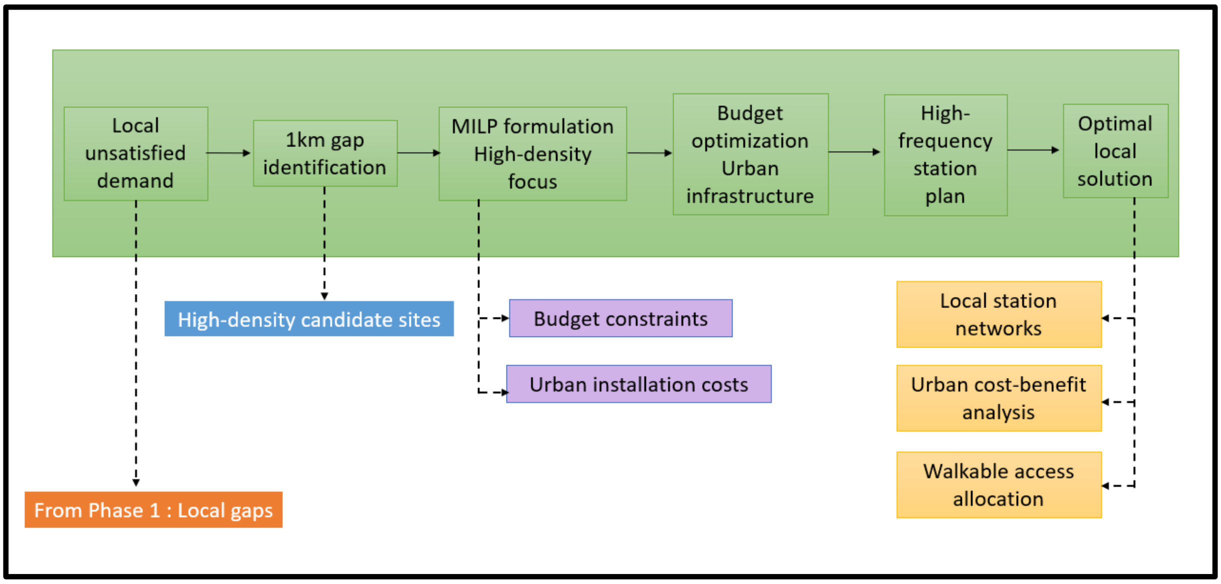


Figure 3: MILP Approach

Maximum Flow Approach

To assess the ability of the existing CS network in Shah Alam's central zone to accommodate current EV charging demand, a maximum flow–based approach adapted from Parent et al. 0 is employed. The methodology begins with the construction of a bipartite graph, where nodes on the left represent EV charging demand and nodes on the right represent existing CS locations. Spatial feasibility between demand nodes and stations is determined using a service radius of 1 km. An edge is created between a demand node and a station node if the station lies within this radius, thereby capturing the spatial accessibility of charging facilities to different travel demands.

The bipartite graph is then transformed into a flow network to model the allocation of charging demand across the system. Each feasible demand–station connection becomes an arc representing a potential charging assignment. A source node is introduced and connected to all demand nodes, while a sink node is added to collect flow from all station nodes. Capacity constraints are incorporated to reflect system limitations: arcs from the source to demand nodes represent the magnitude of charging demand, whereas arcs from station nodes to the sink represent station capacity, determined by the number of available charging bays. This structure allows the model to account for shared demand at each node and simultaneous service by stations with multiple bays. Demand nodes that are not connected to any station are classified as unserved demand, indicating that their entire flow remains unsatisfied under the current infrastructure configuration. The transformation from bipartite representation to flow network is illustrated in Figure 4.

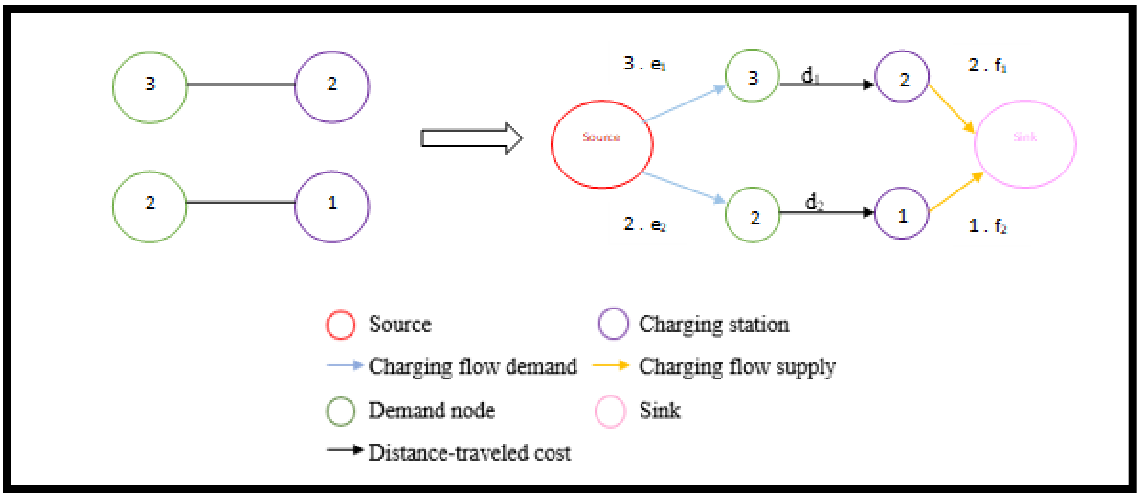


Figure 4: Converting a Bipartite Graph to a Flow Graph

The resulting flow network as shown in Figure 4 is formulated as a Linear Programming (LP) problem. The objective function minimizes total system cost, which includes travel distance between demand nodes and assigned stations, along with a large penalty assigned to unmet charging demand. Flow conservation constraints ensure that all demand is either satisfied by available stations or explicitly accounted for as unmet demand. Additional constraints enforce station capacity limits and non-negativity of all flow variables. The LP is solved using IBM CPLEX, yielding the maximum amount of charging demand that can be satisfied by the existing network. This analysis provides a quantitative assessment of infrastructure performance and highlights spatial and capacity-related weaknesses within the current EVCS network. The concept of maximum flow optimization model applied in this study is visually represented in Figure 2.

MILP Approach

Building on the insights obtained from the maximum flow analysis, the second approach formulates a MILP model to determine strategic infrastructure expansion decisions. While the maximum flow model identifies where and to what extent charging demand remains unmet, the MILP model addresses how the network should be enhanced to alleviate these deficiencies. The model determines suitable locations for new Level 3 (DC) CS and identifies the number of additional charging bays required at both new and existing sites.

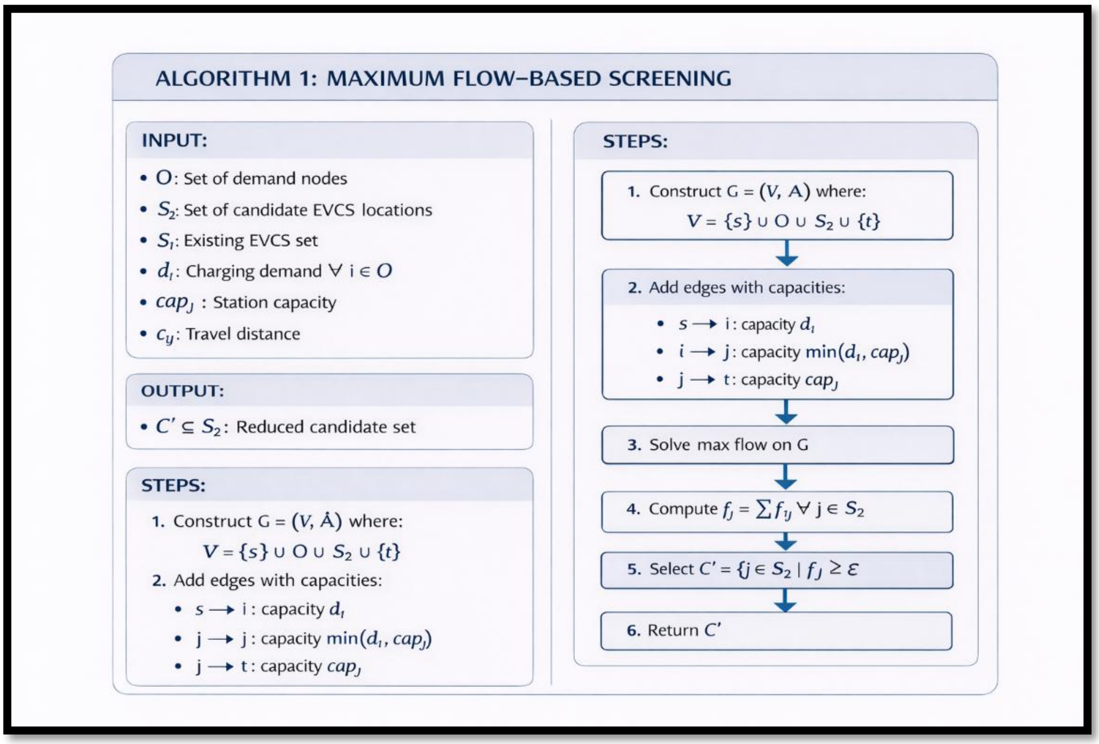
In the MILP model, decisions related to the establishment of new CS are represented by binary variables, while capacity expansion decisions are modelled using integer variables corresponding to the number of charging bays added. All infrastructure investments are assumed to occur simultaneously at the beginning of the planning horizon, providing a static yet realistic representation of expansion alternatives. Station capacity constraints are updated to reflect the increased service potential resulting from infrastructure upgrades, and all decisions are subject to an overall budget constraint. The objective of the MILP is to maximize total satisfied charging demand across the network. By integrating unmet demand information from the maximum flow phase, the MILP model directly targets locations and time periods where charging shortages are most severe, enabling a focused and cost-efficient improvement strategy for Shah Alam’s central zone. A conceptual illustration of the MILP optimization model is provided in Figure 3.

Computational Implementation

The computational experiments conducted in this study aim to validate the applicability of the maximum flow model for estimating charging demand allocation and to evaluate the performance of the MILP model in a real-world urban setting. The case study focuses on intracity travel within Shah Alam, and all optimization models were solved using CPLEX Optimization Studio IDE 22.1.1.

The maximum flow analysis was first implemented using Google Colaboratory (Colab), which offers a cloud-based Python environment with access to libraries for data processing, graph construction, and network optimization. In this phase, a bipartite graph was constructed to represent the relationship between demand nodes and existing CS locations. Demand nodes correspond to Sections 1–24 within Shah Alam’s central zone, while station nodes represent the refined set of 29 existing EVCS locations. Feasible connections were established based on the predefined service radius, and the bipartite graph was subsequently transformed into a flow network to compute maximum flow values and identify unmet charging demand.

Following the demand allocation analysis, the MILP model was implemented and solved using IBM CPLEX to determine optimal infrastructure expansion strategies. CPLEX provides a robust computational platform for handling large-scale integer optimization problems, making it suitable for evaluating location and capacity planning decisions. The integration of Colab-based demand analysis with CPLEX-based optimization ensures that infrastructure recommendations are grounded in observed spatial demand patterns rather than solely on forecasted values. The overall computational workflow of the two optimization models is summarized algorithm in Figure 5 and 6.



ALGORITHM 1: MAXIMUM FLOW–BASED SCREENING

INPUT:

- O: Set of demand nodes
- S_2: Set of candidate EVCS locations
- S_1: Existing EVCS set
- d_i: Charging demand ∀ i ∈ O
- cap_j : Station capacity
- c_{ij}: Travel distance

OUTPUT:

- $C' \subseteq S_2$: Reduced candidate set

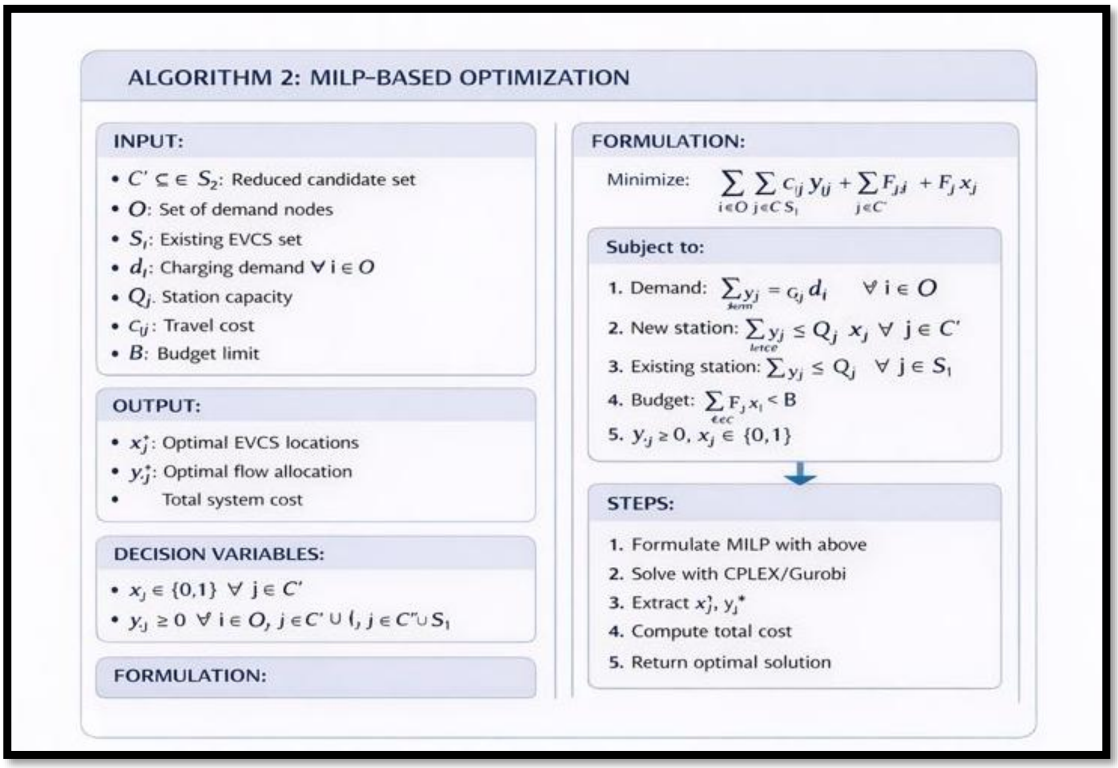
STEPS:

1. Construct G = (V, A) where:
   $V = \{s\} \cup O \cup S_2 \cup \{t\}$
2. Add edges with capacities:
   - $s \longrightarrow$ i : capacity d_i
   - j $\longrightarrow$ j : capacity $\min(d_i, cap_j)$
   - j $\longrightarrow$ t : capacity cap_j

STEPS:

1. Construct G = (V, A) where:
   $V = \{s\} \cup O \cup S_2 \cup \{t\}$
2. Add edges with capacities:
   - $s \longrightarrow$ i : capacity d_i
   - i $\longrightarrow$ j : capacity $\min(d_i, cap_j)$
   - j $\longrightarrow$ t : capacity cap_j
3. Solve max flow on G
4. Compute $f_j = \sum f_{ij}\ \forall\, j \in S_2$
5. Select $C' = \{j \in S_2 \mid f_j \geq \varepsilon$
6. Return C'

Figure 5: Maximum Flow Optimization Workflow Using Optimization CPLEX Software



ALGORITHM 2: MILP-BASED OPTIMIZATION

INPUT:

- $C' \subseteq \in S_2$: Reduced candidate set
- O: Set of demand nodes
- S_1: Existing EVCS set
- d_i: Charging demand ∀ i ∈ O
- Q_j. Station capacity
- C_{ij} : Travel cost
- B: Budget limit

OUTPUT:

- x_j^*: Optimal EVCS locations
- $y_{\cdot j}^*$: Optimal flow allocation
- Total system cost

DECISION VARIABLES:

- $x_j \in \{0,1\}\ \forall\ j \in C'$
- $y_{\cdot j} \geq 0\ \forall\ i \in O,\ j \in C' \cup \{,\ j \in C'' \cup S_1$

FORMULATION:

FORMULATION:

Minimize: $\sum_{i \in O} \sum_{j \in C\, S_1} c_{ij}\, y_{ij} + \sum_{j \in C'} F_{j,i} + F_j x_j$

Subject to:

1. Demand: $\sum y_j = G_j\, d_i \quad \forall\ i \in O$
2. New station: $\sum y_j \leq Q_j\ x_j\ \forall\ j \in C'$
3. Existing station: $\sum y_j \leq Q_j\ \ \forall\ j \in S_1$
4. Budget: $\sum_{\in C} F_j x_1 < B$
5. $y_{\cdot j} \geq 0,\ x_j \in \{0,1\}$

STEPS:

1. Formulate MILP with above
2. Solve with CPLEX/Gurobi
3. Extract x_j^*, y_j^*
4. Compute total cost
5. Return optimal solution

Figure 6: MILP Optimization Workflow Using Optimization CPLEX Software

Algorithm above in Figure 5 and 6 outlines the structured computational workflow adopted in this study, highlighting the sequential linkage between demand estimation and infrastructure optimization. First, the maximum flow approach allocates charging demand among existing stations based on spatial feasibility and capacity constraints, revealing areas of unmet demand and network bottlenecks. Second, the MILP approach incorporates these results to determine optimal locations and capacity expansions for new charging stations. By separating demand allocation from infrastructure planning while maintaining consistency between the two phases, the proposed workflow avoids overreliance on demand forecasting and supports scalable, data-driven EVCS planning. This integrated algorithmic framework provides a systematic and practical approach for improving urban charging infrastructure in Shah Alam.

Result and Discussion

This section presents the results obtained from implementing the proposed two approaches, followed by a detailed discussion of the findings. The first part reports the outcomes of the maximum flow model, which evaluates the capability of the existing EVCS network to satisfy charging demand over a three-month period. This includes an analysis of spatial flow distribution, identification of capacity bottlenecks, and an assessment of user satisfaction based on the proportion of demand that can be met. The second part discusses the results of the MILP optimization model, which determines optimal locations for new CS and appropriate capacity expansions. Together, these results provide insight into the effectiveness and scalability of the proposed optimization models for real-world EVCS planning in Shah Alam.

Maximum Flow Optimization Model for Optimal Existing EVCS

In the maximum flow analysis, demand nodes representing Sections 1 to 24 were placed on the left side of the bipartite graph, while the refined set of 29 existing EVCS locations formed the station nodes on the right. A service radius of 1 km was used to establish feasible connections between demand and station nodes. This threshold was selected based on observed minimum road-to-station distances within the study area and reflects realistic user behavior, as EV users are generally unwilling to travel long distances solely for charging. Figure 7 illustrates the resulting matched bipartite graph generated in Google Colab, while Table 2 summarizes the feasible station connections for each demand node.

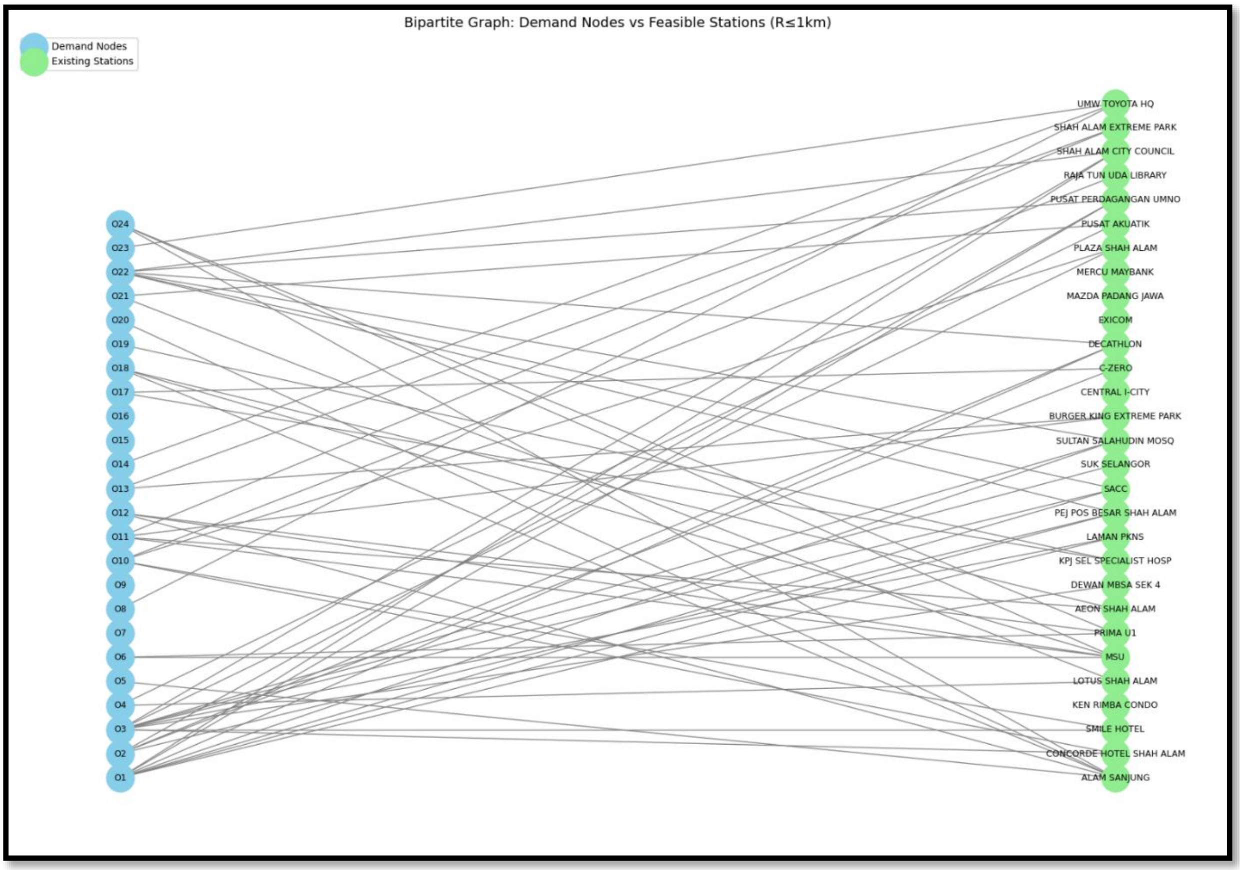


Figure 7: Matched Bipartite Graph Within 1km Radius

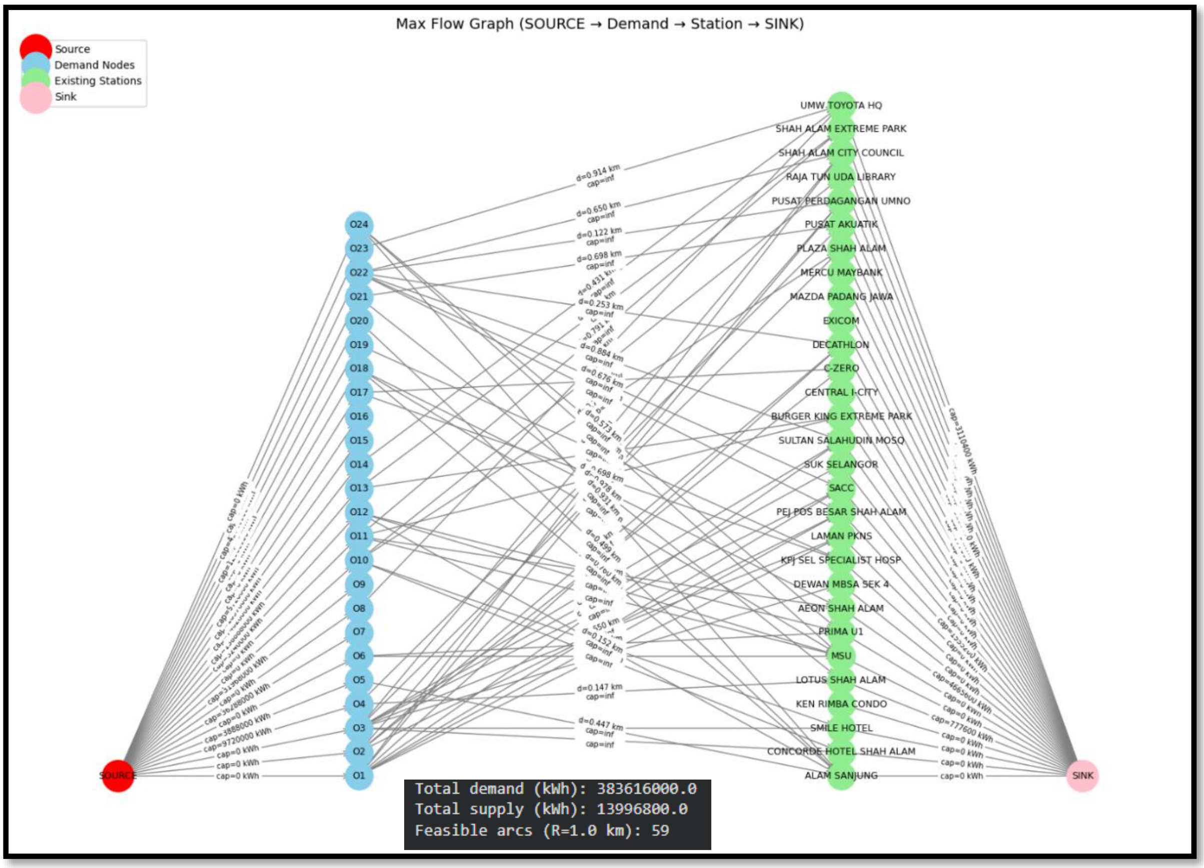
Table 2: Feasible Connections Demand-Stations Existing EVCS

Demand node	Feasible stations
O1	Laman PKNS, Pejabat Pos Besar Shah Alam,SACC, Sultan Salahudin Mosque, Decathlon, Pusat Perdagangan Umno, Shah Alam City Council
O2	Pejabat Pos Besar Shah Alam,C-Zero, Decathlon, Pusat Perdagangan Umno
O3	Concorde Hotel Shah Alam, Smile Hotel, Dewan MBSA Sek 4, Laman PKNS, SACC, Suk Selangor, Sultan Salahudin Mosque, Plaza Shah Alam, Shah Alam City Council
O4	Lotus Shah Alam, Pusat Akuatik
O5	Alam Sanjung
O6	MSU, Prima U1
O7	-
O8	UMW Toyota Ho
O9	-
O10	Concorde Hotel Shah Alam, Smile Hotel, Plaza Shah Alam, Raja Tun Uda Library
O11	Shah Alam Extreme Park, Burger King Extreme Park, Aeon Shah Alam, MSU
O12	Alam Sanjung, MSU, Prima U1
O13	Shah Alam Extreme Park, Burger King Extreme Park
O14	UMW Toyota Ho
O15	-

O16	-
O17	C-Zero, KPJ Sel Specialist Hosp
O18	Alam Sanjung, Lotus Shah Alam, Prima U1
O19	KPJ Sel Specialist Hosp
O20	Alam Sanjung
O21	Pusat Akuatik, Lotus Shah Alam
O22	Pej Pos Besar Shah Alam, SACC, Sultan Salahudin Mosq, Decathlon, Pusat Perdagangan UMNO, Shah Alam City Council
O23	UMW Toyota Ho
O24	Alam Sanjung, MSU, Prima U1

The results presented in Figure 7 and Table 2 indicate that demand nodes located in central and commercial areas of Shah Alam have relatively strong access to nearby CS, whereas many residential sections exhibit limited or no charging coverage. Nodes such as O1, O3, O10, O11, O18, and O22 are connected to multiple stations due to their proximity to commercial, institutional, and mixed-use developments. Key stations, including AEON Shah Alam, SACC, Lotus Shah Alam, MSU, and KPJ Selangor Specialist Hospital, function as major hubs within the current network, serving multiple surrounding demand nodes. In contrast, several sections, notably O7, O9, O15, and O16, have no feasible stations within the defined service radius, revealing clear accessibility gaps. Demand nodes with only a single nearby station, such as O8, O14, O19, and O23, are also vulnerable to congestion due to the absence of alternative charging options.

Following the spatial matching stage, the bipartite graph was transformed into a maximum flow network to evaluate how much demand the existing infrastructure can realistically accommodate. Each demand node was connected to feasible stations using arcs whose capacities were defined based on projected charging demand. Demand values were calculated using estimated user numbers, an average energy requirement of 50 kWh per charging session, and a total analysis period of 2,160 hours (three months). The cost associated with each arc was represented by travel distance multiplied by RM0.50 per kilometer. On the supply side, station capacities were determined by multiplying the number of available Level 3 outlets by 360 kWh and the total analysis period, ensuring that each station's maximum energy delivery potential was accurately reflected. Figure 8 presents the resulting maximum flow network, while Table 3 details the weighted arcs used in the analysis.



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Total demand (kWh): 383616000.0
Total supply (kWh): 13996800.0
Feasible arcs (R=1.0 km): 59
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Figure 8: Maximum Flow Graph with Weighted Arcs

Table 3: Demand Capacity, Distance and Supply Capacity Each Arc from Maximum Flow Graph

Source to demand	Demand capacity (kWh)	Feasible stations	Distance (km)	Supply capacity (kWh)
O1	0	Laman PKNS	0.3611	0
		Pejabat Pos Besar Shah Alam	0.6774	1555200
		SACC	0.1742	0
		Sultan Salahudin Mosque	0.6557	0
		Pusat Perdagangan UMNO	0.7671	0
		Shah Alam City Council	0.1181	0
		Decathlon	0.7390	0
O2	0	Pejabat Pos Besar Shah Alam	0.8486	1555200
		C-Zero	0.3327	0
		Decathlon	0.7930	0

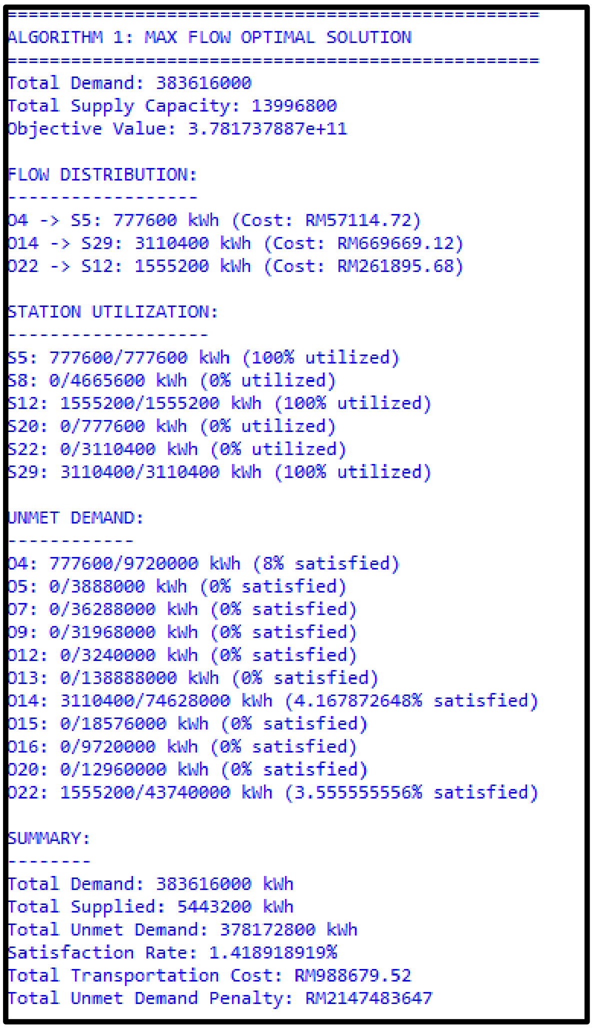
		Pusat Perdagangan UMNO	0.9771	0
O3	0	Concorde Hotel Shah Alam	0.6697	0
		Smile Hotel	0.6576	0
		Dewan MBSA Sek 4	0.9631	0
		Laman PKNS	0.6501	0
		SACC	0.9446	0
		Suk Selangor	0.6972	0
		Sultan Salahudin Mosque	0.1610	0
		Plaza Shah Alam	0.6259	0
		Shah Alam City Council	0.6677	0
O4	97200000	Lotus Shah Alam	0.1469	777600
		Pusat Akuatik	0.3866	0
O5	3888000	Alam Sanjung	0.4471	0
O6	0	MSU	0.7852	0
		Prima U1	0.4320	0
O7	36288000	-	-	-
O8	0	UMW Toyota Ho	0.1983	3110400
O9	31968000	-	-	-
O10	0	Concorde Hotel Shah	0.6262	0
		Smile Hotel	0.8543	0
		Plaza Shah Alam	0.7465	0
		Raja Tun Uda Library	0.6149	0
O11	0	Shah Alam Extreme Park	0.9051	0
		Burger King Extreme Park	0.4942	0
		Aeon Shah Alam	0.8419	4665600
		MSU	0.7913	0
O12	3240000	Alam Sanjung	0.1524	0
		MSU	0.9336	0
		Prima U1	0.9418	0

O13	138888000	Shah Alam Extreme Park	0.0513	0
		Burger King Extreme Park	0.0731	0
O14	74628000	UMW Toyota Ho	0.4306	3110400
O15	18576000	-	-	-
O16	9720000	-	-	-
O17	0	C-Zero	0.6051	0
		KPJ Sel Specialist Hosp	0.6984	0
O18	0	Alam Sanjung	0.7603	0
		Lotus Shah Alam	0.7938	777600
		Prima U1	0.4376	0
O19	0	KPJ Sel Specialist Hosp	0.9518	0
O20	12960000	Alam Sanjung	0.4989	0
O21	0	Pusat Akuatik	0.6976	0
		Lotus Shah Alam	0.9781	777600
O22	43740000	Pej Pos Besar Shah Alam	0.3368	1555200
		SACC	0.6763	0
		Sultan Salahudin Mosq	0.8838	0
		Decathlon	0.2531	0
		Pusat Perdagangan UMNO	0.1216	0
		Shah Alam City Council	0.6497	0
O23	0	UMW Toyota Ho	0.9142	3110400
O24	0	Alam Sanjung	0.9311	0
		MSU	0.8603	0
		Prima U1	0.5735	0

The maximum flow results shown in Figure 8 and Table 3 reveal a substantial imbalance between charging demand and available supply. Total projected demand across the study area is estimated at 383,616,000 kWh, whereas the combined supply capacity of the existing 29 stations is only 13,996,800 kWh. With just 59 feasible arcs linking demand and supply nodes, the results highlight a severe infrastructure shortfall. Although high-demand nodes near commercial centres are connected to multiple stations, the limited number of fast-charging outlets suggests a high likelihood of congestion, queueing, and prolonged waiting times.

Residential demand nodes with fewer or no feasible connections face even greater accessibility challenges. Overall, the flow analysis clearly demonstrates that the existing EVCS network in Shah Alam is unable to support current demand levels, underscoring the urgent need for targeted infrastructure expansion.

The matched demand–station pairs were subsequently converted into structured inputs for the LP formulation of the maximum flow model. Solving the model using CPLEX enables an evaluation of system performance under realistic demand and capacity constraints rather than relying solely on descriptive spatial mapping. The optimization minimizes distance-based assignment costs while imposing a large penalty on unmet demand, thereby prioritizing demand satisfaction wherever feasible. Flow conservation constraints ensure that all demand is either served or explicitly classified as unmet, while capacity constraints prevent stations from exceeding their maximum supply. The resulting outputs include routed flow distributions, unmet demand levels, station utilization rates, and cost components related to both travel and unmet demand. Figure 9 below highlights stations operating near full capacity as well as demand nodes that remain entirely unserved, revealing critical weaknesses in the current network configuration while Figure 10 shows the bar graph for the satisfaction rate.



```
==================================================
ALGORITHM 1: MAX FLOW OPTIMAL SOLUTION
==================================================
Total Demand: 383616000
Total Supply Capacity: 13996800
Objective Value: 3.781737887e+11

FLOW DISTRIBUTION:
------------------
O4 -> S5: 777600 kWh (Cost: RM57114.72)
O14 -> S29: 3110400 kWh (Cost: RM669669.12)
O22 -> S12: 1555200 kWh (Cost: RM261895.68)

STATION UTILIZATION:
-------------------
S5: 777600/777600 kWh (100% utilized)
S8: 0/4665600 kWh (0% utilized)
S12: 1555200/1555200 kWh (100% utilized)
S20: 0/777600 kWh (0% utilized)
S22: 0/3110400 kWh (0% utilized)
S29: 3110400/3110400 kWh (100% utilized)

UNMET DEMAND:
------------
O4: 777600/9720000 kWh (8% satisfied)
O5: 0/3888000 kWh (0% satisfied)
O7: 0/36288000 kWh (0% satisfied)
O9: 0/31968000 kWh (0% satisfied)
O12: 0/3240000 kWh (0% satisfied)
O13: 0/138888000 kWh (0% satisfied)
O14: 3110400/74628000 kWh (4.167872648% satisfied)
O15: 0/18576000 kWh (0% satisfied)
O16: 0/9720000 kWh (0% satisfied)
O20: 0/12960000 kWh (0% satisfied)
O22: 1555200/43740000 kWh (3.555555556% satisfied)

SUMMARY:
--------
Total Demand: 383616000 kWh
Total Supplied: 5443200 kWh
Total Unmet Demand: 378172800 kWh
Satisfaction Rate: 1.418918919%
Total Transportation Cost: RM988679.52
Total Unmet Demand Penalty: RM2147483647
```

Figure 9: Maximum Flow LP Formulation Result by CPLEX

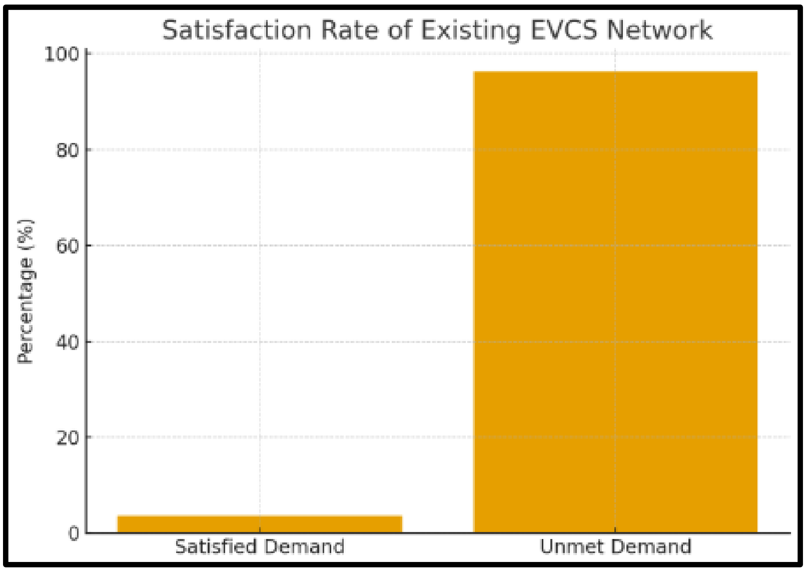


Figure 10: Satisfaction Rate of Existing EVCS

The results illustrated in Figures 9 and 10 expose a substantial and structural imbalance between estimated charging demand and the capacity of the existing EVCS network. Aggregate demand across all sections is estimated at 383,616,000 kWh, whereas the total supply capacity of the 29 operational stations amounts to only 13,996,800 kWh, corresponding to a shortfall of more than 96%. Under these constraints, the maximum flow optimization model was able to allocate merely 5,443,200 kWh, resulting in an overall demand satisfaction rate of 1.42%. Consequently, 378,172,800 kWh of charging demand remains unmet, a disparity that is clearly depicted in the satisfaction profile shown in Figure 10.

A detailed assessment of the flow allocation reveals pronounced spatial and structural limitations within the network. Positive flow was assigned to only three demand–station connections: O4–S4 (777,600 kWh), O14–S29 (3,110,400 kWh), and O22–S11 (1,555,200 kWh). This highly concentrated allocation pattern indicates that fast-charging capacity is not only severely limited but also poorly aligned with spatial demand distribution. Stations S4, S11, and S29 reached full utilization, confirming their role as critical pressure points within the network. The saturation of these stations suggests elevated risks of congestion, prolonged waiting times, and increased stress on local power infrastructure. Conversely, several stations, including S8, S21, and S23, exhibited zero utilization, implying that their locations fall outside practical user accessibility ranges or are situated in low-demand areas. Such unused capacity highlights inefficiencies in infrastructure siting and points to suboptimal network configuration.

The distribution of unmet demand further emphasizes significant service gaps. High-demand sections such as O13 (138,888,000 kWh), O7 (36,288,000 kWh), and O9 (31,968,000 kWh) received no flow allocation, indicating complete absence of effective charging access. Even nodes with partial service, such as O14 and O22, achieved satisfaction rates of only 4.17% and 3.56%, respectively, underscoring the inadequacy of existing supply. From an economic perspective, these shortcomings are reinforced by the cost outcomes of the model. While the total transportation cost is relatively small at RM 988,679.52, the penalty associated with unmet demand reaches RM 2,147,483,647. This disparity confirms that the dominant cost driver is not travel or assignment inefficiency but the fundamental inability of the system to deliver sufficient charging capacity. The resulting objective value of 378,172,800 kWh is therefore largely governed by unmet demand penalties, indicating that the problem is one of physical infeasibility rather than financial inefficiency.

Overall, the maximum flow analysis clearly demonstrates that the current EVCS network in central Shah Alam is both critically undersized and spatially misallocated. The model identifies severely overloaded stations, idle infrastructure, and concentrated clusters of unmet demand, providing essential insights for subsequent network expansion planning. These results indicate that incremental adjustments to the existing system are insufficient. Instead, effective improvement requires a coordinated strategy that combines targeted capacity enhancement at saturated locations with strategic redevelopment or relocation of underutilized assets to address persistent demand shortfalls and promote equitable charging access.

MILP Optimization Model for EVCS Expansion

The identification of extensive unmet demand through the maximum flow analysis provides a critical foundation for the EVCS expansion strategy. Despite the presence of feasible spatial connections, the existing fast-charging infrastructure can satisfy only 1.42% of total system demand, leaving most charging requirements unmet. Several demand nodes emerge as critical hotspots, particularly those corresponding to Sections 7, 9, 13, 14, 15, 20, and 22. These areas encompass major commercial centres, institutional zones, and densely populated residential districts where EV usage is expected to continue growing. The spatial clustering of these high-unmet-demand nodes indicates that key mobility corridors and activity centres within Shah Alam lack sufficient fast-charging coverage.

From a planning perspective, these underserved zones are likely to experience persistent congestion, long waiting times, and reduced charging reliability, which may negatively affect user confidence and slow EV adoption. The fact that only a small number of existing stations reach full utilization further suggests that current infrastructure deployment is both insufficient and unevenly distributed. Consequently, identifying and prioritizing these high-unmet-demand zones is essential for guiding infrastructure expansion decisions in the MILP optimization model.

Candidate locations for new EVCS installations were selected through a structured process informed by the maximum flow results. The analysis began by identifying all demand nodes with non-zero energy consumption, as these represent the primary spatial clusters requiring improved charging access. A total of 32 from 135 candidate locations as listed in Table 4 were initially considered based on official listings of proposed sites within Shah Alam from MEVnet official website. These sites span commercial, residential, and mixed-use areas and were evaluated for their potential suitability for Level 3 fast-charging deployment. To maintain consistency with earlier stages, the same 1 km service radius was applied when matching demand nodes to candidate locations. This threshold reflects observed user behaviour and ensures practical accessibility.

Table 5: Feasible demand-station connections for new candidate EVCS

No.	Candidate locations	Section
1	ST Rosyam Mart	9
2	Waterworld by Icity	7
3	PKNS Complex Shah Alam	14
4	Shah Alam Convention Centre	14
5	IDCC Ideal Convention Centre	15
6	Shah Alam Stadium	13
7	Malawati Stadium	13
8	Giant Hypermarket Shah Alam Stadium	13
9	Petronas S13	13
10	Shah Alam Club	13
11	Wetworld Water Park Shah Alam	14
12	Snowalk Icity	7
13	Icity Theme Park	7
14	Icity Convention Centre	7
15	Denai Alam Recreational and Riding Club	16
16	McDonald S22	22
17	BHP Per. Tengku Ampuan	22
18	MBSA	14
19	UITM Shah Alam	7
20	Petronas Persiaran Kayangan	7
21	UNISEL	7
22	Petronas S7	7
23	Shah Alam Hospital	7
24	Shell Persiaran Kayangan	7
25	Sultan Abdul Aziz Shah Golf & Country Club	13
26	Petronas Merbau Indah	15
27	Doubletree by Hilton Shah Alam I-City	7
28	Alrawsha Restaurant	7
29	IRDKL Mall	16
30	JPJ Negeri Selangor	16
31	Ardence Labs	13
32	Lits Office Charger	7

Following the maximum flow analysis, several critical demand hotspots can be clearly identified. Based on the results presented in Table 5, it can be observed that the MEVnet planning approach does prioritise areas identified as critical, particularly Section 7, which records the highest allocation, followed by Section 13 as the second highest. This indicates a reasonable level of alignment between the MEVnet proposals and the maximum flow results. Other critical hotspots, such as Sections 9 and 22, also appear in Table 5, although with comparatively fewer proposed stations.

However, a key limitation of the MEVnet plan is the lack of specification regarding charger technology and capacity. The plan does not clearly indicate whether the proposed installations are AC or DC chargers, nor does it specify the number of DC charging bays to be deployed at each location. As a result, it remains uncertain whether the proposed infrastructure is sufficient to accommodate the high charging demand observed in these critical zones.

Therefore, this study extends the analysis by explicitly examining whether the proposed locations can adequately support high-demand areas when charger type and capacity constraints are considered. By incorporating demand magnitude and station capacity into the optimization framework, the study provides a more rigorous assessment of whether the planned infrastructure can effectively serve zones with persistently high charging demand.

Using a bipartite matching process, each demand node was connected to all candidate stations within the service radius. Only locations capable of serving at least one high-unmet-demand node were retained for further analysis, resulting in a refined and targeted set of candidate sites. This filtering step reduces unnecessary investment in locations with limited strategic value. The spatial distribution of the refined candidate stations relative to critical demand clusters is illustrated in Figure 11, while Table 6 summarizes their coverage characteristics.

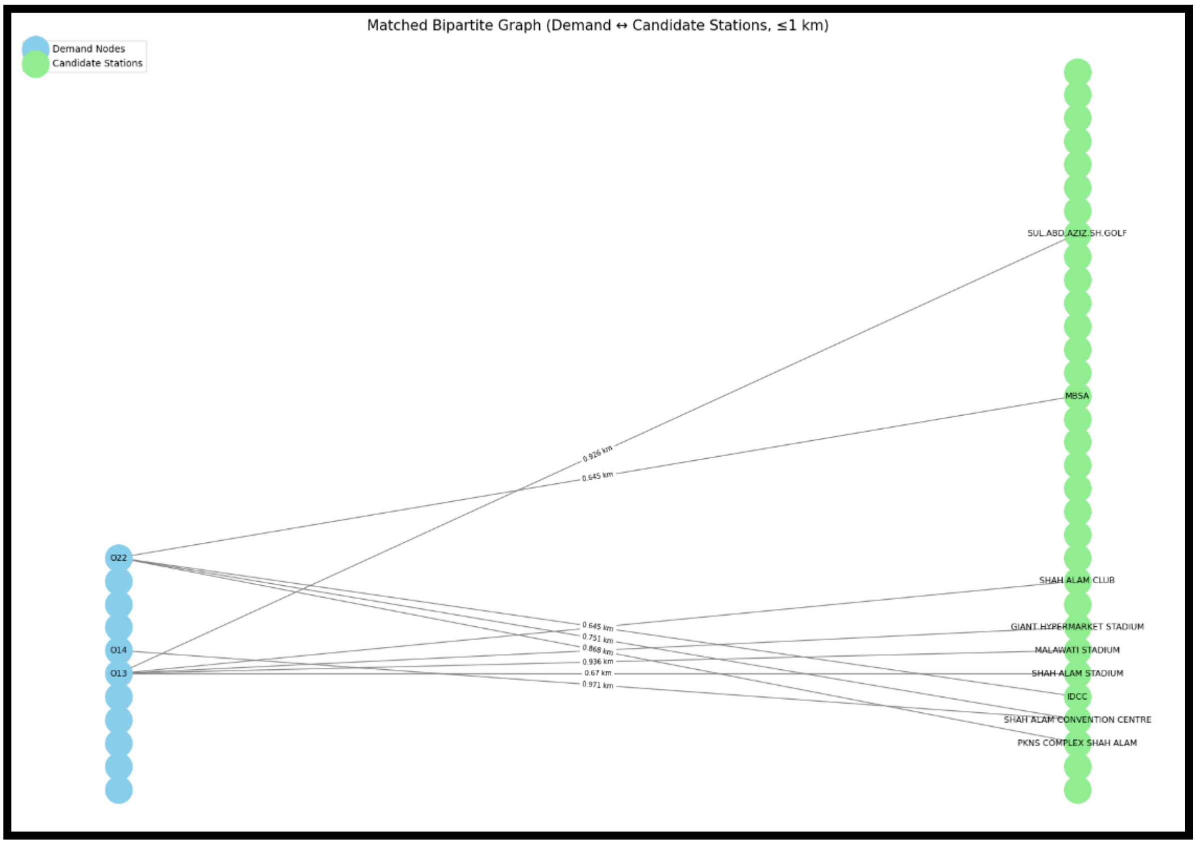


Figure 11: Matched Bipartite Graph for New Candidate Locations by MEVnet

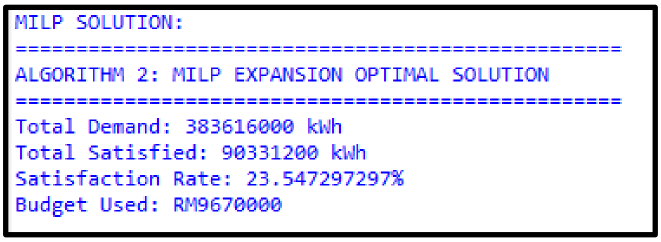
Table 6: Feasible Demand-Station Connections for New Candidate EVCS

Demand node	Feasible stations
O13	Shah Alam Stadium, Malawati Stadium, Giant Hypermarket Stadium, Shah Alam Club, Sul. Abdul Aziz Shah Alam Golf
O14	Shah Alam Convention Centre
O22	PKNS Complex Shah Alam, Shah Alam Convention Centre, IDCC, MBSA

The spatial assessment presented in Figure 11 and Table 6 highlights pronounced shortcomings in the EV charging network proposed under the MEVnet for Shah Alam. When demand nodes were matched to candidate charging sites using a 1 km service radius, only three out of eleven nodes (O13, O14, and O22) were found to have accessible charging options. The remaining eight nodes (O4, O5, O7, O9, O12, O15, O16, and O20) exhibited no feasible connections, revealing considerable spatial coverage gaps within the proposed network. Among the connected nodes, O13 showed relatively strong accessibility with five candidate stations, whereas O14 was linked to only a single site, indicating an uneven spatial distribution that favors central commercial zones while neglecting peripheral and residential areas.

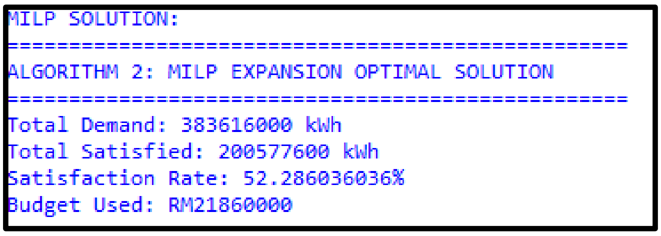
To mitigate these spatial and capacity limitations, a MILP optimization model was formulated with two primary objectives: maximizing satisfied charging demand and minimizing overall system costs. The model incorporates realistic financial constraints derived from Malaysia's national EV infrastructure investment benchmarks, including an estimated cost of RM944,444 per charging station and a total budget ceiling of RM1,000,000. Installation cost parameters were calibrated to reflect prevailing market conditions for Level 3 fast-charging infrastructure, with RM180,000 allocated for new station development and RM70,000 per additional charging outlet. Importantly, the MILP optimization model directly integrates unmet demand values obtained from the preceding maximum flow analysis, ensuring that infrastructure expansion decisions are driven by observed capacity deficiencies rather than projected demand alone. By evaluating both MEVnet-proposed sites and alternative locations identified through spatial gap analysis, the model enables a structured comparison of planning strategies. The consistent application of a 1 km service radius throughout the analysis further maintains alignment with realistic user charging behavior.

The resulting optimized expansion strategy provides a data-driven basis for enhancing Shah Alam's EV charging infrastructure. The model identifies priority locations for new installations and determines appropriate outlet allocations, with particular emphasis on high-demand zones such as O7, O9, O15, O16, and O20 that currently lack adequate coverage. These outcomes demonstrate how targeted optimization can support balanced network expansion within constrained budgets, offering practical guidance for policymakers and urban planners seeking to facilitate sustainable and equitable EV adoption in Malaysian urban environments. The comparative results of the MEVnet-based configuration and the optimization-driven solution are illustrated in Figures 12 and 13, respectively.



```
MILP SOLUTION:
==================================================
ALGORITHM 2: MILP EXPANSION OPTIMAL SOLUTION
==================================================
Total Demand: 383616000 kWh
Total Satisfied: 90331200 kWh
Satisfaction Rate: 23.547297297%
Budget Used: RM9670000
```

Figure 12: Result Using MEVnet Suggested Location



```
MILP SOLUTION:
==================================================
ALGORITHM 2: MILP EXPANSION OPTIMAL SOLUTION
==================================================
Total Demand: 383616000 kWh
Total Satisfied: 200577600 kWh
Satisfaction Rate: 52.286036036%
Budget Used: RM21860000
```

Figure 13: Result Using Optimization Approaches Suggested Location

The MILP optimization outcomes illustrated in Figures 11 and 12 reveal a pronounced performance disparity between the MEVnet-proposed candidate locations and the alternative sites identified through spatial demand analysis. When the optimization was restricted to MEVnet locations, the model achieved a satisfied demand of 90,331,200 kWh, corresponding to a 23.55% satisfaction rate of the total system demand of 383,616,000 kWh. This relatively modest improvement reflects a significant spatial misalignment between the proposed MEVnet stations and the principal unmet demand clusters located around OD7, OD9, OD15, OD16, and OD20. Although the model utilized a total investment of RM9,670,000 under this scenario, the resulting gains were limited, largely due to insufficient coverage of high-demand residential and peripheral areas.

In contrast, the scenario incorporating researcher-identified locations demonstrated substantially stronger performance. Under this configuration, the model satisfied 200,577,600 kWh of charging demand, equivalent to a 52.29% satisfaction rate. This represents more than a twofold increase compared to the MEVnet-only scenario, underscoring the effectiveness of strategically positioning new stations near concentrated unmet demand zones within the same one-kilometre service radius. Improved proximity to high-priority demand nodes enabled greater flow allocation and significantly enhanced outlet utilization. While this scenario required a higher investment of RM21,860,000 due to the activation of additional stations and outlets, the expenditure remains consistent with national EV infrastructure investment benchmarks and delivers substantially higher system performance.

A direct comparison between the two expansion scenarios highlights the importance of demand-responsive planning in EVCS deployment. Although the MEVnet-based configuration increased the number of available stations, it failed to resolve fundamental spatial coverage gaps, particularly in residential clusters and peripheral sections of Shah Alam. As a result, newly added capacity remained underutilized, and unmet demand persisted in the same critical zones. Conversely, the optimized location strategy redirected infrastructure investment toward areas experiencing genuine charging scarcity, producing a more balanced flow distribution and a marked reduction in unmet demand. The difference of 110,246,400 kWh in satisfied demand between the two scenarios clearly demonstrates that effective EVCS expansion must be guided by spatial demand patterns rather than conventional, visibility-driven placement strategies to achieve meaningful improvements in network performance.

Optimization Model Overview

This study adopts two approaches to identify effective EVCS placement in Shah Alam as shown in Figure 14. The first approach assesses the extent to which existing charging infrastructure can meet projected EV charging demand, while the second approach employs a MILP model to determine optimal locations for new installations that maximize demand coverage under budget constraints. Together, these phases provide a systematic approach for evaluating current network performance and designing an expanded charging network that directly addresses unmet demand identified in the initial analysis.

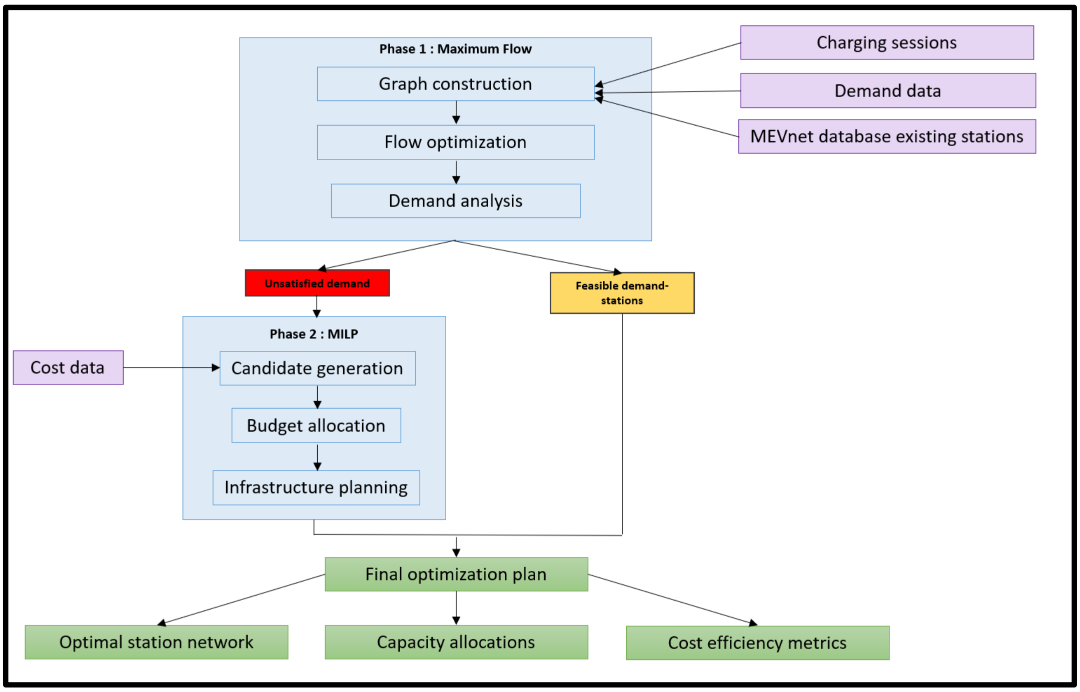


Figure 14: Integrated Maximum Flow and MILP as Optimization Models

In the first phase, illustrated in Figure 14, the problem is formulated as a maximum flow model on a capacitated bipartite network linking demand nodes to existing CS. Feasible connections between demand and station nodes are defined using a walkable service radius, which represents the maximum distance EV users are reasonably willing to travel after parking 0. This constraint ensures practical accessibility by restricting flow assignments to nearby stations 0. The objective of this phase is to determine the maximum amount of charging demand, measured in kWh, that can be routed to existing stations without exceeding their capacity limits.

The maximum flow results provide valuable insights into the performance of the current EVCS network. The model identifies stations operating near full capacity, indicating areas of high demand pressure, and quantifies unmet demand at each node arising from either capacity limitations or spatial inaccessibility. This residual unmet demand defines the local coverage gap and serves as a critical input for the MILP optimization model in the second phase. By explicitly revealing where the existing network fails to provide adequate service, the first-phase analysis guides targeted capacity expansion decisions.

Building on the outcomes of the maximum flow analysis, the second approach in Figure 14 applies a MILP formulation to determine optimal locations for new CS installations. This phase is structured as a budget-constrained optimization problem, where decision variables indicate whether a candidate site is selected for development. The objective is to maximise coverage of the unmet demand identified in the first phase while ensuring that total installation costs remain within the allocated budget. Incorporating location-dependent costs and practical siting considerations ensures that selected stations can operate efficiently within the broader urban network.

The strength of the MILP optimization model lies in its ability to generate an optimal local solution that directly targets spatial demand deficiencies. The resulting allocation plan prioritises sites that achieve the greatest reduction in unmet demand, enabling a structured cost–benefit assessment of expansion strategies. Overall, these two optimization approaches provide a data-driven basis for planning EVCS expansion that improves charging accessibility while adhering to realistic financial constraints.

Conclusion

This study proposes two approaches for EV fast-charging infrastructure planning that integrates maximum flow network analysis with a MILP-based expansion optimization model. Applied to the case of Shah Alam, Malaysia, the first approach revealed a pronounced imbalance between charging demand and existing supply, with only 1.42% of total demand satisfied. This diagnostic analysis clearly identified critically underserved areas as well as stations operating at or near full capacity.

Building on these findings, the second approach employed a MILP formulation to determine optimal locations for new stations and appropriate capacity expansions under realistic budget constraints. By explicitly incorporating unmet demand from the first phase, the optimization model was able to substantially increase satisfied demand while improving station utilization and reducing spatial coverage gaps.

Rather than positioning optimization as a replacement for existing planning tools, this study demonstrates its value as a complementary, evidence-based approach that enhances planning accuracy and transparency. As EV adoption in Malaysia continues to accelerate, integrating such analytical methods into current planning processes can better align infrastructure deployment with actual usage patterns, promote equitable access, and provide policymakers with a scalable and rigorous model for developing a more resilient national EV charging network.

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Ethics Statement:	This study did not involve any human participants, animals, or sensitive data requiring ethical approval. The authors confirm that the research was conducted in accordance with accepted academic integrity and ethical publishing standards.
Author Contribution Statement:	All authors contributed significantly to the development of this manuscript. All authors read and approved the final version of the manuscript prior to submission.

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