



Identifying optimal locations for community electric vehicle charging

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ABSTRACT

This research seeks to identify suitable locations for deploying community Electric Vehicle charging points using a Geographic Information System (GIS)-based approach. The charging infrastructure is classified into *shared-residential*, *en-route*, and *destination* charging types, and each type's selection criteria are chosen according to the characteristics of targeted end-users. The investigation identified 770 ideal locations in Dublin that may be given priority for the initial installation of charging infrastructure. Further, 3080 suitable sites were identified for later implementation to satisfy the charging requirements forecasted by the Dublin Local Authority for 2030. The population served by the proposed residential charging points is determined while considering accessibility by five-minute walking or five-minute cycling. Results from the study can be helpful for practitioners while deploying charging stations in the region. The proposed methodology utilises an open-source GIS-supported approach that can be adapted to similar cities worldwide.

1. Introduction

Increased greenhouse gas (GHG) concentration from urban transport significantly contributes to climate change (United Nations, 2021). In Ireland, 17.7% of GHG emissions were attributable to the transportation sector, with internal combustion engine vehicles (ICEVs) accounting for 94% of all transport emissions (Caulfield & Charly, 2022; Environmental Protection Agency, 2021). Electrification of the vehicle fleet is considered an effective approach to reducing emissions since they are energy efficient, do not generate tailpipe emissions, have fewer maintenance requirements and reduced engine noise (Albatayneh et al., 2020; Ghandi & Paltsev, 2020; Kinsella et al., 2023; Sanguesa et al., 2021; Windsor, 2021). Recent battery manufacturing also aims to use more eco-friendly techniques (Krajinska, 2021).

Despite these benefits, electric vehicles (EVs) have limitations, including limited range and shortage of charging infrastructure which affects their widespread implementation (Bonges & Lusk, 2016; Metais et al., 2022; Morton et al., 2018). Facilitating a smooth and swift transition to EVs requires adequate charging infrastructure to be developed based on the needs and characteristics of the population (Pardo-Bosch et al., 2021; Selena et al., 2022). A lack of sufficient charging infrastructure causes range anxiety in users (Neubauer & Wood, 2014). Range anxiety occurs when an EV driver worries that they will not have

enough battery charge to reach their destination or the next charging station, preventing EVs from being widely deployed (Forrest et al., 2016; Melliger et al., 2018).

These electric vehicle charging station (EVCS) locations are of great significance in accelerating EV use (Frade et al., 2011; Janjić et al., 2021). For instance, a driver's motivation to use EV for a long-distance journey, such as an inter-city trip, would depend on the availability of EVCS along the major roadways (Csiszár et al., 2019). However, for short-distance trips, the driver would require a charging-enabled parking space at the journey's end. Accordingly, charging infrastructure is needed to cater to different types of charging demand, including residential, workplace, en-route, and destination charging (Cluzel et al., 2022). These EVCS should also be widespread and available for everyone to ensure equity (Irvani, 2022). Poor location of charging stations can lead to waste of resources and negatively impact decarbonisation efforts (Ademulegun et al., 2022).

This study seeks to identify the ideal locations to install EVCS for shared-residential, en-route, and destination charging purposes through a Geographic Information System (GIS)-based analysis using Open Street Maps (OSM). Site-selection criteria are chosen, including sociodemographic factors, travel patterns, and availability of appropriate street infrastructure such as lamp posts and parking spaces. A novel methodology using an open-source GIS-supported approach is proposed to identify appropriate EVCS locations. This approach can be adapted to

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Acronyms

EV	Electric Vehicle
EVCS	Electric Vehicle Charging Station
ED	Electoral district
GHG	Greenhouse gas
ICEV	Internal combustion engine vehicle
OSM	Open Street Maps
QGIS	An open-source desktop-based geographical information system (GIS) platform

other cities with similar characteristics.

The main motivation for this paper is to demonstrate how cities worldwide will have to examine the methods by which charging infrastructure is introduced to the urban realm. This changing use of public spaces will need to be achieved if the goals for fully electrifying private and shared vehicles are to be completed. This is shown empirically in the research presented. However, all cities have different characteristics, and the methods presented may need to be tailored to each region. The other motivation for this study is to recognise that not all households have access to private charging facilities in densely populated urban areas. Therefore, more research is needed to determine how cities can facilitate this charging.

Previous studies have considered techniques including multi-criteria analysis to identify optimal EVCS locations (Janjić et al., 2021; Kaya et al., 2020). However, few have categorized the site-selection criteria based on different charging categories and intended purposes (Csizsár et al., 2020; Frade et al., 2011; Schmidt et al., 2020). This research attempts to locate EVCS for various types, including shared-residential, en-route, and destination charging purposes. Moreover, this research considers the potential of utilizing existing lampposts for EV charging, which is not considered in other EVCS locations studies. Considering the urgency and the demand for a high number of charging stations, conversion of lampposts to slow residential charging points could provide a fast and effective solution to local councils to increase the coverage of EVCS with less infrastructure investment while ensuring practical usage (Bruno et al., 2019; Mahdy et al., 2022; Zhang et al., 2019).

Further, this work attempts to satisfy the requirements of EVCS as estimated by the Dublin Local Authority for the period up to 2030 (Cluzel et al., 2022). Hence, the study would benefit policymakers and practitioners while deploying charging infrastructure.

The rest of the paper is organized as follows: Section 2 reviews the literature focusing on methods to identify EVCS locations and objectives of the current study. Section 3 provides a brief of the study area and the data used. Section 4 discusses the proposed methodology and the site-selection criteria considered in the study. Section 5, 6, and 7 give the results and discusses the policy implications and conclusions, respectively.

2. Literature review

This section discusses the site selection criteria and the modelling approaches used in previous studies to identify the optimal location of charging stations.

2.1. Site selection criteria for installation of EVCS

An EV owner's preference towards a particular charging location is primarily influenced by the accessibility, speed, and cost of charging (Fotouhi et al., 2019; Philippsen et al., 2016; Skjølsvold et al., 2022). Studies also suggest that workforce population, mobility aspects within the region, road characteristics and parking spaces seem to influence the optimal location of EVCS (Bitencourt et al., 2021; Gupta et al., 2018; Lee

et al., 2021). However, these factors depend on the charging station type and intended usage. Though studies have attempted to identify ideal locations for EVCS based on several criteria, only a few have considered the requirements based on the type of charging station required for the region (Csizsár et al., 2019; Frade et al., 2011).

The major types of EVCS within local councils' administration are *shared-residential charging*, *en-route charging*, and *destination charging* (Cluzel et al., 2022). *Shared-residential charging*, referred to in studies as nighttime home charging, is expected to cater to residences without off-street parking and is mainly intended for overnight slow charging near houses and apartments (Frade et al., 2011). Appropriate criteria for selecting these shared-residential charging stations would be population density, availability of overnight parking spaces and desirable walking distances (Csizsár et al., 2019; Irvani, 2022).

En-route charging typically caters to long-distance EV travellers, can be located along major roadways near service stations, and would require fast charging (Ademulegun et al., 2022). Nearness to motorways and service stations, location safety and parking potential is relevant for locating ideal en-route charging stations (Janjić et al., 2021; Philippsen et al., 2016).

Destination charging, also called *daytime charging*, aims to provide top-up charging, especially near facilities like supermarkets and shopping centres and can have slow to rapid charging options (Csizsár et al., 2019; Frade et al., 2011). Proximity to social areas and activity centres, availability of parking lots, accessibility by car, and time spent charging or parking are factors considered for locating ideal destination charging stations (Carra et al., 2022; Kaya et al., 2020).

Criteria that are critical for almost all types of charging stations include parking potential (either for a short time or for extended periods), safety (of car, driver and passengers) and distance between stations (Banegas & Mamkhezri, 2022; Carra et al., 2022; Giménez-Gaydou et al., 2016; Kaya et al., 2020). These factors are also highlighted in user perception studies but not considered together while identifying locations previously (Morrissey et al., 2016; Philippsen et al., 2016).

Utilising existing lamp posts for EV charging is also considered an effective method for rapidly expanding public charging points owing to their ease of installation, widespread availability, and lower cost than other technologies (Bender, 2021; Daniel & Lex, 2020). A single-phase lamppost charging point has a power range of 1 kW to 7 kW, making it suitable for topping up and overnight charging (Mahdy et al., 2022; Manning, 2021). Furthermore, the placement of charging points near street lights is expected to improve safety and reduce the inhibitions of drivers while charging EVs, especially in dim-lit and secluded areas (Cuff, 2022).

Studies have also considered the demand for EVs, indicated by the number of EVs in the region, while identifying ideal locations for EVCS (Carra et al., 2022; Kaya et al., 2020). Though this approach can provide better accessibility of EVCS to current or early EV adopters, it could also become unjust and biased towards the privileged segment of the population (Irvani, 2022; Roy & Law, 2022). Moreover, early EV adopters will likely have an independent driveway or off-street parking space for home charger installation. They would not rely on public charging stations as their primary source (Collett et al., 2022).

2.2. Modelling approaches to identify the optimal location of EVCS

Different modelling techniques have been adopted to determine the optimal location of EVCS, including hierarchical clustering approaches and hybrid methods such as an analytical hierarchy process (AHP) combining systematic review with stakeholder interviews (Bitencourt et al., 2021; Karolemeas et al., 2021).

Analytic Hierarchy Process (AHP) has been used in several studies for weighting the EVCS site selection criteria (Carra et al., 2022; Janjić et al., 2021; Karolemeas et al., 2021; Kaya et al., 2020). Carra et al. (2022) used AHP and Monte Carlo Simulation methods to select the critical indicators for sustainable charging point locations. However,

they did not apply the same to any specific case study. Janjić et al. (2021) used AHP and a multi-criteria p-median methodology to optimize charging station numbers and locations in Serbia. This study also considers a Greedy heuristic approach for minimizing walking distances. Ademulegun et al. (2022) adopted a multi-stage decision analysis methodology considering critical and techno-physio-socio-economic and site-specific optimality factors to identify ideal locations for rapid EV charging stations within and across the border regions of Northern Ireland.

Liu (2020) used a multi-agent Stackelberg game model combined with a road segment transmission model, path selection, station selection, and station EV interaction strategy to improve the effectiveness of the charging stations. Multi-criteria analysis using a fuzzy axiomatic design and linguistic weight approach based on literature review, expert comments, and on-site inspection was also used to determine the optimal location of EVCS (Feng et al., 2021). The results demonstrated that the suggested assessment criteria are reliable and consistent and may be applied to various economies.

Pan et al. (2020) proposed a coverage placement model to locate the optimal public charging stations based on the driver's previous charging pattern using a Genetic Algorithm approach. Fotouhi et al. (2019) proposed a stochastic model considering the range anxiety of EVs. Ideal site selection has also been made using a picture-fuzzy environment and Pythagorean Fuzzy VIKOR techniques (Cui et al., 2018; Ju et al., 2019). Data mining techniques such as spectral clustering and a Gaussian Mixture Model were used to determine the ideal location of charging stations in Turkey (Catalbas et al., 2017).

GIS-based multi-criteria decision-making methods, including the Preference Ranking Organization Method for Enrichment of Evaluations (PROMETHEE) and VlseKriterijuska Optimizacija I Komoromisno Resenje (VIKOR), were used for selecting the most suitable EV charging station sites in Istanbul (Kaya et al., 2020). These methods considered five main criteria and nineteen sub-criteria ranked based on AHP. Csiszár et al. (2019) used a two-level multi-criteria approach to identify 300 EVCS locations to support local short-distance trips. This study used a weighted sum model to determine areas based on willingness to use EV and parking behaviour at the macro level and a hexagon-based approach with a greedy algorithm at the micro level (Csiszár et al., 2019). Further, the study considers the factors influencing daytime and nighttime charging separately, which has not been done in many studies. Frade et al. (2011) adopted a mixed integer optimization model to maximize EV demand coverage considering both nighttime and daytime demand. Coverage of EVCS is considered through maximum desirable and maximum acceptable walking distances.

Recent studies also highlight that the previous approach to deploying EVCS led to spatial disparity and inequity (Roy & Law, 2022). Roy and Law (2022) uses a machine learning framework to examine this spatial disparity in the placement of EVCS. They use Kernel density estimation, machine learning models using random forests, multinomial logistic regression and support vector machines to examine the spatial disparity and develop an EV charging inequity index. Iravani (2022) attempts to determine the location of charging stations considering equity and efficiency to maximise accessibility and usage. The study attempts to solve two problems: a set covering location problem to ensure ubiquitous and equitable charging stations and a maximum covering location problem to satisfy the demand of early adopters, thus attempting to strike a balance between the two approaches.

2.3. Insights from literature, problem statement and study objectives

In the current state of EV development, the location of public EVCS is of utmost importance for it to be used efficiently. Previous studies demonstrate that a GIS-based approach is suitable for determining the ideal sites for charging stations. Optimal site selection for an EVCS is also well-recognised as a multi-criteria assessment problem due to diverse influencing factors. Acceptable and desirable walking distances are also



Fig. 1. Map of study area showing the council areas of Dublin City, South Dublin, Fingal, and Dun Laoghaire-Rathdown (Dún Laoghaire-Rathdown County Council, 2013).

considered in studies to estimate the coverage of proposed charging stations.

Several factors, including population density, proximity to amenities or residences, road characteristics, proximity to parking spaces, charging infrastructure available and location safety, influence preference for an EVCS. However, the requirement of a charging station also depends on the type of facility and its intended purpose. Though previous studies have considered some of the factors mentioned above in site-selection criteria, only a few have considered the distinction in the charging category while locating charging points. Some of these criteria are relevant for all charging types as per user perception surveys but not considered together in previous site-selection studies. Furthermore, converting lampposts to EVCS has the potential to assist in the rapid expansion of charging infrastructure. None of the existing studies has used lamppost as a site-selection criterion for installing slow-residential charging points.

This research aims to identify the best locations for EVCS in the Dublin region, using a GIS-based analysis considering the three major categories of charging: *shared-residential*, *en-route*, and *destination* charging. The study attempts to cater to the EV charging requirement outlined by the Dublin Local Authority up to 2030. It suggests the ideal location for installing these chargers while requiring minimal additional infrastructure cost by utilising designated parking areas and proximity to street lamp posts. The analysis provides meaningful insights that other cities with similar characteristics may adopt to improve their public charging infrastructure.

3. Data

This section gives a brief description of the study area and data used.

3.1. Study area

Approximately 28% of the population of Ireland resides in Dublin, the capital city of Ireland, making it the most populous county. County Dublin is divided into four council areas: Dublin City Council, Fingal County Council, South Dublin County Council, and Dún Laoghaire-

Table 1
Projected EV charging requirement for Dublin in 2025 and 2030 according to medium EV uptake scenario (Cluzel et al., 2022).

County	2025 EVCS Requirement			2030 EVCS Requirement		
	Residential	En-route	Destination	Residential	En-route	Destination
Dublin City	65	19	280	247	55	1065
South Dublin	23	13	149	85	38	560
Fingal	23	14	157	86	41	589
Dun Laoghaire-Rathdown	23	11	135	85	33	509
Total	133	57	722	504	166	2723

Table 2
Datasets used in the study and corresponding sources.

No	Charging type	Dataset	Data source	Description
1	Shared-residential, en-route and destination	Car parking spaces	Geofabrik, OSM [#] (https://download.geofabrik.de/europe.html)	Car parks are extracted as a polygon shapefile and converted to a point shapefile.
2	Shared-residential, en-route and destination	Location of lamp posts	Central Statistics Office (2022) (https://data.gov.ie/)	Public lighting for each county council, including Dublin City, South Dublin, Fingal and Dun Laoghaire-Rathdown available as shapefiles.
3	Shared-residential	Population	Central Statistics Office (2022) (https://www.cso.ie)	Extracted for the 2016 ED level and an increment of 7.67% was applied for 2022 (Central Statistics Office, 2022).
4	Shared-residential	Residential apartments and houses	OSM plugin in QGIS*	Extracted from quickOSM [#] plugin, available as point and polygon shape file.
5	En-route	Road network	OSM plugin in QGIS*	Extracted from quickOSM [#] plugin and available as a line shape file.
6	Destination	Amenities	OSM plugin in QGIS*	Extracted from quickOSM [#] plugin, available as point and polygon shape file.
7	Destination	Number of trips to places of work or study	Central Statistics Office (2022) (https://www.cso.ie/en/census/census2016reports/powscar/)	Extracted from CSO and joined to ED shape file.
8	Shared-residential, en-route and destination	Existing EV charging stations	OSM plugin in QGIS*	Extracted from quickOSM [#] plugin and available as a point shape file.

* QGIS: an open-source desktop-based GIS platform

OSM: Open Street Map

Rathdown County Council (Dún Laoghaire-Rathdown County Council, 2013), as shown in Fig. 1. Counties are further divided into Electoral Districts (EDs). Dublin has an extensive network of motorways and primary, secondary, and tertiary roads. The road network in the county totals 3949 km across the four local authorities (Transport Infrastructure Ireland, 2016). The EDs were further divided into grids of

size 1 km² for the present study.

3.2. EV charging requirement in Dublin

Dublin accommodates 25% of Ireland's total car fleet and plays a significant role in decarbonising the country's transport system (Cluzel et al., 2022). The adoption of policies and incentives to encourage EV production has increased its sales over the years (Caulfield et al., 2022; Department of Transport, 2021b). The range of actions advocated toward reducing emissions by half to meet the 2030 EU target and achieving carbon neutrality by 2050 suggests a target of 936,000 EVs, including 845,000 passenger EVs on Irish roads by 2030 (Government of Ireland, 2021). Dublin has over 24,000 registered EVs as of 2022 and is expected to have about 138,000 registered EVs by 2030, of which around 34,000 will solely rely on public EV Charging Stations (EVCS) (Cluzel et al., 2022; Society of the Irish Motor Industry, 2022).

The Dublin Local Authority Electric Vehicle Charging Strategy outlines the EVCS requirement for Dublin based on this projected vehicle stock, EV uptake scenarios and charging behaviour, split by charging type, as shown in Table 1 (Cluzel et al., 2022).

3.3. Data collection

Multiple datasets were used to extract the required information on the criteria used in this study. The data required for this study include the population density of EDs, layout of main roads, number of trips to places of work or study and location of car parking spaces, lamp posts, residences and amenities. The description of data and sources used to gather the data for each charging type are shown in Table 2.

The location of lamp posts and the number of trips to work or study were obtained from the Central Statistics Office (CSO) (Central Statistics Office, 2022). The location of lamp posts is shown in Fig. 2(a). The EDs within the study area were categorised based on the trips attracted, as shown in Fig. 2(b).

The population data at the ED level was also obtained from the CSO (Central Statistics Office, 2022) (Fig. 3(a)). Existing charging point locations were extracted from Open Street Map (OSM) (Fig. 3(b)). The location of residences and amenities were also obtained from OSM (Fig. 4(a) and (b)).

The location of major roads within the study area was extracted from OSM, as shown in Fig. 5(a). Data on designated car parking spaces were obtained from Geofabrik, a part of OSM, and had high spatial accuracy compared to other data sources (Mooney & Minghini, 2017) (Fig. 5(b)).

Information from OSM is considered relatively accurate, with an accuracy of 6 m and 80% overlap with Ordnance Survey digitised motorway objects between the two datasets (Haklay, 2010). These point datasets obtained were cross-checked with google satellite in QGIS to confirm the accuracy of the data.

4. Methodology

The study aims to identify ideal locations for deploying EVCS for shared-residential, en-route and destination charging categories based on suitable parameters appropriate for each type through a GIS-based analysis. This section discusses the workflow, site selection criteria,

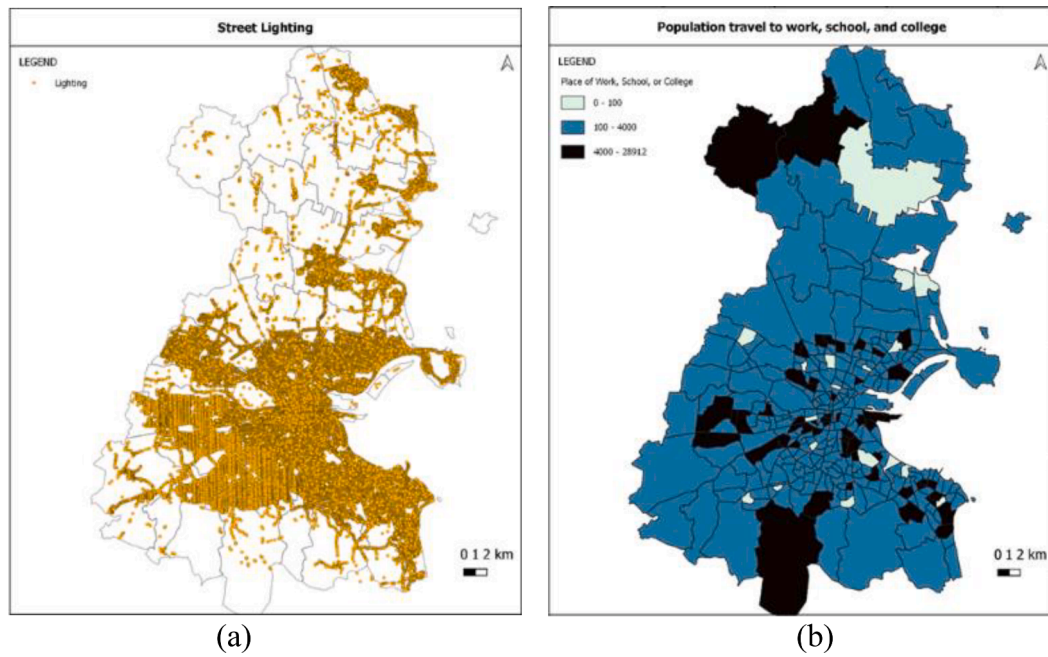


Fig. 2. Map showing (a) the location of lamp posts and (b) the number of trips to places of work or study within the study area.

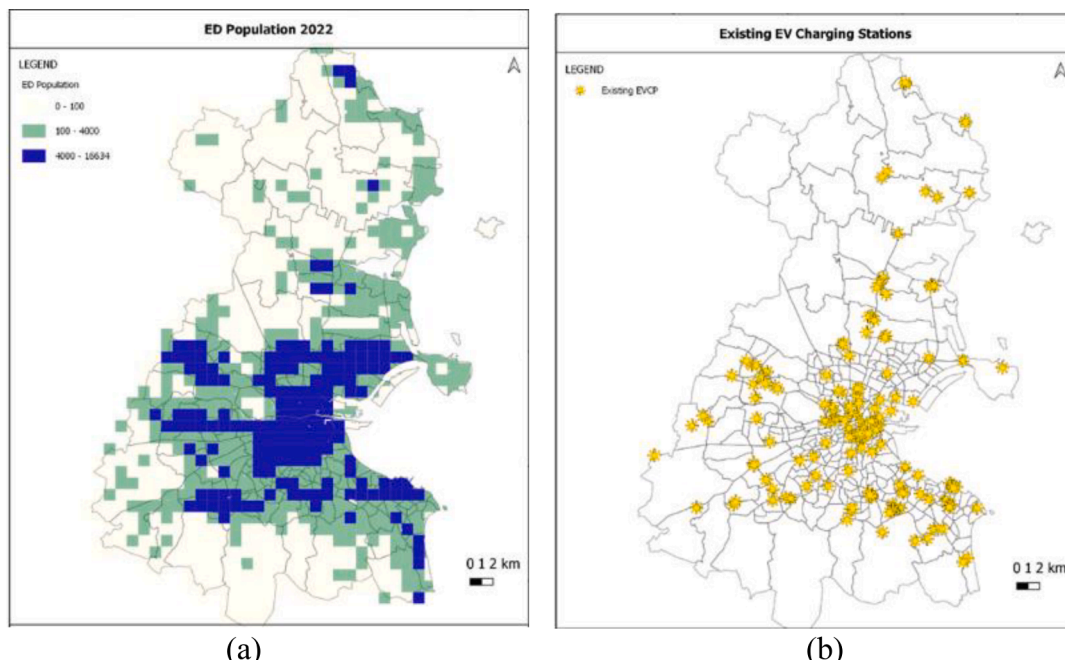


Fig. 3. Map showing (a) the ED population and (b) the location of existing EVCS.

and methodology to identify EVCS locations. The overall workflow to determine the optimal EVCS locations is presented in Fig. 6.

Initially, the criteria for site selection are defined based on literature review, logical reasoning and expected end-user characteristics. The corresponding data is extracted from OSM and obtained from the CSO. This data in vector form is converted into raster form, and proximities are calculated for different data layers. The layers are further classified into high- and medium-priority areas based on their installation priority. Different data layers are combined in OSM, and priority zones are extracted, after which suitable sites are identified based on the availability of designated car parks. The final results provide the optimal EVCS locations for three charging categories, further differentiated

based on their priority. The methodology for identifying optimal EVCS for all types (shared-residential, en-route and destination charging) follows GIS-based analysis differing only in the selection criteria. Each step of the methodology is explained in detail in the following subsections.

4.1. Categories of EVCS

Three EVCS categories are considered in the present study, including *shared-residential*, *en-route* and *destination* charging. *Shared-residential charging* aims to provide charging for residents without access to home charging. *En-route charging* provides charging access along the

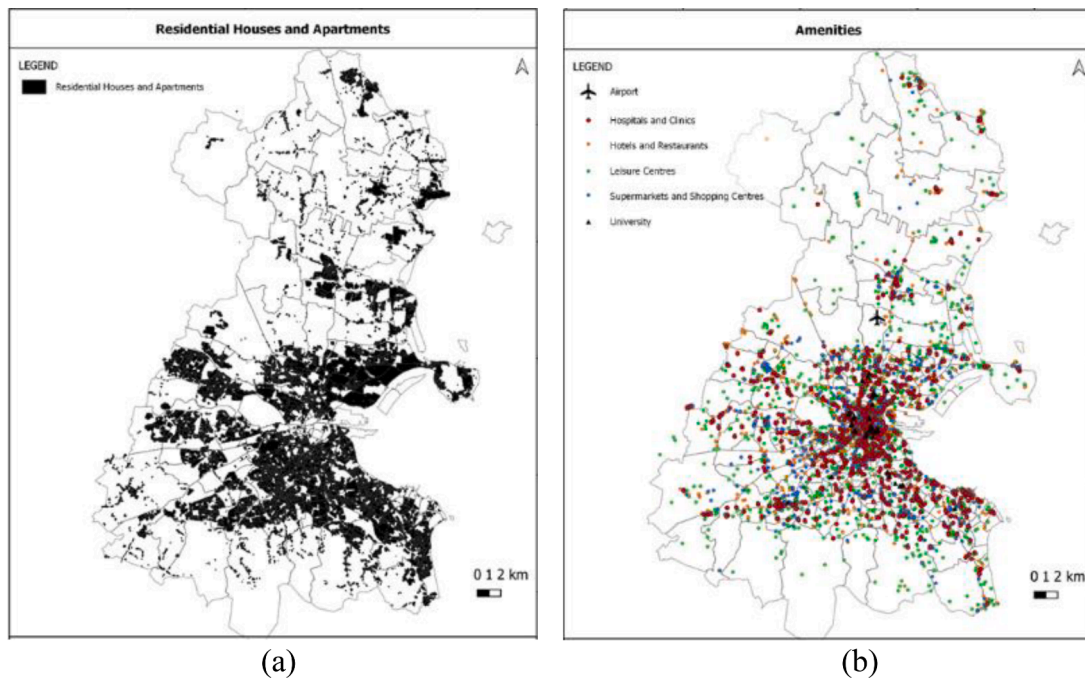


Fig. 4. Map showing the location of (a) residences and (b) amenities within the study area.

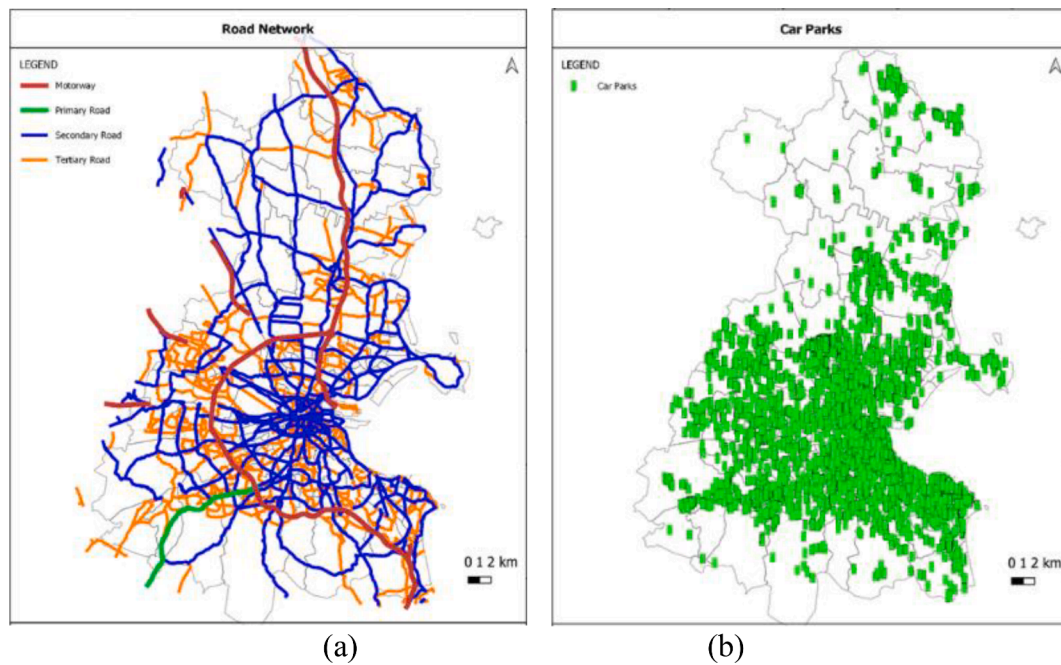


Fig. 5. Map showing (a) road network and (b) car parking spaces within the study area.

motorway, primary, secondary, and tertiary roads to facilitate long-distance travel. *Destination charging* aims to provide charging close to supermarkets, shopping centres, theatres, public parks, and universities. They can serve as a valuable source of *top-up* charging.

4.2. Site-selection criteria

The criteria used for site selection are based on the literature review and characteristics of key user groups expected to be served by each EVCS. These parameters include the population, proximity to major roads, places of work or study, location of car parks, residences, lamp

posts, and existing EVCS. Description of each of these criteria, their reason for inclusion and references from the literature are shown in [Table 3](#).

This study prioritises placing EVCS in areas with high population density. Hence, the study area was divided into smaller grids based on population density. Regions with a population of up to 100 inhabitants per km² were considered low-density, 100 to 4000 were considered moderate-density, and over 4000 were considered high-density. The areas of work or study are also classified into regions of high, moderate, and low activity based on the number of trips attracted per km² area. The study proposes charging stations at a minimum distance from the

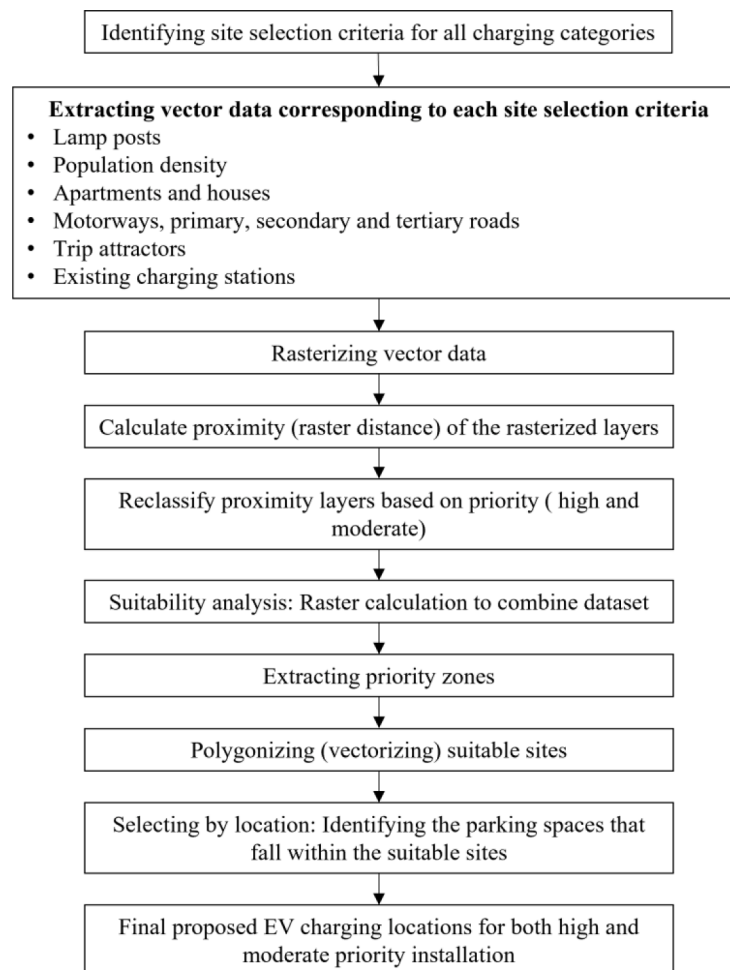


Fig. 6. Overall workflow to identify optimal site locations for EVCS.

existing stations. Thresholds were designed to ensure an adequate distance between the proposed charging point and existing ones to ensure equal distribution of charging stations.

4.3. Level of priority

Regions within the study area are categorised based on their priority level of EV infrastructure installation. Areas with high priority are identified for installing charging stations in the first stage of EVCS deployment. The study assumes these high-priority charging stations are to be installed by 2025 as per the *EV charging strategy for Dublin Local Authority* (Cluzel et al., 2022). Further, charging stations that are required in regions of medium priority are identified for installation at a later stage. The present study assumes that medium-priority charging stations will be installed by 2030 based on the *EV charging strategy*. The present study does not consider charging stations required in regions of low priority.

The priority of EVCS locations is decided based on applying different thresholds for each selection criteria discussed above. Walking distances from an EV owner's residence to nearby charging stations influence charging stations' usage (Janjić et al., 2021). Therefore, charging points are proposed to be placed within 5 min of walking distance from the user's residence while assuming an average walking speed of 4.8 kmph (Caselli et al., 2021; Donoghue & Kenny, 2015; Doorley et al., 2015). Also, high-priority charging points will be placed in regions with high population density and more considerable distances (>1000 m) from existing charging points to ensure fair distribution. All charging points will be located within designated car parks and close to lamp posts (0 to

20 m). Hence their values do not change with the level of priority. Also, all *en-route* charging points are proposed to be placed within 150 m of the road for both priority levels to ensure safety, comfort, and minimal detour. Details of site selection criteria, based on the charging category and priority, are provided in Table 4. The proximities to each of the amenities selected (in Table 4) were selected based on the authors' judgement. Changing these thresholds would change the results; others looking to apply the methods produced should keep this in mind. Given the number of dynamic variables in the research, it was not possible to estimate certainty values around the 2025 and 2030 values. This caveat should be considered when interpreting the results. It also should be noted that some spatial correlation may be present between the spatial selection criteria.

The selection criteria for *shared-residential* charging are car park availability, proximity to lampposts, population density, proximity to houses and apartments and proximity to existing charging stations. As these *shared-residential* charging points are to be placed within car parks, only such car parks located within the area that satisfy all the other parameters are considered. The selection criteria for *en-route* charging are car park availability, proximity to lampposts, proximity to motorways, primary, secondary, and tertiary roads, and proximity to existing charging stations. The selection criteria for *destination* charging are car park availability, proximity to lampposts, amenities and place of work or study, and proximity to existing charging stations.

While identifying charging point locations for the second stage (medium-priority), those proposed in the high-priority stage were included in the existing stations to prevent overlapping locations. While selecting sites for the *en-route* category, the proposed locations of

Table 3
Description of site-selection criteria for locating EVCS.

Sl No	Criteria	Reason for inclusion	Charging category	EVCS location studies that have used this criterion
1	Designated car parking space	Studies show that EV users prefer charging points located within car parks. It is convenient and utilises habit compatibility (Morrissey et al., 2016).	Shared-residential, en-route, and destination	(Carra et al., 2022; Janjić et al., 2021; Kaya et al., 2020)
2	Proximity to a lamp post	Utilising existing lamp posts for EV charging is an effective method for rapidly providing public charging points (Cluzel et al., 2022; Manning, 2021). Lighting also improves driver comfort and location safety (Cuff, 2022).	Shared-residential, en-route, and destination	–
3	Population density	Residents in densely populated regions are less likely to have private driveways and home chargers and would depend on public charging (Gilbert et al., 2020; Schmidt et al., 2020).	Shared-residential	(Carra et al., 2022; Csiszár et al., 2019; Iravani, 2022; Roy & Law, 2022)
4	Proximity to residential apartments and houses	Ensures that the charging points are located near the home-based trip origins and destinations (Gilbert et al., 2020).	Shared-residential	(Frade et al., 2011)
5	Proximity to major roads	Access to EVCS along major roads reduces range anxiety, enables inter-city EV journeys, ensures visibility and offers minimum detours (Csiszár et al., 2019; Guo & Zhao, 2015).	En-route	(Carra et al., 2022; Guo & Zhao, 2015)
6	Proximity to amenities	Amenities are considered favourable locations for top-up charging while parking as they attract trips (He et al., 2013).	Destination	(Ademulegun et al., 2022; Carra et al., 2022; Csiszár et al., 2019; Kaya et al., 2020; Philippsen et al., 2016)
7	Place of work or study	Regions with high trip attraction rates and long hours of parking are suitable locations for top-up charging.	Destination	(Iravani, 2022; Kaya et al., 2020; Philippsen et al., 2016)
8	Distance from existing EVCS	New charging stations should be away from existing	Shared-residential,	(Carra et al., 2022; Csiszár

Table 3 (continued)

Sl No	Criteria	Reason for inclusion	Charging category	EVCS location studies that have used this criterion
		ones to ensure maximum coverage and access.	en-route, and destination	et al., 2019; Kaya et al., 2020)

residential charging points for both high and medium-priority areas were included in existing charging stations to avoid overlap in charging point locations. Similarly, while selecting sites for the *destination* category, the proposed locations of residential and *en-route* charging points for both high and medium-priority areas were included in existing charging stations.

4.4. QGIS analysis and plugins

The steps followed to perform the analysis in QGIS are discussed in detail in this sub-section. A GIS-based approach has been utilised in this study to analyse spatially continuous data to obtain optimal solutions. Vector, raster, and other processing tools, including plugins, were used in QGIS to assemble and evaluate the spatial information and create graphical maps by composing the data. The plugins used in the study are *autoSaver* (to save the project automatically every five minutes), *Qpackage* (used to export the vector layers from one coordinate reference system to the other) and QuickOSM (to download OSM data as shape files).

After the site selection criteria were finalised, the data corresponding to relevant criteria were collected from multiple data sources and collated for the study area. The collated vector data was then converted to a raster format, and a proximity tool was utilised to derive the distances between the raster cells. This tool in the QGIS environment measures the Euclidean distance between two points. The proximity layers were then reclassified into two intervals based on their priority. The reclassified datasets were combined using the raster calculator tool for each category and priority level. The priority regions obtained from the raster calculator were then extracted and polygonised to get priority regions in the vector format. The reclassification analysis and raster calculation are conducted separately for high and medium-priority cases. Finally, all the car parks within the priority regions are highlighted, providing the details of locations suitable for the placement of EVCS. These steps are conducted separately for all three charging types (*shared-residential*, *en-route*, and *destination*) for two priority levels (charging points to be installed by 2025 and 2030).

4.5. Evaluation of the proposed methodology

To evaluate the proposed methodology and ensure that the results follow the proposed selection criteria, vector analysis using a buffer tool is constructed around each parameter. A buffer tool is a vector technique used in GIS to define zones at specific distances from an item or collection of objects (QGIS Project, 2022). They are ideal for analyses with distance restrictions. If the final charging points are inside the designated buffer zones (using euclidean distances), the site meets all requirements and is thus optimal.

For high-priority *shared-residential* charging points, buffer zones with radii of 500 m, 1000 m, and 20 m were built around the respective selection criteria, including houses and apartments, existing stations, and lighting. The EDs having a population beyond 4000 inhabitants per km² were highlighted. For medium-priority *shared-residential* charging points, buffer zones with radii of 1000 m, 500 m, and 20 m were built around the respective selection criteria, including houses and apartments, existing stations, and lighting. The EDs with a population of up to 4000 per km² were highlighted.

Table 4
Criteria for selection of the location of EVCS based on category and priority.

Sl No	Selection Criterion	Charging category			Threshold	
		Shared-residential	En-route	Destination	High priority (2025)	Medium priority (2030)
1	Car parks	Y	Y	Y	availability	availability
2	Proximity to a lamp post	Y	Y	Y	0 to 20 m	0 to 20 m
3	Population density	Y	–	–	> 4000 inhabitants/km ²	100 to 4000 inhabitants/km ²
4	Proximity to apartments and houses	Y	–	–	0 to 500 m	0 to 1000 m
5	Proximity major roads	–	Y	–	0 to 150 m	0 to 150 m
6	Proximity to amenities	–	–	Y	0 to 500 m	0 to 500 m
7	Place of work or study	–	–	Y	> 7000 trip attractions	100 to 7000 trip attractions
8	Proximity to an existing charging station	Y	Y	Y	> 1000 m	> 500 m

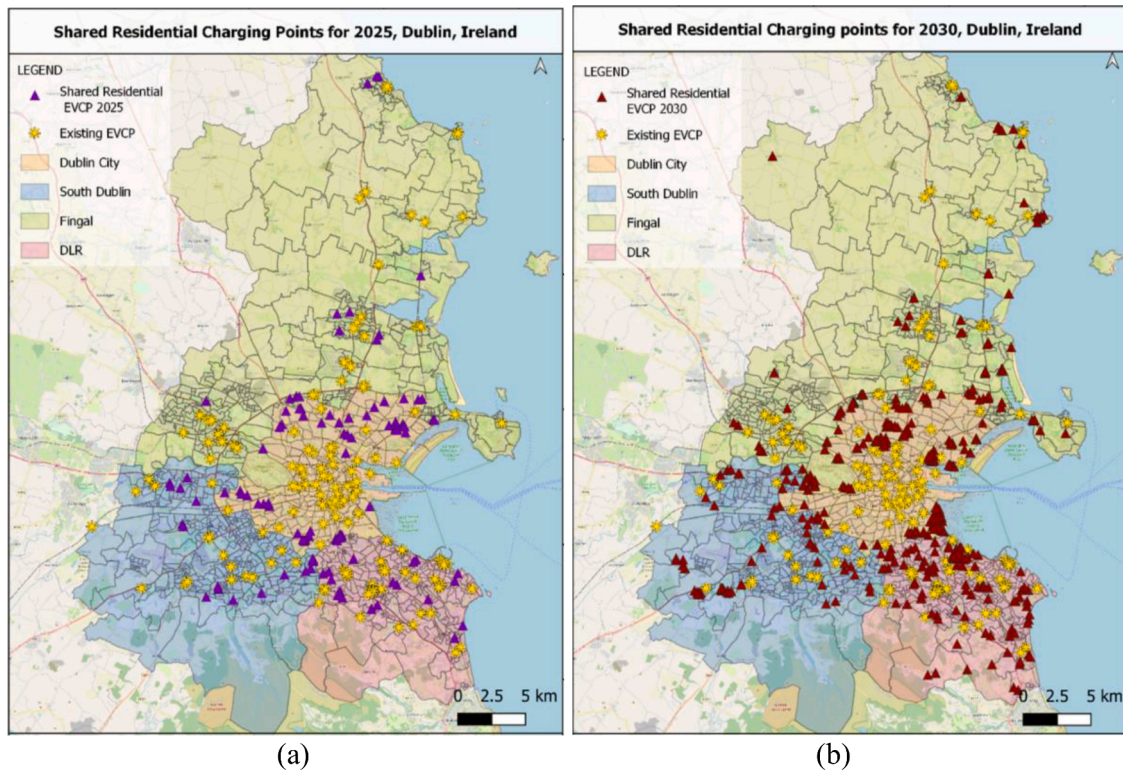


Fig. 7. Map showing the location of proposed shared-residential charging stations for (a) 2025 and (b) 2030, along with existing charging stations.

Similar evaluation and verification are done for *en-route* and *destination* charging categories based on respective site selection criteria to confirm the correctness of results.

4.6. Determining the coverage of proposed shared-residential charging stations

The success of any charging station depends on the number of people who benefit from it. Hence, an attempt was made to determine the population served by each proposed EVCS. Such an estimate also enables the prediction of usage rates, which are crucial for assessing the possible impact of the charging point. Studies show that people are willing to walk for five minutes, also known as a ‘pedestrian shed’, before driving (Morphocode, 2018). A five-minute walk is around 400 m based on the average walking speed, and a five-minute by bicycle covers about 1000 m considering an average cyclist speed of 12 kmph in Dublin Doorley et al. (2015); Irish Cycle (2009).

The population served by each proposed charging point is calculated using vector analysis in QGIS. The buffer tool in the vector analysis defines zones at specific distances from each charging point. The ED population within each buffer zone is extracted, and this value is taken as the population served by the corresponding charging station. The

distances for the buffer are determined by two active modes of travel, including walking and cycling. This study assumes that a charging station is most beneficial to those who can access the same by walking or cycling for less than five minutes.

5. Results

This section presents the results obtained from the GIS-based analysis, including the selected sites for *shared-residential*, *en-route*, and *destination* charging points. Further, the results are verified, and the population to be served by the proposed charging points is estimated. It should be noted that the results presented in this paper assume no changes to the urban dynamics of the city, nor does it postulate future modifications to these dynamics. In the longer term, cities like Dublin may have changing dynamics that could result in different findings than those presented in this paper.

5.1. Suitable locations for shared-residential charging stations

The locations suitable for *shared-residential* charging stations were identified based on proximity to residential apartments, population, distance from existing charging stations, proximity to lamp posts and

Table 5
Details of shared-residential EVCS locations identified for 2025 and 2030.

Sl No	County Council	Number of identified locations_2025	Number of identified locations_2030
1	Dublin City	59	225
2	South Dublin	17	73
3	Fingal	21	87
4	Dun Laoghaire-Rathdown	20	68
	Total	117	453

availability of car parking. These regions are further extracted, and the car parks are highlighted as optimal locations for EVCS. The proposed and existing EVCS locations are shown in Fig. 7.

This study identified 117 EVCS locations for the *shared-residential* category to be installed by 2025. These sites are within 500 m of residential zones and 1000 m from existing charging stations. The proposed locations are dispersed throughout the study area, mainly on the outskirts with high population density due to a concentration of existing charging infrastructure in the city centre. Further, 453 charging point locations in the *shared-residential* category are proposed to be installed by 2030. These charging points are located in regions with medium to low population density within 1000 m of residential areas and at a distance of 500 m from existing EV charging stations. The proposed number of *shared-residential* charging point locations within the study area differentiated by county and level of priority are listed in Table 5.

5.2. Suitable locations for en-route charging stations

The suitable locations for *en-route* charging points were identified based on proximity to major roads, distance from existing stations, proximity to lamp posts, and availability of car parking. The car parking spaces within these regions are highlighted as the proposed en-route charging locations and plotted in Fig. 8.

This study identified 68 potential *en-route* charging stations along the motorway, primary, secondary, and tertiary roads for implementation

by 2025. These locations are situated 150 m from the road and 500 m away from the existing charging infrastructure and are mainly located along the borders of each county council region. For the next stage (implementation by 2030), 165 potential charging point locations are identified within 150 m proximity to roads and 500 m away from the existing charging infrastructure. The proposed number of *en-route* charging station locations within the study area differentiated by county and level of priority are listed in Table 6.

5.3. Suitable locations for destination charging stations

The suitable locations for *destination* charging stations were identified based on proximity to amenities, place of work or study, distance from existing charging stations, proximity to lamp posts and availability of car parks. The proposed locations for *destination* charging stations for high and medium-priority scenarios are shown in Fig. 9, along with existing charging station locations.

In the *destination* charging category, 585 and 2462 ideal EVCSs need to be installed by 2025 and 2030, respectively. These locations are close to trip attractors, such as supermarkets, hotels, and hospitals. The proposed number of *destination* charging station locations within the study area differentiated by county and level of priority are listed in Table 7.

Table 6
Details of en-route charging station locations identified for 2025 and 2030.

Sl No	County Council	Number of identified locations_2025	Number of identified locations_2030
1	Dublin City	22	55
2	South Dublin	13	34
3	Fingal	22	39
4	Dun Laoghaire-Rathdown	11	37
	Total	68	165

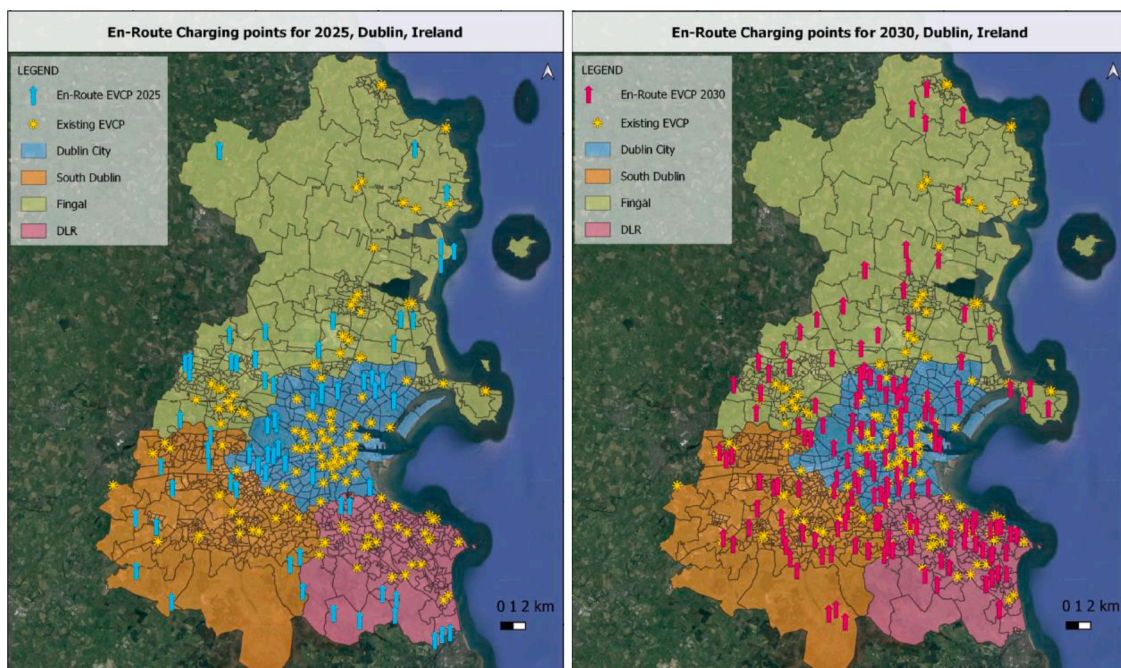


Fig. 8. Map showing the proposed en-route and existing charging stations for (a) 2025 and (b) 2030.

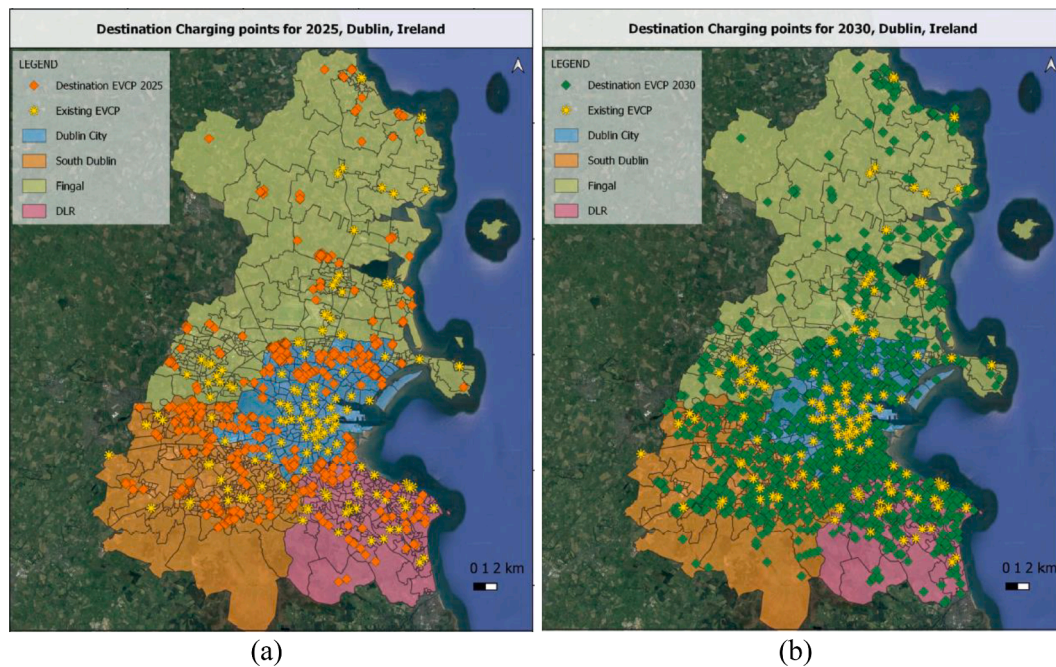


Fig. 9. Map showing the location of the proposed destination and existing charging stations (a) by 2025 and (b) by 2030.

Table 7
Details of destination charging station locations identified for 2025 and 2030.

Sl No	County Council	Number of identified locations_2025	Number of identified locations_2030
1	Dublin City	231	863
2	South Dublin	128	525
3	Fingal	163	586
4	Dun Laoghaire-Rathdown	63	488
	Total	585	2462

5.4. Evaluation of the proposed site-selection methodology

The buffer zones and the highlighted ED population for different levels of priority are displayed in Fig. 10.

The selected car parks were cross-verified to confirm that all the optimal car parks obtained from the analysis fall into buffer zones containing houses, apartments, and lighting and are within the highlighted EDs. It is also ensured that these car parks are located away from the buffer zone of the existing charging stations. Results show that all the proposed charging stations are well within the required buffer zones.

5.5. Population served by the proposed shared-residential charging stations

The overall population served by the proposed charging points considering five-minute walking and five-minute cycling for 2025 and 2030 are shown in Table 8.

The buffer zones around each proposed charging station and the corresponding population served are shown in Fig. 11.

The results show that the deployment of the proposed charging stations will significantly increase the population serviced between 2025 and 2030, and the accessibility of the charging stations will expand over time.

6. Discussion

This research used a GIS-based analysis to identify ideal locations of

EVCS in urban areas based on spatial overlaps between critically relevant criteria specified based on expert opinion and literature. This approach aligns with the current requirements of the Dublin Local Authority and a few previous studies in the adoption of a practical GIS-based analysis to identify EVCS locations which can be implemented with limited resources (Cluzel et al., 2022; Department of Transport, 2021a; Grote et al., 2019). However, in addition to the criteria used previously, this research identifies lamp posts for conversion into slow shared-residential charging stations, which is a significant contribution of this work and aligns with the current advancements in the Internet of Things (Griffiths, 2018). Moreover, the approach also considers the categorisation of EVCS based on targeted end-users and installation priority. The lamp posts at the specified locations could be retrofitted with the EV charging equipment and provide improved coverage of slow charging stations with less infrastructure cost to increase EV penetration (Bruno et al., 2019; Zhang et al., 2019).

Compared to the methodologies adopted in literature (Chen et al., 2013; Csiszár et al., 2019), the GIS-based approach adopted in this study is practical for implementation by local councils as it requires minimum resources and uses open-source data, which is readily available. The study findings demonstrate the need for more charging points further away from the city. As suggested in previous studies, the population served by five-minute walking or cycling to EVCS is critical to the enhanced EV uptake, especially in dense areas with limited access to off-street parking (Janjić et al., 2021; Mahdy et al., 2022). The EVCS locations proposed in this work can provide access to a total of 140,274 people by a five-minute walk in the first level of implementation. The population served will significantly increase between 2025 and 2030. Previous studies have shown that habit compatibility is vital in ensuring the practical usage of EVCS (Philipsen et al., 2016). EVCS locations proposed in this study are synchronous with parking habits, safety perceptions and refuelling demands.

The results presented in this paper have significant implications for policymakers in comprehending potential EV users' charging patterns, mainly where they prefer to charge. With this information, decision-makers may develop intelligent charging policies and offer financial or other incentives that may be helpful for grid load management. The locations proposed in the study can be utilised as a guide when distributing charging stations, resources, and funding. The provision of

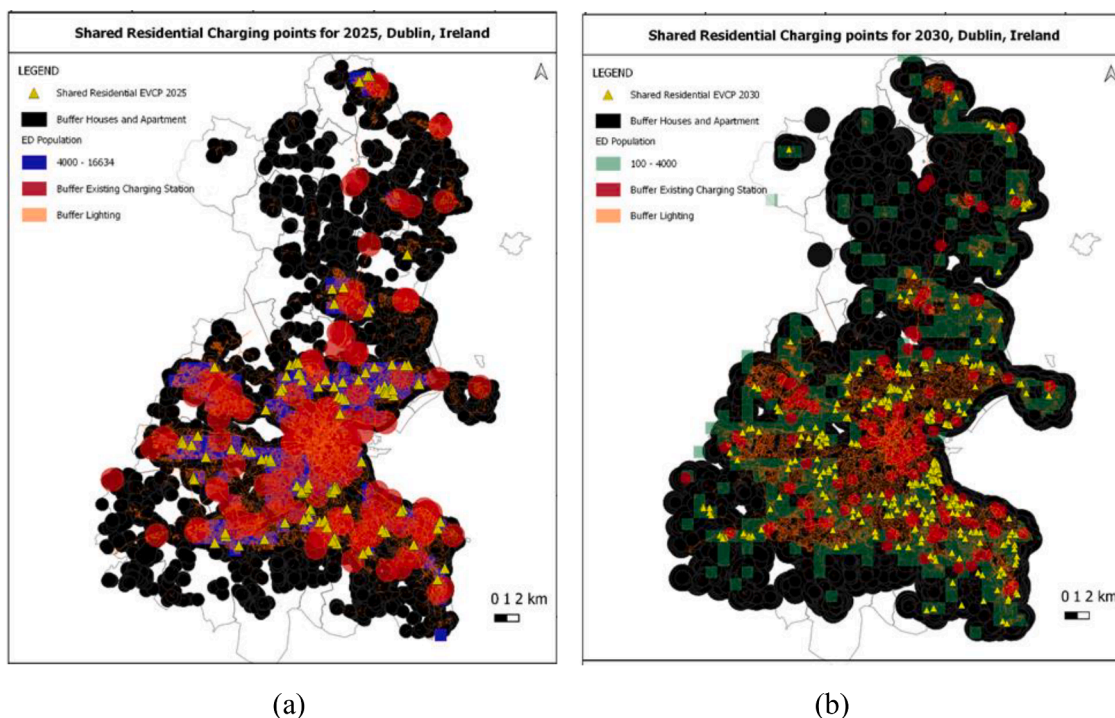


Fig. 10. Map showing buffer zones for selection criteria of shared-residential charging stations (a) by 2025 and (b) by 2030.

Table 8

Total population served by *shared-residential* charging stations.

Level of priority (year)	Population served by <i>shared-residential</i> charging stations	
	Five-minute walking	Five-minute cycling
2025	140,274	553,306
2030	525,630	2041,977

EVCS at these ideal locations can improve the uptake of EVs amongst those who are reliant on cars but do not have access to off-street parking, thus improving EV access equitably as envisioned by the Department of Transport, Ireland (Department of Transport, 2021a; Irvani, 2022). Based on anticipated future development scenarios, the results also contribute to the information on the potential of renewable energy sources to satisfy EV demand.

It may be noted that the present study does not consider judgement criteria or stakeholder preferences in decision-making, as followed in other multi-criteria methodologies (Carra et al., 2022; Kaya et al., 2020). Instead, a practical GIS-based spatial overlap analysis is adopted to identify the ideal locations of EVCS based on expert opinion, literature and the open-source database.

7. Conclusions

This study identified the optimal locations for EVCS for *shared-residential*, *en-route*, and *destination* categories in Dublin region through a GIS-based analysis using OSM. Results from this study can serve as a helpful guide for practitioners and policymakers in deciding the best locations for the successful deployment of charging infrastructure. A significant highlight of this study is the transferability of the proposed approach. As the suggested methodology is based on QGIS and OSM, this research can serve as a model for employing open-source GIS-based analysis to resolve complicated spatial issues. In such cases, the site selection criteria may be chosen based on the targeted end-user characteristics for that region.

This study segregates the proposed charging points into high-priority

sites, which may be installed by 2025 and medium-priority sites, which may be established by 2030. The sites were selected based on population density, availability of parking spaces, distance from existing charging stations, and proximity to residences, lamp posts, roads, amenities, and places of work or study. The study identifies 770 and 3080 optimal charging station locations to be installed by 2025 and 2030, respectively. One hundred and seventeen *shared-residential* charging points are proposed for 2025, expected to serve a population of 140,274 and 553,306, considering accessibility by five-minute walking and five-minute cycling, respectively. Four hundred and fifty-three *shared-residential* charging points are proposed for 2030, which could serve a population of 525,630 and 2041,977, considering accessibility by five-minute walking or cycling, respectively.

The study has certain limitations that might have influenced the interpretation of the research findings. Most of the datasets used in this study are obtained from OSM, which is considered sufficiently accurate (Mooney & Minghini, 2017). However, it is powered by open-source software making the data vulnerable to corruption. Additional selection criteria, such as the number of parking spaces within the car parks, number of EV users per household, traffic volume, distance from 10 kV grid lines, and off-street parking data, were included in the preliminary analysis. However, these criteria were excluded later on due to the unavailability of data. The presumptive proximity distances and the GIS data structure are the other research constraints of the study. Also, for lamp posts to be considered suitable for charging, they should be positioned near the road pavement and have a minimum internal diameter of 140 mm (Cluzel et al., 2022). Another limitation of this study is that it does not consider the electric distribution network in the region.

The results obtained from the GIS analysis can be further enhanced by incorporating additional criteria such as the number of parking spaces within the car parks, number of EV users per household, traffic volume, distance from 10 kV grid lines, building type, availability of driveways in the area and on-street parking behaviour. Considering user charging behaviour, perspectives of municipalities and grid companies, and the impact of pricing on demand fluctuation could further improve the identification of EVCS locations. Also, further research should be completed on the investment priorities of *en-route* and *destination*

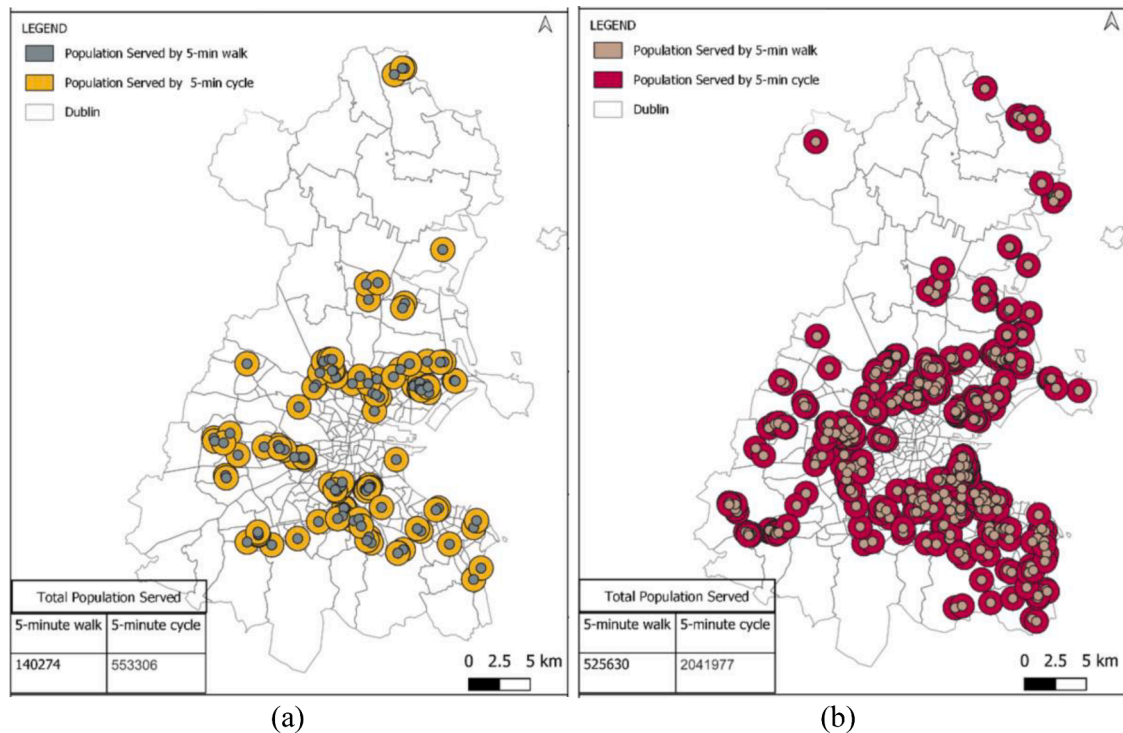


Fig. 11. Buffer zones indicating the population served by proposed shared-residential charging stations (accessible by five-minute walking or cycling) in (a) 2025 and (b) 2030.

charging, especially as battery technology improves and driving range increases.

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

The authors do not have permission to share data.

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