IMPERIAL

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Adaptive multi-year planning of public EV fast-charging capacity under demand uncertainty

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1 Problem statement

As more drivers use electric cars, Dundee must decide whether to expand existing charging sites or open new ones. Building too early leaves chargers underused. Building too late leaves drivers waiting. **This study plans which council car parks should receive fast chargers, how many to add, and when to install them from 2027 to 2035.** The plan is revised each year as new usage data arrive, while checking driving times, waiting times and available grid capacity.

2 Methodology

Annual demand update. Observed mean daily usage is tested against 20,000 empirical resamples per pathway. Compatible pathways are retained and rebased to the latest observation before the following year's investment:

$$\mathcal{S}_u = \{s \in \mathcal{S}_{u-1} : p_{s,u} > 0.05/8\}$$
$$\widetilde{D}_{s,t\,|\,u} = \bar{x}_u\, D_{s,t}/D_{s,u}, \quad D^{\mathrm{rob}}_{u+1} = \max_{s\in\mathcal{S}_u} \widetilde{D}_{s,u+1\,|\,u}$$

S denotes the retained pathway set, p is the two-sided Monte Carlo p-value, x-bar is observed mean usage, and D is pathway demand. The 5% false-elimination budget is divided across eight annual updates under the empirical-day model. Investment protects the largest retained demand. Rejected pathways do not re-enter.

$$\min\Big(\sum_j n_{jt},\ \sum_{j\in J^c} y_{jt},\ \sum_{m,z,j} r_{zj} f_{mzjt}\Big)_{\mathrm{lex}}$$
$$\sum_{j:\,a_{zj}=1} f_{mzjt} = d_{mzt}, \quad \sum_z f_{mzjt} \le 40\, n_{jt}$$
$$n_{jt} \ge n_{j,t-1}, \quad n_{jt} \in \{0,\dots,K_j\}, \quad K_j \le 2$$

Mixed-integer location model. n counts modules, y denotes candidate opening, and f allocates incremental zone demand d under map m. The objectives minimize modules, then new sites, then travel time r. A common installation serves all four maps, with map-specific assignments. Each module provides eight 50-kW positions and a queue-tested planning cut of 40 incremental sessions/day. Road access is limited to ten minutes. Reported parking bays may reduce the two-module site cap. Installed capacity is retained, and reported primary headroom constrains the grid-study years.

3 Data and demand treatment

- **Observed usage:** 40,787 rapid/ultra-rapid sessions (Jan-Aug 2025) and 78,127 accepted 2024 sessions for queue replay.
- **Spatial inputs:** 193 zones, 11 existing facilities and 34 conditional candidates. Demand maps represent population, car ownership, destination activity and traffic exposure.
- **Future demand:** Transport Scotland chargepoint growth transferred to 29 local rapid-position equivalents. Annual compound interpolation assumes a stable rapid share.

Model scope. Council rapid charging only. Existing baseline demand stays at its observed sites. Only additional demand is allocated. Commercial utilisation is excluded. The session input is B0 + 5(P - 29), with B0 = 168.54 sessions/day.

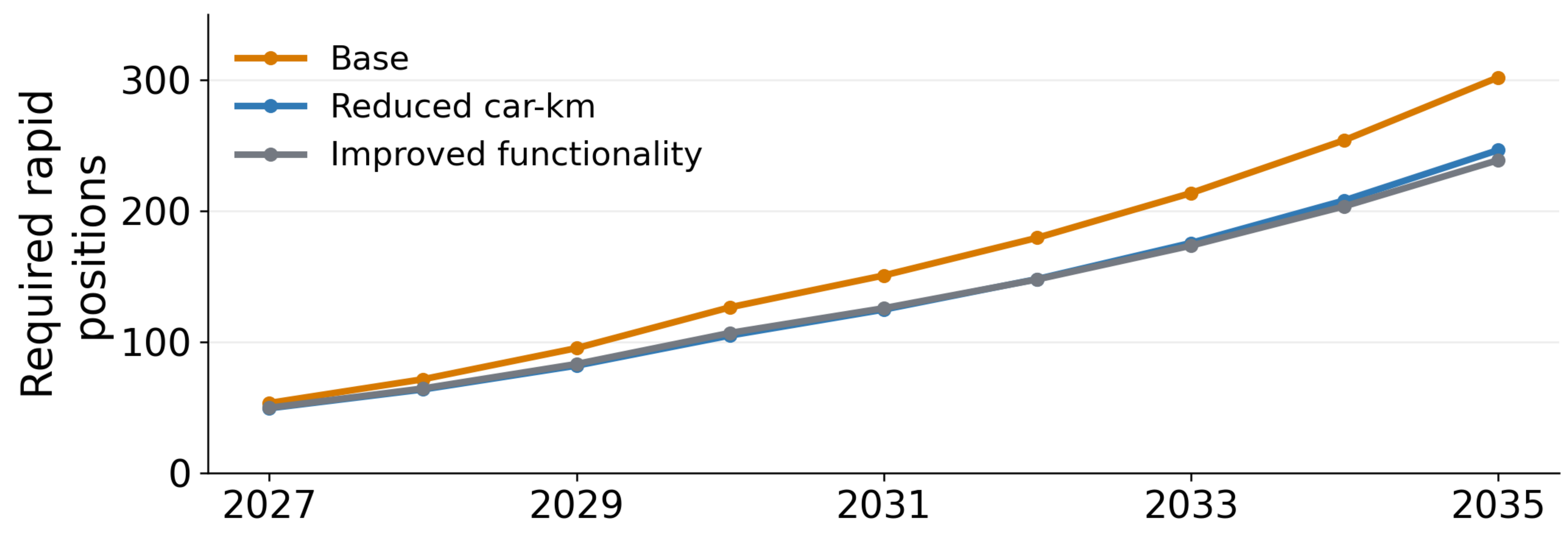


Fig. 1. Annual demand pathways. Transferred requirements reach 302, 246 and 239 positions in 2035. Future observations are simulated. Policy pathways carry no assigned probabilities.

Primary-network connection screen

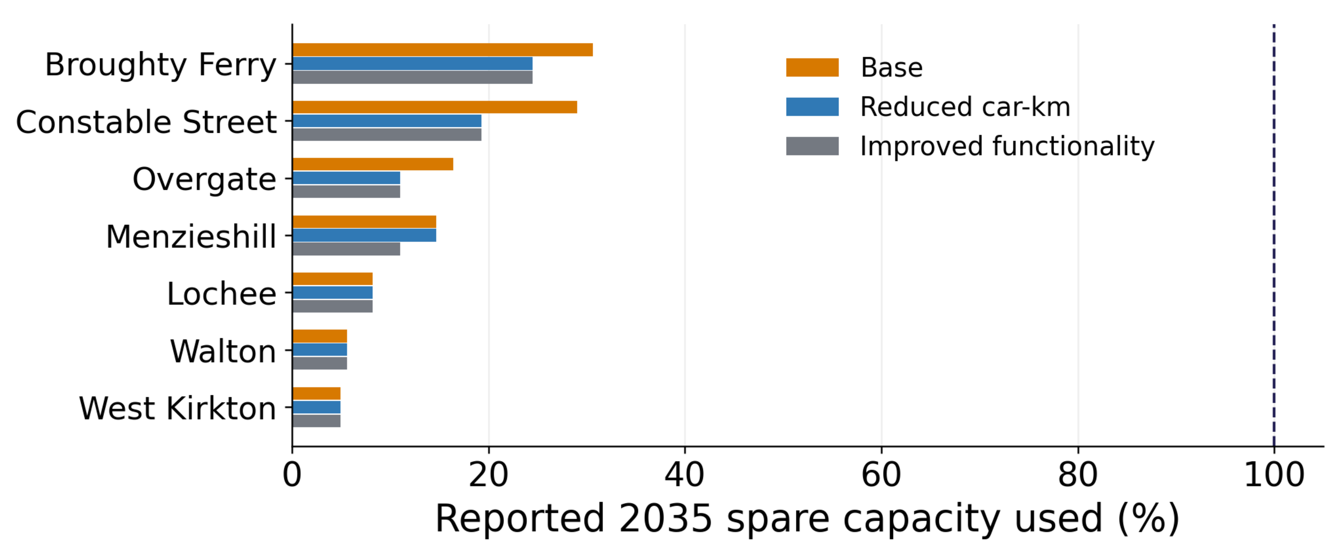


Fig. 2. Primary-area headroom use in 2035. SSEN data support a 68-bus upstream model. The 14.0-MW base-pathway addition produces a maximum incremental voltage drop of 0.01152 p.u. at 0.95 power factor. Headroom use peaks at 30.6% with 0.7 coincidence. These are upstream screening results, followed by site-specific connection assessment.

4 Results

20.0-20.6%
Fewer position-years than fixed base-pathway protection, at the same service standard.

216-280
Added positions required by 2035, depending on pathway.

18 sites
Active by 2035 on the base pathway, including 7 newly opened car parks.

31%
Highest primary-headroom use. No reinforcement triggered in the published-headroom screen.

Position-years sum installed additions over 2027-2035: 984 and 992 on the two lower-demand branches, versus 1,240 under fixed base-pathway protection.

Spatial deployment

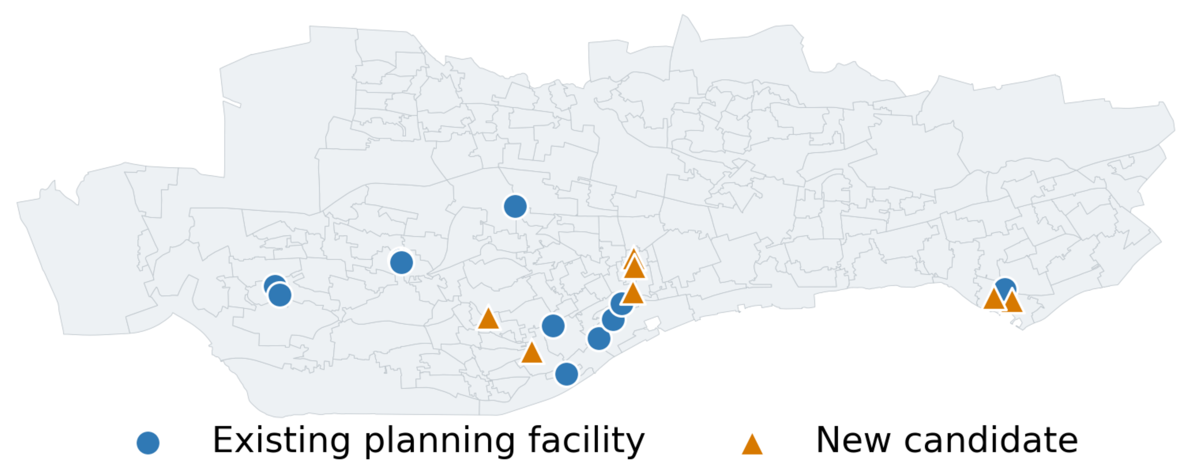


Fig. 3. Base-pathway deployment in 2035. Eighteen sites receive additions, including seven new candidates. The two-module cap limits concentration. Candidate selection is conditional on site and connection assessment.

Annual investment sequence

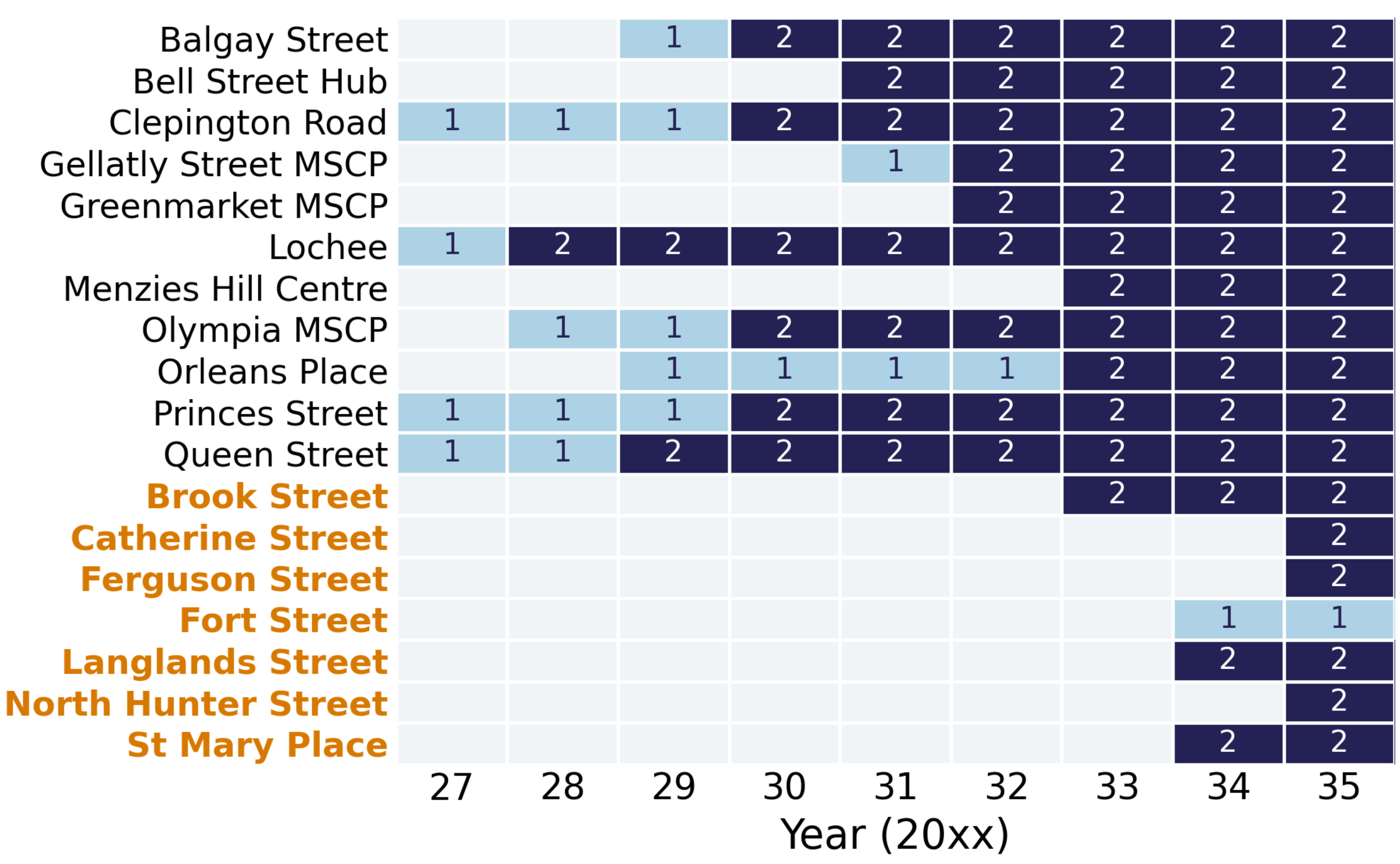
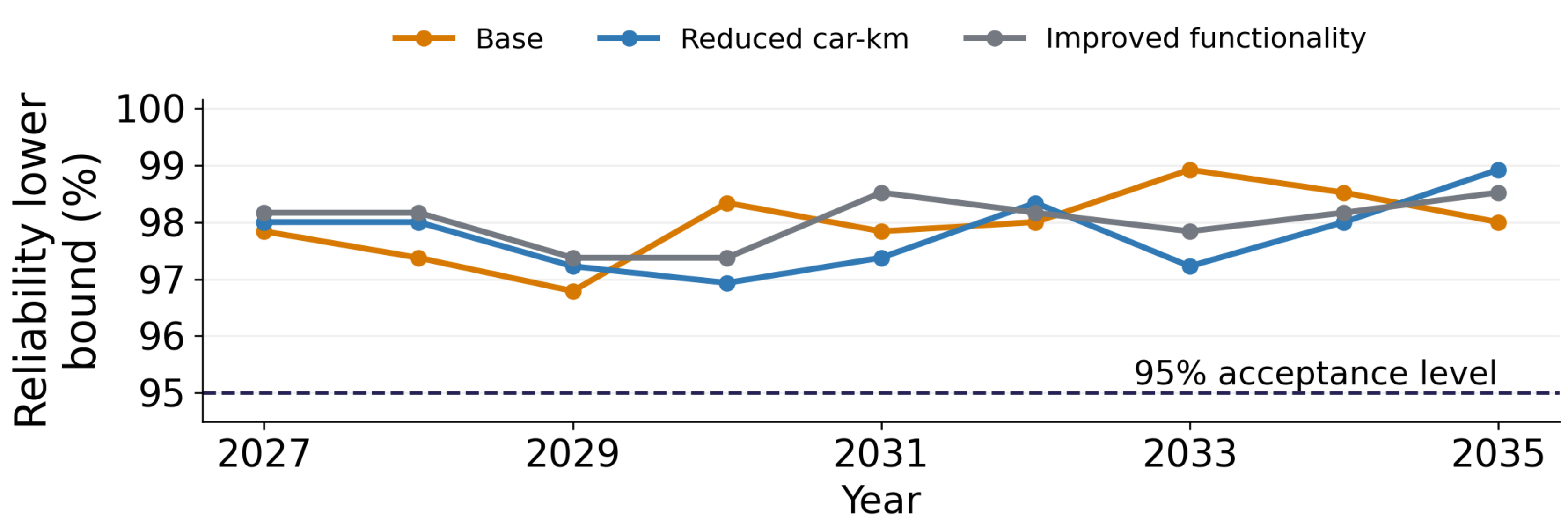


Fig. 4. Cumulative modules by site and year. All branches begin with **32 additions in 2027**. Existing sites accommodate the base pathway through 2032. Brook Street enters in 2033, followed by six candidates in 2034-2035. The adaptive branches require **216-280 added positions by 2035**.

Service reliability



$$L = \mathrm{Beta}^{-1}(0.05/216,\ k, 1000-k+1) \ge 0.95 \quad (k>0)$$

Fig. 5. Familywise service reliability. The current 29-position network fails all nine tested future stress cases, establishing the need for expansion. Replay preserves empirical arrival-duration pairs and overnight carry-in. Success requires **95% of sessions to start within ten minutes at every active site**. For k successes in 1,000 replays, L is the exact binomial lower bound (zero if k = 0). Bonferroni adjustment covers 2 variants x 9 years x 3 pathways x 4 maps. All 216 cases pass: **0.9679-0.9917**. Curves show annual minima across maps and variants.

5 Future work

Include construction and connection lead times, commercial utilisation, verified investment costs and growth-rate updates as new data become available.

6 Acknowledgement

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Key references: L. V. Snyder, IIE Trans. 38(7), 2006 (facility location under uncertainty) · A. H. Golsefidi et al., Appl. Energy 380, 2025 (incremental charging expansion) · D. Bertsimas, V. Gupta, N. Kallus, Math. Program. 167, 2018 (data-driven robust optimization) · B. Phipson, G. K. Smyth, SAGMB 9(39), 2010 · C. J. Clopper, E. S. Pearson, Biometrika 26(4), 1934 · F. Silber et al., IJEPES 155, 2024 (fast-charging simultaneity) · Transport Scotland, draft EV public charging network implementation plan, 2024.

Data: Dundee City Council, Transport Scotland, SSEN, Department for Transport, OpenStreetMap contributors (ODbL). Routing by OSRM.