# Optimizing Vehicle-to-Grid Participation for Household Electric Vehicles under Multi-dimensional Scenarios

A scenario-based economic feasibility framework integrating travel behavior, market prices, energy state and battery capacity

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# Presentation Overview

# 01 Background and Motivation

# Industry Partner: CNBM

**China National Building Material (CNBM)**

- Fortune 500 Company
- Supplying solar panel & smart battery in NZ
- Expanding across clean energy transition solutions

# Renewable Transition:
# A Challenge for Grid Stability

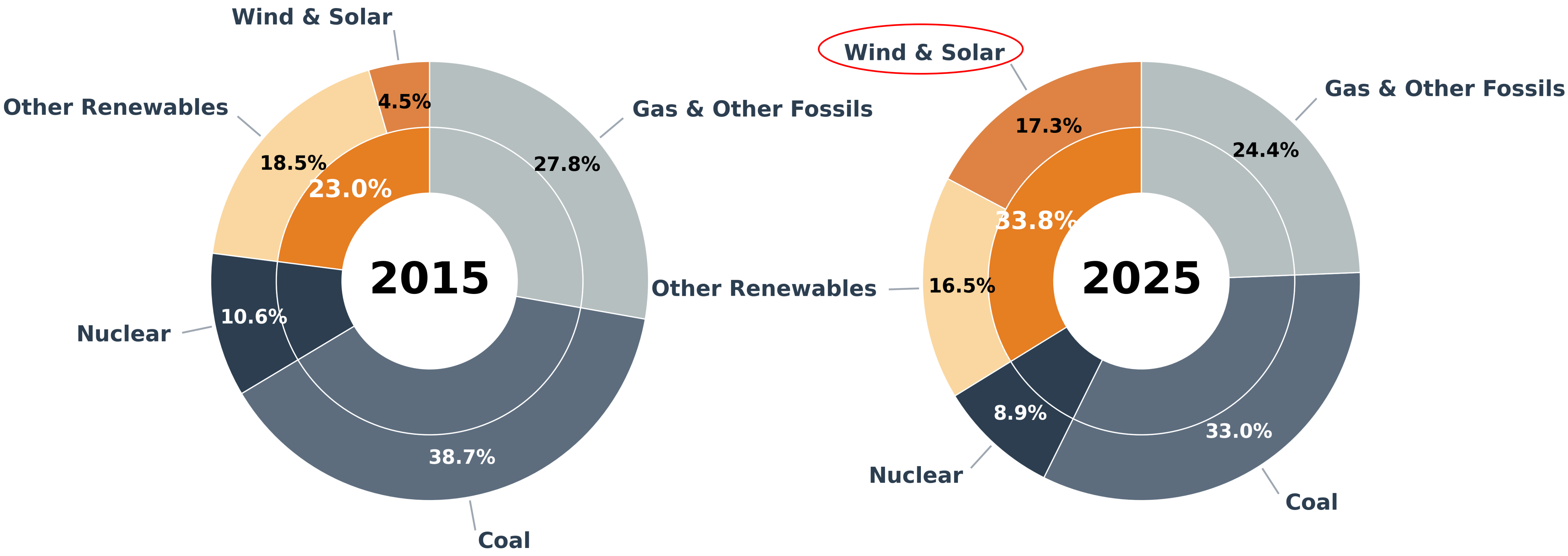



Figure 1. Global Electricity Generation Mix Transition

# Hidden Assets: Millions Batteries on Wheels

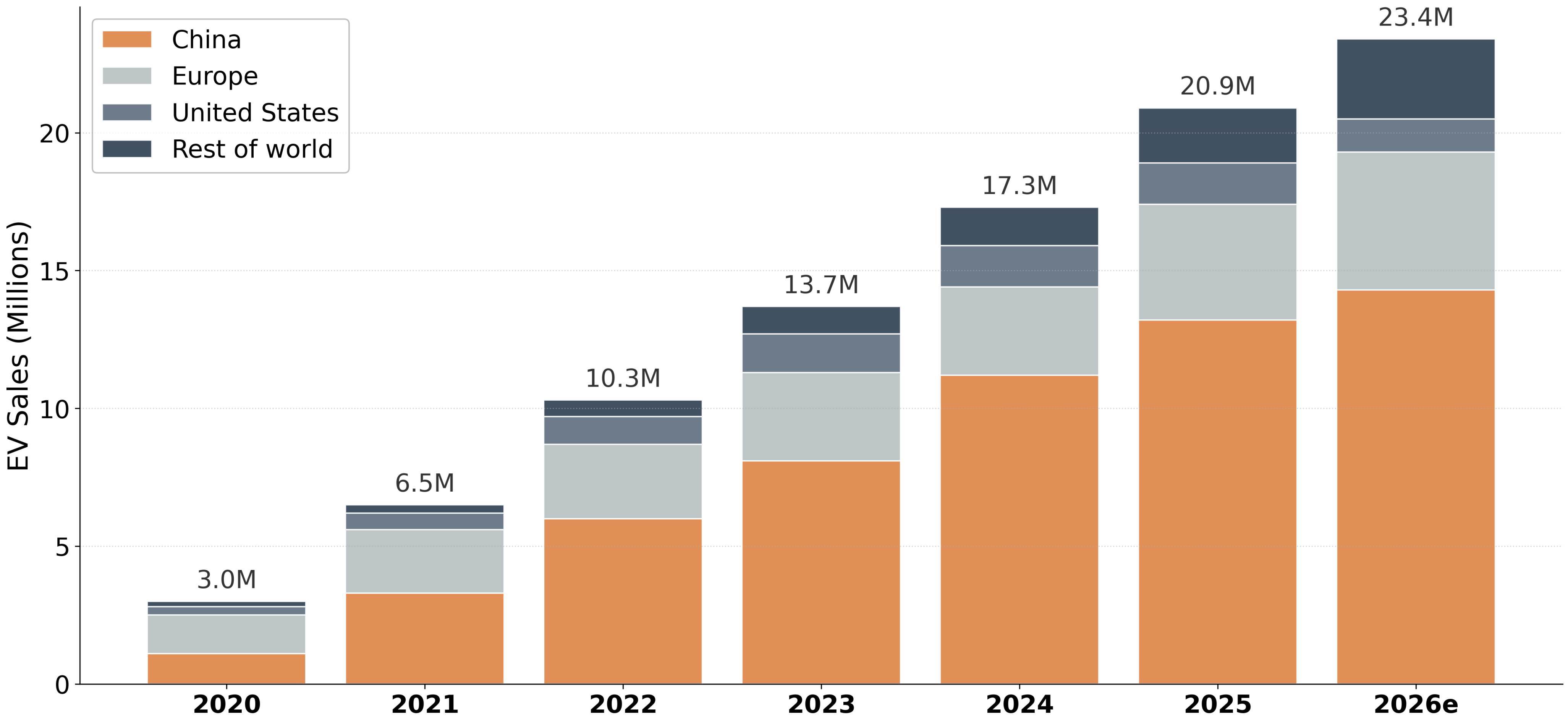



Figure 2. Global Electric Vehicle Sales Trend by Region

# Vehicle-to-Grid(V2G)

**Concept & Mechanism**

- Solution: Vehicle-to-Grid, proposed in 1997
- Bidirectional Flow: Enable discharge back to grid

**Dual Value Proposition**

- Grid: Enhances stability & renewable integration
- Owner: Generates cost savings & trading revenue

**Current Development**

- 30+ Electric Vehicle (EV) models & global pilots

# 02 Project Overview

# Current Research Progress & Gaps

**Current Research Achievements**

- Commercial Fleets: Validated grid support & battery cost reduction
- Residential: Significant savings for household EV charging(up to 80%+)

**Main Gaps**

- Behavioral: Ignores real-world irregular, multi-day driving habits
- Market: Overlooks the impact of diverse electricity pricing
- Parameters: Lacks sensitivity analysis of starting battery levels

# Problem Statement & Research Objectives

- **Core Problem:** Oversimplified models widen the gap between theory and reality
- **Overall Aim:** Evaluate **residential** V2G economic viability across real-world scenarios
- **Specific Objectives:**
    i. Mobility: Evaluate impacts of empirical weekly driving patterns
    ii. Economics: Compare V2G vs. V1G across different price regimes
    iii. Boundaries: Identify critical thresholds for Initial SOC & battery capacity

- UK Focused: Strong shift to renewables, V2G support policy and rich data.
- V1G: Only Charge, No Discharge
- SOC: State-of-Charge, Battery charge levels

# 03 Modeling Framework

# Framework Overview: Part 1

**Data Source:**

**Travel Data:** UK National Travel Survey (NTS, 2024)

**Price Data:** Agile Octopus Time-of-Use (TOU, half-hourly), Electricity Prices (2021-2025).

**Model Inputs:** Parametrized via industry reports and prior studies (e.g., IEA Global EV Outlook).

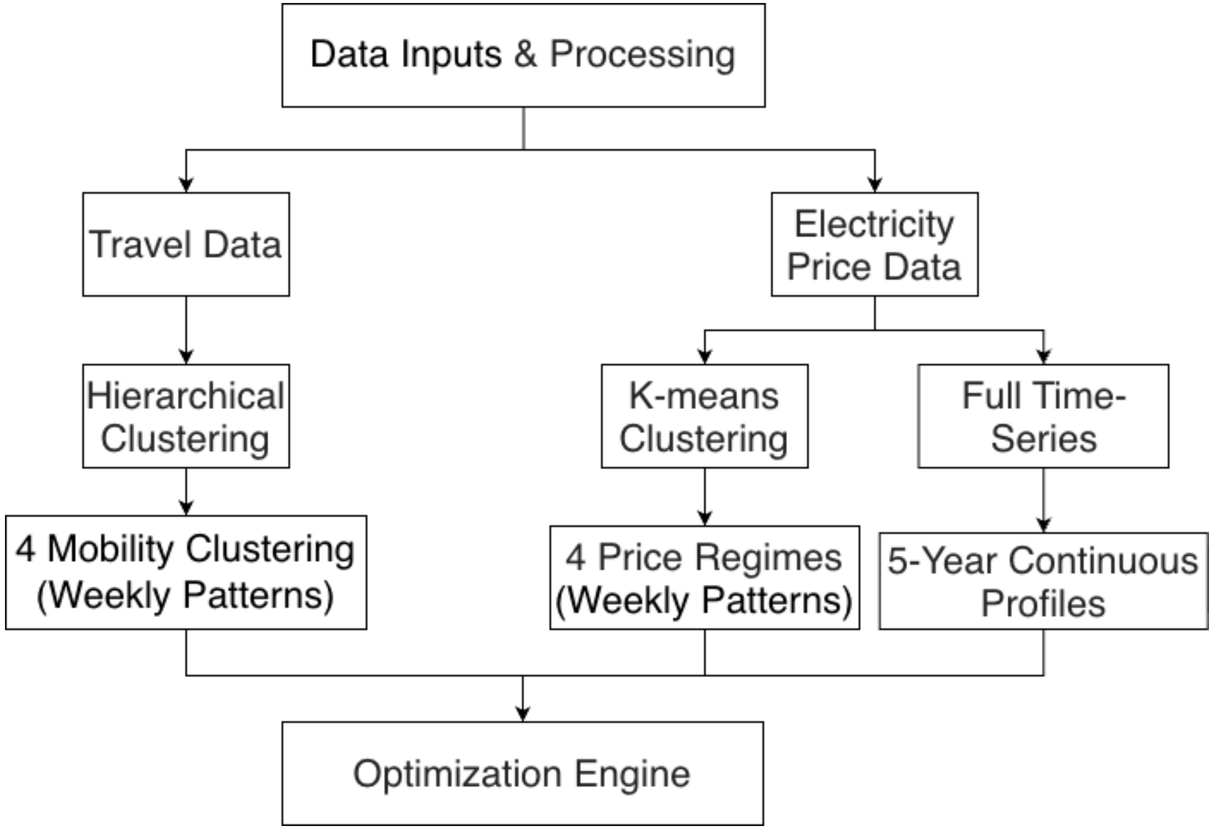



Figure 3. Framework Flowchart (Part 1)

# Mobility Clustering: Hierarchical Approach

- **Algorithm**: Hierarchical Clustering (Ward Linkage).
- **Key Features**:
  - Temporal: Departure / arrival times.
  - Intensity: Travel distance.
  - Residential-stay: Duration and window characteristics.
- **Optimal K (K=4):** supported by Silhouette score, Davies–Bouldin and Calinski–Harabasz indices.

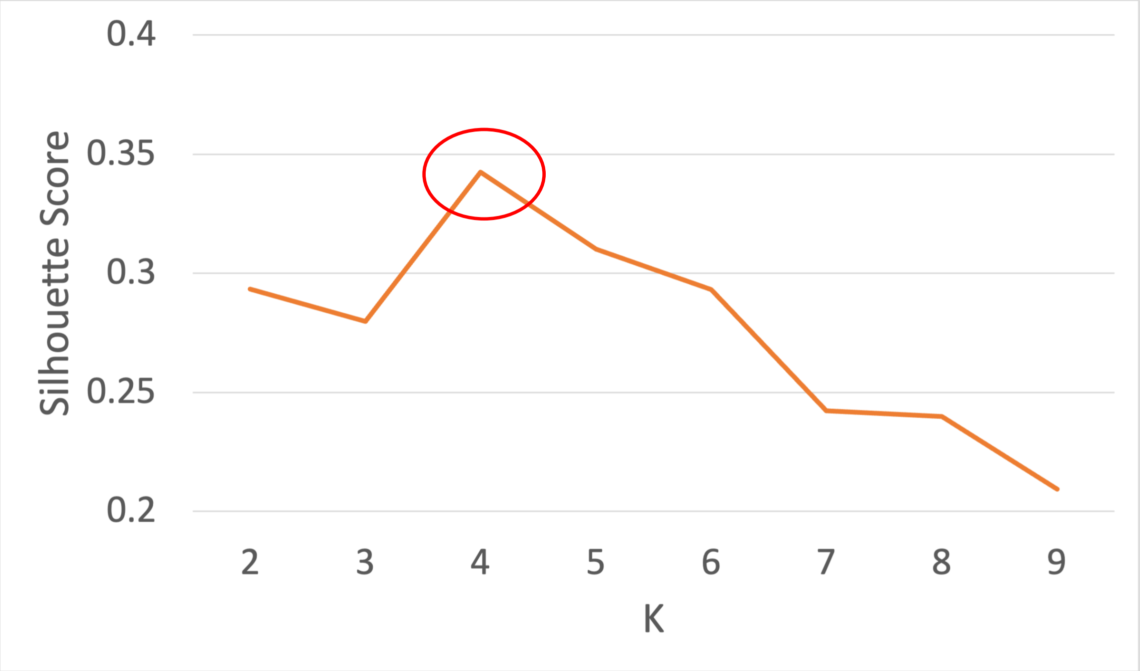



Figure 4. Mobility Clustering: Silhouette Score

# Daily Mobility Archetypes and V2G Availability

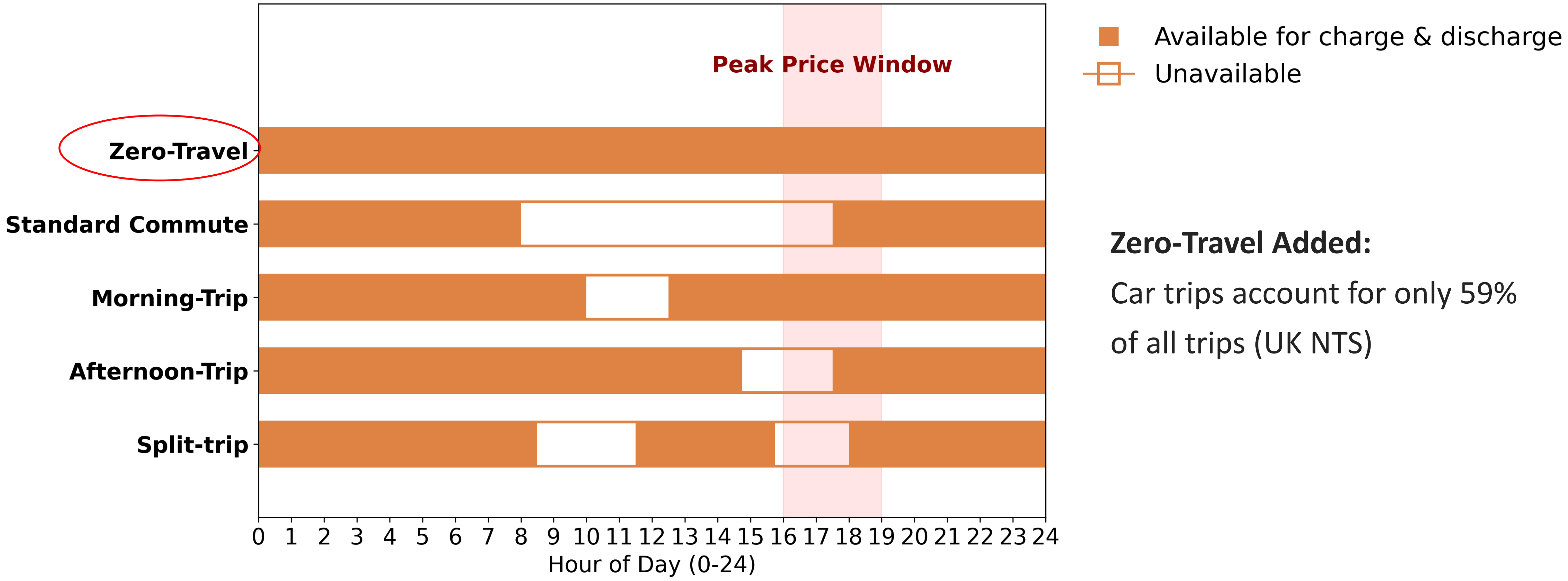



Figure 5. Daily Archetypes: Vehicle Availability

**Zero-Travel Added:**

Car trips account for only 59% of all trips (UK NTS)

# Representative Weekly Mobility Archetypes

ZT: Zero-Travel
SC: Standard Commute
MT: Morning-Trip
AT: Afternoon-Trip
ST: Split-trip

| | Mon | Tue | Wed | Thu | Fri | Sat | Sun |
|---|---|---|---|---|---|---|---|
| **S1** | SC | SC | SC | SC | SC | MT | ZT |
| **S2** | SC | MT | ZT | ZT | ZT | ZT | ZT |
| **S3** | MT | SC | SC | AT | SC | ZT | ZT |
| **S4** | ST | ST | ST | ST | ST | AT | ZT |

Figure 6. Weekly Travel Patterns by Scenario

**Synthesized from Daily Patterns：**

S1: Active Commuter

S2: Residential-Centric

S3: Fragmented Hybrid

S4: Structured Hybrid

# Price Clustering: K-Means

- **Algorithm**: K-means Clustering (post-PCA retaining 86% variance).
- **Key Features**:
  - Level & Volatility: Mean price, Log Std, IQR.
  - Arbitrage & Temporal: Spreads, peak hours.
  - Tail Risk: P95 and spike frequency.
- **Optimal K (K=4):**
  - Silhouette: not optimal
  - DB index & Inertia : optimal at K=4

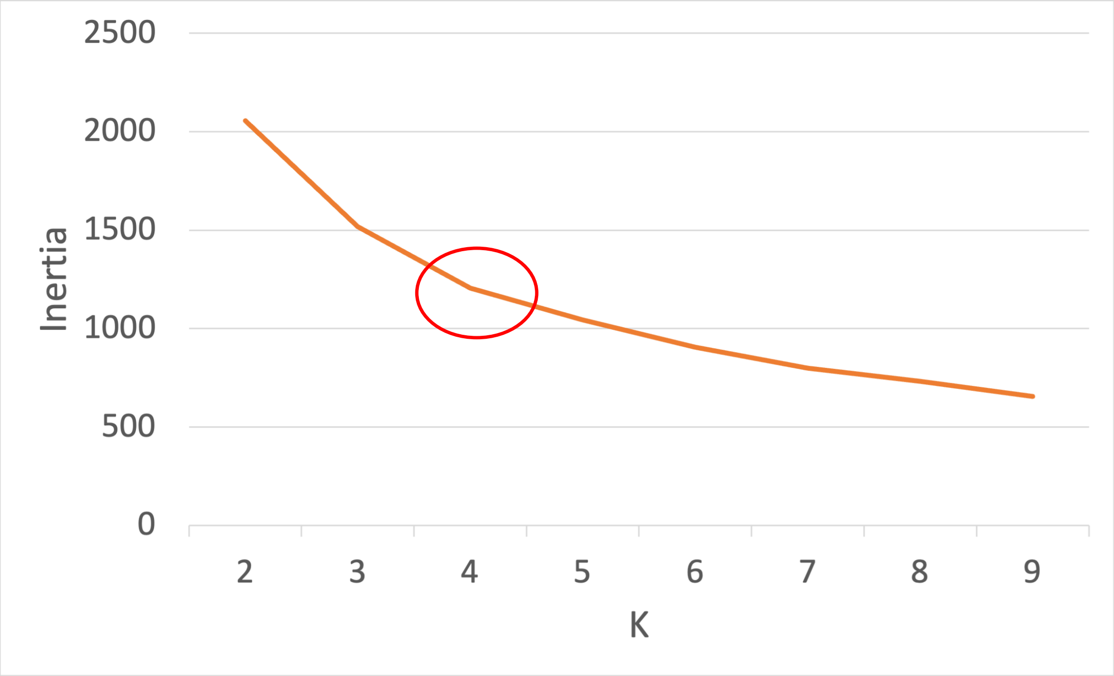



Figure 7. Price Clustering: Inertia (Elbow Method)

# Electricity Price Regimes (2021-2025)

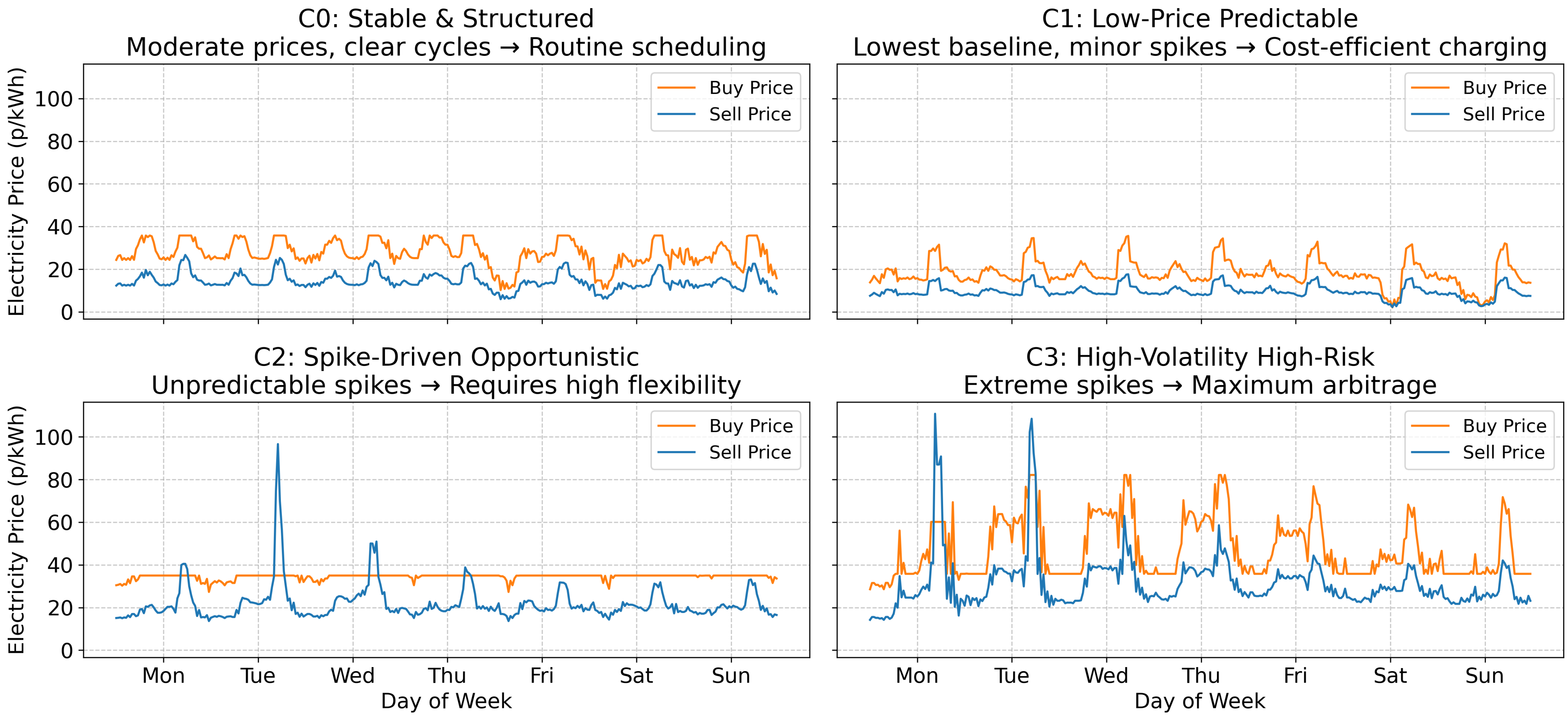



Figure 8. Electricity Price Regimes

# Framework Overview: Part 2

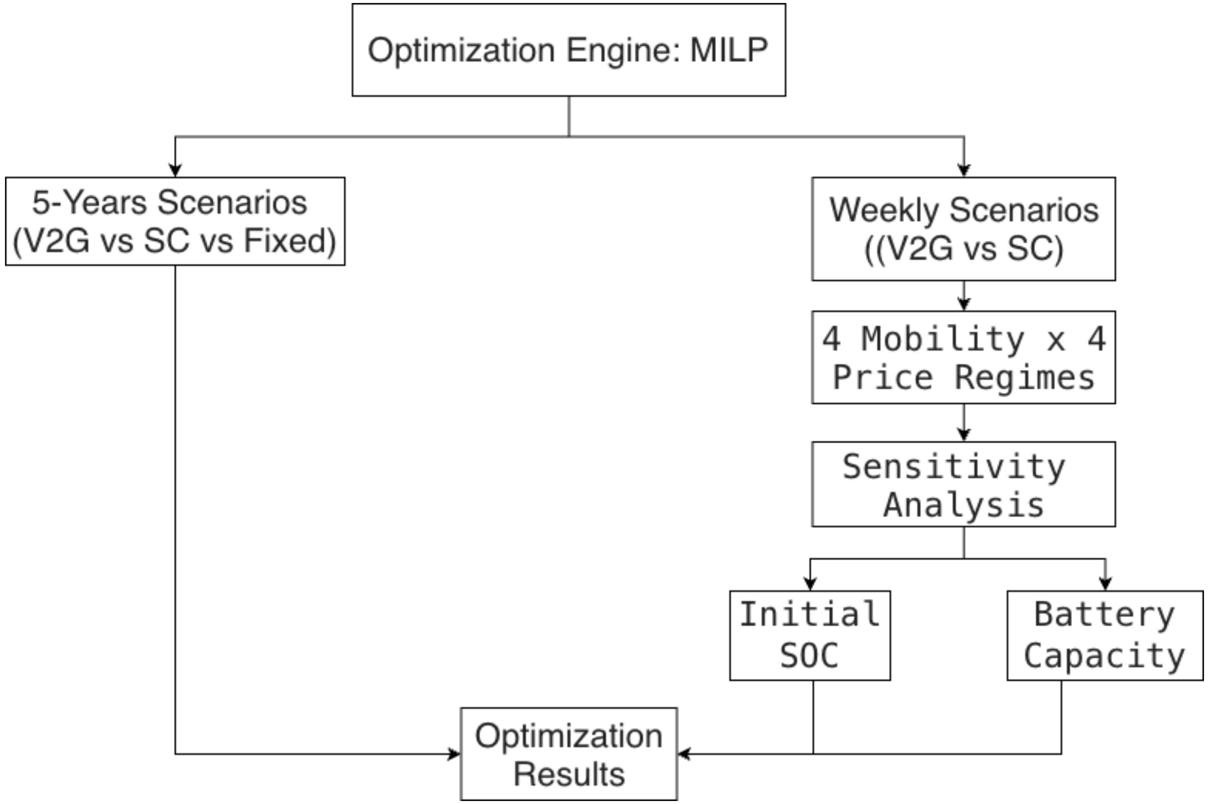
**Scenarios Analysis:**

**V1G (Baseline): Unidirectional (Charge Only)**

- Fixed Price: Annual flat tariff (e.g. 25 p/kWh in 2025).
- Smart Charging: Dynamic TOU tariff, shifts charging to off-peak hours.

**V2G: Bidirectional (Charge & Discharge)**

- Smart Arbitrage: Dynamic TOU tariff, buys low (off-peak) & sells high (peak).




TOU: Time-of-Use, half-hourly

Figure 9. Framework Flowchart (Part 2)

# Minimizing EV Operational Cost

V2G Objective Function: $\min \sum_{t=1}^{T} \left[ \left( \lambda_t^{buy} P_t^{ch} - \lambda_t^{sell} P_t^{dis} \right) \Delta t + Cost_t^{cyc} + Cost_t^{cal} \right], \Delta t = 0.5h$

Battery Cycle Degradation Cost: $Cost_t^{cyc} = \frac{w \cdot w_p}{1 - \mu} \cdot \left( P_t^{ch} + P_t^{dis} \right) \cdot \Delta_t$

Battery Aging Degradation Cost: $Cost_t^{cal} = \frac{CC \cdot B \cdot w}{1 - \mu} \cdot \theta_t^{cal}$

Baseline Comparison (V1G, Charge-Only): $\min \sum_{t=1}^{T} \left[ \lambda_t^{buy} P_t^{ch} \Delta_t + Cost_t^{cyc} + Cost_t^{cal} \right]$

# Key Operational Constraints

State-of-Charge (SOC) Transition: $SOC_{t+1} = SOC_t + \frac{\eta^{ch} P_t^{ch} \Delta t}{B} - \frac{P_t^{dis} \Delta t}{\eta^{dis} B} - \Delta SOC_t^{drive}$

Battery Safety Limits: $\mathrm{SOC_{min}} \leq \mathrm{SOC_t} \leq \mathrm{SOC_{max}}$

Hardware Bounds & Logic: $y_t \in \{0,1\}$, Charge/Discharge Switch

$A_t \in [0,1]$, Plug–in Time Fraction

$0 \leq \mathrm{P_t^{ch}} \leq \mathrm{A_t} \cdot \mathrm{P^{ch,max}} \cdot \mathrm{y_t}$

$0 \leq P_t^{dis} \leq A_t \cdot P^{dis,max} \cdot (1 - y_t)$

# Optimization Methodology

- **Methodology**: Mixed-Integer Linear Programming (**MILP**)
- **Framework**: Gurobi Optimizer via Python (gurobipy)
- **Core Algorithms (Branch-and-Cut)**:
  - **Presolve**: Eliminates redundant constraints to reduce model size.
  - **LP Relaxation**: Solves continuous continuous variables for theoretical bounds (e.g., charging/discharging states).
  - **Branch-and-Bound**: Explores solution tree & prunes non-optimal paths.
  - **Cutting Planes**: Tightens problem space to accelerate convergence.
- **Metric**: **MIP Gap @ 0.01%** (Balances runtime & global optimality)

# 04 Results Analysis

# Operational Constraints of Mobility

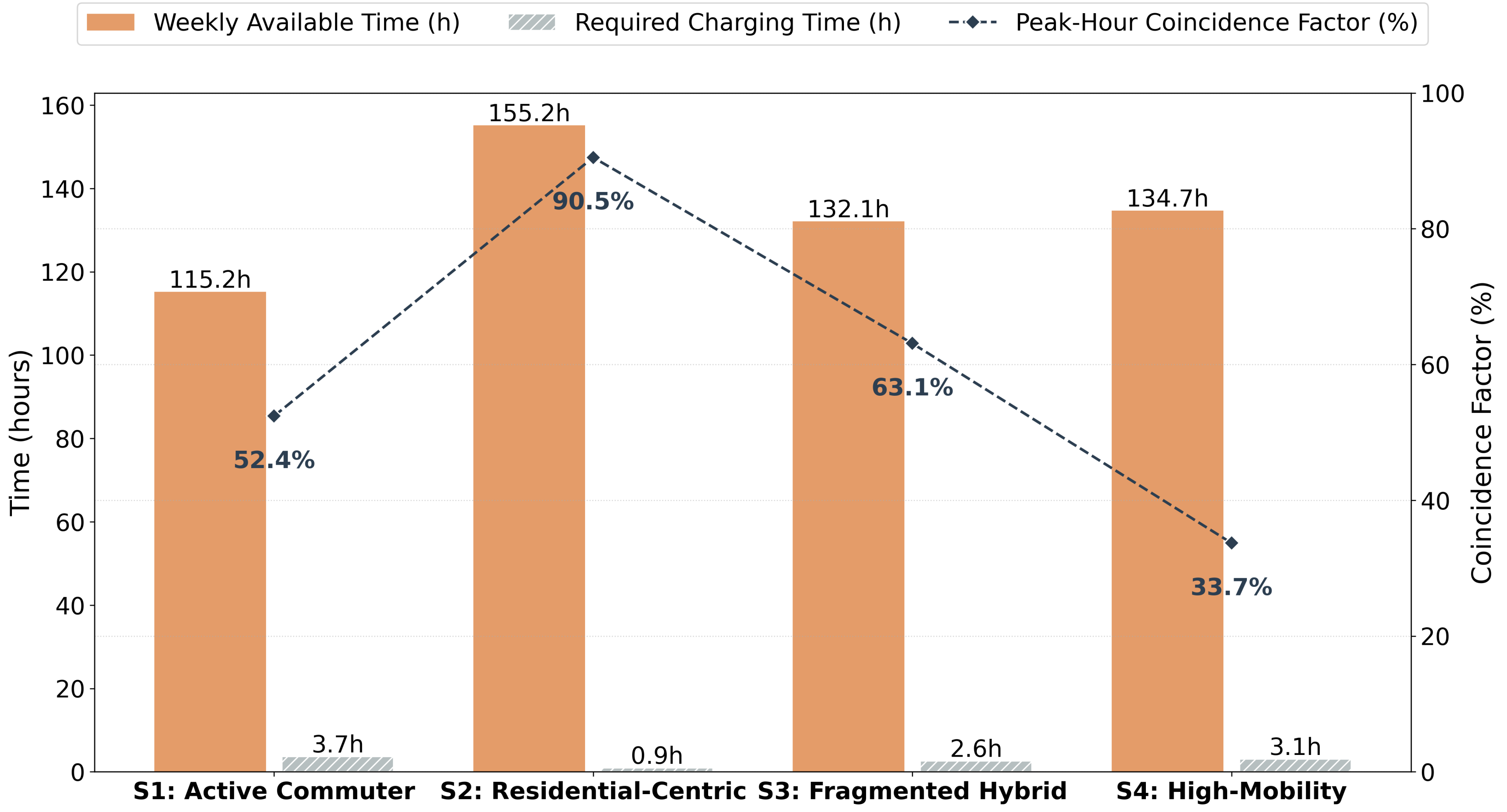



Figure 10. Mobility Metrics & Charging Requirements by Archetype

**Weekly Available Time (h):**

Weekly total available hours for charging & discharging.

**Required Charging Time (h):**

Hours needed to refill the battery after driving.

**Peak-Hour Coincidence**:

Availability percentage during the 4-7 PM high-price selling window.

# Economic Impact: EV Operational Cost (5-Year)

EV Operational Cost: $\min \sum_{t=1}^{T} [(\lambda_t^{buy} P_t^{ch} - \lambda_t^{sell} P_t^{dis})\Delta t + Cost_t^{cyc} + Cost_t^{cal}]$

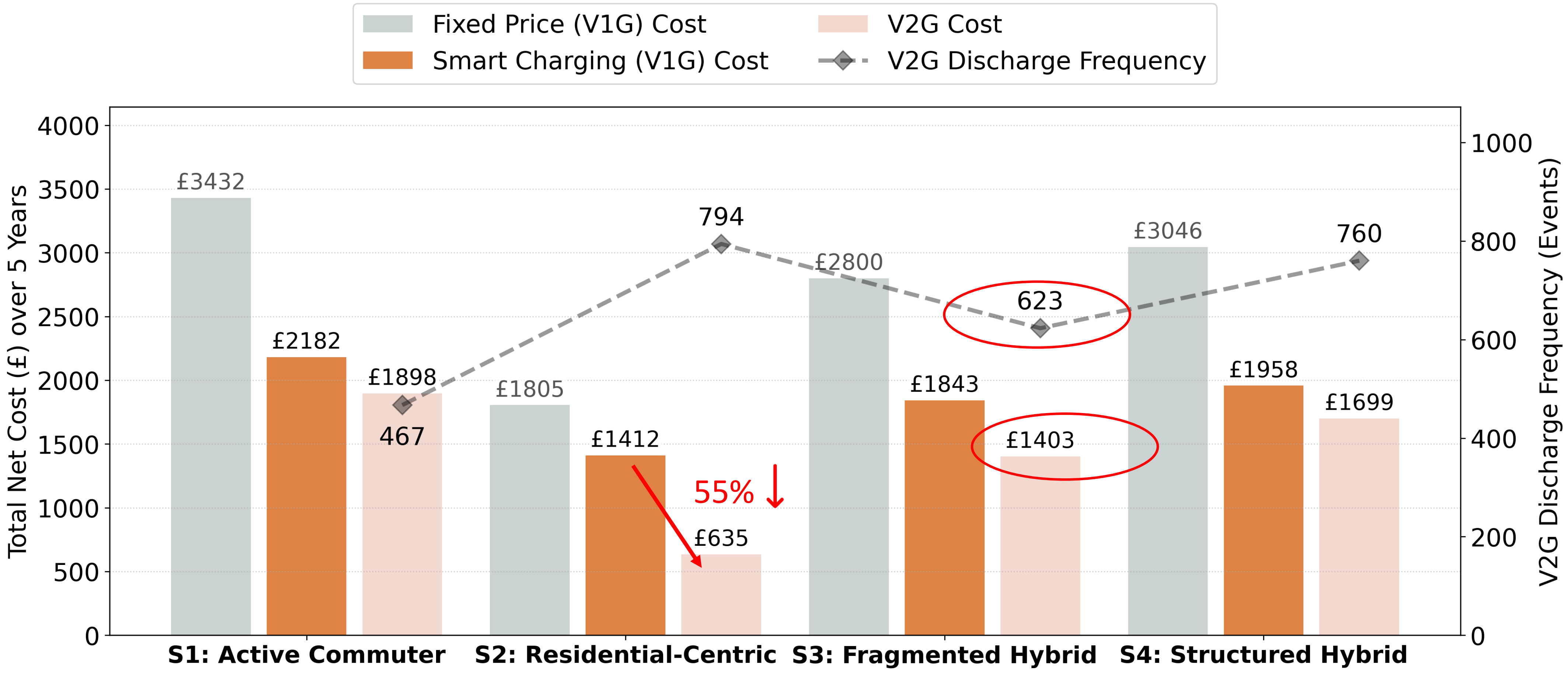



Figure 11. 5-Year Total Net Cost by Pricing & Charging Strategy

# Annual Profitability Analysis(2021-2025)

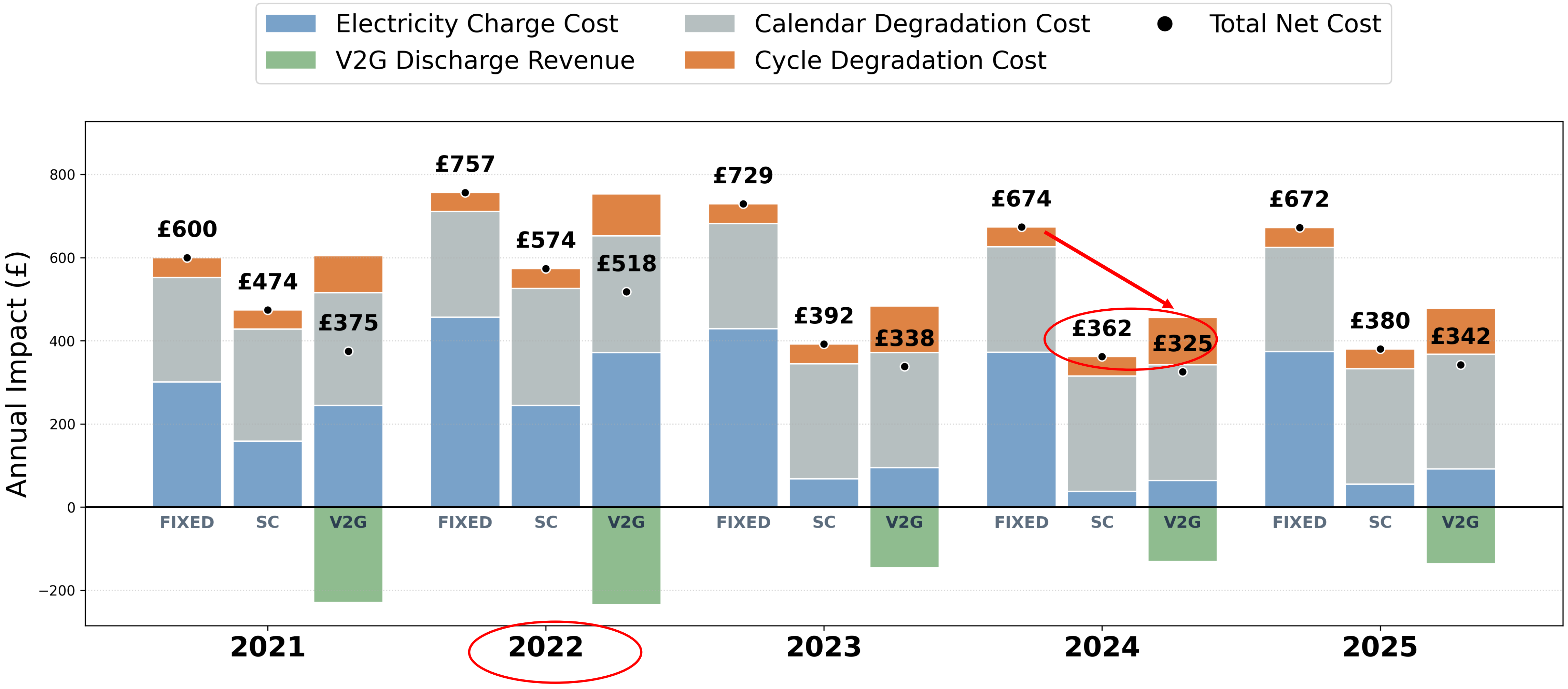



Figure 13. Annual Financial Composition: Archetype S1: Active Commuter

# Annual Profitability Analysis(2021-2025)

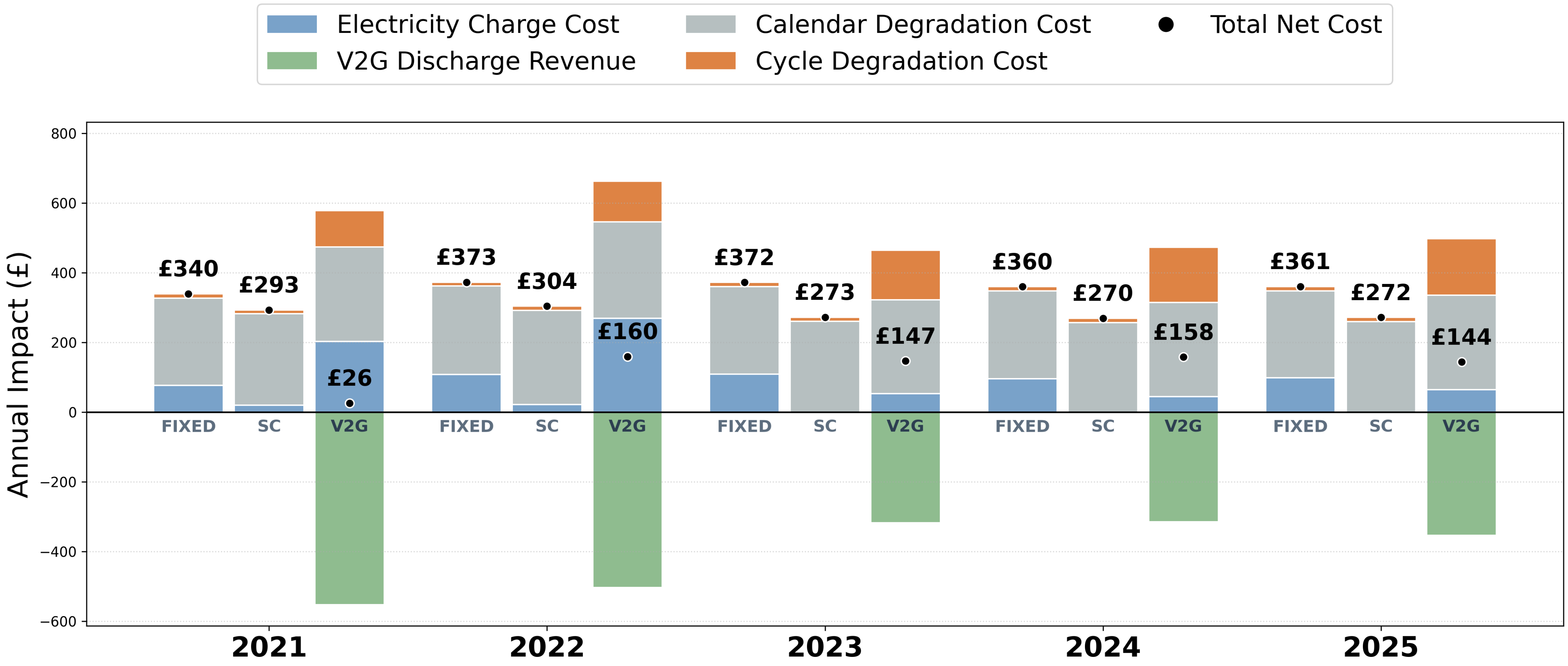



Figure 14. Annual Financial Composition: Archetype S2: Residential-Centric

# Annual Profitability Analysis(2021-2025)

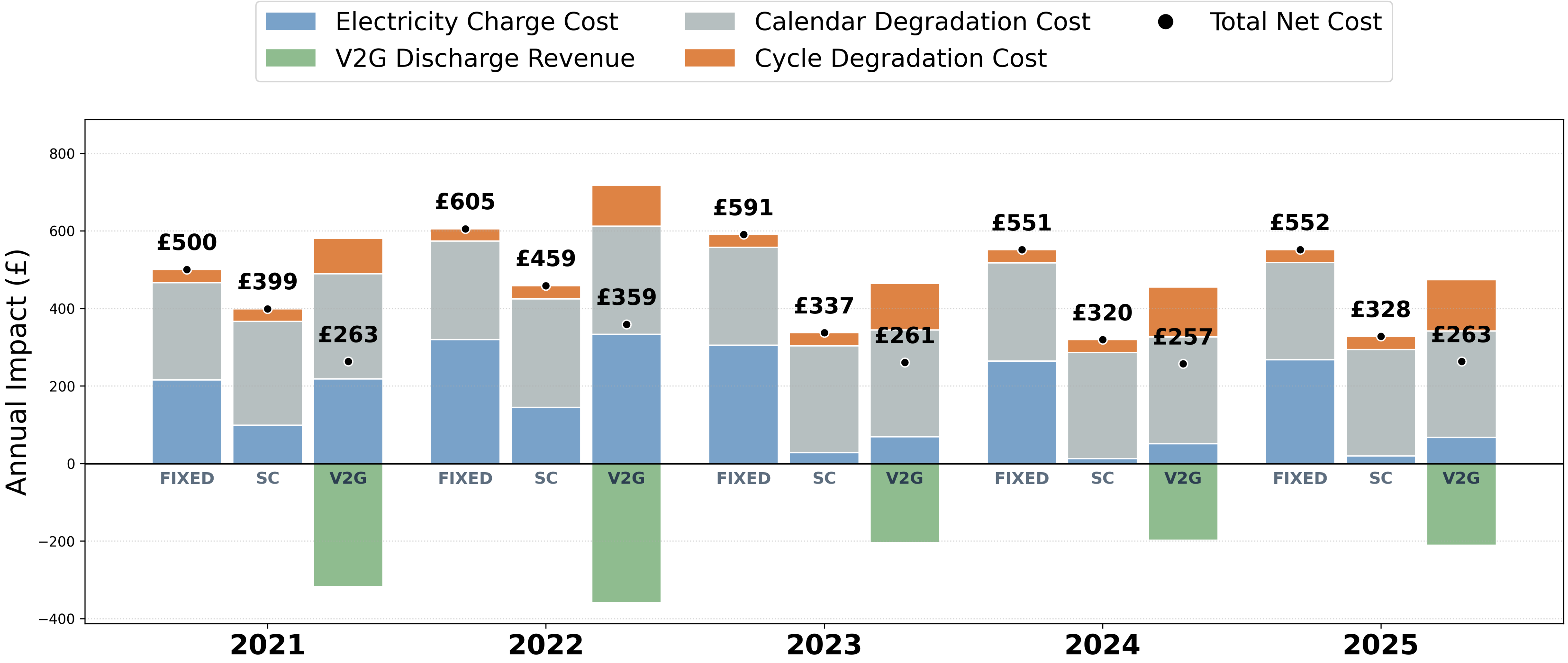



Figure 15. Annual Financial Composition: Archetype S3: Fragmented Hybrid

# Annual Profitability Analysis(2021-2025)

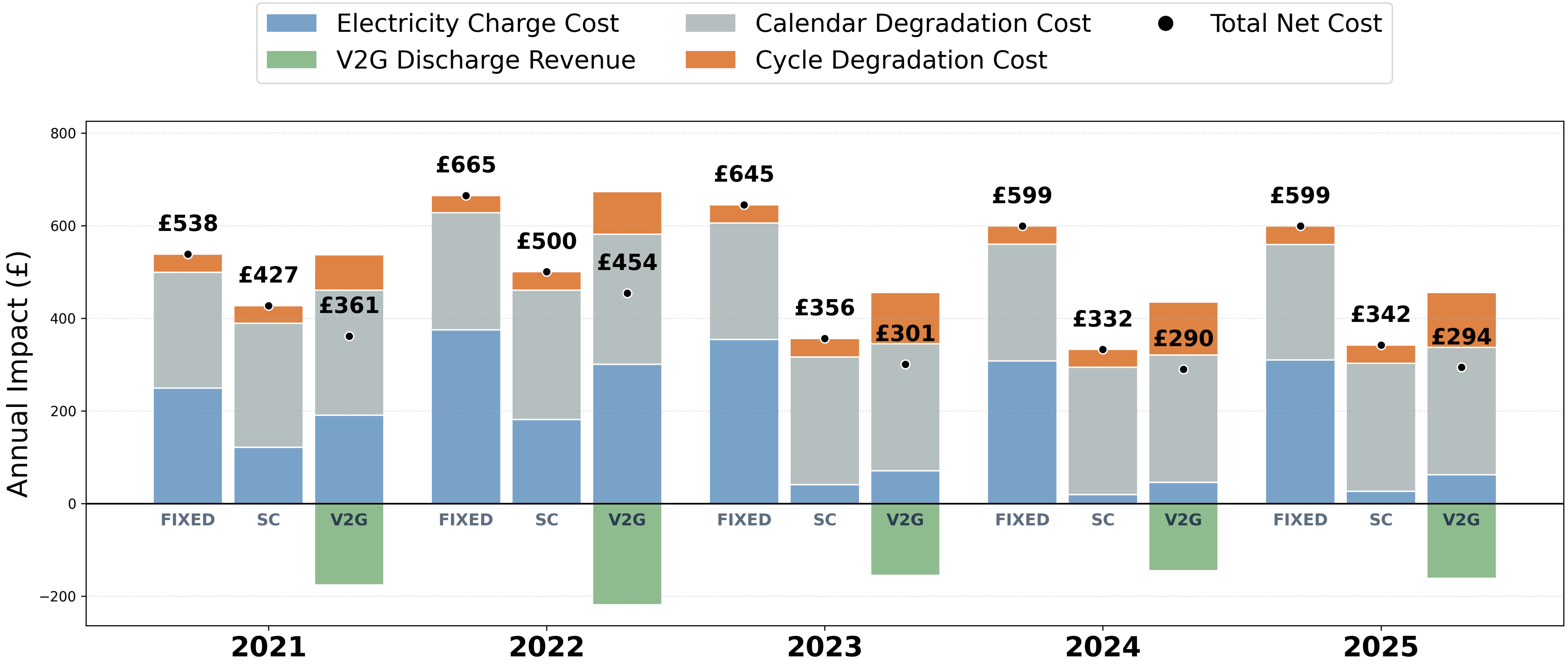



Figure 16. Annual Financial Composition: Archetype S4: Structured Hybrid

# Marginal Economic Value (V2G vs. Smart Charging)

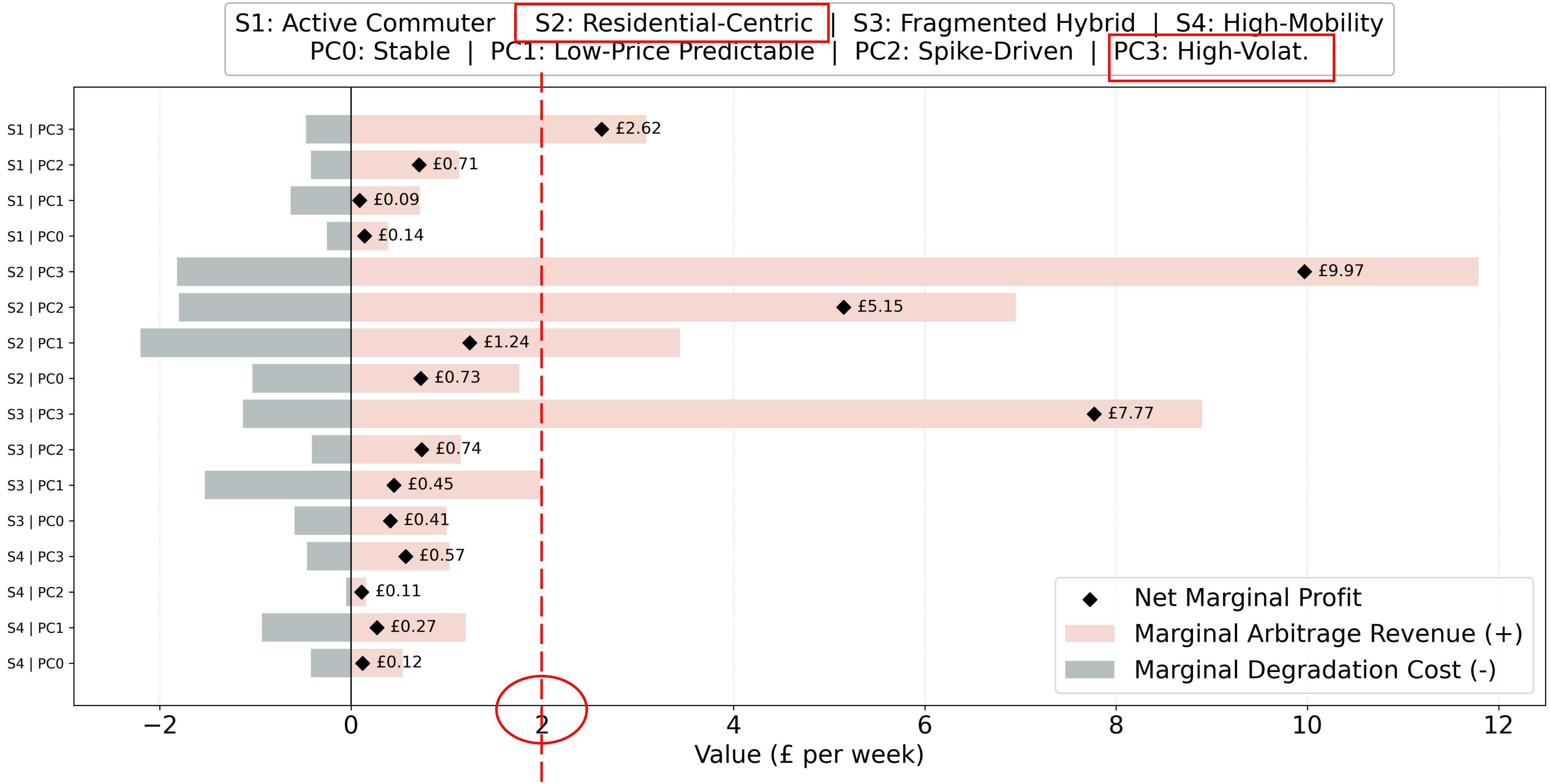



Figure 17. Marginal V2G Revenue vs. Marginal Battery Degradation Cost across 16 Scenarios

# 05 Sensitivity Analysis

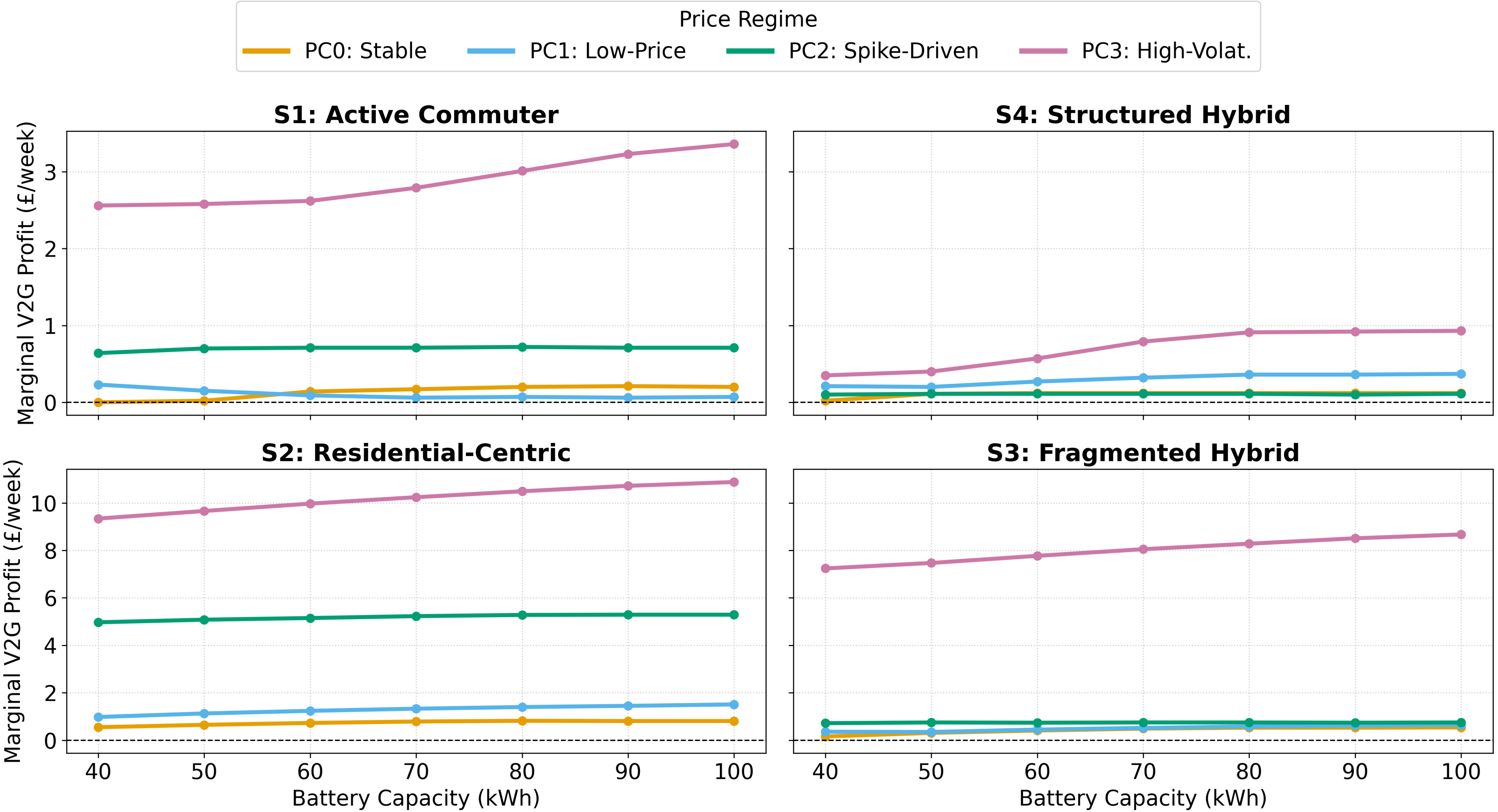



Figure 18. Sensitivity Analysis: Battery Capacity （kWh）（S1 ～ S4）

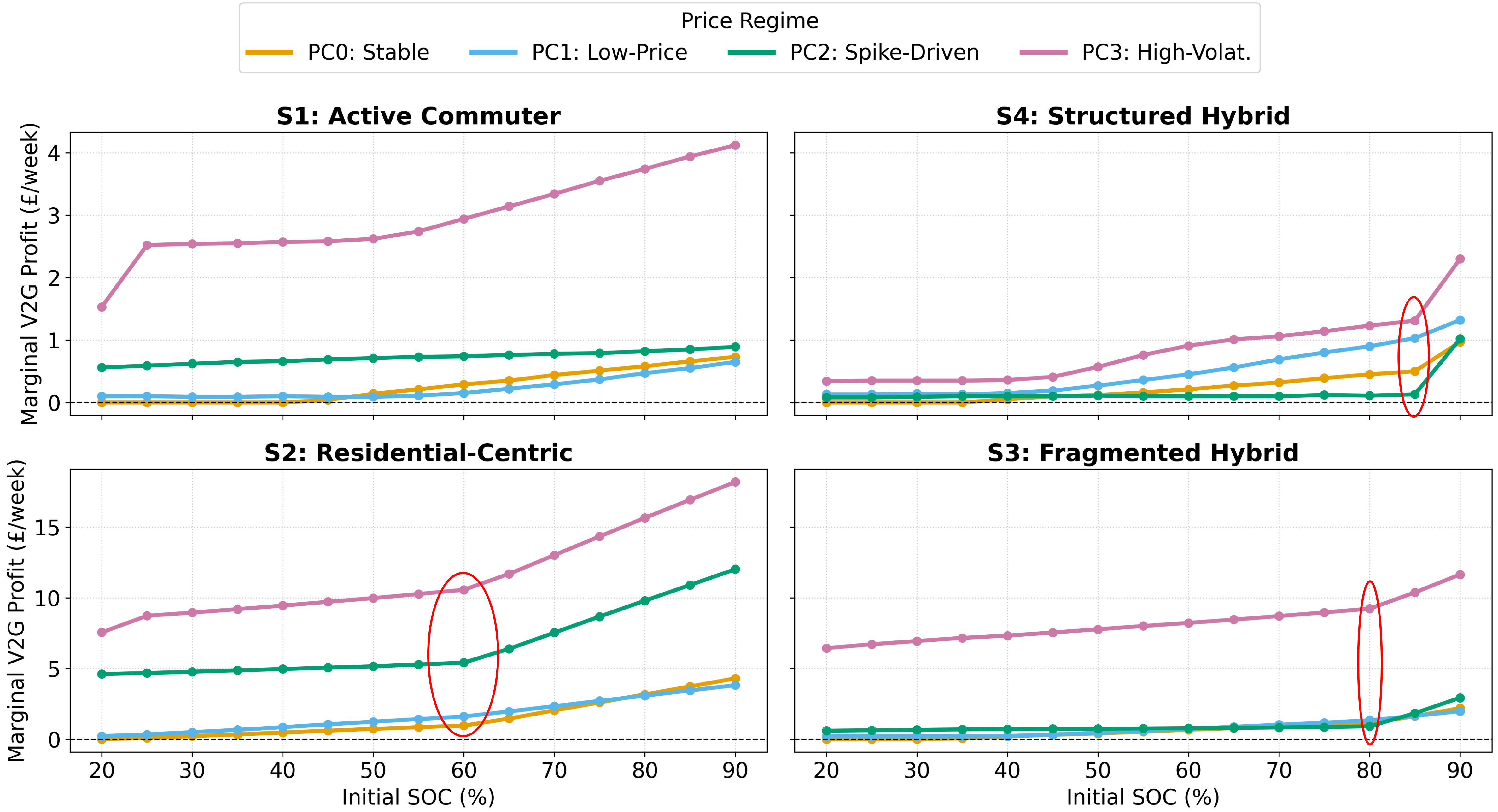



Figure 19. Sensitivity Analysis: Initial SOC（%）（S1 ~ S4）

# Strategic Recommendations

| Stakeholder | Actionable Recommendations |
|---|---|
| EV Owners | **Maximize Starting Energy:**<br>Maintain a high Initial SOC within safety limits to unlock surplus arbitrage.<br>**Target Peak Windows:**<br>Ensure the vehicle is plugged in during critical high-price hours (16:00 - 19:00). |
| Policy Makers | **Financial Incentives:**<br>Offer enhanced tariff rates or direct subsidies to boost residential participation.<br>**Degradation Relief:**<br>Provide battery replacement discounts or extended warranties to alleviate wear anxiety. |

# 06 Limitation & Future Work

# Limitations & Future Work

| Limitations (Current Scope) | Future Work (Next Steps) |
|---|---|
| **Deterministic Modeling**<br>Relies on fixed historical prices and predetermined trips | **Stochastic Modeling**<br>Incorporate dynamic trips and real-time price uncertainty |
| **Simplified Battery Degradation**<br>Uses a simplified linear proxy formula | **High-Fidelity Degradation**<br>Model realistic, non-linear and chemistry-specific degradation |
| **Single Revenue Stream**<br>Focuses purely on electricity trading | **Service Stacking**<br>Include more profitable grid support services (e.g., Frequency Regulation) |

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# Any Questions?