ePower Move

Project deliverable D1.3

D1.3 End user requirements

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EXECUTIVE SUMMARY

Deliverable D1.3 of the ePowerMove project provides a comprehensive analysis of end-user perceptions, expectations, and functional requirements for public slow-charging infrastructure of electric vehicles (EVs). As part of Task 1.4, this work aims to translate diverse and nuanced user needs into actionable design inputs, forming the foundation for the functional architecture and system design of future charging solutions. This deliverable integrates insights from multiple complementary sources: structured workshops conducted in pilot cities (Helsinki, Klagenfurt, and Nicosia), large-scale user-generated data analysis from online platforms such as Reddit, and secondary data from government survey reports. Together, these sources enable a robust and representative understanding of charging behaviours and user requirements across different social, technical, and regional contexts. The analysis is structured around four major thematic areas:

Vehicle-to-Grid (V2G) Charging

Using advanced natural language processing tools for topic modelling and sentiment analysis, this section captures public perceptions around bi-directional charging technologies. It reveals a mix of enthusiasm (e.g., for energy resilience and economic opportunity) and concerns (e.g., battery degradation, lack of standards, and mental load). Users express a stronger preference for vehicle-to-home (V2H) over V2G in many cases. Recommendations include user-centric control interfaces, real-time pricing transparency, and incentive structures to increase adoption.

Physical Design of Chargers

This section outlines user expectations related to hardware design, including appearance, interface usability, connector types, screen positioning, and accessibility. It addresses the needs of diverse user groups, such as private EV drivers, commercial fleet operators, people with disabilities, and female users. Based on the synthesis of real-world feedback and benchmarking of existing products, design recommendations are proposed for inclusive, ergonomic, and accessible charging systems.

Overnight Publicly Accessible Charging

Charging behaviour patterns are analysed through international case studies, highlighting key trends such as the dominance of overnight charging and challenges related to parking availability, safety, and charging cost. The findings point to a strong connection between parking and charging needs and suggest that charging infrastructure must be better integrated into users' routines and urban planning strategies.

Energy-Consuming Convenience Functions (also known as Energy Intensive Vehicle Functions)

The energy impact of heating, ventilation, and air conditioning (HVAC) systems and battery thermal management on EV range is assessed. User behaviours-such as temperature settings, seasonal comfort expectations, and use of pre-conditioning-are analysed to inform smarter system-level energy optimisation strategies. Recommendations are made for both technical improvements (e.g., heat pumps, eco-modes) and user behaviour nudges.

Across all sections, this deliverable pays particular attention to cross-cutting issues such as gender-specific needs, the increasing role of light commercial (N1) vehicles, and the importance of designing for inclusivity and operational practicality. The results of D1.3 provide direct input to WP2 (Low-cost charging solutions and apps) by shaping functional system requirements and user interface design considerations. Furthermore, the deliverable contributes to the wider ePowerMove project by ensuring that user needs are deeply embedded in the technical architecture and policy recommendations, thereby supporting the development of charging systems that are not only technologically advanced but also socially acceptable, economically viable, and environmentally sustainable.

LIST OF ABBREVIATIONS AND ACRONYMS

Acronym	Meaning
ACEA	European Automobile Manufacturers' Association
BER	Bidirectional Encoder Representations
BMS	Battery Management System
BTMS	Battery Thermal Management System
CCS	Combined Charging System
EAC	Electricity Authority of Cyprus
EU	European Union
EV	Electric Vehicle
HBS	Hours Between Sessions
HVAC	Heating, Ventilation, and Air Conditioning
IEA	International Energy Agency
LLM	Large Language Model
MMR	Maximal Marginal Relevance
NFC	Near Field Communication
OEM	Original Equipment Manufacturer
POI	Point-of-interest
QR	Quick Response
RES	Renewable Energy Sources
SA	Sentiment Analysis
SoC	(Battery's) State of Charge
SoH	(Battery's) State of Health
TM	Topic Modelling
UGC	User-Generated Content

Acronym	Meaning
UK	United Kingdom
UMAP	Uniform Manifold Approximation and Projection
US	United States
V2G	Vehicle-to-Grid
V2H	Vehicle-to-Home
V2L	Vehicle-to-Load

1 INTRODUCTION

1.1 Project introduction

As electric vehicle (EV) adoption accelerates across Europe, the availability of affordable, accessible, and efficient charging infrastructure becomes a critical enabler. The ePowerMove project addresses this need by designing flexible, scalable, non-intrusive, efficient, bi-directional slow-charging solutions that are future-proof, user-centric, and grid-friendly. By combining bi-directional charging technology with intelligent energy management, the project aims to reduce infrastructure costs, minimise physical intrusion, and support the wider integration of renewable energy into the power system.

The project is being demonstrated across three real-world demonstration sites, each focusing on a different strategic priority: In Helsinki, Finland, the emphasis is on reducing installation costs and improving the urban user experience. In Klagenfurt, Austria, new business models are explored to scale sustainable mobility solutions across cities. In Nicosia, Cyprus, the focus is on optimising grid integration and ensuring reliable energy flow in evolving electricity systems.

Beyond technical innovation, ePowerMove places strong emphasis on social inclusion, gender-sensitive design, and user acceptability. It leverages advanced digital platforms and participatory design methods to ensure that the charging infrastructure addresses the diverse needs of private drivers, fleet operators, energy managers, and public authorities alike.

Coordinated by ERTICO – ITS Europe and supported by 18 partners across 7 countries, ePowerMove is funded by the Horizon Europe programme, within the 2ZERO Partnership. The project will contribute directly to the EU's broader goals of urban decarbonisation, energy transition, and sustainable mobility by laying the groundwork for widespread deployment of cost-effective, intelligent, and inclusive slow-charging solutions.

For more information, visit the official project website: https://epowermove.eu.

1.2 Overview of this deliverable

Traditional charging station designs exhibit significant shortcomings in terms of user-centred interaction. These include rigid, outdated forms that lack technological sophistication and modern aesthetics, limited functionality, and inadequate human–machine interaction. To facilitate large-scale EV adoption, the development of public slow-charging infrastructure that aligns with user preferences and requirements is essential.

Deliverable 1.3 systematically summarises and categorises user perceptions and requirements associated with existing charging practices. In D1.3, the project team elaborates further on the user requirements to identify common elements between the three demonstrations, also proposing solutions to fulfil each of the formulated requirements. These requirements span several domains, including physical design aspects, overnight charging design aspects, V2G design aspects, and energy-intensive convenience features design aspects. This deliverable reflects the outcomes of Task 1.4 (Translating end user requirements into system design).

1.3 Intended audience

The findings from D1.3 are expected to be utilised by the consortium as a whole, particularly by WP2, the design of user-centric public slow-charging, Apps, and European policymakers in their future policy considerations.

1.4 Structure of the deliverable

This deliverable has the following structure:

1. Introduction
2. Methodology
3. User requirements for V2G charging
4. User requirements for the physical design of chargers
5. User requirements for overnight publicly-accessible charging
6. User requirements for energy-consuming convenience functions
7. Identified User Requirements in ePowerMove – connecting the three demos
8. Conclusions.

2 METHODOLOGY

The methodology that was used includes various means and tools to address the numerous needs of all user categories through literature analysis and in the three demonstration sites. The various user groups at the demo sites in D1.1 provided a rich set of user requirements. The user requirements have been put together from all demo sites, and grouped into four sets of technical, infrastructure, functional, and application-related requirements (Figure 1).

This set was then enhanced with the vast literature analysis within Task 1.4. The literature analysis provided four sets of V2G charging, physical design of chargers, overnight publicly available chargers, and energy-consuming convenience functions (Figure 1). The aggregated set of global ePowerMove requirements and recommendations is the final output from WP1 in favour of WP2.

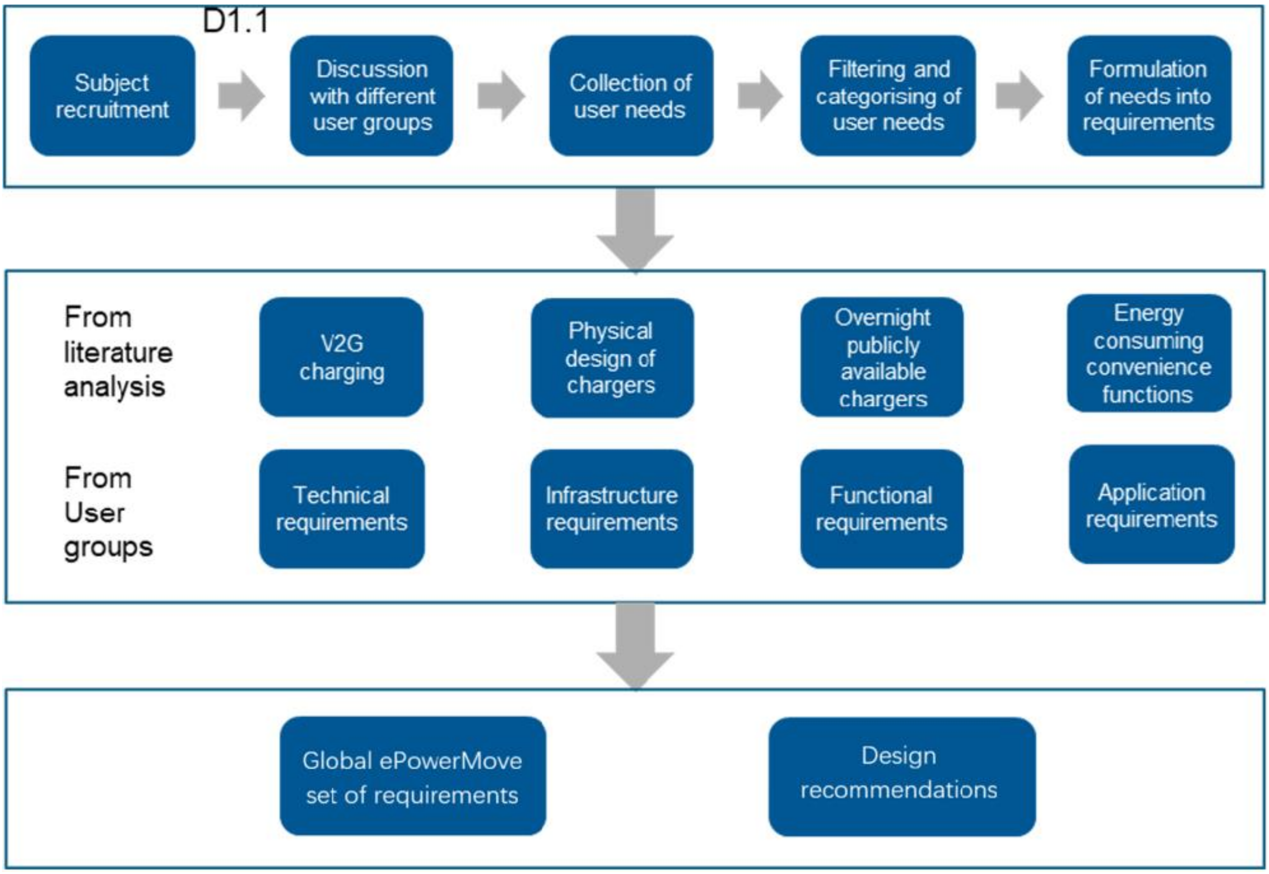


Figure 1. Methodology to acquire the user requirements in the scope of the project.

It is worth noting that Task 1.4 also considered relevant up-to-date results from Tasks 1.2 and 1.3, such as user segments and needs for V2G developments. However, the final results of these tasks will be fully documented in deliveable D1.2 for submission in M36.

2.1 Summary of findings from co-design workshops

2.1.1 Helsinki workshops findings

During the summer of 2025, two user workshops were arranged in the Helsinki demonstration site, one with a group of residents in the demo area of Ruoholahti and the other with VTT personnel at VTT premises; in total, some 17 individuals were addressed.

In general, the users were interested in, e.g., available V2G parking slot locations (near home/work/POIs), winter maintenance of charging slots, availability of V2G capable EVs, and design and facilities of charging areas. With regards to charging application and financial issues, the users were concerned with availability of various payment methods for charging, benefits when allowing bilateral V2G charging, keeping up with interoperability of charging applications and their tariffs and benefits, procedures to update the application, functionalities of the application, and application's capability to pinpoint own location and location of the nearest V2G capable charging slot.

Another major area of concern was the accessibility to charging facilities and services. This is specifically relevant for wheelchair users and people with various disabilities, e.g., the presence of kerb stones, sufficient area around the EV and the charger, handling of fixed charging cables, and availability of preferred payment options.

Regarding N1 class EVs, there were a couple of notions among Ruoholahti residents. The charging slots and area available around the vehicle with a trailer in the parking area were identified as one of the points to improve. Regarding professional EVs like taxis and social and home service EVs suffer from scarce availability of charging slots; however, this is more related to fast charging during their service hours and areas rather than to slow bidirectional V2G charging.

To summarise, there were a few common themes that came up in several responses, namely the reliability of charging and the application is non-negotiable, for everyday use the application, charging procedures, payment and information shall be simple for every user group, useability and maintenance in all weather conditions, and inclusivity and participation of all users are most important design aspects for successful operations.

2.1.2 Klagenfurt workshops findings

As part of the Klagenfurt pilot, two three-hour co-design workshops were conducted – one on-site in Klagenfurt and one online – complemented by five personal interviews and three written interviews. Out of a total of 48 registered participants, 20 attended the workshops, with ten participating on-site and ten online.

Participants highlighted several key aspects of EV charging infrastructure. Technological concerns focused on the reliability and stability of charging points, proper functioning of locking mechanisms, optimised load management, and fully operational touchscreens under various weather conditions. Availability of alternative payment options in case card payments fail was also emphasised.

Functional aspects were equally important. Users stressed the need for intuitive and understandable instructions, clearly readable displays free from obstructions, easily recognisable pictograms, and multilingual user interfaces. All functions should ideally be controllable via a single device, such as a smartphone, with additional support through audible signals, high-contrast signage, and direct feedback channels in case of malfunctions.

Infrastructure design was another major area of concern. Participants requested spacious, barrier-free, and well-lit charging spots, clear signage, weather-protected waiting areas with seating, and aids for handling heavy charging cables. Regular maintenance, winter services, and flexible charging settings, such as adjustable State-of-Charge limits, were considered essential. Transparent pricing and clear indicators of charging station locations were also highlighted.

For specific user groups, such as EV users with trailers or professional EV operators, accessibility and space around the vehicle were noted as points for improvement, while professional EVs also require sufficient charging slots to accommodate operational schedules.

In summary, common themes across workshops and interviews were clear: reliability of the charging infrastructure and associated applications is non-negotiable; usability, simplicity of procedures, payment options, and information for everyday use are critical; infrastructure must function in all weather conditions; and inclusivity and accessibility for all users are essential for successful operations

2.1.3 Nicosia workshop findings

During summer 2025, two user sessions were organised in Nicosia, at the KIOS Research and Innovation Centre (University of Cyprus) on 23 May and 30 May, supplemented by a small number of short one-to-one interviews. In total, 27 individuals took part.

In general, the users requested the practical availability of EV charging units near home, work, university, and key destinations, live status information, clear on-site guidance, and charger/area design suitable for Cyprus conditions (shade or covers, tolerance to heat and dust). Regarding mobile/web applications and pricing, people emphasised multiple payment options (contactless/card/app), transparent tariffs, simple roaming/interoperability, reliable geolocation and filters, and straightforward update procedures. For professional and light-commercial users (e.g., taxis, delivery, social/home-care), the main bottleneck remains convenient daytime fast charging in busy zones; slow charging is better suited to home or depot where parking is predictable and incentives are clear. Regarding V2G and price-responsive charging, awareness was limited, and several participants heard about it for the first time. Those open to it asked for very simple settings, a minimum guaranteed state-of-charge, clear and stable compensation, and reassurance about battery health and cybersecurity.

To summarise, common themes were: reliability of chargers and apps is non-negotiable; everyday procedures, payments, and information must be simple and bilingual (Greek/English); designs must handle local weather; accessibility for all users is essential; and transparent economics and trusted communication matter more than environmental impact alone. Further details are available in D 1.1[1].

2.2 Online sources

This study employed a two-phase approach combining data collection from Reddit and advanced text analysis to understand public perceptions.

2.2.1 Reddit

Reddit was chosen as the primary data source due to its rich ecosystem of user-generated content (UGC) and authentic community discussions around emerging technologies. We targeted 33 relevant subreddits spanning EVs, renewable energy, and technology communities (ranging from general interest forums like r/technology to specialised communities such as r/evcharging and r/energy). Data collection used 24

[1] D1.1 Baseline user demands and results from codesigning.docx

carefully selected keywords and phrases, including "bidirectional charging, "vehicle-to-grid", "V2G", "vehicle-to-home", "V2H," and related variations. No time restrictions were applied to capture the full spectrum of historical discussions through March 2025. The collection process yielded 780 unique posts and 17,430 associated comments across the targeted communities. A comprehensive preprocessing pipeline removed low-quality content, including: (1) Null, empty, or deleted comments, (2) Comments shorter than five words to ensure substantive content, (3) Generic responses (e.g., simple gratitude comments), (4) Bot-generated content and automated responses, and (5) Duplicate entries. After rigorous cleaning and quality control measures, the analysis was conducted on 11,454 high-quality comments specifically relevant to bi-directional charging discussions.

2.2.2 Analysis Framework

We employed Bidirectional Encoder Representations from Transformers (BER Topic), which is an advanced topic modelling (TM) technique that employs transformer-based embeddings and clustering algorithms to uncover the underlying themes [1,2]. Transformer-based embeddings convert textual data into high-dimensional vector spaces, positioning semantically similar texts closer together and effectively capturing deep contextual and semantic nuances. Clustering algorithms subsequently group these embeddings based on their proximity in the vector space, enabling the identification of distinct themes or topics within the dataset [3].

Key Technical Parameters:

- **Embeddings:** OpenAI's text-embedding-3-large model for semantic representation
- **Dimensionality Reduction:** Uniform Manifold Approximation and Projection (UMAP) with n_components=10, n_neighbors=13, min_dist=0.0, metric='cosine'
- **Clustering:** K-means algorithm configured for 50 distinct topics
- **Text Processing**: English stopwords filtering with min_df=10, max_df=0.8, ngram_range=(1,2)
- **Keyword Selection:** Maximal Marginal Relevance (MMR) with diversity parameter=0.5 to balance relevance and diversity
- **Topic Labelling:** OpenAI's GPT-4o-mini model for generating concise, descriptive topic labels

We compared four cost-efficient (Gemini Flash, DeepSeek, GPT-4o Mini, Claude-3-Haiku) and four premium Large Language Models (LLMs) (Gemini-1.5-Pro, GPT-4o, Claude-3-Opus, Grok) against a manually annotated sample of comments (n=600) to determine which LLM achieves the highest classification accuracy for SA of bidirectionally related comments. Authors followed a zero-shot prompting strategy [4], meaning no examples were included in the prompt. By following OpenAI prompting engineering guidelines [5], this study carefully crafted task-specific instructions that leveraged role-playing, instructing the model to act as an SA expert and provide domain context about bidirectional technology to elicit accurate sentiment labels directly from the pre-trained knowledge of LLMs.

2.3 Literature review

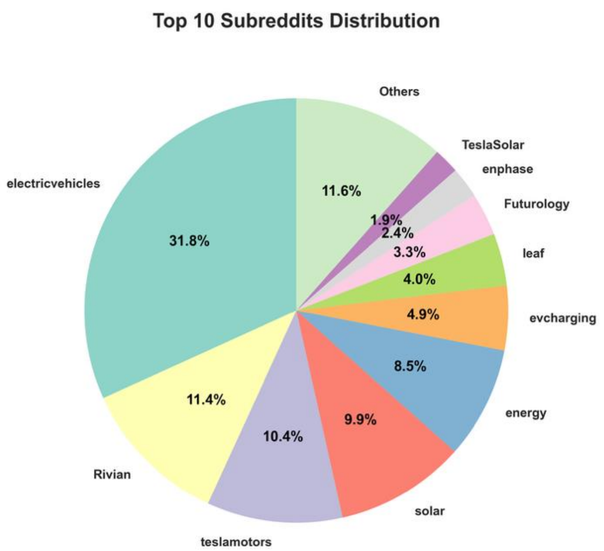
To further supplement the understanding of user requirements and expectations regarding public slow-charging infrastructure for EVs, a qualitative content analysis was conducted based on public reports, literature and surveys. We conducted a systematic literature review across Scopus, Web of Science, and IEEE Xplore, and supplemented this with grey literature (government/industry reports and standards) to capture practice-oriented evidence. Search strings combined terms and synonyms for “public/AC slow charging”, “user needs/preferences”, “V2G/V2X”, “overnight/home-nearby charging”, “accessibility/physical requirements” and “energy-consuming convenience functions”.

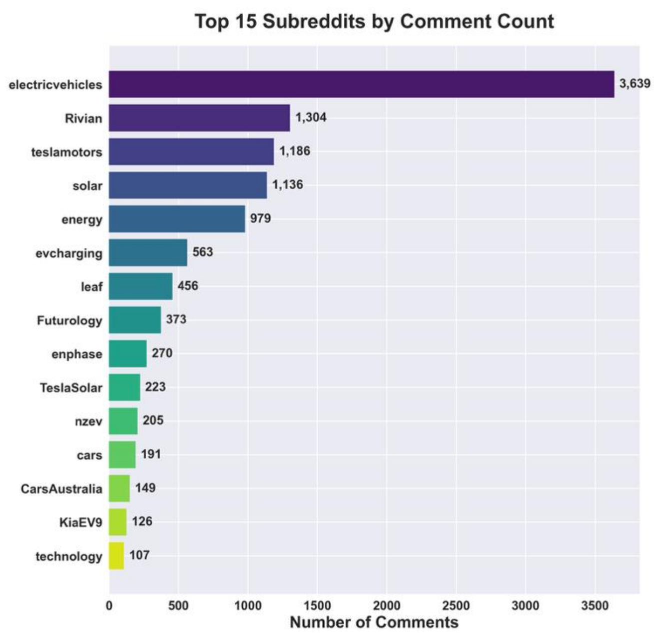
3 USER REQUIREMENTS FOR V2G CHARGING

This analysis examines public perceptions of bi-directional charging, with a primary focus on V2G technology, given its critical relevance to ePowerMove, while also considering V2H and vehicle-to-load (V2L) applications. While V2G remains our primary focus, V2H and V2L discussions were retained because Reddit users frequently discuss these technologies with V2G, and excluding such comments would have resulted in the loss of valuable contextual insights. This study offers a comprehensive overview of key discussion topics and associated sentiments related to bi-directional technology. Using topic modelling and sentiment analysis on Reddit comments, we aim to uncover public concerns and preferences to guide ePowerMove stakeholders. The section is structured as follows: (1) a brief methodology, (2) findings on identified topics and their sentiments, and (3) a summary of key insights with potential implications for ePowerMove. To facilitate further exploration of the findings, an interactive dashboard has been developed using Streamlit's method [6], enabling stakeholders to visualise sentiment distributions, explore topic-specific comments, and analyse keyword trends (https://v2g-dashboard-enn54j33ngdjtmwwvwgflx.streamlit.app/).

3.1 Exploratory Data Analysis

The analysis examined 11,454 high-quality comments spanning from June 2009 to March 2025, with notable growth in discussion activity from 904 comments in 2020 to a peak of 3,611 in 2023 (refer to Figure. 2). Most discussions (72%) occurred within five key subreddits, with r/electric vehicles being the most active community (31.8% of all comments). Comments averaged 63 words, indicating substantive, detailed discussions rather than brief exchanges.





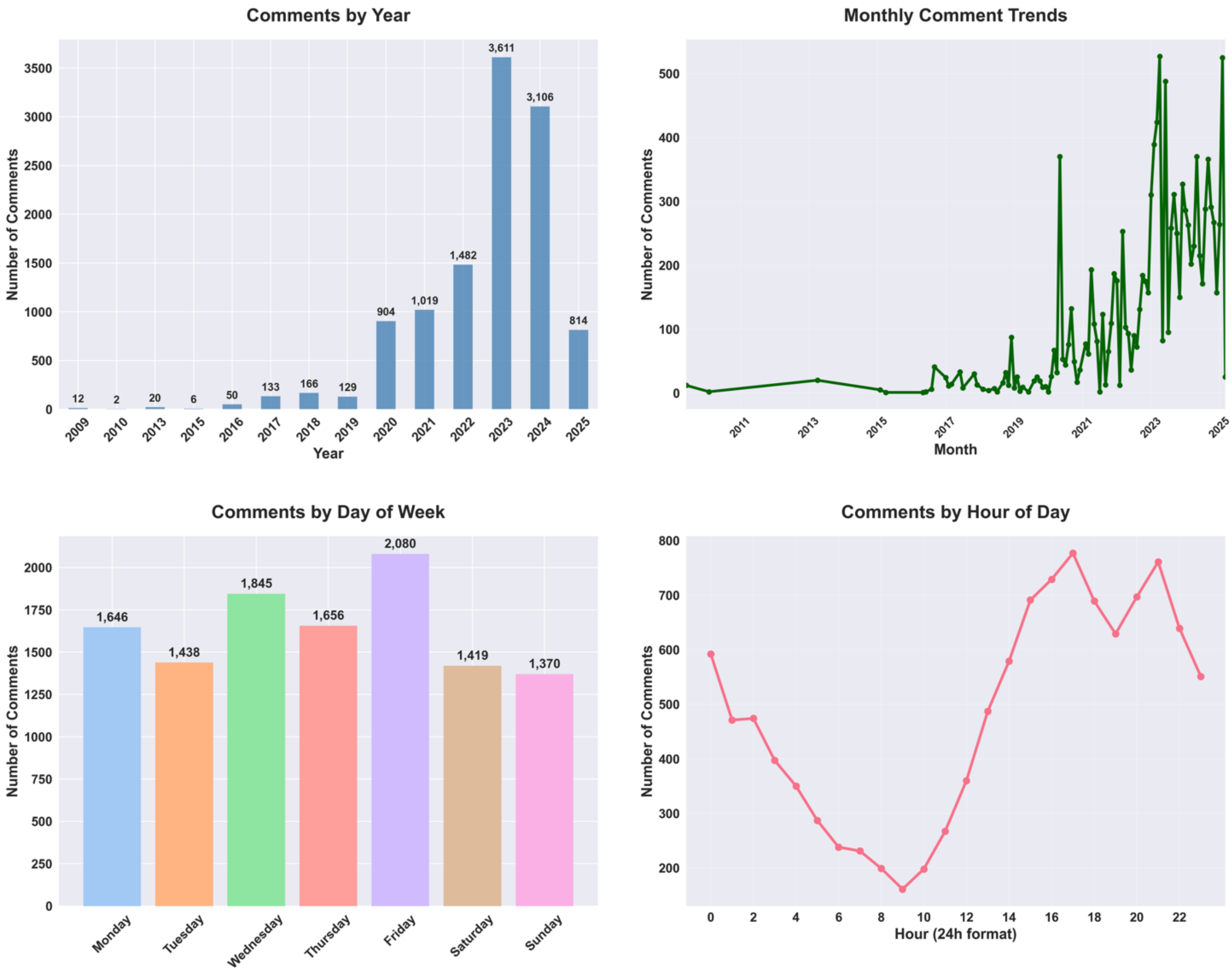


Figure 2. Exploratory data analysis of Reddit comments dataset.

3.2 Topic Modelling

Our advanced topic modelling identified nine distinct thematic areas of public discourse around bi-directional charging, with high topic coherence (0.81) and moderate diversity (0.53), indicating well-defined yet appropriately distinct discussion themes.

Primary Discussion Areas (by prevalence):

- Energy Resilience (19.96%) - The leading topic focuses on EVs as backup power sources during outages, with strong emphasis on home and grid applications. Users frequently discuss comparisons with traditional alternatives like Tesla Powerwalls and gas generators, while showing significant interest in solar panel integration.
- Remuneration (18.23%) - Financial incentives dominate discussions, particularly around grid-level compensation structures and the economics of participation. Users actively evaluate arbitrage opportunities (buying low, selling high), net metering policies, and minimum acceptable compensation rates for participating in V2G programs. Alternative non-monetary incentives like free chargers and parking are also explored, with fleet-scale revenue potential emerging as a particularly compelling business case.
- Hardware (11.27%) - Technical discussions centre on essential components, including transfer switches for safe power switching, inverters for DC-to-AC conversion, and complex installation

requirements. Users debate voltage requirements and safety considerations, comparing the technical complexity differences between V2G and V2H implementations.

- EV Market Landscape (10.79%) - Brand comparisons feature prominently, with Tesla, Rivian, Ford, and emerging players evaluated for bi-directional capabilities alongside traditional factors like pricing, towing capacity, and service availability. Tesla's timeline for V2G support and Ford's F-150 Lightning's current capabilities generate particular interest.
- Charging Standards (9.67%) - Technical standardisation discussions focus on CCS, NACS, and CHAdeMO compatibility, with users navigating complex regulatory frameworks involving multiple standards bodies. CHAdeMO's early V2G leadership through the Nissan Leaf is frequently referenced as a pioneering example.
- V2X Preferences (9.37%) - User preferences and trade-offs between different bi-directional applications (V2G/V2H/V2L) are explored, with specific vehicle models like Ford F-150 Lightning and Hyundai Ioniq frequently cited for their varying capabilities and use cases.
- Battery Longevity (8.35%) - Concerns about battery degradation from frequent charge-discharge cycles, warranty coverage gaps, and comparisons of battery chemistries (LFP, Sodium-ion) for bi-directional applications. Future "million-mile" battery technology is discussed as a potential game-changer for V2G viability.
- Solar Integration (8.26%) - Focus on inverter ecosystems and hardware integration challenges, featuring discussions of leading players (Enphase, SolarEdge, DCbel) and different inverter technologies (microinverters vs. string inverters). The synergy between solar generation and bi-directional EV charging creates particular user excitement.
- Electric School Buses (3.9%) - Fleet applications exploring school bus V2G potential as mobile battery networks, highlighting predictable schedules and extensive idle periods as unique advantages for grid stabilisation and emergency response scenarios.

3.3 Sentiment Analysis

The cost-efficient Gemini Flash achieved the highest accuracy (81.8%), significantly outperforming most competitors, including premium models such as GPT-4o (76.3%) and Claude-3-Opus (70.7%). McNemar's test revealed that Gemini Flash significantly outperformed five of the eight comparison models ($p < 0.05$), with only DeepSeek showing statistically equivalent performance ($p = 0.932$).

Figure 3 depicts the sentiment distribution across all analysed Reddit comments as well as topics. Positive sentiment predominates at 39.1%, reflecting widespread favourable opinions on bi-directional charging. Neutral sentiment accounts for 33%, indicating a significant share of factual or emotionally neutral comments. At 27.9%, negative sentiment is also substantial, highlighting concerns or criticisms that need further investigation. A deeper analysis of sentiment across topics reveals variations in user perceptions. Topics such as Energy Resilience, Remuneration, and V2X Preferences receive the most favourable reactions. Conversely, Battery Longevity receives the highest portion of adverse responses, demonstrating a significant concern among users regarding bi-directional charging.

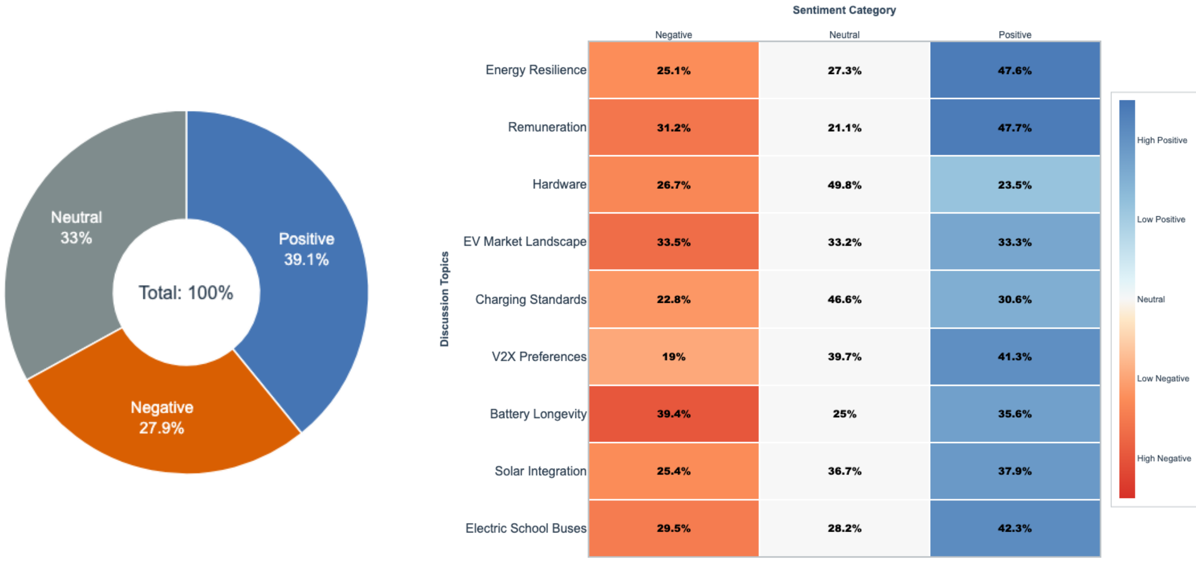


Figure 3. Left: Overall sentiment distribution across all Comments; Right: Sentiment distribution across topics.

3.3.1 Grid Benefits and Infrastructure Value

Regarding the V2G, users recognised its potential for load balancing, emergency support, and infrastructure economics (i.e., "battery EVs are often painted as a huge challenge for the electricity grid, but this way, they could actually be an asset to load balance and serve as an emergency reserve for local grids. Peak power demands can put massive stress on the grid. Having distributed storage available to meet demand when those peaks happen can save tens of millions of dollars in local grid upgrades. As such, users perceive V2G as a critical feature for future EV purchases (i.e., If Tesla did add V2G support, I would be hard-pressed ever to buy anything else! This is an absolute requirement for my next EV").

Online discussions most frequently highlighted electric school buses as ideal candidates for V2G, emphasising their predictable daily schedules and long idle periods as key advantages for distributed energy storage during peak demand or emergencies. The Massachusetts V2X Demonstration Program emerged as the primary real-world example cited by participants, recruiting school and commercial fleets with free bidirectional chargers in exchange for participation and data sharing. Eligible vehicles like electric school buses and the Ford F-150 Lightning were repeatedly mentioned as practical demonstrations of how fleet electrification can deliver measurable grid services while maintaining operational reliability.

Beyond heavy vehicles, the discussion increasingly turned to light commercial (N1) vehicles. Although explicit mentions of light commercial (N1) vehicles were rather infrequent, several comments referred to delivery vans, utility trucks, and small fleet vehicles, all closely aligned with the N1 category. These vehicles were typically discussed in the context of urban logistics and last-mile delivery operations, where they follow regular daily routes and return to central depots for overnight parking. Participants recognised that such predictable duty cycles created opportunities for V2G integration that would be difficult to achieve with private passenger vehicles. What made these commercial vehicles particularly compelling for V2G was their operational predictability and utilisation patterns. Fixed or semi-fixed routes, central depot returns, and consistent overnight parking created reliable connection windows that grid operators and aggregators could reliably schedule and forecast. This operational consistency meant that fleet managers could commit to specific charging and discharging windows without compromising daytime delivery operations. Participants framed V2G adoption in these sectors as fundamentally tied to commercial viability, with profitability, fleet coordination, and operational reliability serving as the key determinants. As one user observed, "different people will have different use cases, but for fleets or delivery trucks that sit idle most of the night, this makes total sense." This reliability fundamentally distinguishes commercial fleets from dispersed private vehicles. Their defined duty cycles generate the dispatchable capacity that forms the basis of the V2G business model, which is relatively more challenging to achieve with private vehicle owners who have less predictable charging patterns and usage schedules.

International analyses reinforce this view of commercial vehicles as the optimal entry point for V2G deployment. A Siemens study [7] projecting Munich's 2030 energy landscape found that commercial vehicles could provide substantial V2G capacity across multiple time horizons. The study estimates that BEVs, including passenger cars, small vans, trucks, and buses, could collectively deliver up to 300 MW of overnight capacity, with commercial passenger cars and small vans alone contributing 190 MW at night and 50 MW during daytime hours. Trucks could provide between 10 MW and 90 MW of daytime V2G power, while buses contribute an additional 20 MW at night. In comparison, private vehicles might supply up to 140 MW total capacity, with 85 MW from home charging, 35 MW from workplace charging, and 20 MW from public charging points. These figures demonstrate that while private vehicles offer significant aggregate capacity, the concentrated operational patterns of commercial fleets, particularly their predictable overnight idle periods, make them a more reliable foundation for grid stabilisation. They offer both daytime and nighttime flexibility that dispersed private vehicle owners cannot guarantee.

3.3.2 V2H Preference Over V2G

However, Reddit users frequently expressed a preference for vehicle-to-home (V2H) solutions over vehicle-to-grid (V2G) integration, prioritising household resilience during power outages over contributing to grid stability. Discussions highlighted scepticism about V2G's value, with many users questioning the usefulness of sending energy back to the grid (i.e., "Why would you inject back into the grid during a power outage? The point would be to power your own home. Almost no one is buying their next car for grid stabilisation, continue giving people V2H options, and they'll at least be able to reduce their demands on the grid during peak hours…"). This insight is in accord with Khezri et al. [8], who reported that Swedish drivers are notably more interested in V2H than in feeding power back to the grid, or a study by Noel Et al. [9], who discovered that in only Norway and Finland were car buyers willing to pay a premium for V2G whereas in other Nordic countries, V2G capability had no significant added value.

3.3.3 Range Anxiety and Safety Concerns

Users' opposing views on using a vehicle's battery to support the grid followed a concern of having no energy left when needed (i.e., "This is why I am not at all interested in V2G, why I would want to drain my vehicle that I now have no way of charging, and soon no way to leave the house because it will be dead in a few days?"). This finding is consistent with other studies (i.e., Liu et al. [10], Bakhuis et al. [11], and Geske et al. [12]). A few comments raised concerns about "backfeeding" electricity into the grid and putting line workers at risk during an emergency (i.e., "You're going to need to be able to disconnect from the grid, otherwise you could electrocute the line worker"). Interestingly, we found no comments addressing privacy concerns commonly discussed in other studies (Goncearuc et al. [13], Bakhuis et al. [11], and Neaimeh et al. [14]).

3.3.4 User Control Requirements and Mental Load

Users identified two key conditions for V2G participation: (1) compensation that exceeds battery degradation costs and (2) control over discharge limits to ensure adequate charge for driving needs. These conditions were also identified in several other studies (e.g., Van Heuveln et al. [15], Liu et al. [10], and Goncearus et al. [13]). Many want to set minimum compensation rates and battery discharge thresholds, with one user noting: "These systems need to have a setting where you can put some minimum price you will accept to sell the power back to the grid...This system needs some intelligence in the app to guarantee that I have enough energy when departing the garage." A specific figure of around 70–80% state-of-charge was often cited, intriguingly close to the 71% found in the Norwegian study of Mehdizadeh et al. [16]. However, others highlighted that constantly managing charge/discharge limits creates mental load and user inconvenience. One user explained: "It requires a bunch more planning on my part...I am going to have to remember to tell it not to do that if I intend to make a longer trip tomorrow...you're going to have to offer me some pretty significant benefits to make that hassle worthwhile."

3.3.5 Compensation Expectations and Economic Reasoning

Desired compensation typically ranged from three to ten times standard electricity purchase prices, reflecting arbitrage as a key adoption driver. Users frequently framed acceptable compensation as ratios relative to baseline electricity costs, with many identifying three times the purchase price as their minimum threshold. Examples included rates of €0.43/kWh, €0.87/kWh, or €1.74/kWh during peak demand, with one user stating: "Very few people would sign up for V2G with a €0.08/kWh arbitrage. I would personally participate at a rate of around 4 times higher than my purchase price." Another commented: "Most people would change their mind on that if they got sufficiently compensated, for example, buy power on off-peak time at €0.08/kWh, sell it out of your car battery at €0.3/kWh." This arbitrage-focused thinking contrasts with traditional survey findings that reported more general preferences for "proper compensation" [16], monthly payments of "100-1,000 SEK" [7], 72% reduction in monthly electricity bills (~€125 off) [16], or €0.6/mi of reduced range with guaranteed minimum battery levels [17], suggesting Reddit users demonstrate more sophisticated economic reasoning about V2G participation. Additionally, some users expressed interest in alternative rewards like free chargers, installation, workplace charging, or perks such as free airport parking (i.e., I lease my cars so wouldn't care much about impact on the battery if it is free airport parking then sure it would be well worth it as long as they guarantee my car is charged to same level or higher when I arrive"). Furthermore, besides users demanding an app feature that would ensure a specified battery level before departure, a few comments additionally emphasised the need for a fundamental real-time pricing feature (i.e., "V2G requires enough price differential for me to accept additional wear on my vehicle's battery; this really requires real-time bidirectional pricing").

While users often attempted informal cost–benefit calculations for passenger cars, estimating potential earnings from bidirectional charging or comparing battery wear against tariff savings, such quantitative reasoning was largely absent when discussing commercial fleets. In these discussions, the focus shifted from numerical analysis to recognising untapped potential, with users highlighting the opportunity for V2G to deliver value at scale. As one participant noted, “it would be valuable to fleet operators if they have a large number of parked vehicles.” This view reflects an intuitive understanding that the financial viability of V2G may be most excellent where vehicles share consistent duty cycles and predictable downtime. This assumption is also supported by empirical evidence. A study by Zhang et al. [18] on pure electric logistics vehicles in Chengdu quantitatively assessed the economic benefits of V2G participation for commercial fleets, utilising data from a 500-vehicle fleet across five groups (moving, express delivery, FMCG, landing match, and fresh). The research established a V2G profit model, revealing profits ranging from 3.94 to 65.54 RMB/vehicle/day (0.47 EUR to 8.30 EUR), influenced by factors such as window duration, start time, SOC lower limit, and discharge price. Key findings indicate that extending window duration and delaying start times enhance profitability by increasing discharge opportunities, while higher discharge prices and lower SOC limits further boost revenue. The express delivery group showed the highest potential profit (up to 68.97 RMB/vehicle/day) due to early work completion and high remaining state of charge (SoC). Another academic study, which developed a net cash flow model for a fleet of electric delivery trucks participating in the US regulation market, reached a similar conclusion regarding V2G's positive financial impact. The research found that revenue from V2G could offset between 5% and 11% of the vehicle's total cost of ownership.

Specifically, providing frequency regulation services was estimated to generate between €600 and €1,200 in revenue per vehicle, per year, depending on the specific type of regulation service offered [19].

3.3.6 Economic Scepticism and Cost Barriers

Nevertheless, significant scepticism exists among users who view V2G as economically unviable and impractical. Critics argue that current compensation levels, ranging from €9-13 monthly to €100 annually, are insufficient to justify battery degradation risks and equipment costs. One user stated: "I just don't see a point to V2G: you're degrading your battery for minimal gain", while another noted: "Nobody is going to sacrifice their driving range for the impersonal concept of 'grid stability' or a pitiful $100 a year." High up-front costs associated with required hardware and installation were also problematic: "V2G is cool, but Ford charges €3385 before installation costs", and "The challenge isn't the cars; the challenge is that V2G costs a fortune to install €2,600-3,500 more than a standard car charger." Many users question V2G's value proposition when simpler alternatives exist, with one noting: "Demand response charging gets you most of the same savings without needing the expensive inverter."

3.3.7 Battery Degradation vs. Battery Optimisation

The Battery Longevity exhibits the highest negative sentiment (39.4%), reflecting users' concerns about the impacts of bi-directional charging on battery health. Users stress concerns about excessive wear from additional charge cycles, claiming car battery chemistry isn't optimised for grid storage. Fears centre on high replacement costs and inadequate compensation, with one user calculating: "I've seen future replacement cost estimates of €10,500 for a Tesla battery...say the V2G participation cuts the lifespan of the battery in half, perhaps from 12 years to 6 years." Another questioned the economics: "Should I use my €26,000 battery to distribute $7 worth of electricity? The 4,000 times I need to do it to pay for my new battery will only add another 1million or so equivalent miles." Warranty concerns were also raised, with users noting that daily household power consumption could add equivalent battery wear. Overall, users fear degradation costs will exceed any savings, resulting in negative net benefits with no reimbursement for battery wear.

On the other hand, around 35% of users held the opposite opinion, stating that shallow discharge cycles (10-20%) have minimal impact on battery degradation. One noted: "The degradation effects of V2G on battery health are significantly overstated. LFP batteries have lifetimes of up to 10,000 full cycles." Some claim V2G could optimise battery condition by balancing ageing factors and maintaining lower average charge states, potentially improving battery health by 8.6-12.3% annually (i.e., "V2G is usually using tiny amounts of power from many cars and, in tests in the United Kingdom (UK), actually improves battery health"). Million-mile batteries are praised for their V2G potential, with users noting: "Small cycles don't degrade the battery in proportion to deep cycle...especially with the coming 'million-mile' batteries." Vehicle lessees showed little concern about degradation since they do not own the batteries long-term (i.e., "I lease my cars so that I would not care much about the impact on the battery"). This finding is like that of Hu et al. [20], who reported that while private EV owners prioritising battery longevity often express concerns about potential accelerated degradation from V2G usage, more technologically confident users demonstrate reduced apprehension. Nevertheless, this polarity in opinions is understandable to some extent, considering there appears to be no consensus in the literature either, as some studies have quantified the impacts of degradation [21]. In contrast, others have shown that V2G can prolong battery life by reducing degradation related to extended storage at high charge levels [22]. In light of the former case, a critical empirical study tracked a fleet of commercially owned EVs (e-NV200) in Denmark that provided a demanding frequency regulation service for 15 hours per day over five years. The results showed significant degradation: the batteries, which started with a usable capacity of 23 kWh, had degraded to an average of 18.9 kWh after five years, a capacity loss of approximately 18% [23].

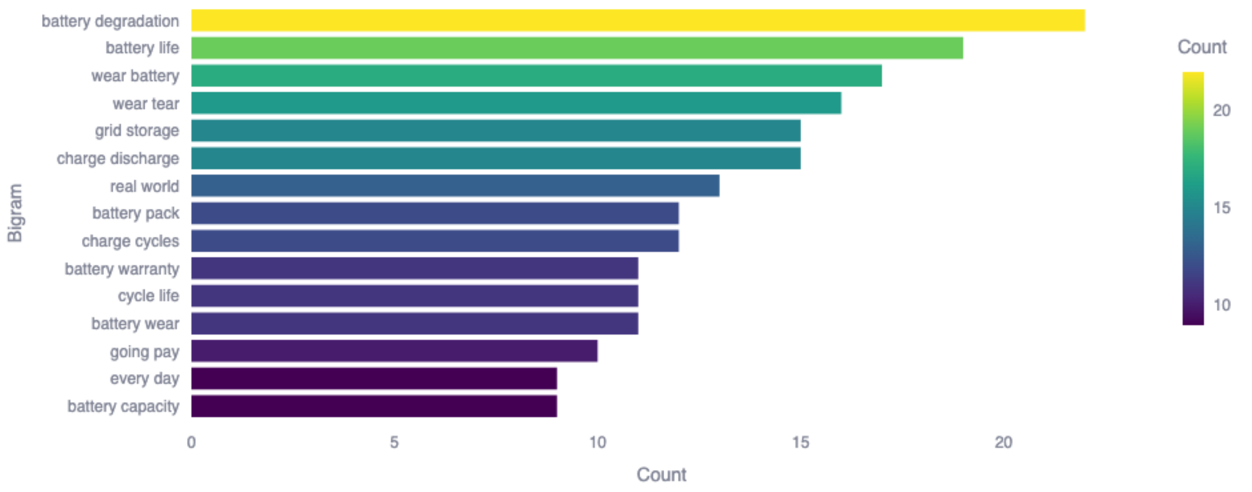


Figure 4. The list of 15 most frequent bigrams in a negative class concerning Battery Longevity.

3.3.8 Strategic Use of Secondary Vehicles

It is worth mentioning that users with multiple EVs favoured the idea of dedicating one vehicle for transportation while using another for stationary energy storage, with older or degraded EVs often serving this purpose. This approach addresses degradation concerns by utilising vehicles where battery wear is less critical to the owner's primary transportation needs. Users noted that even EVs with reduced battery capacity could provide equivalent utility to dedicated home batteries at significantly lower costs while retaining limited mobility functionality, with one commenting: "You can get a cheap used Nissan Leaf with a 30kWh battery for £3,000...Even a 60% state of health (SoH) 24kwh Leaf has equivalent usable capacity to a Powerwall at much lower cost." This finding suggests potential V2G deployment strategies that could mitigate user concerns about battery degradation by leveraging secondary or end-of-primary-life vehicles, potentially expanding the viable V2G participant pool beyond primary vehicle owners.

3.3.9 Hardware Complexity and Technical Challenges

Topic concerning Hardware was primarily neutral (49.8%), as users mostly outlined technical facts without emotional tone. Although it is worth noting that many highlighted V2G hardware complexity, mentioning additional setup requirements like complex wiring, sub-panels, and disconnect switches. One user noted: "I feel like people expecting this to work will mostly be disappointed...many additional boxes are needed for the current gen V2G setup, so much so that you will probably need 4-6 feet of linear space next to the charger." Users consistently highlight that V2G requires expensive inverters - with costs ranging from $2,000-$3,500 for grid-tie inverters, plus installation. One user noted: "V2G requires a very expensive inverter...it is simply impractical."

3.3.10 Standards Development and Market Readiness

From a standards perspective, user discussions revealed widespread awareness of the current "standards gap" within the V2G ecosystem. Most early V2G trials and deployments in the UK have relied on the CHAdeMO protocol, primarily associated with Japanese manufacturers such as Nissan. As one user observed, "V2G right now only works with CHAdeMO charging cars like the Leaf… CCS doesn't do V2G yet, but it will likely be added to the spec soon." CHAdeMO was praised for being designed with bidirectional capability from its inception and for demonstrating reliable real-world performance through vehicles like the

Nissan Leaf and chargers such as the Wallbox Quasar. These examples were often cited as proof that V2G is technically feasible and already available, influencing some users' purchasing decisions. However, the discussions also reflected frustration over the lack of standardisation beyond CHAdeMO. Participants emphasised that "there needs to be a unified standard before this becomes something worth the cost of implementing." This sentiment aligns with broader industry challenges, as the Combined Charging System (CCS), which dominates the European market, is still in the process of commercialising its V2G capability through the ISO 15118-20 standard. Widespread implementation of CCS-based bidirectional charging is expected around 2025–2026, creating a short-term market friction. As several users noted, this leaves consumers and fleet operators facing a difficult choice: to invest in a limited pool of older CHAdeMO-equipped vehicles to access V2G immediately, or to wait for the CCS ecosystem to mature. Discussions on Reddit demonstrated optimism that this standards gap will close within the next few years, with several users referencing ongoing development of chargers compliant with ISO 15118 and SAE J2847. Some participants expressed particular interest in upcoming products such as the Enphase bidirectional charger supporting ISO 15118-20, viewing such solutions as critical enablers for V2G/H functionality, especially for backup power during winter outages. Overall, while technical enthusiasm for V2G remains high, users perceive the lack of unified standards as a temporary but significant barrier to large-scale adoption.

3.4 Recommended solutions

Table 1. Requirements and recommendations for public slow EV chargers.

User requirements	Recommended solutions
User Control	ePowerMove could add smart-energy-management features that let drivers set a lower-limit SoC (e.g., 70 – 80 %) and preferred charge/discharge windows. The app might send real-time notifications when transfers approach user-defined limits and include an emergency "boost-charge" button for unplanned trips.
Transparency & Battery Health	ePowerMove could offer a transparent battery-health dashboard with predictive degradation forecasts. Real-time cycle counts and state-of-health estimates, backed by Machine Learning models, could be paired with concise FAQs or short animations that explain what the numbers mean for longevity.
Financial rewards & Alternative Incentives	ePowerMove might display live V2G price signals in the charger interface, allow users to set a minimum payout before exporting, and include a payback tracker that compares earnings to estimated wear costs. Non-monetary perks (e.g., free public charging, discounted parking, local loyalty points) could appear in a dedicated rewards tab.
Real-Time Pricing Integration	Users requested "real-time bidirectional pricing." The abovementioned financial rewards section could therefore be enhanced with: (1) Live market rate displays, (2) Price prediction algorithms, (3) Automated bidding based on user-set thresholds.
AI-Driven Scheduling	ePowerMove could employ machine learning to learn typical driving patterns and auto-adjust V2G participation, while addressing the privacy concern. An advanced settings view might let users review and override the AI's schedule at any time.
Secondary/Older EV Integration	ePowerMove could enable multi-vehicle management with distinct optimisation profiles - primary vehicles maintaining conservative discharge limits for transportation needs, while secondary/older EVs allow deeper discharge cycles.

4 USER REQUIREMENTS FOR THE PHYSICAL DESIGN OF CHARGERS

4.1 Requirements of various user groups

4.1.1 Private EV users

In 2024, across 16 European markets where fleet registrations can be identified (including Germany, the UK, France, and Spain), more than 40% of new EVs were purchased by private buyers [24]. Although BEV purchases by private users are concentrated mainly in the M1 category, it is worth noting that L7e vehicles, owing to their excellent energy efficiency and compact form factor, are attracting growing attention for low-speed, short-distance private urban travel. In 2024, sales of L7e class EVs in Europe exceeded 27,151 units [25]. While the current market share of L7e remains small compared with M1 class BEVs, it is undeniable that this new mode of mobility is becoming increasingly appealing. Accordingly, future user-centric public slow-charging infrastructure should consider both M1 and L7e class EVs.

The physical design of public slow-charging infrastructures should fully consider their specific application scenarios. Therefore, when designing charging stations, it is essential first to realise users' charging behaviours and the typical scenarios in which slow charging takes place.

The UK Department for Transport surveyed in 2022, involving 724 private EV users who regularly use public charging points. Among the findings, statistics on preferred locations for slow charging revealed that 40% of drivers believed more slow chargers were needed at places such as supermarkets and public car parks, 38% wanted more at workplaces, and 33% indicated a need for additional slow chargers on residential streets near their homes [26].

Table 2. Types of additional publicly-accessible charge points desired. [23]

	NET: More chargers	More chargers 43kW+ (rapid)	More chargers up to 22kW (slow/fast)	No additional chargers needed
At service stations	92%	81%	18%	8%
At other destination (e.g., supermarket, public car park)	91%	65%	40%	9%
At a dedicated EV charging hub	90%	78%	22%	10%
At workplace / place of education	68%	36%	38%	32%
On a street near my home	66%	39%	33%	34%
On a street directly outside my home	56%	32%	28%	44%
Somewhere else	64%	50%	25%	36%

Q.23 What kind(s) of additional publicly-accessible chargepoints, if any, would you like to see? Base: All except those who only charge at home (n=724)

In 2025, Zapmap company conducted a data analysis covering over 65,000 charge points across the UK. The study found that for slow on-street or destination chargers, the most common charging-start time windows were 8:00 to 10:00 AM (when drivers arrive at their destination) and 5:00 to 7:00 PM (when drivers return home). Although slow charge points (below 50kW) were used less frequently, on average, less than once per day, they had longer usage durations, with an average session lasting around 4 hours [27].

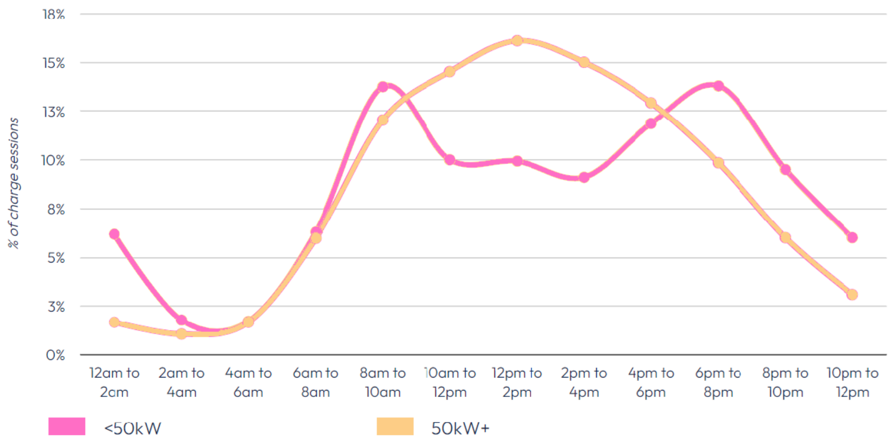


Figure 5. Public charging start time.

The above analysis indicated that the primary locations currently requiring additional charging stations are supermarkets, workplaces, and residential streets, with charging sessions most frequently occurring during morning and evening commuting hours.

Based on the survey report and the literature review, we have identified several physical-level issues that private EV users care most about regarding public slow-charging stations, as follows [28-31].

1. Appearance: The findings indicate that users prefer the charger's exterior design to deliver an experience that remains reachable, visible, low-intrusive, and easy to maintain even in harsh weather and cluttered public environments. For example, when snow or other obstacles build up in front of the parking bay, users should still be able to easily retrieve/stow and plug/unplug the connector, parking bays should be clearly marked and complemented by intuitive LED status indicators to enable quick wayfinding and assessment of occupancy/operating status, the unit's form and placement should minimise physical and visual intrusion; and the exterior surfaces and structure should be easy to clean and resistant to dirt and sticker residue, maintaining long-term cleanliness.

2. Screen: Users would like the EV charger to provide a high-legibility, low-effort screen and interaction experience. For example, adopt a separate layout for information display and payment/operational controls so that text, buttons, and the payment flow are easy to distinguish. Use sufficiently large font sizes with clear touch/physical button feedback, complemented by audio cues or voice guidance, and align the screen's height and tilt with the user's line of sight to reduce glare and low-angle readability issues, ensuring smooth operation across different user heights and lighting conditions.

3. Multi-connectors: Users would like the EV charger to ensure dependable access at public and workplace sites, especially during working hours and in city centres. In practice, this means higher plug/bay counts per site, expanded coverage, and high uptime, complemented by real-time availability information and optional queuing/reservations, so that public and workplace charging can serve as a true fallback without long waits or uncertainty.

Table 3. Requirements for public slow EV chargers from EV owners.

Product Requirement	Recommended Specification
Plug height should not be too low	• The plug interface should be positioned above the common snow height
Surface materials should be easy to clean	• Use anti-fingerprint coatings or anti-adhesive films
Marked parking lines + LED status indicators on the charger	• Indicator lighting • LED status lighting: available/in-use/fault (colour coded)
Compact design and understated colour	• Semi-concealed forms and black colour
Separate areas for text, buttons, payment, and support audio prompts	• Large font size, audio cues
Position the screen at an optimal viewing angle within the user's visual field	• Optional tiltable or adjustable screen, anti-glare screen coating
At least 2 connectors per charger	• Connector count ≥ 2

4.1.2 Commercial EV users

According to 2024 statistics from the UK Department for Transport, the number of N1-category light commercial vans totalled 74,000 units [32]. Compared to 2023, the growth rate of newly registered N1 electric vans in 2024 was 3.3%, surpassing the 2.8% growth rate of new M1 EV registrations [33]. This trend highlights the rapid development of electric urban delivery vehicles, short-haul freight vans, and service vehicles, driven by maturing battery technology, lower operational costs, and supportive government policies. When designing user-centred public slow-charging infrastructures, the specific charging demands of large-volume N1-type vehicles deserve increasing attention. This section emphasises exploring the special charging demands of N1-type commercial vans, including slow-charging power, specific charging requirements, and so on. The results are presented below.

In the European market, among N1-class light commercial EVs (vans), several high-selling models and their battery capacities are as follows: the Ford E-Transit has a battery capacity of approximately 64 kWh [34]; the Mercedes-Benz eVito van is equipped with an 85 kWh battery [35]; the Nissan e-NV200b has a 40 kWh battery [36]; and the Volkswagen ID. Buzz Cargo comes with a 77 kWh battery pack [37]. In actual charging practice, vehicle batteries are typically not charged from 0% to 100%; instead, the commonly used charging range is from 20% to 80%. The charging efficiency (η) is generally around 0.9 [38,39]. Commercial fleets usually prefer to complete charging overnight. Assuming an available charging time of 8 hours, the required charging power of the charging station can be calculated using the following formula. By setting a fixed charging duration and analysing battery capacities of N1 vehicles, we can estimate the lower limit of required charging power.

$$P_{charger} = \frac{60\% C_{battery}}{t \times \eta}$$

Where $P_{charger}$ is the required power of the charging station, $C_{battery}$ is the battery capacity, t is the charging time, and η is the charging efficiency. Based on this, the minimum required charging power of the charging infrastructures can be roughly calculated. Taking an 8-hour charging time as an example, if 60% of the battery capacity needs to be charged within 8 hours, then the charging power required for the four standard vehicle types mentioned above would be approximately 5.3 kW, 7.1 kW, 3.3 kW, and 6.4 kW, respectively.

In addition, understanding the charging needs of different vehicle categories is critical for the future design of public slow-charging infrastructure. N1 EVs are primarily used for commercial purposes. Their typical usage pattern involves intensive daytime operation and overnight charging, often carried out at company depots or private residences. The following are the specific requirements and recommendations of N1 EV users regarding public slow-charging stations [40, 41].

1. Charging safety: Users would like the EV charger to ensure secure, tamper-resistant nighttime charging. For example, the connector should lock to the vehicle for the duration of the session, block unauthorised unplugging, and provide alerts/logs for tamper attempts, supported by adequate lighting and simple re-authentication to end a session.

2. Charger shortage: Users would like the EV charger to deliver reliable availability with minimal queuing. For example, make suitable sites easier to find, increase plug/bay counts and site coverage, and offer real-time status plus optional queue/booking features to reduce excessive wait times.

3. Undersized parking bays: Users would like the EV charger to provide properly sized, accessible bays. For example, spaces should prevent vehicles from overhanging sidewalks, allow comfortable door opening even when adjacent bays are occupied, and include options sized for N1-class vehicles where relevant.

4. Insufficient cable length: Users would like the EV charger to feature adequate-reach, easy-to-handle cables. For example, lengths should accommodate different inlet locations without requiring repeated vehicle repositioning, and intuitive cable management should reduce strain and trip hazards while enabling straightforward plug-in.

Table 4. Requirements for public slow EV chargers from users of N1 vehicles.

Product Requirement	Recommended Specification
Support plug locking to prevent unauthorised unplugging during work hours	• Tamper detection and mechanical locking
Reservable charger	• Introduce booking systems, for example, allowing primarily commercial (N1) users to reserve a spot up to 10 minutes in advance.
Optimised app data	• In-vehicle navigation should display charging points with filters for: “N1-compatible space”, real-time availability, and power output.
Comfortable parking layout for vans	• Design longer bays (≥5.5 m) with clear ground markings indicating that only N1-type vehicles are allowed. • In some retrofit projects, standard 2.4 m-wide bays are widened to 2.8 m to accommodate broader vehicles, with charging poles placed at corner positions to improve access for large vans.
Extended charging cables suitable for N1 vehicles	• Charging points should be equipped with retractable cables of at least 6 meters in length. • Ground markings should indicate the maximum cable reach to guide proper vehicle positioning.

4.1.3 EV users with disabilities

People with disabilities make up approximately 23% of the total EU population; around 60% of them hold a driving licence and are capable of driving independently. This means that about 13.8% of EU adults are drivers with disabilities. Additionally, a survey investigating the willingness of people with disabilities to purchase EVs found that, without an adapted charging infrastructure, only about 25% would consider buying an EV. However, if the charging infrastructure were made accessible, this proportion could rise to 61%. Therefore, designing public charging infrastructures with accessibility in mind is also essential to promoting the widespread adoption of EVs [42].

This section highlights the key concerns of users with disabilities, focusing on the accessibility, usability, and physical placement of public charging infrastructure. These users face unique challenges that standard public slow-charging infrastructure designs often overlook. Table 6 provides the corresponding recommendations based on specific concerns [43,44].

1. Payment terminal: Users would like the EV charger to ensure accessible payment interactions: position the payment terminal within a seated reach range (including wheelchair users), avoiding overly high placement; provide clear labelling and simple, consistent steps for payment.

2. Installation location: The findings indicate that users would like the EV charger to be sited within easy reach: avoid placing terminals behind kerbs or too far from the bay; ensure a barrier-free, level approach with minimal setback so users can plug in without stepping into traffic or negotiating obstacles.

Table 5. Requirements for public slow EV chargers from users with disabilities.

Product Requirement	Recommended Specification
Interactive components should not be designed too high	• The screen, card reader, and plug should not be too high from the ground
Accessibility of payment terminals	• Reduce the height of payment terminals
Accessibility of charging terminals	• Reduce the distance between the charging terminal and the kerb

4.1.4 Female EV users

Amid the rapid adoption of EVs, charging station design must prioritise the needs of users of different genders, especially women. According to the 2023 ACEA report and a survey by Bonnet, female EV users account for only about 10% of EV owners in Europe, a significantly lower proportion than men. This highlights various barriers women face when using EVs and related infrastructure. Women generally pay more attention to the safety, ease of operation, and comfort of charging stations. The lack of these desig n considerations often leads to resistance or even avoidance of public charging facilities. Charging infrastructure optimised for women's needs not only enhances user experience but also promotes the comprehensive development of the EV market, fostering a more inclusive and sustainable future for green mobility. This section outlines the key concerns of female EV users, highlighting their unique needs, and Table 7 provides the corresponding recommendations based on specific concerns [45,46].

1. Safety: Users would like the EV charger to ensure safe, well-lit, and monitored nighttime charging. For example, site chargers in visible, camera-covered areas near basic amenities should provide bright lighting and a clear line of sight. They should also include emergency call/SOS and quick session-end/connector-lock controls, ensuring users don't feel "trapped" in dark, isolated car parks.

2. Operation: Users would like the EV charger to offer simple steps, clear on-unit and in-app instructions with a guided mode so confusing startup procedures don't deter newcomers.

Table 6. Gender specific requirements for public slow EV chargers.

Product Requirement	Recommended Specification
Easy-to-use interface with straightforward steps	• Set up a "Beginner Tutorial Mode" or a "Charging Operation Demo Video" for the charging station. • Use icons and brief text explanations, avoiding technical jargon; keep regular steps to a maximum of 3 (e.g., "Insert plug – Confirm – Charge").
Charging safety assurance	• The installation site is close to public lighting. • Use motion-activated lighting, ensuring the LED lighting covers the usage area with a certain brightness. • CCTV cameras. • Emergency alert button.
Cables should be easy to clean	• Use a waterproof coating or cable hook.

4.2 Competitor review in the physical design aspect

In the physical design of public slow-charging EV chargers, numerous mature products on the market can serve as benchmarks and references. For specific design requirements, we can systematically sort and quantify the key characteristics of best-selling models to establish a baseline set of design guidelines. The concrete steps include: selecting a sample set of competing products and compiling statistics on key physical design features.

4.2.1 Competitor selection

As of May 2025, the charging network with the most significant number of charge points in the UK market is Shell Recharge Ubitricity, with nearly 9600 charge points. Connected Kerb follows it with 6400 charge points, Pod Point with 5800, and Char.gy with 3950 [47]. However, Shell Recharge's network is primarily deployed at locations such as fuel stations, service areas, and motorways, offering fast DC charging services (50-360 kW). In contrast, Connected Kerb, Pod Point, and Char.gy, which ranked second, third, and fourth in market share, focus mainly on destination slow charging. Their charge points are predominantly slow AC chargers (7-22kW), typically installed at supermarkets, workplaces, car parks, and roadside. Therefore, we have selected representative products from the companies Connected Kerb, Pod Point, and char.gy for competitive analysis to inform our product design and understand user feedback.

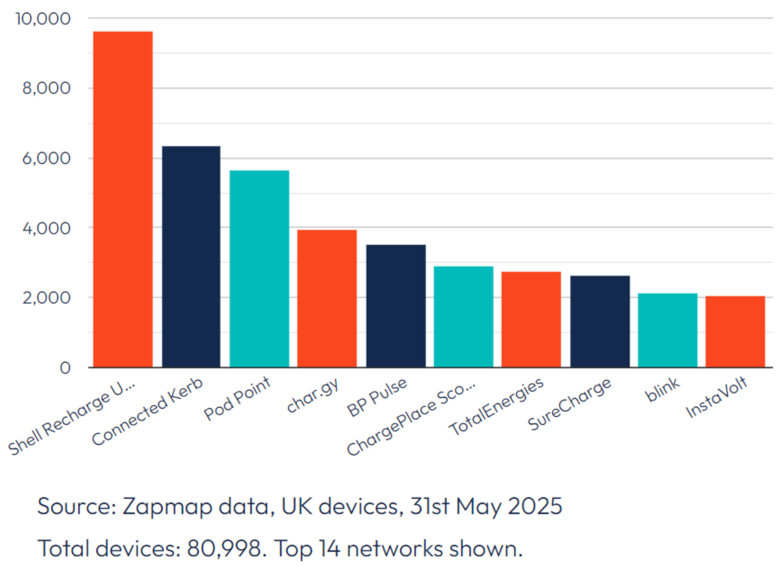


Figure 6. Total number of public EV charging devices by April 2024.

We have selected Pod Point's representative slow chargers — the Twin Charger, Connected Kerb's Chameleon and Char.gy's CP01 for competitive product analysis. The specific product appearances are shown in Fig. 7.

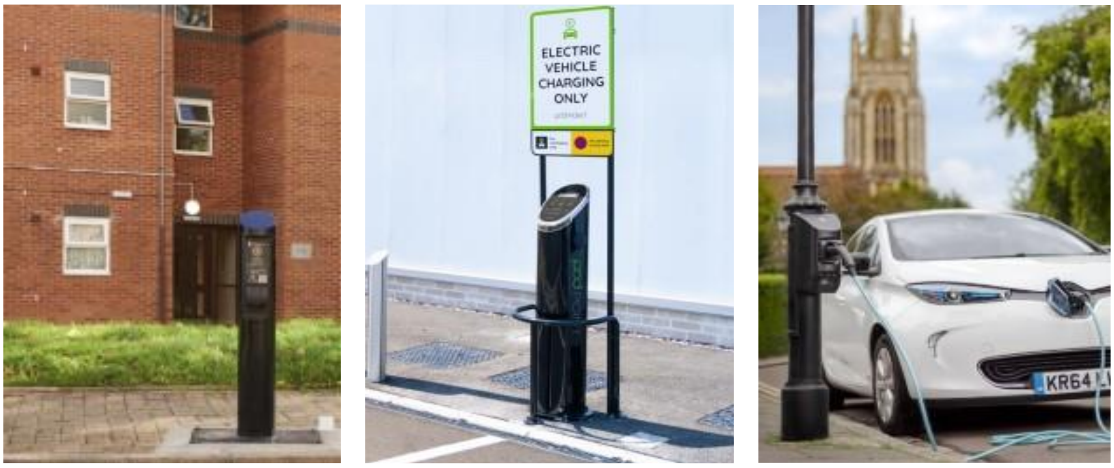


Figure 7. Representative slow-charging devices: (a) Chameleon, (b) Twin, (c) CP01.

4.2.2 Key physical design features

The product specifications are summarised in Table 8. The Chameleon offers charging power of 7 kW or 22 kW and can charge up to two vehicles simultaneously. Users only need to bring a cable compatible with their vehicle's connector. Notably, the Chameleon features a compact design with a height of less than 1000 mm, which meets the "Permitted Development" criteria outlined in the UK's General Permitted Development Order 2015. As a result, it does not require Planning Permission. Additionally, its black colour allows it to blend seamlessly into the streetscape, helping to reduce visual clutter—an advantage that has made it popular with local authorities. Its low height also makes it accessible for wheelchair users [48].

The Twin charger also offers 7 kW or 22 kW charging power and supports simultaneous charging for up to two vehicles. A distinctive feature is the LED status indicator on the top, which allows users to monitor the charging status remotely, thereby improving usability. Its casing is finished with an anti-graffiti coating, ensuring the charger remains clean and presentable in public spaces [49].

Among the three, the CP01 is the most compact and cost-effective in terms of hardware and installation. By leveraging existing lamppost infrastructure, it minimises the carbon footprint associated with installing new charging stations. The lamppost-integrated design avoids adding clutter to urban streets, enhances aesthetic appeal, makes efficient use of public space, and provides a convenient roadside charging solution [50].

Table 7. Competitive specifications.

Technical specifications	Chameleon	Twin	CP01
Power output	7 and 22 kW (AC)	7 and 22 kW (AC)	7 kW (AC)
Socket type	2×Type 2	2×Type 2	1×Type 2
Cable	User-supplied cable	User-supplied cable	User-supplied cable
Ingress/Impact Rating	IP54/IK10	IP54/IK10	IP55/IK10
Standard colours	Black	Black and White	Black

Technical specifications	Chameleon	Twin	CP01
Lighting	LED status indicator	LED status indicator	LED status indicator
Material	Powder-Coated Steel	Powder-Coated Steel	Polycarbonate
Height/Width/Depth	900/200/200 mm	1330/241/295mm	383/197/199 mm
Finish	N/A	Anti-graffiti Finish	N/A

5 USER REQUIREMENTS FOR OVERNIGHT PUBLICLY-ACCESSIBLE CHARGING

5.1 Current publicly-accessible charging behaviours

5.1.1 Overview

Overnight charging, encompassing both home-based and publicly accessible slow charging, is a common strategy among EV users due to vehicle inactivity during overnight hours and, in some cases, reduced off-peak electricity rates. Home overnight charging offers convenience and cost advantages, particularly for users with private parking and dedicated chargers, but when adopted at scale, it can lead to significant grid stress by increasing evening peak loads—especially in regions with high EV penetration and low grid load capacity. Conversely, public overnight charging provides an alternative for urban residents lacking private parking; however, it presents additional concerns, including concerns for limited overnight charging spaces, safety issues in poorly lit or isolated areas, and potential charging interruptions due to unreliable infrastructure. From a systematic perspective, wide-scale reliance on overnight charging may misalign with the availability of renewable energy sources like solar, prompting researchers to advocate for a greater shift toward controlled or daytime charging patterns.

5.1.2 Current case studies

5.1.2.1 Helsinki, Finland

The study [51] is based on approximately 25,000 charging sessions recorded at various charging sites in the Helsinki metropolitan area, Finland, between September 2017 and July 2019. The key finding is that peak loads at charging sites can be reduced by up to 55%. Notably, such load reduction through low-power charging is feasible only when the average parking duration exceeds 3 hours, ensuring no negative impact on user experience. The analysis also reveals that the average parking time exceeds the actual charging time by more than 2 hours, highlighting the substantial potential of EVs for peak shaving. It is also found that the load at public charging stations during nighttime hours is relatively low, indicating underutilisation of these facilities.

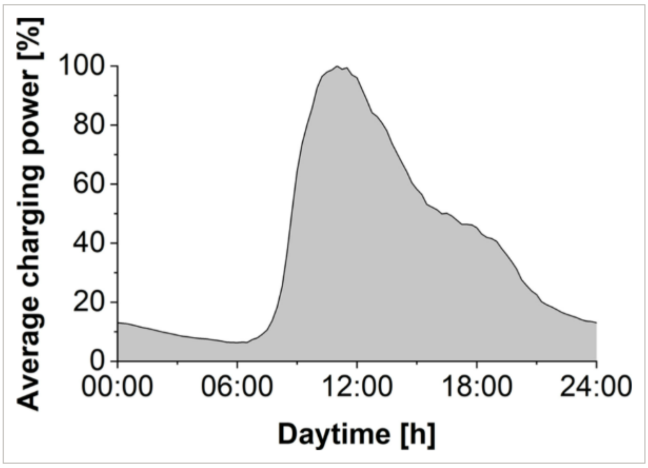


Figure 8. Aggregated normalised load curve of the public charging sites.

5.1.2.2 Vienna, Austria

This study [52] aims to investigate the future distribution of charging demand across various types of charging stations, to provide a foundation for assessing infrastructure needs — including quantity, design, and cost-effectiveness. For the Austrian case study, a novel method was applied that uses demographic variables and decision rules to derive the allocation of charging events. The results indicate that 88% of charging takes place at home, aligning with findings in the existing literature. Notably, workplace charging accounts for only around 8.8%, which is a significant observation of this study and underlines the relative importance of workplace charging. Only 1.7% of charging occurs at "public charging infrastructure" (e.g., public car parks, supermarkets; it should be noted that charging at designated but freely chosen parking spaces while the vehicle owner is at home is still classified as home charging), and 1.5% takes place at "fast-charging infrastructure" (i.e., along motorways). The analysis shows that public charging infrastructure accounts for only a small fraction of total charging activity. Taken together, the findings suggest that some public or fast-charging stations may not be economically viable based on charging revenues alone and may instead depend on alternative business models.

Table 8. Comparison between different locations of charging stations in Vienna.

	Share (%)	Power capacity	Time idle	Loss of time
Charging when user is at home	88.0	Low	~10 h	None
Work charging	8.8	Low	~10 h	None
Public charging	1.7	Medium	~2 h	None
Fast charging	1.5	High	Duration of charging	Duration of charging

5.1.2.3 Cyprus

In Cyprus, the development of electric mobility remains at an early stage, though a basic infrastructure and policy framework are already in place [53]. As of 2021, only 114 electric passenger vehicles were registered in the country, significantly fewer than conventional petrol and diesel vehicles, indicating a relatively low adoption rate of electric cars. To accommodate future growth in electricity demand, it is estimated that if electric vehicles travel an average of 7,000 kilometres per year, Cyprus will require an additional 480 GWh of electricity annually.

The charging network in Cyprus is managed by the Electricity Authority of Cyprus (EAC), which has installed 33 semi-fast charging stations with a capacity of 22 kW each, supporting Mode 3 charging and the simultaneous charging of two vehicles. The country applies a flat-rate tariff system, with fast charging prices reaching up to €0.40/kWh in the second half of 2022—significantly higher than Malta's off-peak rates. In addition, Cyprus plans to enhance its renewable energy capacity and grid reliability by constructing solar thermal power plants with storage (e.g., 50 MW with 8 hours of storage) and by reinforcing reserve capacity (e.g., 60 MW constant reserve plus dynamic reserves linked to PV and wind output).

5.1.2.4 Brussels, Belgium

This study [54] analyses a real-world charging dataset from Brussels, Belgium, comprising over 5,000 EV users, aiming to address gaps in the existing literature regarding EV charging behaviours at public charging stations and to further explore the impact of these behaviours on the efficient utilisation of public charging infrastructure. Unsupervised learning methods (i.e., clustering analysis) were employed to classify drivers into distinct behavioural clusters based on their charging activity patterns at public charging stations, thereby revealing diverse charging patterns and their differences.

The study finds that users who predominantly charge at night are characterised by a high proportion of nighttime charging (on average accounting for 62% of all charging sessions), a high charging frequency (once every 2–3 days), and a high spatial concentration of charging within the same area (with an average distance to home of 29 metres, indicating that almost all charging occurs at or near their most frequently used charging station) (see the following figures). Additionally, these users exhibit a low energy Gini coefficient, suggesting that their energy consumption is evenly distributed across different charging periods. Although they typically engage in long-duration overnight charging, their average energy consumption per session is 10 kWh, which is lower than the overall average of 14.8 kWh for all frequent EV drivers. This may indicate an interrelation between parking and charging needs among EV drivers.

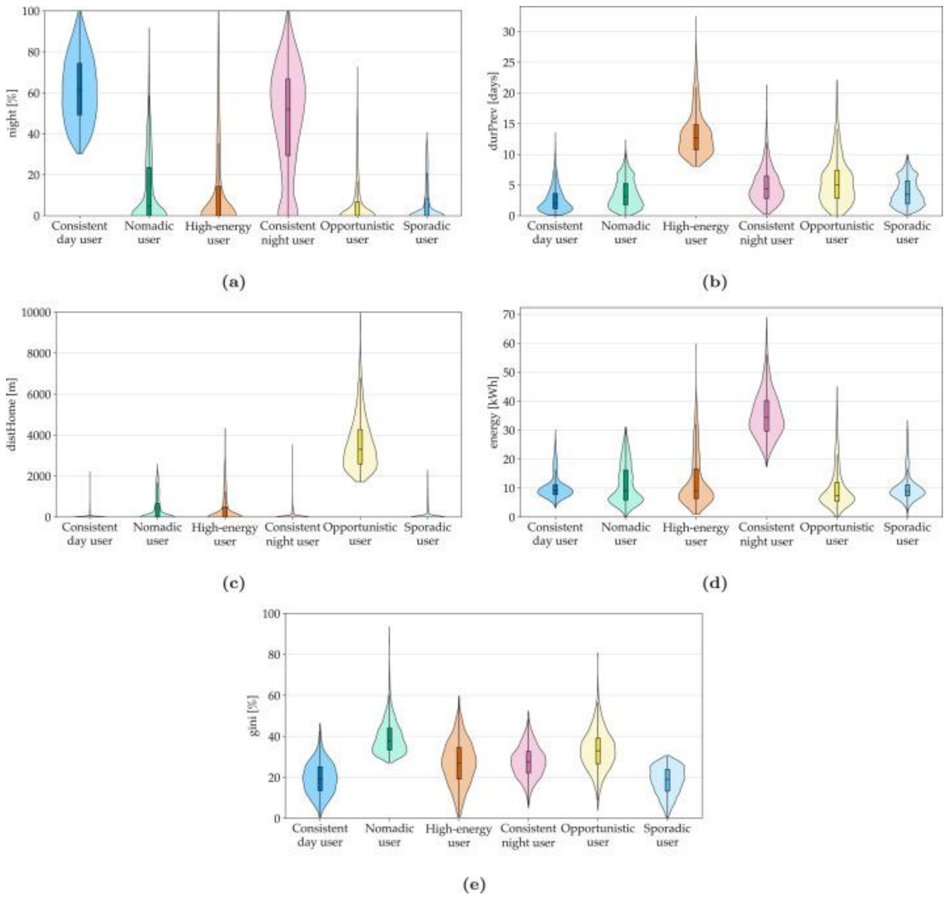


Figure 9. Violin plot showing the probability distribution functions of the five behavioural metrics.

5.1.2.5 Dutch metropolitan areas, Netherlands

In this study [55], based on 4.9 million charging transactions recorded between January 2017 and March 2019 and data from 7,079 public Level 2 charging points across the four largest cities and metropolitan areas in the Netherlands, the authors identified patterns of charging behaviour and electric vehicle user types involving approximately 27,000 users. A bottom-up, data-driven two-step clustering approach was applied to overcome predefined stereotypes of user behaviour. This method first clustered individual charging sessions and then clustered users based on the composition of their charging sessions. The initial clustering, using a Gaussian Mixture Model, revealed 13 distinct types of charging sessions: 7 daytime charging types (4 short-duration and 3 medium-duration sessions) and 6 overnight charging types (see the following figure).

There were six overnight charging session types found in the dataset, of which OverNight-SameLocation-MediumDuration-NarrowMedium (ON-SL-MD-NM) Hours Between Sessions (HBS) (8% of all sessions) is the most stereotypical. This session type typically relates to overnight charging (at home locations) during weekdays. It has a very specific start time, at around 18:00, and an end time at around 8:00. This results in a very narrow connection distribution of around 14 h. The HBS peaks at 10 h, which implies that the previous session ended at around 8:00. The previous session is in 99% of the sessions another overnight session, and 35% of the same type. There is no distance between sessions in this session type, meaning that the previous session was at the same location.

The OverNight-SameLocation-LongDuration-NarrowShortHBS (ON-SL-LD-NS) (2.2%) session type shows approximately the same start and end time properties but differs on the connection time. This session type is an overnight charging type that lasts typically for 40 h, which is an overnight session plus one day. The distribution of sessions over the weekdays shows that this session typically starts on Saturday, which means that it lasts until Monday morning the first day of the work week. This session type refers to users—typically commuters—who plug in their electric vehicles on Friday or Saturday and leave them connected throughout the weekend, only disconnecting on Monday morning.

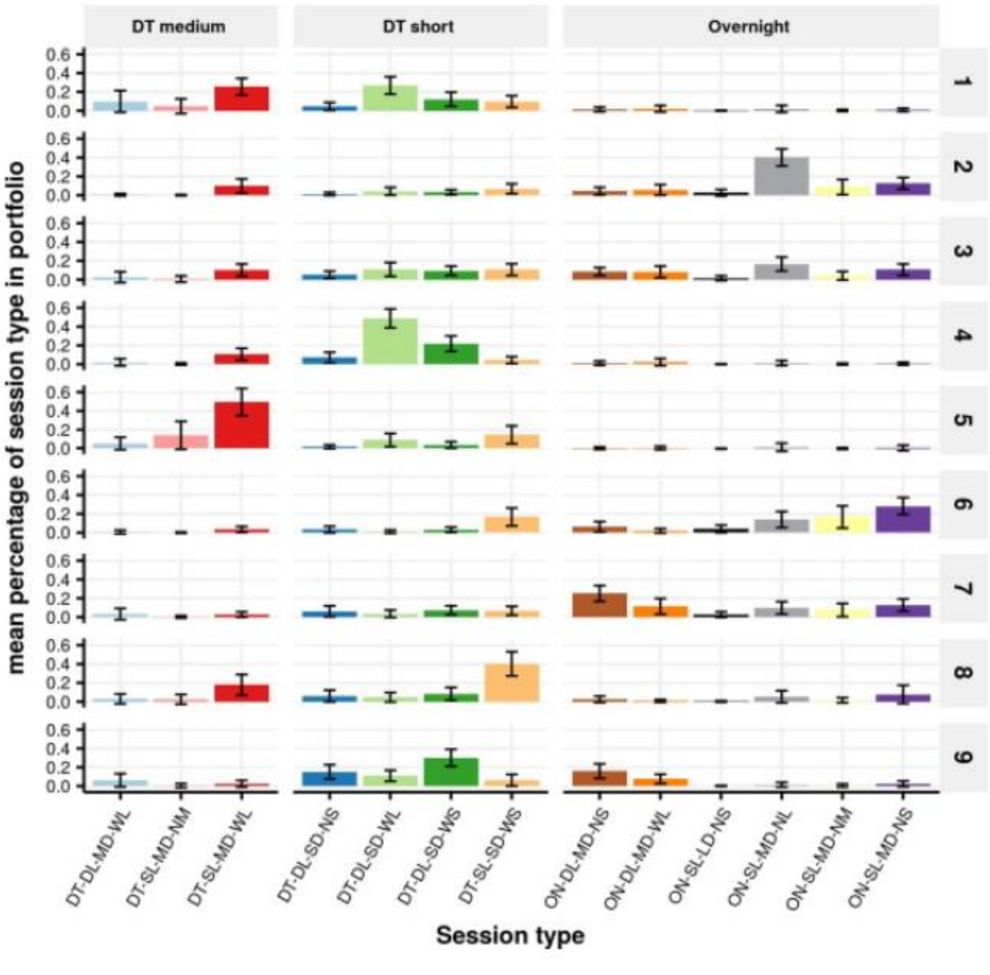


Figure 10. Portfolio of charging sessions per user type in the Netherlands.

The OverNight-SameLocation-MediumDuration-NarrowLongHBS (ON-SL-MD-NL) (12.4%) displays a long disconnection duration, which distinguishes this session from the other overnight types. This session type has a pattern of start and end times similar to ON-SL-LD-NS. The HBS feature appears to skip several days: 1 (44%), 2 (19%), 3 (11%), 4 (7%), and more. Interestingly, almost 30% of this session type follows a session of the same type, which indicates a regular pattern of successive sessions that skip several days.

The OverNight-SameLocation-MediumDuration-NarrowShortHBS (ON-SL-MD-NS) (14.4%), on the other hand, has a specific short duration between two sessions peaking at less than 2 h. The arrival time of this session is also later than the standard overnight session. Having a short time between this session and its predecessor at the same location may indicate that an EV user comes home, connects at 17:00, say leaves at 19:30 to go shopping, then returns at 21:30 for an overnight charge. This session does follow upon DaytTime-SameLocation-ShortDuration-WideShortHBS (DT-SL-SD-WS) in 25% of the sessions.

Two overnight charging session types where the current charge station and previous charge station are at different locations are OverNight-DifferentLocaton-MediumDuration-NarrowShortHBS (ON-DL-MD-NS) (9%) and OverNight-DifferentLocation-MediumDuration-WideLongHBS (ON-DL-MD-WL) (4.9%). Both session types have a start connection time that is slightly skewed to later times compared to the most stereotypical overnight session at the same location (ON-SL-MD-NM). This may point to an early evening session at a different location than its predecessor. Both sessions have an identical distance distribution with significant peaks at distances less than 1,500 m. A reason for the displacement of an overnight charging session with a walking distance between the current session and the previous may be the occupation of the previous station. A closer look at the data confirms that for distances less than 1000 m, 60–70% alternative CPs to the current CP in the surroundings of 0 to 750 m were occupied at the time of arrival of the EV user. This means that in most cases, none of the CPs in the vicinity is available as an alternative to the EV user, whereas the occupation rate of stations for larger distances, 5 km, was significantly lower.

5.1.2.6 N1 electric trucks in Germany

The analysis [56] of real-world activity patterns for light-duty electric trucks operating in regional delivery transport in Germany indicates a high reliance on depot-based charging infrastructure. First users overwhelmingly view recharging at the Home Depot as the most practical and least expensive option compared to utilising public charging stations. As a result, all vehicles consistently return to the depot for charging at the end of a trip or day.

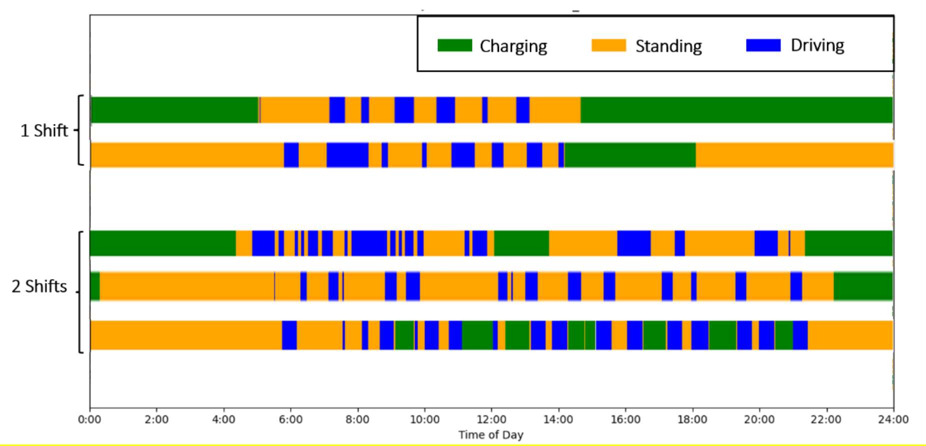


Figure 11. Exemplary charging pattern for different use cases and charging strategies.

Charging at public stations is minimal, occurring only for some vehicles and generally in exceptional cases. The observed activity patterns are tied to the vehicle's operational schedule, distinguishing between one-shift and two-shift operations. These patterns, exemplified in Figure 11, show that one-shift operation typically involves a single, extended night-time charging session or a long session starting in the early afternoon. In contrast, two-shift operation necessitates intermediate daytime charging during loading/unloading to cover the higher daily driving distances, often supplemented by a shorter night-time charge. Furthermore, due to the practical constraints of vehicle range, the charging process and overall vehicle use are often managed with a predetermined and inflexible 'charging plan'.

5.1.2.7 Summary

Overnight charging is a dominant and recurring behaviour among EV users across different contexts. It is typically characterised by a high frequency of use, a strong spatial concentration near users' homes, and long-duration but relatively low-energy charging sessions. Many EV users prefer to charge during evening or late-night hours—commonly between 20:00 and 24:00—when vehicles are parked for extended periods. This behaviour reflects a close relationship between charging and parking needs.

While home-based overnight charging offers convenience and aligns with user routines, it can also contribute to localised grid stress, especially in areas lacking private chargers and relying heavily on public slow charging infrastructure. In contrast, public charging stations are often underutilised during nighttime hours, indicating a mismatch between demand and supply. These findings suggest significant potential for managing overnight charging more effectively—through strategies such as optimised charger placement, time-of-use pricing, and integration with energy storage systems to balance loads and improve infrastructure utilisation. In conclusion, no matter for passenger or freight usage, charging has become an integral part. Players compete to offer end-to-end solutions, but challenges among vehicles, charging, and the grid remain to be solved at scale.

5.2 User key concerns about publicly-accessible charging

5.2.1 Charging Cost

While overnight charging at public slow chargers can be more economical due to off-peak electricity tariffs, users remain concerned about the lack of pricing standardisation. Prices often vary significantly across operators, regions, and even time slots, making it difficult for users to predict and control their charging expenses. The increasing use of dynamic pricing models, though efficient from a grid management perspective, can lead to uncertainty for users. Additionally, concerns about future price inflation—especially as EV adoption rises and electricity demand increases—contribute to doubts about the long-term affordability of public charging.

5.2.2 Parking Availability

In high-density urban environments, securing a parking spot with charging capabilities overnight is increasingly challenging. Residential areas often lack dedicated EV charging infrastructure, forcing users to compete for limited spaces. In many cases, non-EV vehicles occupy charging bays, or EVs remain parked after charging is complete, blocking access for others. These issues are particularly acute in older neighbourhoods where retrofitting infrastructure is difficult. Users report that the uncertainty of finding an available spot discourages reliance on public overnight charging.

5.2.3 Charging Reliability and Speed

Although slow charging aligns with overnight charging behaviours, reliability remains a persistent concern. Users often encounter faulty chargers, limited maintenance response times, or poor user interface design. These issues can result in failed or incomplete charging sessions, leaving users without sufficient range for the next day. Additionally, concerns arise about the speed of charging—especially for users with irregular schedules or unexpected next-day travel needs. The lack of real-time information on charger availability and status further exacerbates frustration.

5.2.4 Safety and Convenience

Charging at public facilities late at night often raises personal safety concerns. Users report feeling vulnerable when accessing chargers located in dimly lit or secluded areas, such as the edges of public car parks or behind commercial buildings. These fears may discourage solo users, particularly women or elderly individuals, from using public charging overnight. Beyond safety, the inconvenience of walking between home and the charger—sometimes in poor weather or over long distances—adds to the perceived burden of public charging. The absence of amenities (e.g., shelters, lighting, surveillance) also diminishes the user experience.

5.2.5 Access Equity and Infrastructure Distribution

Many users express concern over unequal access to public charging infrastructure, especially in lower-income or less-developed urban areas. While some districts benefit from municipal investment or private-sector partnerships, others remain underserved. This disparity can reinforce existing mobility inequalities and limit the broader adoption of EVs among disadvantaged groups. Users also worry that future infrastructure rollouts may prioritise commercial zones or affluent areas, further marginalising already underserved communities.

5.2.6 Interoperability and Payment Friction

The lack of a unified standard for charging access and payment is another pain point. Users often face the inconvenience of managing multiple apps, cards, or subscription accounts to access chargers from different operators. Inconsistent user interfaces and opaque billing methods further add to confusion. This fragmented experience stands in contrast to the seamless refuelling expertise associated with traditional petrol stations, underscoring the need for standardisation and integration.

5.3 Recommendations

Table 9. Requirements and recommendations for public slow EV chargers, with a special focus on overnight charging.

User requirements	Recommended solutions
Encourage Time-of-Use Pricing	Implement and promote transparent off-peak electricity pricing to incentivise overnight charging. Clear price signals can help users plan charging sessions more economically.
Expand Residential Charging Infrastructure	Increase the number of slow chargers in residential areas, especially in apartment complexes and public parking lots, to alleviate parking and charging space shortages.
Cable Safety	Leaving an EV plugged in overnight can create a trip hazard. Always place cables neatly to avoid blocking walkways or causing accidents.
Charging Safety	Overnight charging may cause heat buildup or battery swelling over time. While modern chargers have protection features, it's safer to check the charger occasionally or unplug after charging completes.
Clean Energy Usage	Overnight charging cannot directly use solar power, so a common solution is to equip energy storage batteries that store solar energy generated during the day for use at night. This enables efficient utilisation of clean energy for charging.
Using Electric Bus Depots for Public Charging	Due to the limited availability of charging locations, using bus depots as public charging points overnight has become an effective solution. This approach maximises the utilisation of idle resources at bus depots while mitigating the pressure on other public charging stations.
Affordable and accessible charging options for light-duty electric trucks	Expand public slow-charging infrastructure in urban logistics zones and install chargers in public parking areas and delivery hubs to promote the application of light-duty electric trucks.

6 USER REQUIREMENTS FOR ENERGY-CONSUMING CONVENIENCE FUNCTIONS

EVs rely entirely on battery power not only for propulsion, but also for "convenience" functions like cabin climate control and battery thermal management systems. Unlike internal combustion cars that can reuse engine heat for warming, EVs must dedicate battery energy to these functions, which can significantly impact driving range and efficiency. This section examines User Requirements for Energy-Consuming Convenience Functions in EVs, essentially, how meeting user needs for cabin comfort and battery performance affects energy use. We present quantitative data on the energy consumption of EV HVAC systems and battery thermal management in typical private passenger vehicles. Key comparisons are made between cabin heating vs. cooling and battery heating vs. cooling. We explore how these demands vary with seasonal conditions, comparing winter vs. summer operation and the associated range impacts, and highlight geographical/climatic influences (for instance, the challenges faced in a Nordic winter versus a mild climate). Further, we discuss user behaviour and preferences: how drivers tend to use climate control (common temperature set-points, use of features like seat heaters), habits like pre-conditioning the car while plugged in, and the extent of user awareness regarding HVAC energy draw. These behavioural insights are important because savvy usage (e.g., pre-heating the cabin from grid power or choosing an "Eco" HVAC mode) can mitigate range loss, whereas aggressive HVAC use can exacerbate it. Throughout this analysis, we draw on recent reputable sources to ensure up-to-date and realistic figures. The goal of this section is to understand the trade-offs between user comfort requirements and energy efficiency in EVs, and how this understanding informs strategies for future energy management and charging. The following subsections will first quantify the energy use of HVAC and battery thermal systems (6.1), then examine user behaviours and preferences in using these systems (6.2), discuss key user concerns arising from these factors (6.3), and finally recommend technical and behavioural solutions to better meet user needs with minimal range impact (6.4).

6.1 Energy Use of HVAC Systems in EVs

Cabin Heating (Winter): Heating the interior in cold weather is one of the most energy-intensive auxiliary functions in EVs. Studies have shown that running the cabin heater in freezing conditions can double an EV's energy consumption per mile [57]. For example, in tests at –7°C (20°F), a 2018 BMW i3 used nearly twice as much energy per mile with the heater on as with it off. On average, engaging cabin heat at 20°F caused about a 41% decrease in driving range for several EV models, compared to mild 75°F conditions [58]. This aligns with findings that cold temperature alone reduces range by ~10–12%, but the additional load of cabin heating can amplify total range loss to roughly 40–50% in winter [59]. Cabin heating draws significant power (often several kilowatts); EVs without heat pumps typically use electric resistance heaters that can consume ~5–7 kW during warm-up. Modern EVs increasingly use heat pump HVAC systems, which are far more efficient in cold weather. In fact, EVs equipped with heat pump heating have been shown to achieve 15%–22% higher driving range at –10°C compared to those using resistive heaters. This is because heat pumps transfer external heat (even from cold air) into the cabin rather than generating heat purely from battery electricity. However, at extremely low temperatures (e.g., –40°C), even heat pumps face limitations and may provide only modest improvement [60]. Overall, cabin heating can be the single largest auxiliary drain on an EV battery in winter, often accounting for the bulk of efficiency losses in sub-freezing driving.

Air Conditioning (Summer): Cooling the cabin in hot weather also uses battery energy, though generally less than heating. Air conditioning (A/C) in EVs is essentially a heat pump in cooling mode (or an electric compressor system) and is more efficient than resistive heating. In typical summer conditions (e.g. ~90°F / 32°C), using A/C has only a minor impact on range – real-world data from tens of thousands of EVs show only about a 5% range reduction at 90°F due to A/C use [60]. Even at 95°F (35°C), EV tests found roughly a

17% range loss with the A/C on (compared to 75°F baseline), which is significant but still much less severe than the effect of cabin heating in winter. It’s typically not until extremely high temperatures (≥100°F / 38°C) that A/C usage causes more substantial range loss – about 17–18% on average at 100°F, according to real-world data [60]. In the most extreme scenarios (very hot and humid days with stop-and-go traffic), air conditioning can temporarily become a dominant load; the International Energy Agency (IEA) reported that in hot, humid climates, the A/C can potentially cut an EV’s range by up to 50% under peak cooling demand [61]. Such cases (e.g., running maximum A/C while stuck in traffic) are outliers – during normal highway driving in summer, A/C typically uses far less energy than cabin heating in winter. One reason is the smaller temperature delta: cooling a cabin from, say, 95°F down to 70°F (35°C to 21°C) is a 25°F change, whereas heating a cabin from 20°F up to 70°F (–7°C to 21°C) is a 50°F change. The greater the required temperature difference, the more energy is needed. Additionally, EV A/C systems do not have to counteract engine waste heat (unlike A/C in gasoline cars) and can cool efficiently even when the vehicle is stationary or at low power output [60].

Power Consumption and Efficiency: Both cabin heating and cooling tend to draw the most power at the start, then level off. When a car is heat-soaked in summer (the cabin is extremely hot) or frigid in winter, the HVAC works at full power to reach the set temperature. For example, cooling a sun-baked interior can initially draw 3–5 kW until the target temperature is reached, after which only ~1 kW or less may be needed to maintain the cool cabin. Likewise, heating a frozen cabin can pull 5+ kW initially. Because “warming up” the cabin is energy-intensive, it’s more efficient to maintain the temperature than to let the car interior swing to ambient extremes. EV owners are often advised to pre-heat or pre-cool the cabin while the car is still plugged in so that the initial HVAC surge comes from grid power rather than the battery [60]. Many EVs have a scheduling function or smartphone app to start cabin pre-conditioning before departure. Once the cabin is at a comfortable temperature, the power required to keep it there is much lower (for instance, keeping a cooled cabin at 70°F might use ~1 kW as noted, whereas initially cooling it from 95°F took 5 kW). This strategy preserves battery charge for driving. In summary, air conditioning’s impact on range is modest in most cases, and modern EV AC systems are quite efficient. Heating is more challenging – without an engine’s waste heat, an EV must supply a lot of energy for warmth. The adoption of heat pumps and better thermal insulation in newer EV models is mitigating this, but cabin heating remains a primary range limiter in winter.

Energy Use of Battery Thermal Management Systems: Beyond cabin comfort, EVs expend energy to maintain the battery pack’s temperature within an optimal range. Battery cells operate most efficiently and safely around ~15–25 °C (59–77°F) (Esparza et al., 2025). In both cold winters and hot summers, BTMS will either heat or cool the pack to keep it within this band. These systems can be active (electric heaters, coolant pumps, chillers), and they draw power from the battery unless the vehicle is plugged in.

Battery Heating (Cold Weather): In low ambient temperatures, a lithium-ion battery’s internal resistance increases, and its chemical reactions slow down, reducing available power and capacity [57]. To prevent extreme voltage drop and to enable regenerative braking and fast charging, many EVs will heat the battery when it’s very cold. This can happen automatically (for example, a Tesla will actively warm its battery even when parked if the pack gets too cold, to protect battery health [59] or in response to user actions (such as engaging a battery pre-conditioning mode before a fast charge). The energy cost to heat a cold battery is non-trivial. A simulation study found that at –10°C (14 °F), an EV’s battery thermal management could consume up to 0.15 kWh per km just for battery heating. In the same conditions, the cabin HVAC load was estimated at about 0.2 kWh per km. In other words, roughly 40–45% of the total energy used at that cold temperature could go into warming the battery and cabin, on top of the energy needed to move the car. By contrast, at a mild 20°C (68°F), the BTMS cooling load was negligible (~0.02 kWh per km) because the battery is already near optimal temperature. These figures illustrate that battery heating can be almost as significant as cabin heating in deep cold. In practice, the BTMS will run as needed to keep cells above certain thresholds (some EVs won’t even allow fast-charging until the battery is warmed). Pre-conditioning the battery is commonly recommended in winter: for instance, an EV may automatically start heating its battery when you navigate to a DC fast charger, ensuring the battery is warm enough on arrival to accept a high charging rate [62]. This uses some battery energy (often on the order of a few kWh – one user observed about 8 kW draw for 30 minutes, ~4 kWh, to preheat a cold battery) but it is worthwhile because it dramatically reduces charging time at the station. Manufacturers like General Motors suggest allowing on the order of 30 - 60 minutes for battery preheating in very cold weather for large packs. Overall, battery heating ensures the EV can deliver power and regen in winter, but it can noticeably drain the battery if the car is used or left outside in frigid conditions.

Battery Cooling (Hot Weather): In high ambient temperatures, battery packs need cooling to prevent overheating, which can cause accelerated degradation or safety issues. EVs use liquid cooling loops or refrigerant systems to keep the battery in check during fast charging and high-power use in hot weather. Power drawn for battery cooling is generally modest during driving, often with fans or coolant pumps cycling on and off. However, extreme heat can trigger continuous active cooling. Notably, many EVs will even run cooling systems while the vehicle is parked and off, if the battery's temperature rises above a safe limit (Tesla vehicles are known to do this) [59]. This means on a very hot day, an EV parked outdoors might consume some energy to protect the battery, potentially slightly reducing state of charge over time if not plugged in [57]. Drivers in scorching climates are often advised to keep their EV plugged in when parked or at least avoid leaving the car with a very low charge, so that the battery cooling won't run it completely flat. Quantitatively, battery cooling typically uses much less energy than cabin cooling under the same conditions, because only the battery mass needs to be cooled (and it's often insulated within the pack). For instance, one analysis noted that at a comfortable 20°C ambient, the BTMS cooling load was only 0.02 kWh/km – essentially negligible. Even at high temperatures, the continuous cooling draw might be on the order of 1–2 kW during fast charging or hard driving, which is relatively small compared to motor power. That said, during a DC fast-charge session on a hot day, you may hear cooling fans roaring – the energy from the grid is partly going to cool the pack. In summary, battery cooling is an important but generally smaller energy consumer than either cabin heating or A/C. It's critical for battery longevity and safety, and manufacturers design thermal systems to minimise impact on range (for example, using chillers only when needed and otherwise relying on passive cooling).

Summary of Thermal Management Loads: Both HVAC and battery thermal management can significantly affect the effective energy per mile of an EV, especially outside mild weather. In winter, energy that could have propelled the car must instead go into heating the cabin and the pack. In summer, some energy goes into cooling the cabin and, to a lesser extent, keeping the battery cool. These auxiliary loads directly translate to reduced driving range. If an EV consumes, say, 0.20 kWh/km for propulsion at 21°C, that might increase to ~0.35–0.40 kWh/km at –7°C with heaters running [57]. In hot weather, the increase might be to ~0.25–0.30 kWh/km with A/C active. Thus, understanding and optimising these auxiliary uses is key to improving real-world EV efficiency.

Table 10. Energy consumption of HVAC and battery thermal management systems.

Function	Conditions	Typical Power Consumption (kW)	Energy Consumption (kWh/km)	Range Impact (%)
Cabin Heating (Resistance Heater)	Winter (–10°C to 0°C)	4–7	0.15–0.25	30–50%
Cabin Heating (Heat Pump)	Winter (–10°C to 0°C)	2–4	0.10–0.15	15–25%
Air Conditioning	Summer (30°C–35°C)	1.5–3	0.05–0.10	5–15%

Function	Conditions	Typical Power Consumption (kW)	Energy Consumption (kWh/km)	Range Impact (%)
Battery Heating (Pre-heating)	Winter (–10°C or colder)	4–8 (initial surge)	~0.05–0.15	~10–20%
Battery Cooling	Summer (≥35°C or fast-charging)	1–2	≤0.05	<5%

6.2 User Behaviour and Preferences

How drivers use climate control and thermal features has a big influence on real-world energy consumption. User behaviour – such as climate settings, preconditioning habits, and use of auxiliary heating – can either mitigate or exacerbate the impact of HVAC and thermal management on an EV's range.

Cabin Temperature Preferences: Most drivers tend to set their cabin to a comfortable temperature similar to a typical room. Surveys indicate that the vast majority of EV users prefer interior climates in the range of about 22–24°C (72–75°F). Most EV drivers select moderate cabin temperatures (around 22–24°C), as illustrated by a survey of user settings. Only a small fraction chooses extreme A/C settings below 20°C or above 25 °C, reflecting a common preference for comfort within a narrow band. This moderate range implies that in summer, people aren't often blasting the A/C at max cold (which would be <20°C cabin) and in winter, they're not overheating the cabin above 25°C. They generally aim for a pleasant mid-20s°C, which is good news for efficiency – extreme settings would consume more energy. Educating drivers to use reasonable climate settings can help preserve range: every degree of difference matters. For example, setting the heat to 19°C (66°F) instead of 22°C could save energy, though at some comfort sacrifice. In warm climates, keeping the A/C at, say, 24°C (75°F) instead of a colder 20°C (68°F) can reduce how often the compressor must run [63]. Automakers often include "Eco" climate models that limit HVAC power or adjust setpoints to be more energy-efficient, and informed drivers use these when they need to extend range.

Preconditioning Habits: Preconditioning means conditioning the car (cabin and/or battery) before driving, typically using grid power while the vehicle is plugged in. This practice is highly recommended by manufacturers, especially in extreme climates [57]. In cold regions, it has become routine for EV owners to remotely start heating their car in the morning while it's charging. For instance, many Norwegians, who often charge overnight, will time the cabin pre-heat for the morning so they get into a warm, defrosted car without using battery energy for that [64]. Doing so can save a considerable amount of range on the subsequent drive, as the battery doesn't have to supply the initial heating energy. A Norwegian research experiment measuring preconditioning in five popular EV models found that a typical preheat session lasted 15–45 minutes, drawing 3–8 kW at the start and later tapering to 2–4 kW as the cabin warmed up. The total energy used for preheating was about 2 kWh on average, with a worst-case of ~5 kWh in very cold conditions. Using grid power for this means that 2–5 kWh is not taken from the car's battery – effectively extending driving range by that equivalent amount (for context, 5 kWh could be 20–25 km of driving in winter). Consequently, a large share of EV owners in winter do preheat whenever possible. Similarly, in summer, pre-cooling the cabin while plugged in (or at least before driving off) is a common habit, though perhaps used with slightly less urgency since the range impact is smaller and a hot cabin, while uncomfortable, is not as safety-critical as an icy windshield. Still, many EV mobile apps have a "remote start A/C" button that users employ on hot days, so the cabin is cool when they begin driving.

Interestingly, new insights suggest that preconditioning behaviours are evolving. Traditional advice was to always use grid electricity in the morning to precondition (since it preserves battery range). However, research by SINTEF in Norway points out that this can create a strain on the electric grid during morning peak hours, for relatively little benefit if the driver doesn't actually need a full battery for a short commute [65].

They found that a lot of people preheat on cold mornings at the exact time when grid demand is highest (and electricity prices peak). Because the energy used for preheating is small in the grand scheme but concentrated at peak times, they recommend that, unless a driver truly needs 100% range, it may be better to preheat using the car's battery (having charged overnight) rather than drawing additional power from the grid at 7–8 am. In other words, if your daily driving only uses, say, 30% of the battery, using 5% of the battery to heat the car is fine and avoids extra grid load. This nuanced view is gaining attention in regions with high EV penetration and constrained grids. For the individual user, of course, preconditioning from grid power remains a convenience and range-maximising tactic, but these findings may inform future "smart charging" policies (like utilities incentivising off-peak conditioning or EVs themselves deciding whether to draw from battery vs grid based on grid status).

Use of Auxiliary Features: EV drivers often leverage auxiliary comfort features to reduce HVAC dependency. Heated seats and heated steering wheels are especially popular in winter. These devices warm the occupants directly and are highly efficient – they typically consume on the order of 50–200 W each, which is a fraction of the power required to heat the entire cabin. Many EV owners will thus turn on the seat and wheel heaters and set the cabin air temperature a bit lower to save energy. While exact data is not broadly published, it's widely accepted in the EV community that using seat heaters can significantly cut down on cabin heater usage. Automakers encourage this by including seat heaters even in lower trims in cold-weather markets, knowing it helps with range. Additionally, EVs have features like front and rear window defrost (essential for safety in winter). These are essentially resistive heaters on glass and do consume noticeable power, but usually for short durations. Users typically will defrost windows during preconditioning (again, ideally on grid power) so that once driving, they can keep HVAC in a more efficient recirculate mode rather than blowing damp cold air on a windshield. In hot weather, simple behaviours like using a sunshade or parking in the shade can reduce cabin heat buildup and thus A/C load – some EV owners pay attention to this, and some EVs even offer remote window venting or solar reflecting windshields to mitigate heat. User choices in clothing also matter: a driver dressed in a t-shirt in winter will likely crank the cabin heat higher than one wearing a sweater or heated jacket. Although individual habits vary, surveys and anecdotal evidence suggest that many EV drivers become quite energy-conscious and adapt their behaviour (within comfort limits) to maximise range – for example, tolerating a slightly cooler cabin or using "Eco Climate" mode on long trips in winter.

Table 11. User behaviour and preferences in HVAC usage.

Behaviour	Description	Prevalence (%)
Cabin Pre-heating	Regularly pre-heat the cabin during winter while plugged in	60–80% (Europe, northern United States (US))
Cabin Pre-cooling	Regularly pre-cool the cabin during summer while plugged in	30–50% (US, southern Europe)
Moderate HVAC Settings	Cabin temperature set to 22–24°C (72–75°F)	70–85%
Use of Heated Seats/Wheel	Regularly use heated seats/wheel to minimise cabin heating	50–70%
Awareness of HVAC Impact	Drivers are aware that HVAC significantly affects EV range	60–75%
Eco Mode HVAC Usage	Drivers frequently use Eco HVAC modes	40–60%

Frequency of Use: It's useful to note that not all drivers always use these features to the same extent. For instance, some EV owners in mild climates might rarely use heating or A/C, so their energy consumption is dominated by driving. Others, like those in Phoenix (very hot summers) or Montreal (very cold winters), will use climate control heavily for many months. User preference plays a role: one driver might prefer a cold cabin and rarely use A/C, whereas another might insist on 70°F year-round. That said, the majority aim for the aforementioned comfort range (around 22°C). Many EVs allow individual customisation like scheduling a daily departure with a target cabin temperature – uptake of this convenience is growing as people realise the benefit. A study encompassing driver surveys noted that educating users on efficient HVAC usage and tools like pre-conditioning can improve range consistency and alleviate range anxiety associated with using climate control [63]. As EVs become more common, there's an increasing awareness among drivers about these behaviours – it's part of the learning curve of transitioning from gas cars (where blasting heat has negligible fuel cost if the engine is warm) to EVs (where any HVAC use draws from your "fuel" reserve directly).

Seasonal and Climatic Variations in Consumption: The energy impact of HVAC and battery management varies strongly with season and climate. Cold winters and hot summers present opposite but equally important challenges for EV efficiency:

Winter (Cold Climate) Effects: Cold weather is notorious for cutting EV range. As noted, at 20°F (–7°C) with cabin heat on, range can drop ~40% or more [58]. Even at a milder freezing point (~0°C), drivers often see on the order of 15–25% range reduction [59]. In Norway and other northern European regions, winter range loss of 20–30% is commonly reported, and in extreme cold, it can be higher. A U.S. study by AAA found a 12% range reduction at 20 °F, even without cabin heat (due to battery internal effects), and up to 41% reduction with the heater running. In the most extreme climates, the impact can be severe: an NREL field study in Fairbanks, Alaska (with temperatures down to –40°F/C) observed range dropping by as much as ~69% for EVs stored outdoors in those conditions. (Notably, vehicles stored in heated garages fared much better, highlighting how mitigating cold soak is beneficial.) The cold also slows down charging – often tripling charge times at sub-freezing temperatures if the battery isn't preheated– which can indirectly increase energy use (longer time running battery heaters, etc.). Winter conditions involve not just low temperatures but also additional loads like defrosting windows and higher rolling resistance from snow or cold tires. All these factors together make winter the most demanding season for EV energy consumption.

Summer (Hot Climate) Effects: Hot weather has a more modest effect on EV range in comparison. At 95°F (35°C), AAA tests showed only about a 4–5% range loss with no A/C (vs 75°F) [58], stemming from minor battery efficiency changes. With A/C running at full blast, range loss averaged 17% at 95 °F [58]. Real-world connected car data similarly show minimal impact up to around 90°F (32°C) – just ~5% range loss – and then a larger hit (15–20%) in very high heat (~100°F), mainly due to A/C [60]. Importantly, most drivers don't notice a huge drop in summer range because the relative hit is small, and EV ranges have grown. However, specific scenarios can stress EVs: for example, a combination of 100 °F+ heat and high humidity (which forces the A/C to dehumidify heavily) and urban stop-go traffic (where energy per mile is low, making the A/C a bigger fraction of total draw) can push consumption much higher. Under such worst-case conditions, as the IEA reported, A/C could temporarily consume up to 40%–50% of the energy used by the vehicle [61]. This might occur in tropical climates or heatwaves. Additionally, if an EV is fast-charged repeatedly on a very hot day, the battery thermal system might run continuously to reject heat, drawing a few extra kW and possibly limiting power output if the pack nears thermal limits. Nevertheless, summer range reduction is typically much less pronounced than winter. For example, an EV that gets 300 km of range in spring might still get ~250–270 km on a hot summer day with A/C, whereas it might drop to 180–220 km on a frigid winter day with heat on.

Table 12. Seasonal impact of HVAC and battery management on EV range (% reduction vs. baseline).

(Typical private passenger EV, baseline at 20°C / 68°F)

Season	Cabin HVAC (%)	Battery Thermal Management (%)	Total (%)
Winter (-10°C)	30-50%	10-20%	40-60%
Spring (15°C)	5-10%	<5%	5-10%
Summer (35°C)	10-15%	<5%	10-20%
Autumn (10°C)	5-10%	<5%	5-10%

Shoulder Seasons & Temperate Climates: In spring and fall or in mild climates (e.g. coastal California, much of Western Europe's temperate zone), the outside temperature is near the battery's and humans' comfort optimum. In these conditions, EVs achieve their best efficiency – one study noted EV energy consumption is minimised around ~20°C ambient. Drivers may not need either heating or cooling, or only minimal use, so the range is close to the rated ideal. For instance, the difference in energy use between 20°C and 10°C can be significant: at 20 °C an EV might only use a few hundred watts for occasional A/C or battery cooling, whereas at 10°C some heating is usually running. This is why EV owners often observe that cool, dry weather in the ~15–25°C range yields the longest range per charge.

In summary, seasonal variation is a key factor for EV energy consumption. Winter can increase energy use per mile by 30–50% in many cases (combining both battery and cabin heating needs), while summer might increase it by 5–20% due to A/C (unless in extremely hot conditions). Such variations translate to different charging needs – for example, EV drivers in cold climates must charge more often or have larger buffers in winter. It also affects geographical differences: EVs in Nordic countries or the northern US inherently use more energy per mile on average than those in Southern California or Spain, due to the climate. Automakers respond to this by equipping vehicles in cold markets with features like heat pump HVAC, battery insulation, and heated components (seats, steering wheels, battery heaters), while in hot markets, ensuring robust cooling systems and perhaps offering tinted windows or solar-reflective glass to reduce cabin heat gain.

Table 13. Typical energy consumption share of HVAC & battery thermal management.

Season	Driving/Motor	Cabin Heating	Battery Heating	Other
Summer (35°C)	80%	12%	5%	2%
Winter (-10°C)	60%	30%	8%	3%

6.3 User key concerns

6.3.1 Range Anxiety Due to HVAC Energy Use

Driving range remains a major concern for EV users, significantly influenced by energy-intensive HVAC systems. In cold weather, cabin and battery heating can substantially reduce EV range due to high power demands. Telematics data indicates range reductions of up to 50% in severe cold conditions, meaning an EV capable of 300 km under moderate temperatures might achieve only half of that in freezing conditions [66]. Real-world tests by the Norwegian Automobile Federation confirmed that typical winter conditions (around 0°C) led to an average range reduction of 18.5% across various EV models, compared to official WLTP ratings [67]. Even greater range losses, over 30%, are reported at temperatures below –10°C [68]. Consequently, many drivers either plan additional charging stops or minimise heater use, highlighting the anxiety associated with climate control functions.

Summer conditions also challenge the range due to air conditioning (A/C) use, especially in hotter regions like southern Europe. Operating A/C at high settings in temperatures of 35–40°C can notably impact range, with some models projecting reductions of up to 40% in extreme heat [68]. However, real-world scenarios like an ADAC simulation suggest a somewhat lower impact: using about 12 kWh over 8 hours (around 16% battery depletion or ~64 km range loss), manageable but still notable [69].

A further element contributing to user anxiety is the unpredictability of HVAC-induced range changes. Many drivers expect consistent range performance, so sudden, climate-driven deviations can lead to confusion or disappointment if the cause is not communicated. European EV users have expressed surprise upon discovering the substantial impact cold weather has on driving range [67]. Thus, providing transparent and accurate range estimation that explicitly accounts for HVAC usage remains crucial. In summary, effectively managing HVAC-related energy consumption is essential for improving user confidence and satisfaction with EVs.

6.3.2 Cabin Comfort Challenges in Extreme Climates

European EV users prioritise cabin comfort in both winter and summer conditions, emphasising the need for robust and responsive climate control without compromising on range or convenience. In conventional vehicles, excess engine heat readily warms the cabin; however, EVs must generate heat directly from battery power, leading to challenges in rapid and efficient heating, particularly in very cold weather. Early EV models employing simple resistive heaters sometimes struggled to warm cabins quickly, causing concerns around inadequate defrosting and compromised comfort when drivers limited heater use to conserve range. Such scenarios are especially problematic in regions like Scandinavia or the Alps, where reliable heating is crucial for safety and comfort during prolonged sub-zero conditions [67].

Summer cooling, although generally effective in modern EVs using electric compressor-driven air conditioning systems, brings a related concern: drivers may hesitate to fully utilise A/C due to fears of significant range reduction, particularly in southern European regions experiencing increasingly intense heatwaves [69]. For professional drivers and fleet operators, cabin comfort directly influences productivity and satisfaction. Delivery vans (N1-class vehicles), frequently losing warm air due to repeated door openings, exemplify scenarios where standard HVAC systems struggle, leading to increased battery usage as heaters work overtime to maintain temperatures.

An additional comfort requirement is effective cabin pre-conditioning, which involves warming or cooling the interior while the EV remains plugged into the grid, thereby conserving battery energy for actual driving. Although most modern EVs feature remote-controlled pre-conditioning via smartphone apps, usability issues or concerns about battery depletion when unplugged can discourage regular use. Users strongly prefer seamless, grid-powered pre-conditioning to start trips in optimal comfort, significantly enhancing user satisfaction and preserving driving range, especially beneficial during harsh European winters or hot summers [70].

Overall, European EV drivers expect climate control systems to deliver rapid, reliable, and energy-efficient heating and cooling comparable to or surpassing combustion vehicles. Successfully addressing these expectations is essential for broad EV adoption, as an uncomfortable vehicle will remain unpopular regardless of its environmental benefits.

6.3.3 Energy Efficiency and Cost Considerations

Beyond range concerns, EV users and policymakers are increasingly focused on the overall energy efficiency of auxiliary systems such as HVAC. From an owner's perspective, energy used unnecessarily for heating or cooling equates directly to higher electricity costs and more frequent charging, a significant concern given Europe’s typically high and often tiered electricity prices. For commercial fleets, even a small daily HVAC energy excess per vehicle accumulates into substantial operational costs over time. Studies highlight that HVAC energy consumption can account for approximately 20% to 40% of total EV energy use under certain conditions, particularly extreme cold weather requiring constant heating [68]. Such significant energy allocation away from propulsion presents clear opportunities for improving efficiency, as energy saved in climate control directly translates into extended driving range.

Environmental sustainability further underscores the need for efficient auxiliary systems. EVs are marketed on their superior drivetrain efficiency and lower carbon footprint, especially as Europe's energy grid becomes greener. However, inefficient auxiliary loads diminish these advantages. For instance, while an EV motor might achieve efficiencies above 90%, using a resistive heater continuously at 1–2 kW significantly reduces the effective overall efficiency. Regulators and environmentally conscious consumers seek holistic efficiency improvements, not merely high drivetrain efficiency, but smarter energy management across climate control and other vehicle systems. The EU explicitly supports such efficiency advances through initiatives like the Horizon 2020 JOSPEL project, aiming for a minimum 50% reduction in cabin heating/cooling energy use and a 30% reduction in battery cooling demands via advanced thermoelectric and heat pump technologies [71].

Optimising HVAC systems not only reduces running costs for private owners but also improves operational logistics for fleet managers by extending intervals between charges and lowering electricity expenses. Moreover, minimising battery stress through efficient thermal management, such as adopting heat pumps and intelligent algorithms, indirectly enhances battery longevity, reducing maintenance costs. Ultimately, EV users desire technical solutions that deliver essential cabin comfort while minimising energy consumption, essentially heating and cooling smartly, not wastefully. Key technologies to achieve this include heat pumps, improved insulation, targeted heating/cooling, and advanced energy recovery methods, collectively maximising comfort while minimising energy draw.

6.3.4 Charging Convenience and Battery Thermal Management

European EV users place significant importance on battery thermal management due to its direct impact on charging convenience. One of the key advantages of EVs, rapid charging capability, can be compromised by suboptimal battery temperatures. Lithium-ion batteries charge more slowly when cold, as the BMS restricts charging rates to prevent lithium plating and battery damage [72]. This can notably extend charging times in winter conditions, potentially doubling expected charge durations, thus causing frustration and uncertainty for drivers planning longer trips, such as winter ski journeys or cross-border travel. Furthermore, cold temperatures can temporarily reduce regenerative braking effectiveness and power output, affecting overall driving experience, although typically to a lesser extent.

Conversely, overheating can significantly limit battery performance, particularly during repeated rapid charging or hot summer conditions. Early EV models without active thermal management, such as first-generation Nissan Leafs, demonstrated drastic reductions in charging speeds (known as "rapidgate") due to battery overheating. For example, a Norwegian test showed that the Renault Zoe, lacking liquid cooling, could only sustain charging at around 45 kW initially and slowed to 24 kW nearing 80% charge, resulting in charge times exceeding an hour. In contrast, vehicles with effective battery thermal management, such as the Audi e-tron 55, consistently maintain high charging rates, achieving a 10–80% SoC increase in approximately 27 minutes even in winter conditions [67]. These examples illustrate the essential role thermal management plays in meeting users' expectations for reliable and rapid charging across Europe's expanding fast-charging network.

To address these concerns, EV users strongly favour battery pre-heating before charging sessions and active cooling during high-load driving or charging. Modern EVs increasingly offer automated solutions, such as pre-emptive battery heating triggered when navigation identifies a fast charger destination, eliminating the need for manual temperature management. However, users remain mindful of potential energy trade-offs involved in battery preconditioning, expecting clear communication from vehicles regarding temperature-induced charging delays or additional energy use.

Ultimately, European EV users require smart, automated thermal management systems that consistently maintain optimal battery temperatures for charging and driving, minimising complexity and enhancing convenience. Effective battery thermal management not only ensures rapid and predictable charging but also maintains vehicle performance across diverse climatic conditions, significantly improving user confidence and satisfaction with EVs.

Having outlined the major user concerns, range anxiety, climate comfort, energy efficiency, and charging convenience, we turn to recommended solutions. The following section is structured in a two-column format, pairing each User Requirement with our Recommended Solution, and includes examples of state-of-the-art implementations in Europe's EV industry and research sector.

6.4 Recommended solutions

Table 14. Requirements and recommendations for public slow EV chargers, considering energy-consuming convenience functions

User requirements	Recommended solutions
<u>Minimise Range Impact of Cabin Heating/Cooling</u> Drivers need to preserve driving range even when using HVAC in extreme weather.	1. Adopt High-Efficiency Heat Pump Systems Heat pumps transfer ambient or waste heat into the cabin instead of generating it with electricity, achieving 2-4 times the efficiency (COP) of resistive heaters. Modern heat pumps typically use only 1-2 kW to provide the same heating output as 4-8 kW resistive systems, significantly reducing battery drain. At highway speeds, switching from resistive heating (~8 kW) to a heat pump (~2 kW) can reduce range loss from ~40% to ~10%. 2. Enhance Cabin Thermal Insulation Upgraded insulation, such as double-glazed windows, infrared-reflective coatings, and improved body insulation, reduces thermal transfer, minimising HVAC load. The EU's QUIET project showed that enhanced insulation combined with efficient HVAC increased EV driving range by 26% under both cold and hot conditions [73]. 3. Implement Targeted Heating for Occupied Zones Direct heating of localised areas (e.g., seats, floor mats, door panels) using infrared or surface heating consumes much less energy than heating the entire cabin volume. Ford engineers found that such solutions reduced HVAC energy demand by ~13%, resulting in approximately 5% more driving range during winter operation [70]. 4. Use Grid-Powered Cabin Pre-Conditioning Pre-heating or pre-cooling the cabin while the vehicle is plugged in (using grid power) improves comfort and preserves driving range, as the battery does not have to power the HVAC system at trip start. This feature is particularly valuable in extreme climates and is widely supported by modern EV platforms through mobile apps. Summary: European EV manufacturers are increasingly adopting heat pumps, advanced insulation, and localised heating to reduce HVAC-related energy consumption. These measures ensure that even in extreme weather (–10°C winter or 35°C summer), the energy used for cabin comfort is minimised, preserving battery capacity for propulsion. Backed by real-world results and EU initiatives, high-efficiency HVAC design is essential for extending range, improving efficiency, and enhancing the EV user experience.
<u>Maintain Cabin Comfort in Extreme Climates</u>	1. Enable Grid-Powered Pre-Conditioning Before Departure Pre-conditioning the cabin and battery while the EV is plugged in ensures comfort and preserves battery charge for driving. This feature should be

User requirements	Recommended solutions
Drivers require reliable cabin heating, cooling & defogging without delay, even in very cold or hot conditions.	seamlessly integrated with user-friendly scheduling and remote control via smartphone apps. For example, Ford's Scheduled Pre-Conditioning on the Mustang Mach-E and E-Transit allows intelligent control based on ambient conditions. At 0°C, pre-heating from the grid improves the available range by ~9% compared to battery-powered heating. 2. Use Localised Heating Features (Seats, Steering Wheel, Surfaces) Heated seats and steering wheels use only 50-100 W each, far less than a 3 kW air heater, and provide direct comfort, allowing lower cabin air temperatures without sacrificing user warmth. These features are energy-efficient and increasingly common in European EVs. "Eco climate" modes now prioritise such localised heating automatically to save energy. 3. Integrate Infrared and Surface Heating Panels Heating elements embedded in floor mats, door panels, and dashboards warm occupants through radiant heat, minimising air heating needs. Ford tested this approach in an E-Transit, achieving improved comfort and lower energy use, especially beneficial for delivery drivers who frequently open doors. 4. Ensure Fast Cabin Response and Automated Controls A fast-responding HVAC system that defrosts quickly and heats or cools rapidly enhances the user experience. This is achieved through a combination of resistive elements, for instance, heat and heat pumps for sustained efficiency. Features like automated rear defrosters and remote A/C start further improve convenience in extreme weather. Summary: Pre-conditioning and smart, localised thermal strategies allow EV users to enjoy both comfort and range. By leveraging grid energy, targeted heating, and passive/active cooling technologies, OEMs can deliver energy-efficient climate control that works seamlessly across all seasons
<u>Maximise Energy Efficiency of Thermal Systems</u> Users (and fleet operators) want HVAC and thermal management to use as little energy as possible, improving overall efficiency and reducing cost.	1. Integrate Waste Heat Recovery into Charging Thermal Loops During fast charging or high-load operation, the motor, inverter, and battery generate substantial heat. Instead of dissipating this energy, thermal loops should capture and redirect it to maintain battery or cabin temperature. Ford's implementation of such systems in its EVs shows that integrating drivetrain cooling with cabin heating reduces battery energy consumption and maintains thermal stability during charging. 2. Use Thermal Energy Storage to Reduce Battery Heating Load Phase-change materials (PCMs) can store excess thermal energy generated during charging or driving and release it later to regulate battery or cabin temperatures without drawing power from the battery. The EU Horizon 2020 QUIET project successfully demonstrated that PCM-based storage can shift thermal loads away from critical charging windows, improving energy efficiency. 3. Apply Smart Predictive Thermal Control for Charging Readiness Advanced HVAC control algorithms can precondition the battery based on route planning and ambient temperature. Predictive strategies (e.g., using navigation data to begin pre-heating before arrival at a fast-charger) ensure the battery is within its optimal temperature range to accept high-power charging, minimising charging time and maximising efficiency. Model predictive control has been shown to save 4-7% energy while maintaining comfort and readiness. 4. Leverage User Feedback and Interface Design Real-time HVAC energy consumption displays (e.g., in Nissan and Tesla vehicles) encourage drivers to choose more efficient settings, like using seat heaters instead of high cabin air temperatures. Summary: To optimise EV charging performance, manufacturers should focus on reusing waste heat, shifting thermal loads through storage, enabling predictive pre-conditioning, and leveraging user feedback and interface design. These strategies reduce charging time, lower energy consumption during

User requirements	Recommended solutions
	thermal regulation, and ensure that batteries operate within ideal temperature ranges, directly supporting faster, more efficient, and user-friendly charging experiences.
<u>Fast & Convenient Charging in All Conditions</u> Drivers want quick charging times and no hassle from battery temperature issues (cold “slow charging” or hot weather limits).	1. Implement Active Liquid-Based Battery Thermal Management Liquid-based heating and cooling systems with coolant loops and chillers ensure efficient heat transfer, crucial for maintaining optimal battery temperatures during fast charging and high-load driving conditions. 2. Pre-Condition Batteries Before Fast Charging Automatically pre-heating batteries to optimal temperatures (~20–30°C) prior to charging significantly reduces charging time. For instance, tests demonstrate that pre-conditioned batteries can charge nearly twice as fast (up to 150 kW) compared to cold batteries (approximately 50 kW at 0°C). Tesla’s "Navigate to Supercharger" and Ford's "Smart Fast Charging" features are effective examples of this approach. 3. Ensure Robust Cooling During High-Power Charging Effective cooling systems prevent overheating during rapid charging sessions (150+ kW), thus maintaining consistently high charge rates and reducing charge tapering. Vehicles without adequate cooling, such as early Nissan Leaf or Renault Zoe models, exhibit severely slowed charging, whereas vehicles like the Audi e-tron maintain consistent high charging speeds. 4. Incorporate Adaptive User Alerts and Feedback Clearly informing users about battery warming or cooling actions, such as estimated delays due to temperature adjustments ("Warming battery for optimal charging, estimated extra time: 5 minutes"), enhances trust and user satisfaction, reducing uncertainty during charging. 5. Explore Next-Generation Battery Technologies with Self-Heating Capability Emerging battery technologies, such as lithium-ion cells with integrated nickel foil heating elements, can rapidly self-heat (e.g., achieving ~60°C in under 30 seconds), enabling ultra-fast charging even at sub-zero temperatures. Though experimental, these could potentially eliminate charging slowdowns in cold conditions. Summary: proactive battery thermal management, combining active heating and cooling, battery pre-conditioning, user-friendly communication, and exploration of advanced battery technologies, ensures consistent, efficient, and rapid charging performance, greatly enhancing user confidence and EV usability across Europe's diverse climates.

In summary, cabin climate control (HVAC) and battery thermal management significantly affect EV energy consumption, particularly in extreme climates. Cabin heating in cold conditions can increase energy usage to 0.30–0.40 kWh/km, reducing range by 30–50%, whereas air-conditioning in hot weather typically has a more modest effect (around 5–15% range reduction). User behaviours, such as moderate temperature settings (22–24°C), preconditioning from grid power, and using auxiliary heating features (heated seats and steering wheels), play a crucial role in reducing these impacts. Advances in technology, notably heat pumps, improved cabin insulation, active battery thermal management, and predictive energy management, are increasingly mitigating these energy penalties. Effective integration of these user-centred strategies and technologies is essential for enhancing EV performance, user confidence, and broader adoption across diverse climates.

7 IDENTIFIED USER REQUIREMENTS IN EPOWERMOVE – CONNECTING THE THREE DEMOS

For the system design, the identified user requirements are classified as Technical (technology-related), Infrastructure (external to chargers), Functional (charging functions), and Application (mobile application for charging, including payment, not UI on the charger itself) requirements. Each demo has collected the user requirements in the previous task (T1.1) and classified them accordingly. These are discussed in D1.1.

As already discussed, the user requirements are defined by each demo based on the needs that various user groups and individuals brought to the table in the context of ePowerMove outreach. In this deliverable, D1.3, the requirements are aggregated to form the global ePowerMove community set of requirements for synergic architecture design, system design purposes, and to form a possible feedback loop.

In synergic architecture design, the common focus is on creating integrated and adaptable stand-alone solutions that will produce a bigger impact than if they worked independently. This emphasises the concept of 'functionality following form', with the solutions using its unique, individualistic design. Key principles include incorporating user-centric design for sustainability and adapting to changing use conditions. 'Function following form' highlights the ultimate use of available solutions in their operating environment in determining their final form.

System design principles are based largely on identified and integrated requirements set to guide the solution development process to fulfil the viewpoints of various user categories (e.g., general public, handicapped individuals, elderly people). It is a process to define the overall solutions and their integration to meet the functional and non-functional requirements.

When aggregating the full sets of user requirements, the path to design and deployment can be tracked for revision, refinement and problem-solving. This can be called a sustainable *feedback loop* of design.

7.1 Technical requirements

In the framework of technologies, several sub-domains emerged:

- EV as part of the V2G value chain,
- Reliability of technology.

The table below identifies the dependencies between demos.

Table 15: Technology requirements' sub-domains grouped by design principle and demos

Sub-domain	Topic	Design principle	Helsinki	Klagen-furt	Nicosia
EV as part of V2G	Pilot EVs to support AC V2G charging with easily manoeuvrable bidirectional charging cables	system	x		
Reliability	Stable and uninterrupted operation with a proper locking mechanism and load management	system		x	

There were also technical requirements that were related to other sub-domains, and these will be handled in the functional requirements chapter, namely, the user interface and financial topics.

7.2 Infrastructure requirements

Regarding the surrounding infrastructure of the charging stations, there were several relevant sub-domains:

- Guiding ("traffic signs") to the charging stations,
- Maintenance of the charging stations,
- Access to the charging stations

The table below identifies the dependencies between demos.

Table 16: Infrastructure requirements' sub-domains grouped by design principle and demos

Sub-domain	Topic	Design principle	Helsinki	Klagen-furt	Nicosia
Guiding/ Signs	Users' assigned parking slot close-by home and public charging stations are clearly marked and close to key POIs Clear signage and sufficient lighting for "EV Only" parking slots are supported by efficient measures to prevent ICE vehicles on EV charging slots	system	x	x	x
Maintenance	Maintenance-capable remote management system of charging infrastructure Winter maintenance service for the charging station and user interface full accessibility in all weather conditions	system, synergic architecture.	x	x	
Accessibility	Barrier-free access without any tripping hazards, spacious Access for vehicles with trailers ensured and subsidised for professional vehicles, N1 class	system	x	x	x

There were some sub-domains like the Protection against elements and Professional N1 category vehicles that are largely more relevant to extra-urban driving and charging, and specifically to DC fast charging stations, where the user may want to wait by the charging station or nearby for a short period of time to have sufficient SoC in their EV. It is worth noting that these topics are not directly relevant to this project and will not be discussed further. However, these topics will be made available for possible future reference.

- Protection against elements of the charging stations and users,
- Professional drivers/N1 category vehicles,
- Private home charging,
- Highway and extra-urban surroundings

7.3 Functional requirements

In this context, the functional requirements are related to the functionalities and user interface of the V2G chargers themselves rather than the user application; the application-related topics are covered in the next chapter below. In some cases, the user interface installed in the charger station may be rather limited since the majority of functionalities are implemented in the user application. Here, the following sub-domains were referred to:

- User interface (related to chargers),
- User-initiated settings (at large),
- Financial factors (transparency, compensation model),
- Car-sharing,
- Support services

The table below identifies the dependencies between demos.

Table 17: Functional requirements' sub-domains grouped by design principle and demos

Sub-domain	Topic	Design principle	Helsinki	Klagen-furt	Nicosia
User interface	Clear visual fault identification in the charger touch screen, it is to be fully operational, clear and readable in all weather conditions. All texts and icons to be horizontal, texts and instructions intuitive, sufficiently large using a simple font, and high-contrast, clear pictograms.	system, synergic architecture.	x	x	
	All functions to be accessible via smartphone with multi-lingual options. Audible signals and announcements provided. User profile shows prompts about system safety and long-term values. Information on V2G impacts on battery SoH to be accessible.	system, synergic architecture.		x	x
	Charging system links EV charging to renewable energy sources (RES) and emphasises green grid integration and UI to display when renewable energy is used or prioritised	system, synergic architecture			x
User-initiated settings	Charging automation to be user configurable, and allow setting of charging and/or discharging. Allowed to opt out of delayed charging or V2G sessions via a simple override	system, synergic architecture, feedback loop		x	x
Financial factors	Clear and transparent bilateral charging compensation model and its benefits. Price-dependent charging reflects dynamic tariffs and user-set thresholds, current prices shown, and clear information on compensation per kWh.	system, synergic architecture, feedback	x	x	x
	Various payment means are in use in addition to card payment, e.g., Apple Pay and Google Pay.	synergic architecture	x	x	
	Financial incentives for both V2G and delayed charging. Transparency of savings and payments users can expect when using flexible charging.	system, synergic architecture, feedback loop			x

Sub-domain	Topic	Design principle	Helsinki	Klagen-furt	Nicosia
Car-sharing service	Clear rules for connecting shared vehicles to V2G charging, e.g., a penalty when not plugged in after use.	system, feedback		x	
Support services	Human support, feedback connection, and fault response are available for users.	system, feedback	x	x	
	Clear accountability and responsibility between all actors are defined and made available for user-related issues	system, feedback	x		
	Charging system links EV charging to renewable energy sources and emphasises green grid integration and charging system display when renewable energy is used or prioritised	system, synergic architecture			x

In addition to these, there was one sub-domain that is more relevant to DC Fast charging than for this project: fixed charging cables of the charging station. AC slow charging work-in-progress uses mainly cables available in the EV.

7.4 Application requirements

Regarding the user application, there were some sub-domains to be covered:

- User interface (related only to mobile application),
- User settings (directly application related, e.g., usability),
- Smart charging,
- Financial factors (costs, payment means, charging pricing, reliability, compensation)

Table 18: Application requirements' sub-domains grouped by design principle and demo

Sub-domain	Topic	Design principle	Helsinki	Klagen-furt	Nicosia
User interface (Mobile app)	The App uses navigation and login that are simple and intuitive, with no automatic sign-off The App informs users of charger availability and location, and informs the user when charging is completed	system	x		x
	The App should be interoperable with other operators and suppliers' charging stations	system, synergic archit.	x		
User settings	The user can set the desired start and end of charging until the battery reaches the desired SoC	system, synergic archit.	x		
Smart charging	The demo platform includes visual elements on the environmental benefits of Smart charging to charge EVs when electricity is at its cheapest or when the supply is greatest	system, synergic archit.	x		x

Sub-domain	Topic	Design principle	Helsinki	Klagen-furt	Nicosia
Financials	The App shows all fees upfront, warns of roaming charges, and gives an accurate payment summary Secure automatic payments and billing	system, synergic archit.	x		

8 CONCLUSIONS

Drawing on co-design workshops across three demo sites, large-scale online discourse analysis, and literature review, this study distils actionable end-user requirements and recommendations for public slow-charging.

First, public perceptions of bi-directional charging are nuanced: users acknowledge grid and resilience value yet often prefer V2H over V2G, citing range anxiety, battery wear, compensation, and interaction complexity. Design responses should include explicit user control of charge/discharge thresholds, transparent real-time price signals, and low-friction participation scheduling.

Second, physical charger design must prioritise inclusive ergonomics and accessibility (readable displays, manageable cable weight/height, safe and well-lit bays) while integrating into streetscapes with compact, modular hardware. Needs vary across private drivers, N1 light-commercial users, women, and drivers with disabilities; multi-connector capability, status indicators, and tamper-resistant features consistently improve usability.

Third, overnight publicly-accessible charging is a dominant pattern, especially where private parking is scarce, but its uptake is limited by parking scarcity, safety, and pricing opacity. Interventions should combine residential-adjacent siting, improved lighting/surveillance, and transparent time-of-use tariffs; storage coupling can mitigate local grid strain.

Fourth, energy-consuming convenience functions—notably HVAC and battery thermal management—materially affect range, particularly in winter. Heat-pump adoption, predictive pre-conditioning, and user-facing eco-modes (with clear feedback) can reduce penalties while preserving comfort.

Fifth, the user requirements of the three demo cities were divided into four layers: Technical, Infrastructure, Functional, and Application. Technical priorities include AC-V2G readiness, stable locking/load management, and lightweight bidirectional cables. Infrastructure priorities include—residential-adjacent overnight siting, good lighting/CCTV, clear EV-only signage/wayfinding, barrier-free access (aisle width, inlet height), and remote maintenance/winter service. Functional priorities include—readable all-weather UI (high contrast, optional audio), multilingual phone access, low-friction scheduling with overrides, transparent V2G compensation, and clear fault reporting. Application priorities include—simple navigation/login, real-time availability and completion alerts, roaming, SoC and start–end time settings, intelligible smart-charging visuals, upfront pricing, and multiple payment options.

Overall, Deliverable D1.3 offers a comprehensive foundation for user-centric public slow-charging infrastructure design. By translating nuanced user requirements into actionable design principles and technical recommendations, this document directly supports the ePowerMove objective of creating inclusive, efficient, and scalable charging systems. The findings serve as a critical input for the design activities in WP2 and offer strategic guidance for future deployment and policy considerations.

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