World Electric Vehicle Journal

MDPI

Article

Comparative Evaluation of Electric Vehicle Charging Scenarios and Battery Capacities Using Driving Pattern Data in Oman

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Abstract

Charging availability and battery capacity both determine whether drivers of current internal combustion engine vehicles can switch to electric vehicles (EVs). This study evaluated the charging scenarios and battery capacity required to meet the driving profiles collected for Muscat Governorate. The state of charge (SoC) of each profile was calculated after every trip for battery capacities from 20 kWh to 110 kWh under eleven charging scenarios. The scenarios combined home charging (none, Mode-2 at 3.1 kW or Mode-3 at 7.4 kW) with semi-public charging at the workplace on weekdays or public charging at shopping destinations on weekends, at 7.4 kW, 23 kW or 50 kW. A profile was counted as eligible when the SoC remained at or above 20% during every trip and at or above 80% at the start of each day. The driving share was defined as the percentage of eligible profiles, while the elbow capacity was defined as the battery capacity beyond which further increases produce negligible improvements in driving share, indicating that the curve approaches asymptotic behavior. Mode-2 home charging alone (S1) limited the driving share to 21.43% on weekdays and 26.98% on weekends, regardless of battery capacity. Combining Mode-3 home charging with workplace charging (S5, S8 and S11) reached 96.03% at 20 kWh on weekdays. Adding Mode-3 home charging to workplace charging at 7.4 kW (S3 → S5) reduced the elbow capacity from 70 kWh to 30 kWh. Raising the semi-public/public charging power from 23 kW to 50 kW did not change the driving share under either scheme. Weekend driving set the capacity requirement: a 90% driving share required 40 kWh on weekends against 20 kWh on weekdays (scenarios 5, 8 and 11). For weekday and weekend driving schemes, to achieve a 90% driving share, a 40 kWh battery capacity is recommended, considering that Mode-3 (7.4 kW) charging is implemented at home, at the workplace, and at public locations (S5). Within these technical-feasibility assumptions, the results suggest that Oman's charging infrastructure policy could prioritize a dedicated combined charging approach of AC-mode charging at home and at semi-public/public locations.

Keywords: electric vehicles; state of charge; driving share; charging mode; battery capacity; charging scenarios

Academic Editors: Yanbo Ge, Ching-Ming Lai and Sanchari Deb

Received: 30 September 2026
Revised: 12 November 2026
Accepted: 24 November 2026
Published: 27 November 2026

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1. Introduction

There is no doubt that vehicles are one of the most common modes of passenger road transportation in the world nowadays, as approximately 1.6 billion vehicles are currently in use worldwide [1], of which only about 5% were electric at the end of 2025 [2]. Needless to say, this large number of ICEVs results in equally large amounts of CO_2 emissions (around 3 billion metric tons) globally, as reported in 2015 [3]. This represents roughly 8% of the 36.3 billion metric tons of CO_2 emitted globally from fossil fuels and industry in the same year [4]. The danger of CO_2 emissions arises from the fact that they directly account for around 80% of global warming [5]. An obvious solution to this issue is to transition to electric vehicles (EVs), which are powered by one or more electric motors and therefore produce no tailpipe CO_2. According to their dependence on electric motors to provide the required propulsion power, EVs can be split into four main types:

(i) Battery electric vehicles (BEVs): These are fully dependent on electric motors for mobility, powered by a rechargeable battery pack, and hence have no ICE, do not require any fossil fuels, and produce no tailpipe emissions. Such EVs are charged directly by an external power source (i.e., an electrical charging station).

(ii) Plug-in hybrid electric vehicles (PHEVs): They have both a smaller rechargeable battery than BEVs and an ICE. This allows for dual driving modes, where the vehicle can either run on fossil fuel in ICE mode or on battery power in electric mode. As a result, these EVs are 'charged' both electrically (using electrical charging stations) and by fossil fuel stations.

(iii) Hybrid electric vehicles (HEVs): This type of vehicle includes a non-rechargeable battery in addition to an ICE. The term 'non-rechargeable' means it cannot be recharged directly using an electrical charging station. Instead, it is charged by the coupled generator powered by fuel combustion in the ICE and is therefore often referred to as a self-charging hybrid vehicle.

(iv) Range-extended electric vehicles (REEVs): These are driven entirely by one or more electric motors, powered by a rechargeable battery pack, but additionally include a small onboard internal combustion engine that acts solely as a generator to recharge the battery when its charge is depleted. Unlike HEVs, the ICE in an REEV is never mechanically coupled to the wheels and serves only to extend the driving range. As a result, these EVs are charged primarily electrically (using charging stations) and by fossil fuel stations for the range-extending generator. The power components and charging methods of the four types are presented in Figure 1.

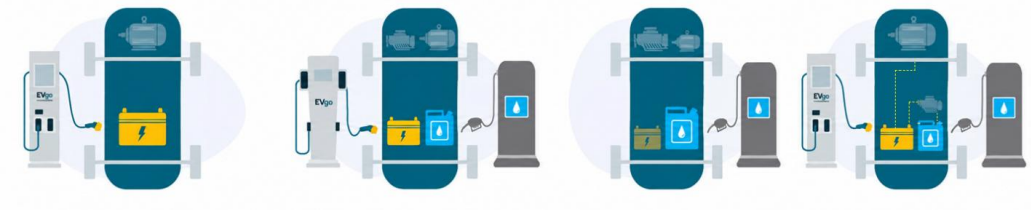


Figure 1. Power components and charging methods of BEVs (**left**), PHEVs (**middle left**), HEVs (**middle right**), and REEVs (**right**) [6].

In light of rapidly rising CO_2 emissions, EVs have been heavily marketed as a potential solution in recent years. The global market share of EVs has risen steeply in recent years. EVs accounted for roughly 4% of new car sales in 2020 [7]; electric cars exceeded 20% of global sales for the first time in 2024 and reached approximately one-quarter of all new cars sold worldwide in 2025 [8]. Despite the rapid worldwide diffusion of EVs, as

https://doi.org/10.3390/wevj17120629

evidenced by their significant market growth, EV adoption remains hindered by several factors.

Kim et al. [9] conducted a comprehensive study of the factors affecting EV diffusion in the Korean market. They identified five main obstacles that could slow EV diffusion: high cost, insufficient vehicle capabilities, charging concerns, insufficient EV-related policies, and limited public perception. They concluded that charging concerns were the dominant factor, accounting for 32.4%. When this conclusion is paired with conclusions from other similar studies [10–12], which, combined, analyzed the factors impacting EV diffusion across 30 countries in total around the world, it can be concluded that charging concerns are the most obstructive factor that affects EV diffusion. These charging concerns, also often referred to as range anxiety (a generic term that collectively describes the fear of running out of charge before reaching the designated destination or the closest charging station), include concerns due to limited driving ranges (especially when combined with the lack of availability and/or the poor distribution of charging infrastructure), as well as the long charging periods required as compared to fueling periods for ICEVs. Such anxiety can be attenuated by increasing the number of public charging stations, as suggested by [13,14], or by upgrading their charging speeds, as suggested by Illmann and Kluge [15]. In addition, accelerating research on battery technology can produce higher-capacity batteries at lower prices. This approach has been shown to positively affect EV diffusion [16]. If adopting such an approach is difficult, selecting a battery capacity that meets individuals' needs is still essential.

Since charging-related concerns were proven to be the most dominant factor facing the diffusion of EVs, researchers have started focusing on battery capacity and charging infrastructure whenever the diffusion process is analyzed or simulated. Upon pairing them with the state of charge (SoC) (a parameter that provides an indication of the energy level stored in an EV battery expressed as a percentage of its capacity) and the driving share (DS) (the percentage of current ICEV drivers who can theoretically shift to an EV), researchers were able to determine the relationship between the charging system and EV diffusion. For instance, Gnann et al. [14] simulated and assessed EV (BEV and PHEV) diffusion in the US and Germany by proposing different charging systems and observing their corresponding effects on the DS using surveyed daily driving profiles. They found that a DS of 65% can be achieved with relatively small battery capacities (<10 kWh) when BEVs can charge only at home in both the US and Germany. For PHEVs, more than 60% of drivers in these two countries could complete 80% of their driving profiles with a 10 kWh battery, given the same limited charging infrastructure. These findings show that EV diffusion in the US and Germany is quite promising, even with a relatively weak charging infrastructure. However, these findings derive from temperate, high-income contexts; their transferability to Oman is uncertain given its hot climate, which affects both battery range and air-conditioning load, its high rate of private garage ownership, and the prevalence of large SUVs.

Oman has recently committed to a national EV strategy with staged adoption targets and a mandate for charging provision at fuel stations. As part of its net-zero-by-2050 strategy, the Ministry of Transport, Communications and Information Technology (MTCIT) targets electric vehicles constituting a substantial share of new light vehicles by 2035–2040, with a full transition to zero-emission vehicles by 2050 [17]. This strategy sets a clear decarbonization trajectory for the vehicle sector, targeting a reduction in vehicular CO_2 emissions from a 2025 baseline of 102 million tonnes to zero by 2050, with a staged reduction of approximately 18% by 2030, 38% by 2035, 64% by 2040, 86% by 2045, and 100% by 2050 [17]. This transition now requires robust, evidence-based data to guide which charging configurations and battery capacities to prioritize. This study estimates the share of current driving profiles in Muscat that an EV could serve under different charging

arrangements and battery capacities, as one input to charging-infrastructure planning. The main contributions of this study are highlighted below:

- To the authors' knowledge, this study is the first assessment of the battery capacity and charging provision required for an electric vehicle transition in Oman, based on recorded driving profiles and national charging regulations, including the two-hour limit on Mode-2 charging from a domestic socket-outlet, which restricts each home session to 6.2 kWh. Findings from other countries are only partially applicable [18], as they are based on different travel patterns and charging regulations.
- Oman's progress toward its Vision 2040 objectives is driving a significant transformation in the transportation sector, particularly through the increasing adoption of electric vehicles (EVs). This study's findings will provide critical guidance for decision-makers in identifying the most appropriate charging infrastructure to meet the nation's growing demand.
- Communities in Oman often face the question of which battery capacity best meets their driving needs. This study offers a comprehensive guide for selecting the optimal battery capacity by assessing the required battery capacity. The concept of 'elbow capacity' is introduced to indicate the point at which increasing battery size no longer affects the driving cycle of individuals.

2. Electric Vehicle Charging Systems and Standards

The charging of electric vehicles can be done at (i) domestic (private) places, e.g., charging at home, multi-dwelling buildings or business premises; (ii) semi-public places, which are accessible only to a specific group of users, such as workplaces, hotels, universities and hospitals; or (iii) public places, which are accessible to all EV users, such as roadside charge points, public parking areas, service stations, shopping malls, supermarkets and restaurants. Whatever the location, energy is delivered to the vehicle by one of three methods: inductive charging, conductive charging or battery swapping (Figure 2). Conductive charging is further divided into on-board (AC) and off-board (DC) charging, and battery swapping into side, rear and bottom swapping according to where the battery pack is removed from the vehicle.

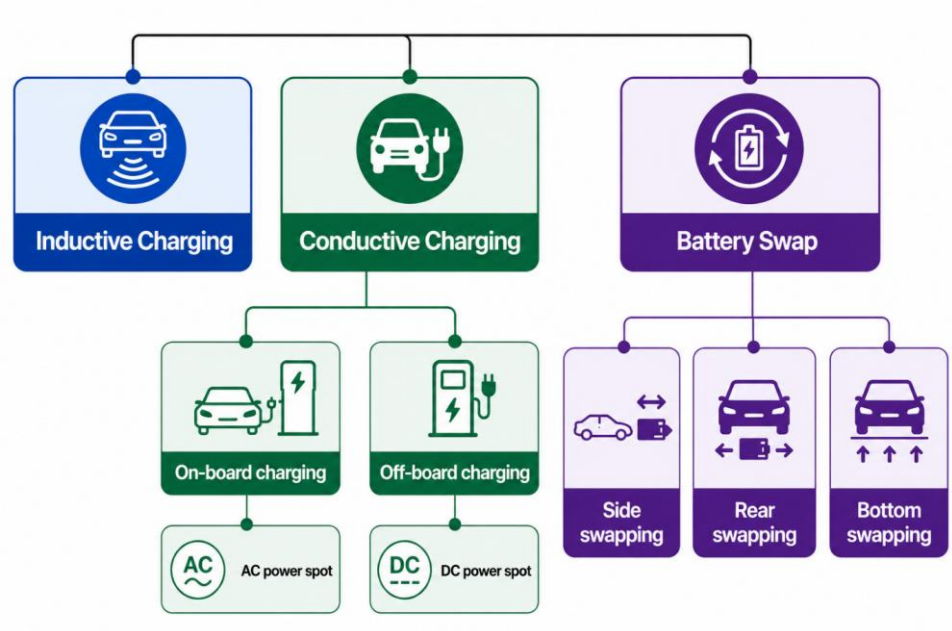


Figure 2. Layout of EV charging methods.

Method 1: Inductive Charging

This method uses electromagnetic induction between two coils to enable charging. It is also known as wireless power transfer (WPT). This charging mode enables safe, convenient EV recharging via standard coupling technology, even while the vehicle is in motion [19]. Despite these benefits, this technology has major drawbacks: generally weak inductive power transfer and a limited air-gap range between the transmitter and receiver coils. The air gap should be in the range of 20–100 cm for efficient power transmission [20]. In addition, eddy current loss is another issue in WPT if the transmitter coil is not turned off. Information transfer between the transmitter and the EV should be real-time, which means communication latency may occur [21].

Method 2: Conductive Charging (CC)

This type of charging requires an electrical connection between the EV and the charging inlet. It provides vehicle-to-grid (V2G) technology that helps reduce losses, maintain voltage levels, prevent power loading, and provide reactive power compensation by using the vehicle's battery [22]. However, V2G can negatively impact battery lifespan because frequent charging and discharging shorten it. The rate at which charging adds range to the EV depends on the vehicle, the battery energy capacity, the type of electric vehicle supply equipment (EVSE), and the size of the vehicle's internal charger. The International Electrotechnical Commission (IEC) has defined four modes (see Table 1) of conductive charging (IEC 61851-1) by considering some parameters such as the kind of power received by the EV (AC or DC), the voltage levels, the presence or absence of grounding and control lines, and the presence and location of the protection device. The Society of Automotive Engineers (SAE) developed the J1772 standard levels, which cover the general physical, electrical, and performance requirements for EV charging systems used in North America. Accordingly, the EV charging system has been classified into three levels, as listed in Table 1.

Table 1. The European and US EV charging infrastructure.

Type/Standard	Phase (Power Source)	Supply Voltage	Max. Current	Power Output	Remarks & Applications	Ref.
Level 1—SAE	1-PH (AC)	120 V	16 A	1.9 kW	Often called "trickle" or "emergency" charging; standard cable included with EVs; uses home outlet.	[23,24]
Level 2—SAE	1-PH (AC)	208–240 V	40–80 A	Up to 19.2 kW (Typically 12 kW in real-world use)	Most popular for home and public overnight charging; uses J-plug (SAE J1772).	[23,24]
Level 3—SAE	Direct Current (DC)	200–1000 V	500 A	Up to 350 kW	Uses CCS Combo 1; ideal for highways and rapid recharging during short breaks.	[23,24]
Mode-1-IEC	1-PH or 3-PH (AC)	230 V (1-PH)/400 V (3-PH)	16 A	Up to 3.7 kW	No communication between EV and grid; prohibited in many countries due to lack of shock protection.	[24]
Mode-2-IEC	1-PH or 3-PH (AC)	230 V (1-PH)/400 V (3-PH)	Up to 32 A	7.4 kW (1-PH)/22 kW (3-PH)	Uses an in-cable control and protection device (IC-CPD) for safety; semi-fast charging.	[24]
Mode-3-IEC	1-PH or 3-PH (AC)	230 V (1-PH)/400 V (3-PH)	Up to 63 A	Up to 43.5 kW	Standard for regular AC charging in Europe; requires a dedicated	[24]

				(Commonly 22 kW in real market)	charging station (wall box) with digital communication.	
Mode-4-IEC	Direct Current (DC)	200–1000 V	150–500 A	Up to 350 kW (or higher)	Off-board DC fast charger (CCS Combo 2); includes robust safety features and real-time monitoring.	[24]

Both Level 1 and Level 2 use the onboard charging (OBC) concept, in which the supplied AC power and the energy conversion are carried out through an onboard battery charger device. The charging rate in such a concept is strongly dependent on the AC plug/cable's current capability and the OBC's power rating. Due to lower power transfer, a larger battery capacity is required, which could add additional weight to the vehicle [25]. Therefore, it requires a longer charging period than the off-board charging configuration. DC charging is considered a fast-charging solution. The charging capability is much higher than that of OBCs, resulting in less time to fully charge the vehicle.

Method 3: Battery Swap

Conductive or inductive charging may not suit heavy-duty EVs on tight schedules; for example, short charging periods require very high charging rates. Although conductive charging can handle very high charging power levels, batteries may become overstressed, leading to degradation in performance and cycle life. To address this challenge, battery swapping appears to be the optimal solution. Swapping stations require much more complex, expansive, and expensive infrastructure than conductive or inductive charging. Each swapping station requires a very large storage area, which might not be available in certain areas.

Of the charging methods reviewed above, this study focuses exclusively on conductive charging, as it is currently the dominant and most widely deployed technology and forms the basis of the charging infrastructure being introduced in Oman. Inductive charging and battery swapping are therefore not considered further. Within conductive charging, the IEC charging modes (Table 1), as applied in Oman's national guidelines [26], are adopted to define the charging scenarios analyzed in the following sections.

3. Research Methodology

The research methodology adopted in this study follows a scientific approach and consists of four sequential phases, as shown in Figure 3.

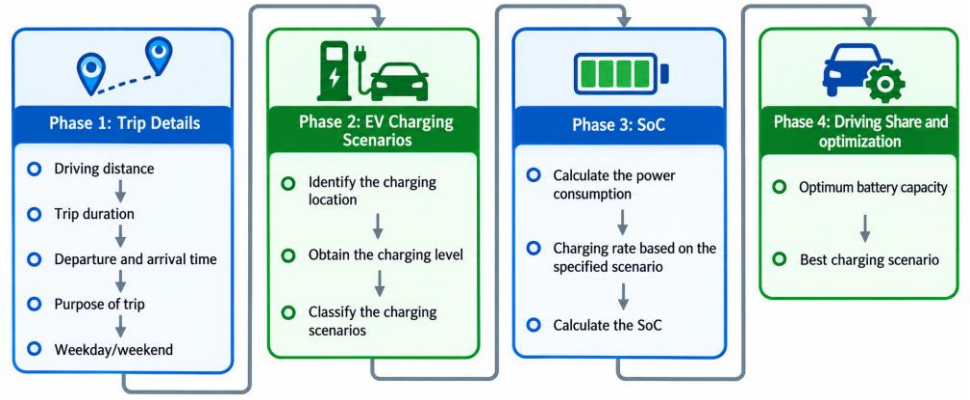


Figure 3. Research methodology phases.

In Phase I, the questionnaire was purpose-designed for this study and captured several categories of information for each respondent. Demographic and licensing details were recorded first, comprising year of birth, gender, educational level, employment

status, and year of driving-license issuance. Respondents, who are current internal-combustion-engine-vehicle (ICEV) drivers, then reported their driving behavior, including self-declared driving style, annual driving distance, and monthly fuel consumption. Daily and weekend driving distances were collected separately and disaggregated by speed band (below 80, 81–100, and 101–120 km/h). For each of the weekday and weekend schemes, a driving profile was obtained giving trip duration and the distance traveled within each speed band, from which trip distances and durations were established.

Trip distances and durations were self-reported by respondents and subsequently cross-checked against corresponding Google Maps (https://www.google.com/maps) routes to assess their plausibility. In the present study, the questionnaire was distributed to respondents of both genders aged between 20 and 60 years, drawn from Muscat Governorate, with the sample structured to reflect the area's demographic distribution. Of the 700 questionnaires returned, 323 were excluded because the weekday or weekend trip record was incomplete and 135 because the reported distances and durations could not be reconciled with Google Maps, leaving 242 complete, validated responses. A further 116 of these provided similar or near-identical information and were removed, so 126 distinct respondents provided complete weekday and weekend profiles. All driving shares are percentages of these 126 profiles under each scheme, so one profile corresponds to 0.79 percentage points.

After analyzing the data from the questionnaires, the trip details in terms of the daily driving distances and trip duration during both weekend and weekday driving schemes for each driver were obtained, as well as driving style, parking places, and the available parking period. To assess the eligibility of a vehicle for use during a driver's specified driving trip, the state of charge (SoC) parameter *must* be determined. State of charge is a relative quantity that describes the current battery level at a given moment [27] and is used for human–machine interaction and internal vehicle system control [28]. A fully charged battery has an SoC of 100%, while a fully discharged battery has an SoC of 0%. If the state of charge for a given battery falls below zero at any point during the day, it means the EV has run out of charge, and its driver can no longer fit it into their daily driving profile. In other words, the driving distance of that trip was longer than the electric driving range of the EV. *SoC* was calculated according to Equation (1) below:

$$SoC_{(t)} = 100 \times \frac{E_{(t)}}{C} \quad [\%] \tag{1}$$

where $E(t)$ is the energy stored in the battery in kWh. It is calculated after every trip and parking period following Gnann et al. [14]:

$$E_{(t+\Delta t)} = \begin{cases} E_{dis} = E_{(t)} - d_{\Delta t}\, c_{size}, & while\ driving\ (Discharging) \\ E_{ch} = \min\{[E_{dis} + P_{loc}\Delta t_{ch}, C]\}, & while\ parked\ \ (Charging) \end{cases} \tag{2}$$

where Δt_{ch} is the charging period available at the semi-public/public location, and the initial condition is E(0) = *C*. E_{dis} is the energy remaining after discharging in kWh while E_{ch} is the energy regained after charging in kWh. $d_{\Delta t}$ is the distance in km covered during a period of time $t + \Delta t$ in hour, c_{size} is the vehicle energy consumption in kWh/km that depends on the car size, and P_{loc} is the available charging power at a given location, in kW (determined by the charging mode). *C* is the usable (net) battery capacity.

Battery capacity (*C*) varies with EV category, from small urban models to large SUVs [29–31]. Based on the vehicle specifications listed in the EV Database [32], this study considers battery capacities between 20 kWh and 110 kWh, grouped by EV category as shown in Table 2.

Table 2. Range of battery capacity (*C*) in terms of EV category.

EV Category	Approximate Usable Capacity
Small urban EV	21–40 kWh
Small/compact EV	40–60 kWh
Medium family EV	60–85 kWh
Large SUV/luxury EV	85–110 kWh
Very large/long-range EV	110–141 kWh

Secondly, c_{size} was set to a constant value of 0.239 kWh/km for all battery capacities. This value corresponds to the real-world energy consumption of a large battery electric vehicle. The regression of real-world consumption on battery capacity reported by Weiss et al. [29] gives 0.239 kWh/km at 110 kWh, which is the upper limit of the Large SUV/luxury EV category in Table 2; the size-dependent state-of-charge models from which Equation (2) is taken also assign 0.224–0.251 kWh/km to large battery electric vehicles [33,34]. The value is 14% above the real-world mean consumption of battery electric passenger cars in Europe, 0.21 ± 0.04 kWh/km [35], and sits inside the 0.230–0.249 kWh/km range of combined US EPA ratings for current large three-row and luxury SUVs [36]. The value was adopted for two reasons: it exceeds the consumption of the small and medium vehicles in Table 2, so it is conservative, and SUVs are the dominant light-duty vehicle class in Oman [37]. Charging losses between the grid and the battery are neglected, so P_{loc} is taken as the power delivered to the battery.

The hot climate of Oman was also considered. Measurements of a vehicle operating at 43 °C in Kuwait extrapolate to a summer consumption of 0.246 kWh/km, roughly 32% above the winter value for the same vehicle [38]. That summer figure is only 2.9% above the 0.239 kWh/km adopted here and lies inside the 0.224–0.251 kWh/km band assigned to large battery electric vehicles by the models cited above, so the effect of the Omani climate is already embedded in the consumption range used. The power consumption values stated above are calculated for real-world driving cycles covering different speed bands [29,35,36]. The speed bands in this study (24.8% below 80 km/h, 24.5% at 80–100 km/h, and 50.0% at 100–120 km/h) sit within those of the previous studies, and Weiss et al. [29] reported that 0.239 kWh/km is suitable for a 110 kWh battery capacity, which is the upper limit of this study.

If the EV is in use ($d_{\Delta t} > 0$), the battery will be in the discharge process to provide the required energy for driving the distance $d_{\Delta t}$. Otherwise, if $d_{\Delta t} = 0$, the battery will be in the charging process for a period of time (Δt) where $P_{loc} > 0$. The P_{loc} of this study was determined using the designated charging mode at the specified locations.

Oman does not use the US charging-level classification as its primary reference for EV charging because the US system is based on North American electrical standards, in which Level 1 charging typically uses 120 V. In contrast, Oman operates on a 240 V single-phase and 415 V three-phase electrical supply at 50 Hz. Accordingly, Oman follows the IEC charging-mode classification in its national EV charging regulations (Table 3). According to the Authority for Public Services Regulation [26], Oman prohibits Mode-1 charging because it lacks the current limitation and protection features required for safe EV charging. Standard domestic socket-outlets in Oman are generally intended for AC loads up to 13 A, so Mode-2 charging is allowed only for occasional use, limited to 13 A, single-phase operation, and no more than two consecutive hours.

The use of extension cables and conversion adapters is also not permitted. For domestic Mode-3 installations, stand-alone chargers of up to 32 A can be used, giving typical charging powers of about 3.7 and 7.4 kW on a single-phase supply. Oman's guideline specifically recognizes domestic stand-alone Mode-3 chargers up to 32 A, corresponding to approximately 7.4 kW at 240 V, single-phase. For semi-public and public places, Mode-

3 typically operates at 32 A, corresponding to approximately 23 kW at 415 V, three-phase. Mode-3 charging in Oman is also limited to one-way charging, meaning that vehicle-to-grid (V2G) operation is not currently allowed. For Mode-4, it is better not to assign a fixed current, because the DC current depends on the charger's output voltage and rated power. Oman defines Mode-4 as DC fast charging, typically starting at 50 kW and above, with the charger permanently connected to the AC grid and converting AC to DC before supplying the vehicle battery. Mode-4 is used for DC fast charging, and V2G operation is similarly not permitted for this mode.

Table 3. EV charging infrastructure appropriate for Oman [kW].

Charging Level	**Domestic (Private)** *Charging at Home*	**Semi-Public Places** ***Places That Are Accessible to a Specific Group of Users, Customers, or Employees. Examples Include Workplaces, Hotels, Universities, and Hospitals.***	**Public Places** ***Places Where EV Charging Stations Are Generally Accessible to All EV Users Without Requiring Membership in a Particular Organization. Examples Include Public Parking Areas, Service Stations, Municipal Parking Facilities, Transport Hubs, Shopping Malls, and Supermarkets.***
Mode-2 *(1-PH, 240 V AC, up to 13 A)*	up to ≈3.1 kW *For incidental domestic charging. Not more than two consecutive hours*		
Mode-3 *(1-PH, 240 V AC, up to 32 A)*	3.7–7.4 kW *Standard domestic—typical*	3.7–7.4 kW	3.7–7.4 kW
Mode-3 *(3-PH, 415 V AC, up to 32 A)*	-	22–23 kW	22–23 kW
Mode-4 *3-PH, 415 V AC input; DC output to EV*		Typically ≥50 kW	Typically ≥50 kW

To fully understand EV charging behavior in Oman and the effects of charging infrastructure and battery capacity on it, 11 charging scenarios were identified for both weekday and weekend driving schemes. These scenarios represent all possible combinations of (i) domestic charging, in this study represented by charging at home only, in which the charging station operator (CSO) is the house owner themselves, and (ii) charging away from home, which is represented on weekdays by semi-public charging at the workplace, where the charging station operator is the employer, and on weekends by public charging at shopping centers, supermarkets, restaurants and similar places, where the CSO is the owner of these places. Table 4 summarizes the identified charging scenarios.

Table 4. Charging scenarios considered for the study.

Weekday Driving Scheme		**Charging at Semi-public/public Places** *Charging at semi-public places. Charging stations are available at workplaces where the charging station operator is the employer.*			
		No Charging	**Mode-3 (7.4 kW)**	**Mode-3 (23 kW)**	**Mode-4 (50 kW)**
Charging at Home *Charging Station Operator (CSO) is the house owner*	**No Charging**	-	Scenario 3	Scenario 6	Scenario 9
	Mode-2 (3.1 kW)	Scenario 1	Scenario 4	Scenario 7	Scenario 10
	Mode-3 (7.4 kW)	Scenario 2	Scenario 5	Scenario 8	Scenario 11
Weekend Driving Scheme		**Charging at Semi-public/public Places** *Charging at public places. Charging stations at shopping centers, supermarkets, restaurants,* etc., *where the CSO is the owner of these places.*			
		No Charging	**Mode-3 (7.4 kW)**	**Mode-3 (23 kW)**	**Mode-4 (50 kW)**
Charging at Home *Charging Station Operator (CSO) is the house owner*	**No Charging**	-	Scenario 3	Scenario 6	Scenario 9
	Mode-2 (3.1 kW)	Scenario 1	Scenario 4	Scenario 7	Scenario 10
	Mode-3 (7.4 kW)	Scenario 2	Scenario 5	Scenario 8	Scenario 11

The suitability of each charging scenario and battery capacity was quantified by a parameter called the driving share, defined as the percentage of drivers theoretically capable of switching to EVs while maintaining their internal combustion engine (ICE) driving profile. With the collected trip profile data, the battery capacity, and the suggested charging scenarios listed in Table 4, the SoC for each EV was calculated using Equation (1) after every trip under weekday and weekend driving schemes (see Figure 4).

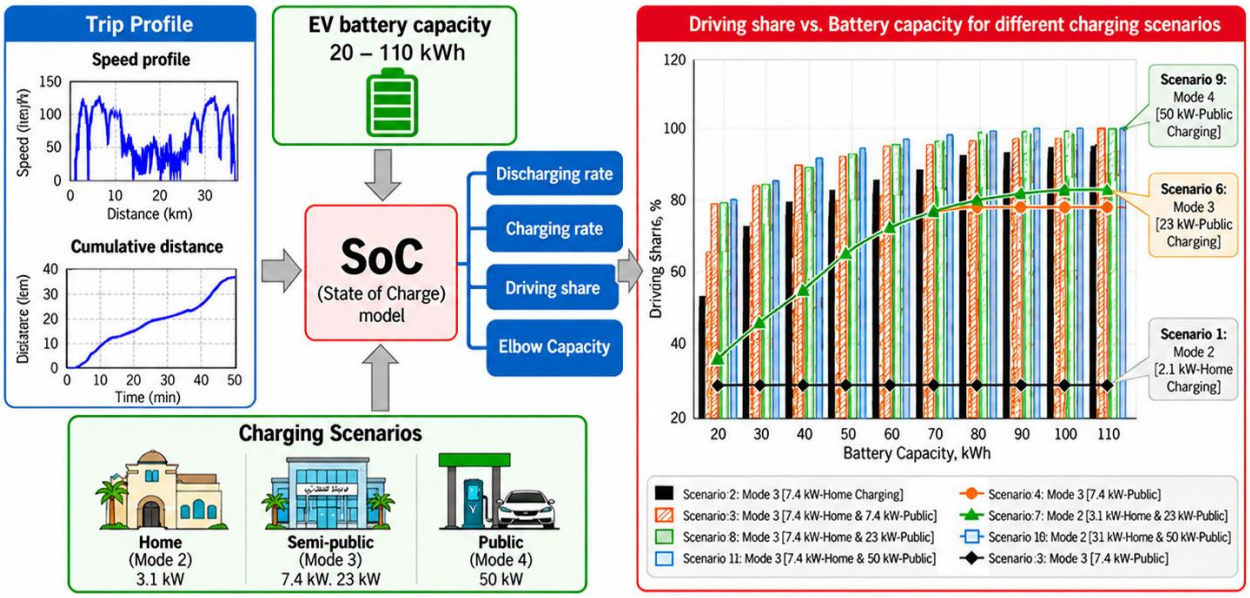


Figure 4. Methodology for evaluating charging scenarios and battery capacities.

For each of the charging scenarios, while the battery capacity varies from 20 to 110 kWh, the driving share a user would achieve was determined, i.e., drivers eligible for an EV transition are those who always met the following two conditions: (i) the SoC values (i.e., battery level) remain greater than or equal to 20% during the trip, and (ii) the battery is replenished to at least 80% of its capacity by the end of the day, such that batteries are neither deeply discharged nor left partially depleted on a daily basis, as this is not sustainable.

The lower bound of 20% follows the operating window recommended in the literature for lithium-ion traction batteries. Kostopoulos et al. [39] reported, from the cycling studies they reviewed, that the fastest capacity fade occurs when cells are cycled below 25% and above 75% of SoC, together with a rapid rise in internal resistance, whereas cells operated between 20% and 80% of SoC showed reduced capacity degradation. Their own real-world measurements gave average energy losses above 80% of SoC exceeding 20%, approximately double the losses recorded within the 20–80% window. The same measurements returned about 71 km of driving per hour of charging within 20–80% of SoC, against about 44 km per hour within 80–100%. Marra et al. [40] identified a preferable SoC usage window from charging and discharging tests on a lithium iron phosphate cell. The cell voltage remained comparatively flat up to about 80% of SoC and increased exponentially between 80% and 90%, so that charging current and power stayed controllable only up to about 90% of SoC. Sagaria et al. [41] adopted the same two values, 20% and 80%, as the minimum and maximum SoC preferred by BEV owners in their co-simulation of battery degradation. The lower bound of 20% therefore limits the degradation associated with deep discharge, while the 80% start-of-day condition ensures that each day begins with most of the usable window still available. The 80% value is a minimum to be met at the start of the day, i.e., the model charges the battery to 100% whenever the parking duration and the available charging power allow.

To assess the driving share, the term ‘elbow capacity’ was used, defined as the point at which increasing the battery capacity produces no significant change in the driving share, as the curve approaches asymptotic behavior, as defined by Equation (3):

$$\Delta DS = DS_{@(C)} - DS_{@(C-10)} < 5\ percentage\ points \quad (3)$$

The elbow method comes from Thorndike [42] and is used whenever a benefit that keeps improving is weighed against a cost that keeps rising, with the elbow marking where the extra cost stops paying off [43]. Here, the benefit is driving share, and the cost is battery capacity, the most expensive part of an electric vehicle. Because the study uses 126 driving profiles, one driver equals 0.79 percentage points, so a five-percentage-point threshold in driving share value means about six extra eligible drivers per 10 kWh added in battery capacity.

The following assumptions were also made when analyzing the above scenarios.

- Collected driving distances and periods are those traveled from home to the workplace and back home (weekday driving scheme), or from home to a public place and back home (weekend driving scheme). No other driving is considered during the rest of the day.

- The available parking period at the workplace equals the working hours per day in Oman, which is 8 h [44], while the parking period at public places is taken as 6 h, the estimated period for residents of Oman going shopping or dining outside. Workplace charging is not assumed to occupy the full parking period and is limited to a maximum of 4 consecutive hours. This limit represents shared-access operation, in which one charging point serves more than one employee and vehicles are moved at midday; the U.S. Department of Energy [45] adopts a 4 h Mode-3 session as its reference case for oversubscribed workplace charging. The value is consistent with measured behavior: in the 2.6 million real-world charging events analyzed by Märtz et al. [46], the cluster identified as workplace charging had a mean plug-in duration of 8 h 8 min, of which 3 h 58 min was idle time with the charging process already completed, giving an effective charging duration of approximately 4 h. The same 4 h limit is applied to charging at public places under the weekend scheme.

The home parking period is derived for each driver profile so that the day closes on 24 h. The day of each driver is made up of three parts: driving, parking away from home, and parking at home. The home parking period is the remainder of the day, given by Equation (4):

$$t_{home} = 24\,h - t_{parking\ away} - t_{driving} \quad (4)$$

where $t_{parking\ away}$ is the parking duration away from home, 4 h both at the workplace on weekdays and at the semi-public place on weekends, and $t_{driving}$ is that driver's total driving time for the day, comprising the outbound and the return trip. Figure 5 illustrates this construction for one weekday profile.

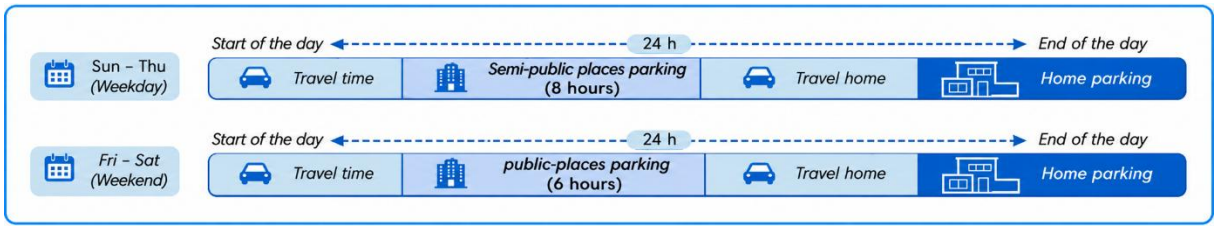


Figure 5. Construction of the daily time budget: driving time, parking away from home and home parking sum to 24 h.

- Home charging in Mode-2 is limited to a maximum of 2 consecutive hours per session. This follows the national requirement in Oman, where Mode-2 charging through a standard domestic socket-outlet is permitted only for occasional use, at up to 13 A single-phase, and for no more than two consecutive hours [26]. At the assumed Mode-2 charging power of 3.1 kW, the limit caps the energy delivered per home charging session at 6.2 kWh. No corresponding duration limit is applied to Mode-3 home charging, which uses a dedicated stand-alone charger.
- The EV is assumed to be connected to the charging station whenever it is parked at home, at the workplace or at a public place, subject to the two duration limits stated above and to the charging options defined for each scenario. No fixed step width Δt is used; instead, each individual trip duration Δt or parking duration Δt is used directly.
- Each driver begins the day at the state of charge reached at the end of the preceding day. For every scenario and battery capacity, each driving profile was evaluated as a sequence of four stages: the outbound trip, parking away from home, the return trip, and home parking. The recorded day was then repeated, with each repetition starting from the previous day's end-of-day stored energy, until the start-of-day state of charge no longer changed between successive repetitions; no fixed number of

repetitions was imposed. A driver whose charging replaced the energy consumed during the day therefore converged to a steady state, whereas a driver whose charging was insufficient lost the same quantity of stored energy on successive repetitions until one of the eligibility conditions was breached. At convergence, the end-of-day state of charge equals the start-of-day state of charge of the following day. A profile was counted as eligible when SoC ≥ 20% of C after every trip and SoC ≥ 80% of C at the start of the day, and the driving share is the eligible fraction of the 126 profiles. The home parking period was calculated for each driver as 24 h minus the time spent away from home minus that driver's total driving time.

4. Results Analysis and Discussion

The results are organized around one question that recurs at every battery capacity and in every charging scenario: whether the battery or the charging session sets the limit on what a driver can do. Where the battery is the limit, additional capacity raises the driving share; where the session is the limit, it does not. The weekday scheme is analyzed first, and the weekend scheme afterwards. The elbow capacity is determined as defined in Section 3.

4.1. Weekday Driving Scheme

4.1.1. Effect of Battery Capacity on Driving Share

Figure 6 shows driving share against battery capacity for the two single-source charging modes: (a) home-only charging (scenarios 1 and 2); (b) semi-public-only charging (scenarios 3, 6 and 9). In both charts, the driving share rises steeply at small battery capacities and then flattens, approaching an asymptotic trend at a specific point defined as the elbow capacity, where increasing battery capacity yields no significant increase in driving share. In other words, the gain over the preceding 10 kWh increment falls below five percentage points and remains below it.

The two home-only charging approaches behave differently (Figure 6a). Scenario 1 remained at 21.43% across the whole range from 20 kWh to 110 kWh, so no elbow is defined. S2 returned 66.67% at 20 kWh, 87.30% at 30 kWh, 96.03% at 40 kWh, and 98.41% at 50 kWh, then flattened at 99.21% from 60 kWh onwards, giving an elbow capacity at 50 kWh. The separation between them was 45 percentage points at 20 kWh and 78 percentage points at 110 kWh, so a larger battery widened the gap rather than closing it. S2 corresponds to the once-daily home charging assumed by Needell et al. [47], who found that an existing, affordable EV could meet the energy requirements of 87% of vehicle-days in the United States; S2 reached 87.30% at 30 kWh, although the two figures are not directly comparable, since the present study counts drivers rather than vehicle-days.

The three semi-public-only charging approaches returned identical values up to 70 kWh despite rated powers of 7.4 kW, 23 kW and 50 kW, rising from 30.16% at 20 kWh to 90.48% at 70 kWh (Figure 6b). Above 70 kWh they separated: S3 plateaued at 94.44%, whereas S6 and S9 continued to 98.41% at 110 kWh. All three exceeded S1 at every capacity examined, by 8.73 percentage points at 20 kWh and by 76.98 points at 110 kWh under S6 and S9.

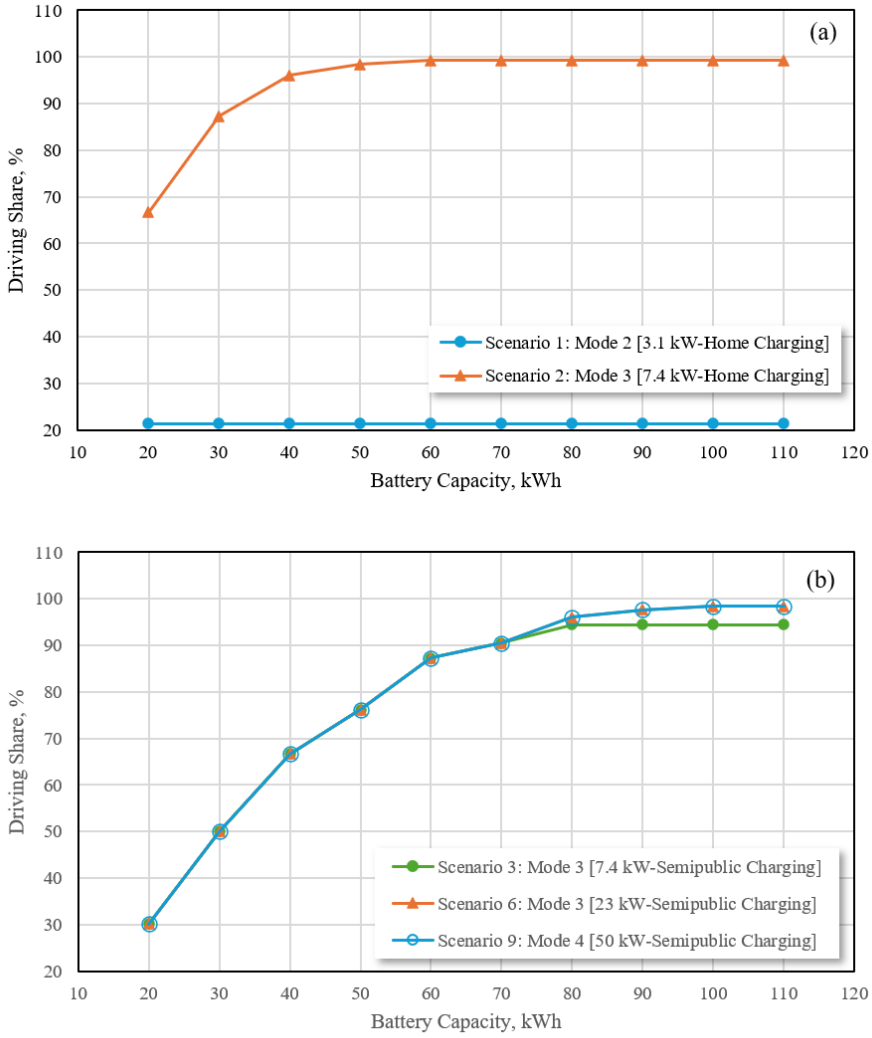


Figure 6. Driving share against battery capacity for the single-source charging modes: (**a**) home-only charging (scenarios 1 and 2); (**b**) semi-public-only charging (scenarios 3, 6 and 9).

Two quantities determine whether a driving profile can meet the two eligibility conditions defined in Section 3, i.e., an SoC at or above 20% throughout each trip and an SoC of at least 80% at the end of the day. The first is the daily energy demand, obtained from the daily driving distance and a specific energy consumption of 0.239 kWh/km. The second is the energy transferable per charging session, equal to the charging power multiplied by the maximum permitted session duration. Figure 7 compares the two distributions. When daily energy demand exceeds transferable session energy, the charging session cannot replace what the day consumed, and the difference is drawn from stored energy on every repetition of the day until one of the conditions is breached. A larger battery delays that outcome but does not prevent it, because the same difference recurs each day while the stored energy is finite.

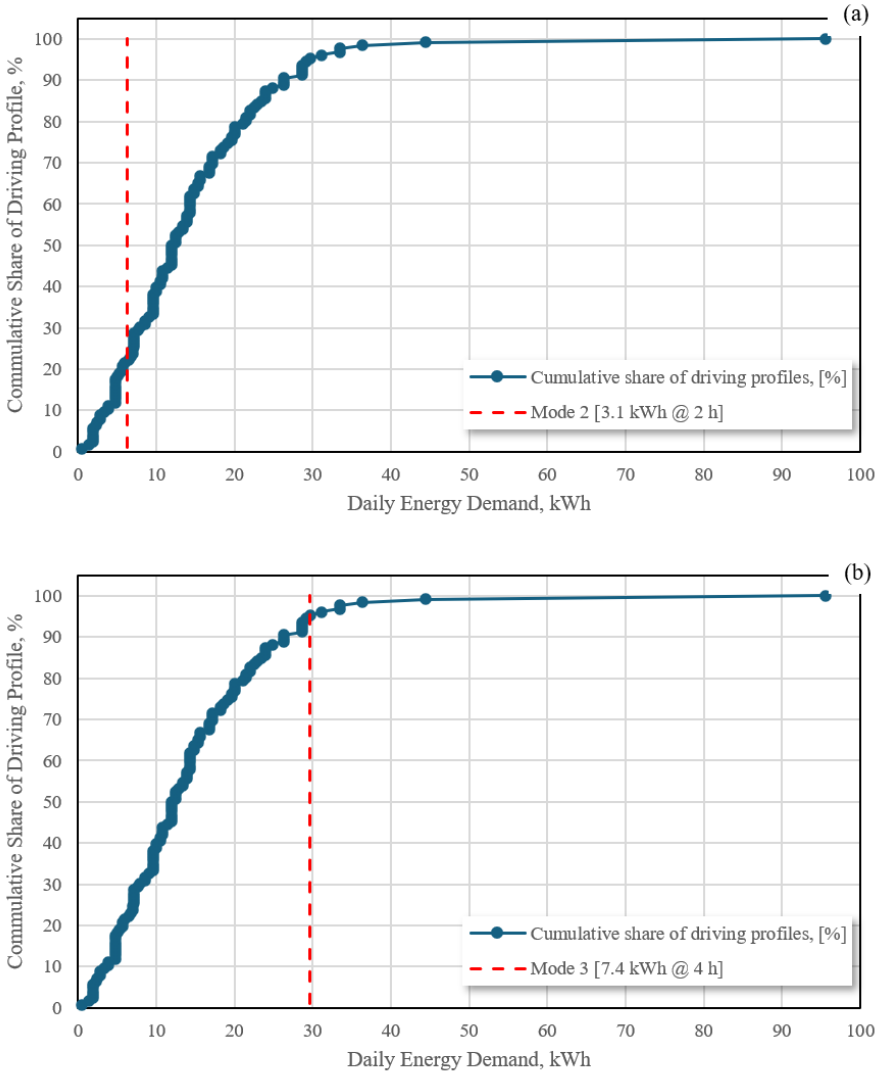


Figure 7. Cumulative share of driving profiles against daily energy demand, compared with the energy transferable per charging session: (**a**) Mode-2 home charging, 3.1 kW over 2 h; (**b**) Mode-3 semi-public charging, 7.4 kW over 4 h.

Figure 7 covers all three behaviors shown in Figure 6 and serves as the reference point for the results that follow. A Mode-2 home session at 3.1 kW (S1) over 2 h transfers at most 6.2 kWh, which covers the daily energy demand of 21.43% of the recorded profiles (Figure 7a); the driving share of S1 equals that same share at every capacity, so battery capacity confers no eligibility under a home connection restricted to two consecutive hours. With a home parking period of 13 h, which is the minimum home parking period across the 126 driving profiles (13.33–15.92 h), Mode-3 home charging at 7.4 kW (S2) is not subject to a session limit and returns 96.2 kWh overnight. Accordingly, this restores any capacity in the range to 100% overnight, so the session replaces the daily energy demand of almost every profile, and the battery becomes the limit; this is why the S2 curve rises with capacity until the start-of-day condition alone is binding.

A semi-public session at 7.4 kW (S3) within the 4 h window transfers 29.6 kWh, which covers the daily energy demand of 94% of the profiles (Figure 7b), and S3 plateaued at that value. Raising the semi-public power to 23 kW or 50 kW raises the transferable session energy to 92.0 kWh and 200.0 kWh, which cover the remaining profiles, so S6 and S9 continued to rise above 70 kWh where S3 could not. Below 70 kWh, the three coincided because the battery, not the session, limited how much could be stored.

The single-source results establish that eligibility depends on which of the two quantities binds. The combined approaches are examined next to determine whether a second charging location moves that limit. Figure 8 shows the driving share against battery capacity for the combined charging approaches, in which home charging is added to each of the three semi-public options: (a) semi-public charging at 7.4 kW, (b) at 23 kW, and (c) at 50 kW. Each panel keeps the semi-public-only scenario as a baseline and then adds Mode-2 home charging at 3.1 kW and Mode-3 home charging at 7.4 kW.

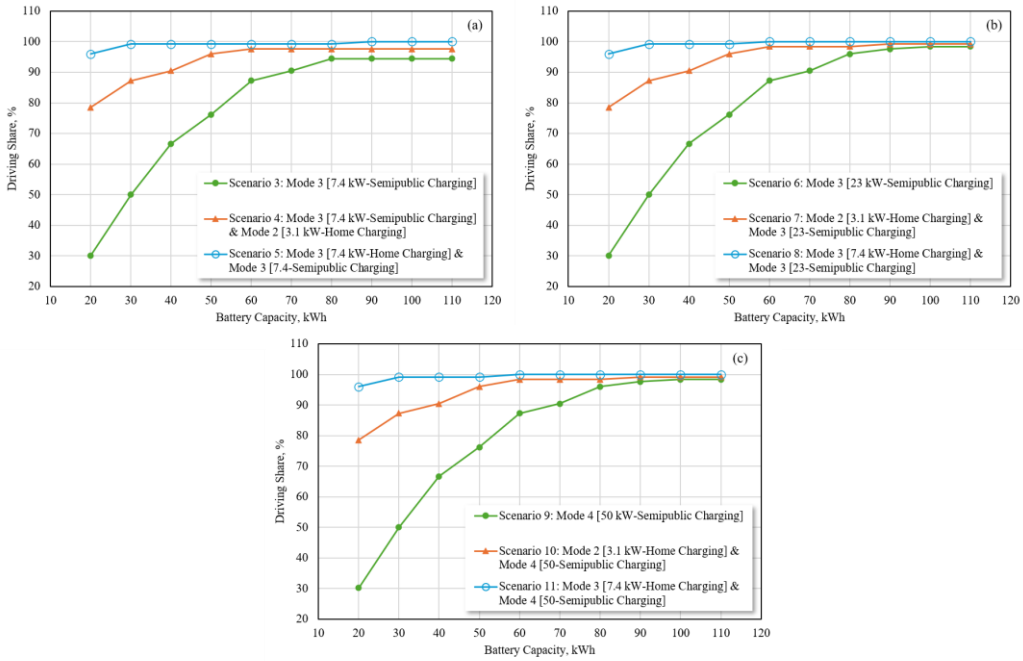


Figure 8. Driving share against battery capacity for the combined charging approaches, each compared with its semi-public-only baseline: (**a**) semi-public charging at 7.4 kW (scenarios 3, 4 and 5); (**b**) semi-public charging at 23 kW (scenarios 6, 7 and 8); (**c**) semi-public charging at 50 kW (scenarios 9, 10 and 11).

In all three panels, adding a home charging option raised the driving share at every battery capacity, and the size of the increase fell steeply as capacity grew. Relative to semi-public charging at 7.4 kW alone (Figure 8a), adding Mode-2 home charging raised the driving share by 161% at 20 kWh and 75% at 30 kWh, with the increase falling to 8% at 70 kWh and 3% from 80 kWh onward. Adding Mode-3 home charging instead gave 218% at 20 kWh and 98% at 30 kWh, falling to 10% at 70 kWh and to between 5% and 6% from 80 kWh onwards. These are relative increases over the semi-public-only baseline, not differences in percentage points.

The same increases recurred at the higher semi-public powers. At 23 kW (Figure 8b) and at 50 kW (Figure 8c), adding Mode-2 home charging gave 161%, 75%, 36% and 26% at 20, 30, 40 and 50 kWh, and adding Mode-3 home charging gave 218%, 98%, 49% and 30% at the same four capacities, matching the values recorded at 7.4 kW. The semi-public charging power therefore had no effect on eligibility at 50 kWh and below, for the reason established in Figure 7: a 4 h session at 7.4 kW already transfers 29.6 kWh, which exceeds half the capacity of every battery in that range, so the additional energy available at 23 kW and 50 kW cannot be stored. Below 50 kWh, the entire benefit of a combined approach comes from the additional home session. The three panels differ only above 50 kWh, where the increases fell to between 1% and 2% for Mode-2 home charging and between

2% and 4% for Mode-3 home charging at the two higher semi-public powers, against 3% and between 5% and 6% at 7.4 kW.

The relative increases understate the change at small capacities because the baseline is small. At 20 kWh, semi-public charging at 7.4 kW alone (S3) admitted 30.16% of the recorded profiles (Figure 8a); adding Mode-2 home charging (S4) raised this to 78.57% and adding Mode-3 home charging (S5) to 96.03%. Semi-public charging at 7.4 kW alone (S3) did not reach 96.03% at any capacity examined, plateauing at 94.44% from 80 kWh, and Mode-3 home charging at 7.4 kW alone (S2), the strongest single-source approach, required 40 kWh to reach 96.03% (Figure 6a). A second charging location therefore substitutes for battery capacity, and the size of that substitution is quantified in Section 4.1.5.

4.1.2. Overall Comparison of the Charging Scenarios

Figure 9 plots the eleven scenarios on a single set of axes, allowing the scenarios to be ranked in groups by achieved driving share at each capacity rather than pairwise comparison. The eleven scenarios reduce to five groups. The highest group comprises scenarios 5, 8, and 11, which combine Mode-3 home charging with semi-public charging; this group reached 96.03% at 20 kWh and exceeded 99% from 30 kWh onward, and other groups required at least 40 kWh of battery capacity to achieve the driving share that this group reached at 20 kWh. For instance, the second group comprises scenarios 4, 7, and 10, combining Mode-2 home charging with semi-public charging, and achieved 78.57% driving share at 20 kWh, which is 17.46 pp less than the first group. The third group is scenario 2 alone, which achieved 66.67% driving share at 20 kWh and reached 96.00% at 40 kWh. The fourth group comprises scenarios 3, 6, and 9, at 30.16% at 20 kWh. This group can reach the driving share achieved by the first group only when high-capacity batteries are used (90 kWh onward). The lowest share occurred in the fifth group, scenario 1 alone, with a fixed driving share of 21.43%. This is due to the charging-period limitation associated with Mode-2 home charging.

The grouping is determined by the home charging arrangement and by the presence of a second charging location, and not by the semi-public charging power. In addition, the second group returned identical values up to 50 kWh, compared to 70 kWh associated with the fourth group, despite semi-public powers spanning 7.4 kW to 50 kW. Raising the semi-public power therefore moved no scenario between groups anywhere in the figure. Raising the home charging power from 3.1 kW to 7.4 kW moved a scenario up one group in every case (S1 → S2, S4 → S5, S7 → S8, S10 → S11), and adding a second charging location moved it up two. Battery capacity separates the groups only below 60 kWh (Figure 9). Between 20 kWh and 60 kWh, the driving share spans 21.43% to almost 100%, whereas from 80 kWh onwards only scenario 1 and the semi-public-only group (S3, S6 and S9) remain distinguishable, and additional capacity changes the outcome for no scenario. Above 60 kWh, the charging arrangement alone determines the result.

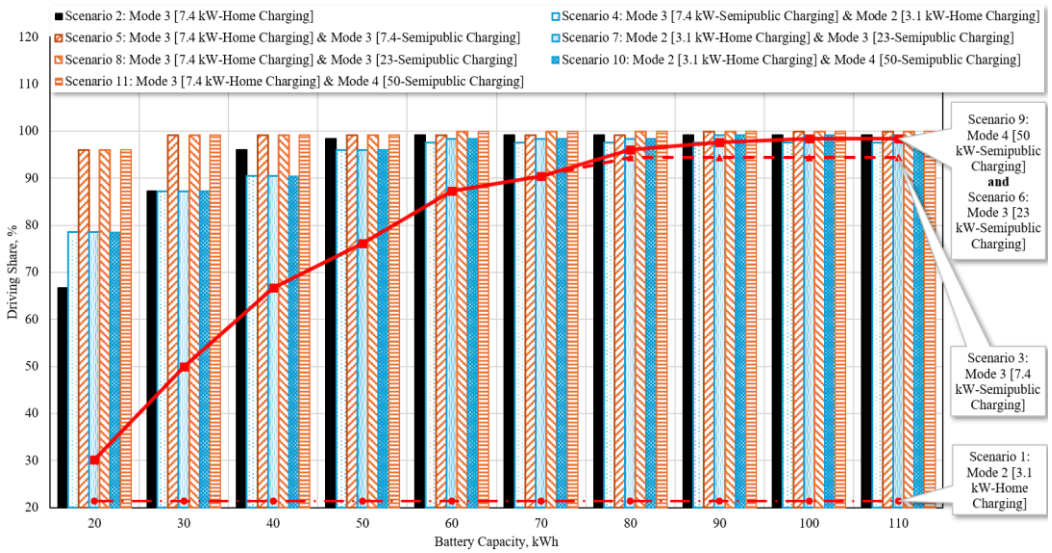
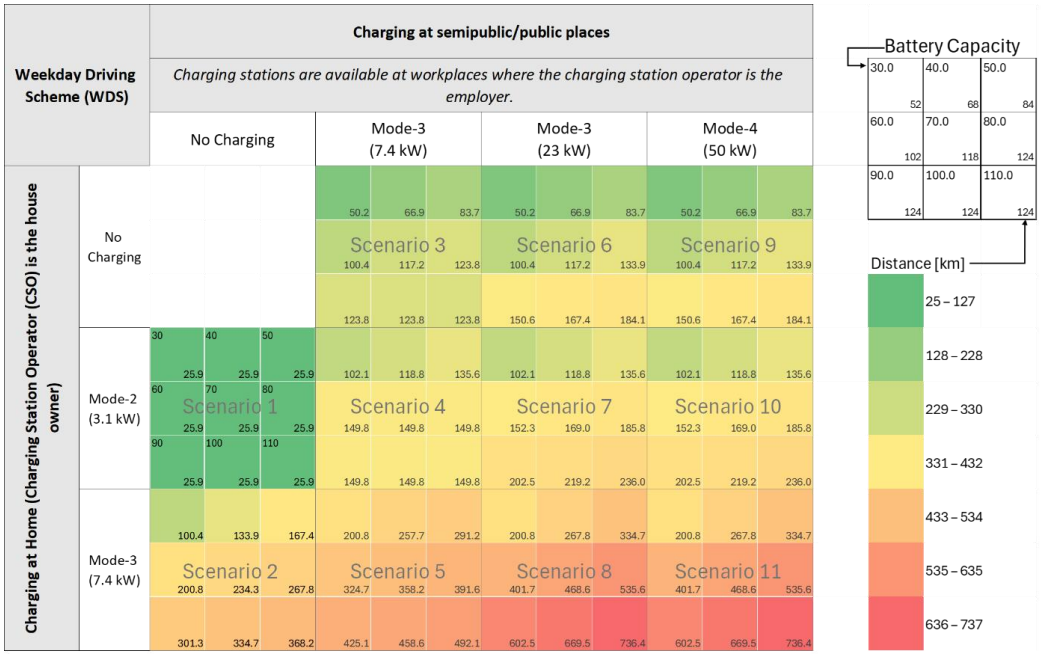


Figure 9. Driving share against battery capacity for all eleven charging scenarios under the weekday driving scheme.

4.1.3. Maximum Supported Driving Distance

The driving-share results describe how many drivers a scenario admits. Scheme 1 describes how far a driver can travel under it, which is the practical quantity behind that share and the one that continues to differentiate the scenarios after the driving share has saturated. Scheme 1 presents the maximum distance that a driver can travel under each specified battery capacity and scenario until the SoC falls below 20%.



Scheme 1. Maximum achievable driving distance, in km, for each combination of home and semi-public charging under the weekday driving scheme. Each scenario cell contains nine values corresponding to battery capacities from 30 kWh to 110 kWh, arranged as shown in the key.

Battery capacity raises the attainable distance in ten of the eleven scenarios and does so across the whole investigated range (20–110 kWh) in eight of them. Four patterns appear in Scheme 1. Scenario 1 is flat at 26 km at every capacity, because a Mode-2 home session returns 6.2 kWh regardless of battery size. Scenarios 3 and 4 rise and then flatten,

at 124 km from 80 kWh and at 150 km from 60 kWh, once the energy their sessions can resupply becomes the binding limit. Scenarios 2, 6, 7, 8, 9, 10 and 11 rise across the whole range, because the battery rather than the session limits them throughout. Scenario 5 also rises throughout but changes slope at 40 kWh, running 124 km above scenario 2 at every capacity above that point; this difference is the 29.6 kWh semi-public session (7.4 kW over 4 h) expressed as distance.

Scenarios 8 and 11 achieved the greatest distance at every capacity (Scheme 1), reaching 134 km at 20 kWh and 738 km at 110 kWh. Scenario 5 matched them at 20 and 30 kWh and fell progressively behind above that capacity, reaching 494 km at 110 kWh. This is the first result in which scenarios 5, 8 and 11 are not equivalent: their driving shares are identical at seven of the ten capacities and differ by one profile (0.79 pp) at 60–80 kWh; the mean relative difference is 0.2 pp.

Table 5. Effect of upgrading charging on driving share for the weekday driving scheme.

Charging Approach		Upgrading Charging Mode		Upgrading Scenarios		Percentage Point Difference in Mean Driving Share, 20–110 kWh [pp]	Effect (pp)
FROM	TO	FROM	TO	FROM	TO		
Single	Single	Mode-2 (3.1 kW) @ home	Mode-3 (7.4 kW) @ home	S1	S2	+72.9	↑ Large (≥10 pp)
		Mode-3 (7.4 kW) @ semi-public	Mode-3 (23 kW) @ semi-public	S3	S6	+1.3	↑ Marginal (1–5 pp)
			Mode-4 (50 kW) @ semi-public	S3	S9	+1.3	↑ Marginal (1–5 pp)
		Mode-3 (23 kW) @ semi-public	Mode-4 (50 kW) @ semi-public	S6	S9	0.0	→ Not affected (0 pp)
Single	Combined	Mode-2 (3.1 kW) @ home	Mode-2 (3.1 kW) @ home + Mode-3 (7.4 kW) @ semi-public	S1	S4	+72.4	↑ Large (≥10 pp)
			Mode-2 (3.1 kW) @ home + Mode-3 (23 kW) @ semi-public	S1	S7	+73.1	↑ Large (≥10 pp)
			Mode-2 (3.1 kW) @ home + Mode-4 (50 kW) @ semi-public	S1	S10	+73.1	↑ Large (≥10 pp)
		Mode-3 (7.4 kW) @ home	Mode-3 (7.4 kW) @ home + Mode-3 (7.4 kW) @ semi-public	S2	S5	+4.8	↑ Marginal (1–5 pp)
			Mode-3 (7.4 kW) @ home + Mode-3 (23 kW) @ semi-public	S2	S8	+5.0	↑ Moderate (5–10 pp)
			Mode-3 (7.4 kW) @ home + Mode-4 (50 kW) @ semi-public	S2	S11	+5.0	↑ Moderate (5–10 pp)

	Mode-3 (7.4 kW) @ semi-public	Mode-2 (3.1 kW) @ home + Mode-3 (7.4 kW) @ semi-public	S3	S4	+16.0	↑ Large (≥10 pp)
		Mode-3 (7.4 kW) @ home + Mode-3 (7.4 kW) @ semi-public	S3	S5	+21.3	↑ Large (≥10 pp)
	Mode-3 (23 kW) @ semi-public	Mode-2 (3.1 kW) @ home + Mode-3 (23 kW) @ semi-public	S6	S7	+15.4	↑ Large (≥10 pp)
		Mode-3 (7.4 kW) @ home + Mode-3 (23 kW) @ semi-public	S6	S8	+20.2	↑ Large (≥10 pp)
	Mode-4 (50 kW) @ semi-public	Mode-2 (3.1 kW) @ home + Mode-4 (50 kW) @ semi-public	S9	S10	+15.4	↑ Large (≥10 pp)
		Mode-3 (7.4 kW) @ home + Mode-4 (50 kW) @ semi-public	S9	S11	+20.2	↑ Large (≥10 pp)
Combined	Mode-2 (3.1 kW) @ home + Mode-3 (7.4 kW) @ semi-public	Mode-3 (7.4 kW) @ home + Mode-3 (7.4 kW) @ semi-public	S4	S5	+5.3	↑ Moderate (5–10 pp)
Combined	Mode-2 (3.1 kW) @ home + Mode-3 (23 kW) @ semi-public	Mode-3 (7.4 kW) @ home + Mode-3 (23 kW) @ semi-public	S7	S8	+4.8	↑ Marginal (1–5 pp)
Combined	Mode-2 (3.1 kW) @ home + Mode-4 (50 kW) @ semi-public	Mode-3 (7.4 kW) @ home + Mode-4 (50 kW) @ semi-public	S10	S11	+4.8	↑ Marginal (1–5 pp)
Combined	Mode-2 (3.1 kW) @ home + Mode-3 (7.4 kW) @ semi-public	Mode-2 (3.1 kW) @ home + Mode-3 (23 kW) @ semi-public	S4	S7	+0.7	↑ Very marginal (<1 pp)
Combined	Mode-2 (3.1 kW) @ home + Mode-3 (7.4 kW) @ semi-public	Mode-2 (3.1 kW) @ home + Mode-4 (50 kW) @ semi-public	S4	S10	+0.7	↑ Very marginal (<1 pp)
Combined	Mode-2 (3.1 kW) @ home +	Mode-2 (3.1 kW) @ home + Mode-4 (50 kW) @ semi-public	S7	S10	0.0	→ Not affected (0 pp)

Mode-3 (23 kW) @ semi-public					
Mode-3 (7.4 kW) @ home + Mode-3 (7.4 kW) @ semi-public	Mode-3 (7.4 kW) @ home + Mode-3 (23 kW) @ semi-public	S5	S8	+0.2	↑ Very marginal (<1 pp)
Mode-3 (7.4 kW) @ home + Mode-3 (7.4 kW) @ semi-public	Mode-3 (7.4 kW) @ home + Mode-4 (50 kW) @ semi-public	S5	S11	+0.2	↑ Very marginal (<1 pp)
Mode-3 (7.4 kW) @ home + Mode-3 (23 kW) @ semi-public	Mode-3 (7.4 kW) @ home + Mode-4 (50 kW) @ semi-public	S8	S11	0.0	→ Not affected (0 pp)

Raising the home charging power from 3.1 kW to 7.4 kW (S1 → S2, S4 → S5, S7 → S8, S10 → S11) produced the largest single change in Scheme 1. Without semi-public charging (S1 → S2), it raised the attainable distance from a fixed 26 km to 102–370 km, turning a fixed driving-distance limit into a variable driving distance that responds to battery size.

Adding semi-public charging to home charging gave comparable gains: adding semi-public charging to Mode-3 home charging (S2) raised the distance from 102 km to 2024 km at 30 kWh, and from 370 km to 494 km at 110 kWh with a 7.4 kW connection (S5), or to 738 km with a 23 kW connection (S8). Adding semi-public charging to the restricted Mode-2 connection (S1) increased the driving distance from 26 km to 104 km at 30 kWh and to 150 km with a 7.4 kW connection (S4) or 236 km with a 23 kW connection (S7) at 110 kWh. The two upgrades release some restrictions. Semi-public charging releases the requirement that the whole day be completed on a single charge, since the battery is refilled part-way through. A higher-power charging mode at home removes the "session too small to refill the battery overnight" constraint, which held scenario 1 at 26 km at every capacity.

Raising the semi-public charging power altered the outcome only where the smaller session had become binding. Scenarios 6 and 9 are identical at every capacity, as are scenarios 7 and 10 and scenarios 8 and 11, so no increase beyond 23 kW changed any value in Scheme 1. Below 40 kWh, increasing charging power from 7.4 kW to 23 kW also changed nothing, since a 29.6 kWh session already exceeds what those batteries can accept. The benefit appears only above 40 kWh and only where the semi-public session limits the day, which is why scenario 4 flattens at 150 km, while scenario 7 continues to 236 km; scenario 5 reaches 494 km, while scenario 8 reaches 738 km.

Improved charging availability substitutes for battery capacity across the whole range. For a 20 kWh battery capacity, no scenario reached 134 km except scenarios 5, 8, and 11. Home charging alone (S2) did not reach 134 km below 40 kWh. Workplace charging alone at 7.4 kW (S3) did not reach 134 km at any battery capacity. At 23 kW or 50 kW (S6 or S9), workplace charging reached 134 km only with an 80 kWh battery. A 30 kWh battery in scenario 8 achieved 202 km, matching the range of a 60 kWh battery in scenario 2 and exceeding the range of a 110 kWh battery in scenarios 3, 6, or 9. A second charging opportunity therefore halved the battery capacity required for that journey. Studies that assume a single overnight charge per day treat daytime recharging as one of the

adaptations that extend the share of drivers a limited-range vehicle can serve [48]. For the recorded Omani profiles, adding a workplace session to Mode-3 home charging halved the capacity required for a 202 km day, from 60 kWh under scenario 2 to 30 kWh under scenario 8 (Scheme 1).

4.1.4. Benefit of Upgrading Between Charging Configurations

Figures 6–9 compare scenarios at fixed capacities. Table 5 addresses a distinct question: how much a driver benefits from transitioning between configurations (upgrading the charging mode). This perspective aligns with the practical context in which infrastructure decisions are made. The increases range from no change to a difference of 73.1 percentage points (pp) on average across the ten battery capacities (20–110 kWh). Each upgrade is classed by the change it produces in the mean driving share as large (10 pp or more), moderate (5–10 pp), marginal (1–5 pp), very marginal (below 1 pp) or not affected (0 pp).

The change reported in Table 5 is the change in the mean driving share, in percentage points, over the ten capacities from 20 kWh to 110 kWh, defined by Equation (5):

$$\Delta DS_{rel}(S_i \rightarrow S_j) = \sum_{C=20}^{C=110} \frac{DS_{j@(C)}}{10} - \sum_{C=20}^{C=110} \frac{DS_{i@(C)}}{10} \; [pp] \tag{5}$$

where i is the existing scenario and j is the upgraded scenario. $DS_{i@(C)}$ and $DS_{j@(C)}$ are the driving shares of the existing and upgraded scenarios at capacity C, and all sums run over C = 20, 30, …, 110 kWh.

The largest increases in the mean driving share occurred when the single-mode home charging scenario S1 was upgraded to combined-mode charging, each being a change in the mean driving share averaged over the ten battery capacities: 73.1 pp when moving to Mode-2 home charging combined with semi-public charging at 23 kW or 50 kW (S1 → S7 and S1 → S10), 72.9 pp when upgrading the home connection to Mode-3 (S1 → S2), and 72.4 pp when combining the existing Mode-2 connection with semi-public charging at 7.4 kW (S1 → S4). They are close to one another and far above every other entry, which reflects the very low driving share of the configuration being replaced rather than any property of the upgrades. Almost any change to a home connection restricted to two consecutive hours produces a large increase. The ranking within them is nonetheless informative: upgrading the home connection alone was more effective than combining the restricted connection with semi-public charging at 7.4 kW.

Setting scenario 1 aside, the effect of an upgrade depends on which charging opportunity it supplies (Table 5). Adding a home connection to a semi-public-only approach raised the mean driving share by between 15.4 and 21.3 pp on average across the ten battery capacities, whereas adding semi-public charging to an existing Mode-3 home connection raised it by between 4.8 and 5.0 pp. The same physical infrastructure therefore returns three to four times more when it is the home connection that is missing. Within the first group, a Mode-2 home connection gave 16.0, 15.4 and 15.4 pp at semi-public powers of 7.4 kW, 23 kW and 50 kW, and a Mode-3 home connection gave 21.3, 20.2 and 20.2 pp, so the Mode-3 connection returned between 4.8 and 5.3 pp more than the Mode-2 connection, at the cost of a dedicated charging point in place of a domestic socket-outlet.

Upgrading the home charging mode while holding the semi-public arrangement unchanged gave 5.3 pp at a semi-public power of 7.4 kW (S4 → S5) and 4.8 pp at 23 kW and 50 kW (S7 → S8 and S10 → S11), on average across the ten battery capacities, so the benefit of a stronger home connection falls as the semi-public power rises, the two partly substituting for one another. By contrast, upgrading the semi-public charging power

while holding the home arrangement unchanged produced the smallest increases in Table 5. With no home charging, raising the power from 7.4 kW to 23 kW (S3 → S6) gave 1.3 pp, and raising it further to 50 kW (S6 → S9) gave no change. With a Mode-3 home connection the corresponding values were 0.2 pp (S5 → S8) and none (S8 → S11). Returns therefore diminish steeply between 7.4 kW and 23 kW and disappear above 23 kW.

Seven upgrades in Table 5 left the driving share unchanged or nearly so on average across the ten battery capacities: S6 → S9, S7 → S10 and S8 → S11 at 0.0 pp, S4 → S7 and S4 → S10 at 0.7 pp, and S5 → S8 and S5 → S11 at 0.2 pp. Every one of these supplies faster charging but no new opportunity to charge, and because a 4 h session at 7.4 kW already delivers more energy than most of the recorded profiles consume in a day, the additional power cannot be absorbed. This agrees with real-world charging records: across the 2.6 million charging events analyzed by Märtz et al. [46], an average of 9.24 kWh was delivered per session, and home and workplace sessions were those most likely to be associated with long idle periods and lower charging powers.

The upgrade offering the best return relative to the infrastructure it requires is the addition of a Mode-2 home connection to a semi-public-only approach (S3 → S4 in Table 5), which raised the mean driving share by 16.0 pp, on average across the ten battery capacities, using only a standard domestic socket-outlet. Upgrading that connection to Mode-3 adds a further 5.3 pp (S4 → S5) and requires a dedicated charging point, which is a reasonable further step but a smaller one. Raising the semi-public charging power from 7.4 kW to 50 kW (S3 → S9) requires substantially heavier electrical infrastructure and returned 1.3 pp.

4.1.5. Target and Elbow Capacity

As defined in Section 3, the elbow capacity was obtained for each scenario as the point where driving share no longer increases significantly with increasing battery capacity. The obtained results are presented in Figure 10. Most scenarios achieve driving shares between 97.62% and 99.21% at their respective elbow capacities, while scenario 3 reaches 90.48%. Notably, scenarios 5, 8 and 11 achieve 99.21% at only 30 kWh, compared with 90 kWh for scenario 9. These results indicate that combining Mode-3 home charging with semi-public charging can achieve a high driving share at a substantially lower battery capacity.

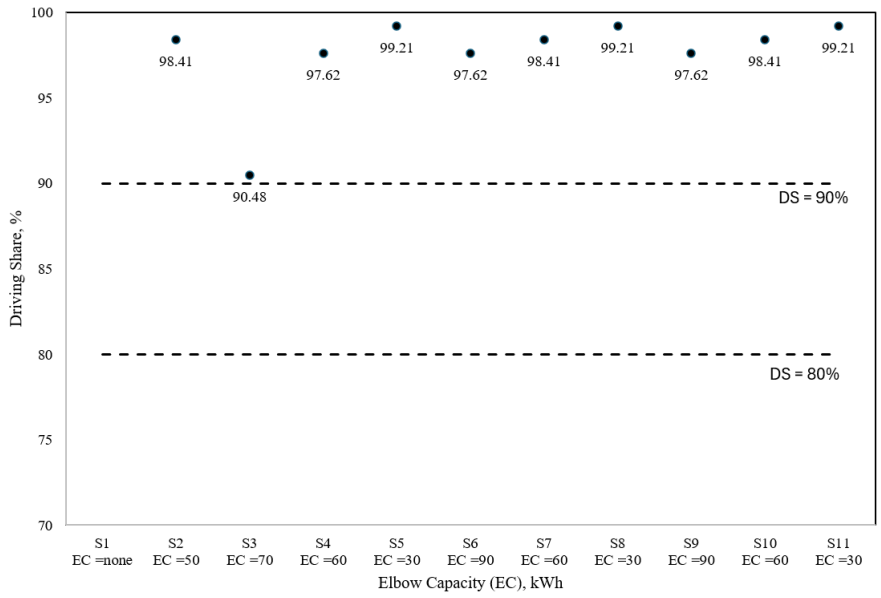


Figure 10. Driving share achieved at the elbow battery capacity for each charging scenario. Dashed lines indicate the 80% and 90% driving-share targets.

Although the elbow capacity identifies the point of diminishing returns, it does not establish the minimum battery capacity required to achieve a specified driving-share target. To complement this assessment, Figure 11 presents the minimum battery capacity required to achieve driving shares of 80%, 90%, and 100% under the eleven charging scenarios. Where a target could not be achieved within the investigated 20–110 kWh range, the corresponding requirement is reported as exceeding 110 kWh.

Target driving share (%)	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11
80	> 110	30	60	30	20	60	30	20	60	30	20
90	> 110	40	70	40	20	70	40	20	70	40	20
100	> 110	> 110	> 110	> 110	90	> 110	> 110	60	> 110	> 110	60

Figure 11. Minimum battery capacity, in kWh, required to reach a target driving share of 80%, 90% and 100% under each of the eleven charging scenarios.

At the 80% and 90% targets, the smallest requirement was 20 kWh, obtained by scenarios 5, 8 and 11, each of which reached both targets at the smallest capacity examined. Each scenario except scenario 1 reached both targets within the investigated range; scenario 1 did not reach 80% at any capacity, as follows from its flat curve in Figure 6a.

The 100% target distinguishes the scenarios more clearly (Figure 11). Only scenarios 8 and 11, at 60 kWh, and scenario 5, at 90 kWh, achieved this target within the evaluated range. The remaining eight scenarios, including all cases without a home charging option and those limited to Mode-2 home charging, did not meet the target at any capacity. Thus, the choice of charging arrangement matters most at the highest target: at 80% it determines whether a driver needs 20 kWh or 60 kWh, while at 100% it determines whether the target is achievable at all. Full coverage is also the hardest target in the wider literature: Needell et al. [47] concluded that even as batteries improve and charging infrastructure expands, the highest-energy days would still require other vehicle technologies.

Three groups returned identical requirements at every target in Figure 11: scenarios 3, 6 and 9 at 60 kWh, 70 kWh and beyond the range; scenarios 4, 7 and 10 at 30 kWh, 40 kWh and beyond the range; and scenarios 8 and 11 at 20 kWh, 20 kWh and 60 kWh. Raising the semi-public power therefore changed the required capacity at one point only in the entire figure: at the 100% target, in the presence of Mode-3 home charging, moving from 7.4 kW to 23 kW reduced the requirement from 90 kWh to 60 kWh. Moving from 23 kW to 50 kW changed nothing anywhere. Adding a second charging location produced much larger changes. Adding semi-public charging at 7.4 kW to Mode-3 home charging reduced the requirement from 30 kWh to 20 kWh at 80% and from 40 kWh to 20 kWh at 90%, and made 100% attainable at 90 kWh where home charging alone did not reach it. Added to the restricted Mode-2 connection, it converted a scenario that reached no target within the range into one requiring 30 kWh for 80% and 40 kWh for 90%.

A comparison of Figures 10 and 11 highlights the distinction between the two capacity indicators. For example, scenarios 8 and 11 reach their elbow at 30 kWh, achieving 99.21% driving share, but require 60 kWh to achieve 100% coverage. Thus, the elbow criterion identifies where additional battery capacity provides relatively small incremental

benefits, whereas the target-based criterion identifies the minimum capacity needed to achieve a predetermined driving-share level. Both indicators are therefore necessary for interpreting battery-capacity requirements.

Table 6 reports the same question in terms of the elbow capacity, that is, the capacity defined by Equation (3). A negative value indicates that the upgraded configuration reaches its elbow at a smaller battery capacity.

Table 6. Percentage change in the elbow capacity resulting from each charging upgrade under the weekday driving scheme, relative to the capacity required by the original configuration.

Charging Approach		Upgrading Charging Mode		Upgrading Scenarios		Change in Elbow Capacity	Effect
FROM	TO	FROM	TO	FROM	TO	[%]	
Single	Single	Mode-2 (3.1 kW) @ home	Mode-3 (7.4 kW) @ home	S1	S2	NA	S1 has no elbow
		Mode-3 (7.4 kW) @ semi-public	Mode-3 (23 kW) @ semi-public	S3	S6	+28.6%	↑ Large (>15%)
			Mode-4 (50 kW) @ semi-public	S3	S9	+28.6%	↑ Large (>15%)
		Mode-3 (23 kW) @ semi-public	Mode-4 (50 kW) @ semi-public	S6	S9	0.0%	→ Not affected
Single	Combined	Mode-2 (3.1 kW) @ home	Mode-2 (3.1 kW) @ home + Mode-3 (7.4 kW) @ semi-public	S1	S4	NA	S1 has no elbow
			Mode-2 (3.1 kW) @ home + Mode-3 (23 kW) @ semi-public	S1	S7	NA	S1 has no elbow
			Mode-2 (3.1 kW) @ home + Mode-4 (50 kW) @ semi-public	S1	S10	NA	S1 has no elbow
		Mode-3 (7.4 kW) @ home	Mode-3 (7.4 kW) @ home + Mode-3 (7.4 kW) @ semi-public	S2	S5	−40.0%	↓ Large (>15%)
			Mode-3 (7.4 kW) @ home + Mode-3 (23 kW) @ semi-public	S2	S8	−40.0%	↓ Large (>15%)
			Mode-3 (7.4 kW) @ home + Mode-4 (50 kW) @ semi-public	S2	S11	−40.0%	↓ Large (>15%)
		Mode-3 (7.4 kW) @ semi-public	Mode-2 (3.1 kW) @ home + Mode-3 (7.4 kW) @ semi-public	S3	S4	−14.3%	↓ Moderate (5–15%)
			Mode-3 (7.4 kW) @ home + Mode-3 (7.4 kW) @ semi-public	S3	S5	−57.1%	↓ Large (>15%)
		Mode-3 (23 kW) @ semi-public	Mode-2 (3.1 kW) @ home + Mode-3 (23 kW) @ semi-public	S6	S7	−33.3%	↓ Large (>15%)
			Mode-3 (7.4 kW) @ home + Mode-3 (23 kW) @ semi-public	S6	S8	−66.7%	↓ Large (>15%)
			Mode-2 (3.1 kW) @ home +	S9	S10	−33.3%	↓ Large (>15%)

	Mode-4 (50 kW) @ semi-public	Mode-4 (50 kW) @ semi-public				
		Mode-3 (7.4 kW) @ home + Mode-4 (50 kW) @ semi-public	S9	S11	−66.7%	↓ Large (>15%)
	Mode-2 (3.1 kW) @ home + Mode-3 (7.4 kW) @ semi-public	Mode-3 (7.4 kW) @ home + Mode-3 (7.4 kW) @ semi-public	S4	S5	−50.0%	↓ Large (>15%)
	Mode-2 (3.1 kW) @ home + Mode-3 (23 kW) @ semi-public	Mode-3 (7.4 kW) @ home + Mode-3 (23 kW) @ semi-public	S7	S8	−50.0%	↓ Large (>15%)
	Mode-2 (3.1 kW) @ home + Mode-4 (50 kW) @ semi-public	Mode-3 (7.4 kW) @ home + Mode-4 (50 kW) @ semi-public	S10	S11	−50.0%	↓ Large (>15%)
	Mode-2 (3.1 kW) @ home + Mode-3 (7.4 kW) @ semi-public	Mode-2 (3.1 kW) @ home + Mode-3 (23 kW) @ semi-public	S4	S7	0.0%	→ Not affected
Combined Combined	Mode-2 (3.1 kW) @ home + Mode-3 (7.4 kW) @ semi-public	Mode-2 (3.1 kW) @ home + Mode-4 (50 kW) @ semi-public	S4	S10	0.0%	→ Not affected
	Mode-2 (3.1 kW) @ home + Mode-3 (23 kW) @ semi-public	Mode-2 (3.1 kW) @ home + Mode-4 (50 kW) @ semi-public	S7	S10	0.0%	→ Not affected
	Mode-3 (7.4 kW) @ home + Mode-3 (7.4 kW) @ semi-public	Mode-3 (7.4 kW) @ home + Mode-3 (23 kW) @ semi-public	S5	S8	0.0%	→ Not affected
	Mode-3 (7.4 kW) @ home + Mode-3 (7.4 kW) @ semi-public	Mode-3 (7.4 kW) @ home + Mode-4 (50 kW) @ semi-public	S5	S11	0.0%	→ Not affected
	Mode-3 (7.4 kW) @ home + Mode-3 (23 kW) @ semi-public	Mode-3 (7.4 kW) @ home + Mode-4 (50 kW) @ semi-public	S8	S11	0.0%	→ Not affected

Of the twenty-five upgrades listed, twelve reduced the elbow capacity, by 14.3% to 66.7%, two increased it, seven left it unchanged, and four begin from scenario 1. The largest reductions in Table 6 were obtained by adding a home connection to a semi-public-only approach: a Mode-3 connection gave 57.1% at a semi-public power of 7.4 kW, moving the elbow from 70 kWh to 30 kWh, and 66.7% at 23 kW and 50 kW, moving it from 90 kWh to 30 kWh; a Mode-2 connection gave 14.3% at 7.4 kW and 33.3% at 23 kW and 50 kW, moving the elbow to 60 kWh in each case. Adding semi-public charging to an existing Mode-3 home connection gave 40.0% at every semi-public power level, moving the elbow from 50 kWh to 30 kWh. Upgrading an existing home connection from 3.1 kW to 7.4 kW reduced the elbow capacity by 50.0% wherever semi-public charging was present, from

60 kWh to 30 kWh, identically at all three semi-public power levels. Adding a Mode-3 home connection gave the largest reductions, and upgrading an existing Mode-2 connection to Mode-3 (50.0%) reduced the elbow capacity more than adding a Mode-2 connection did (14.3% to 33.3%), so both the presence and the rating of home charging matter.

Two results follow that hold across the whole of Section 4.1. First, once a home charging option is present, the elbow depends entirely on the home charging mode (Table 6): every scenario combining Mode-2 home charging has an elbow at 60 kWh, and every scenario combining Mode-3 home charging has an elbow at 30 kWh, regardless of the semi-public power. Second, for the scenarios without home charging (3, 6, and 9), raising the semi-public power from 7.4 kW to either 23 kW or 50 kW increases the elbow capacity from 70 kWh to 90 kWh. This increase is not a penalty: at 23 kW or 50 kW the curve keeps rising to 97.62% at 90 kWh, whereas at 7.4 kW it stops at 94.44%, so the higher elbow reflects a longer useful range rather than a larger requirement. The battery capacity required for an EV transition is therefore set by the availability and rating of home charging.

Measured in kWh, the substitution identified in Figure 8 is large. A driver with semi-public charging alone at 7.4 kW (S3) requires 70 kWh to reach the elbow, and the same driver with a Mode-3 home connection added (S5) requires 30 kWh. The charging upgrade removes 40 kWh from the requirement, which no increase in semi-public charging power approaches anywhere in the table.

The driving-share and capacity results diverge in one respect worth noting. Adding a second charging option to a configuration that already worked (S2 → S5 and S4 → S5) raised the driving share by only about 5% (Table 5), because coverage was already near its ceiling, yet the same upgrades still removed 40% of the required capacity for S2 → S5 and 50% for S4 → S5 (Table 6). Driving share saturates and the capacity requirement does not, so an upgrade that appears marginal in coverage terms can still remove a large share of vehicle cost. This is consistent with Lin [49], who found that improved charging infrastructure shifts the optimal BEV driving range towards shorter ranges.

4.1.6. Weekday Results

Under the weekday scheme, the driving share is governed by the number of charging opportunities available to a driver, then by the rating of the home connection, and only marginally by the semi-public charging power. Battery capacity differentiates the scenarios below 60 kWh and not above it (Figure 9), while the supported distance continues to differentiate them across the whole range (Scheme 1). Scenarios 5, 8 and 11 form the highest group at every capacity, reaching 96.03% at 20 kWh and above 99% at 30 kWh, and are the only scenarios that reach full coverage within the investigated range. Their elbow lies at 30 kWh, the smallest of any scenario with a rising curve.

The recommendation depends on the target adopted. If an 80% to 90% driving share is accepted, scenario 5 is the least demanding configuration, reaching both targets at 20 kWh and exceeding 99% at 30 kWh with no charging point above 7.4 kW at either location; scenarios 8 and 11 return on average 0.2% more (Table 5) and require a semi-public charging point rated at 23 kW or 50 kW. If full coverage is required, scenario 5 needs 90 kWh, whereas scenarios 8 and 11 need 60 kWh, and the higher-rated semi-public point earns its cost. In either case, scenarios 7 and 10 are dominated, requiring 40 kWh for a lower share. The choice of target is not purely technical, since EV users' range preferences have been found to exceed their average range needs substantially, although the gap narrowed with driving experience [50].

4.2. Weekend Driving Scheme

The weekend scheme uses the weekend profiles of the same 126 respondents and a public charging opportunity located at shopping centers, supermarkets and similar places rather than a semi-public one at the workplace. The mechanisms established in Section 4.1 are not repeated below; the weekend results are reported against them, and the discussion concentrates on where the two schemes differ.

4.2.1. Effect of Battery Capacity on Driving Share

As in the weekday scheme (Figure 6a), battery capacity had no effect under scenario 1 and a substantial effect under every other approach (Figure 12a). Scenario 1 remained at 26.98% at every capacity, admitting the same 34 weekend profiles throughout, since a Mode-2 session returns 6.2 kWh and 26.98% of the weekend profiles have a daily energy demand within that figure. Scenario 2 rose from 54.76% at 20 kWh to 95.24% at 110 kWh, a gain of 40.48 percentage points, with its elbow at 50 kWh and 84.13%. Upgrading the home connection from 3.1 kW to 7.4 kW (S1 → S2) therefore doubled the driving share at 20 kWh and more than tripled it at 110 kWh, and it is that upgrade which makes a larger battery worth purchasing at all.

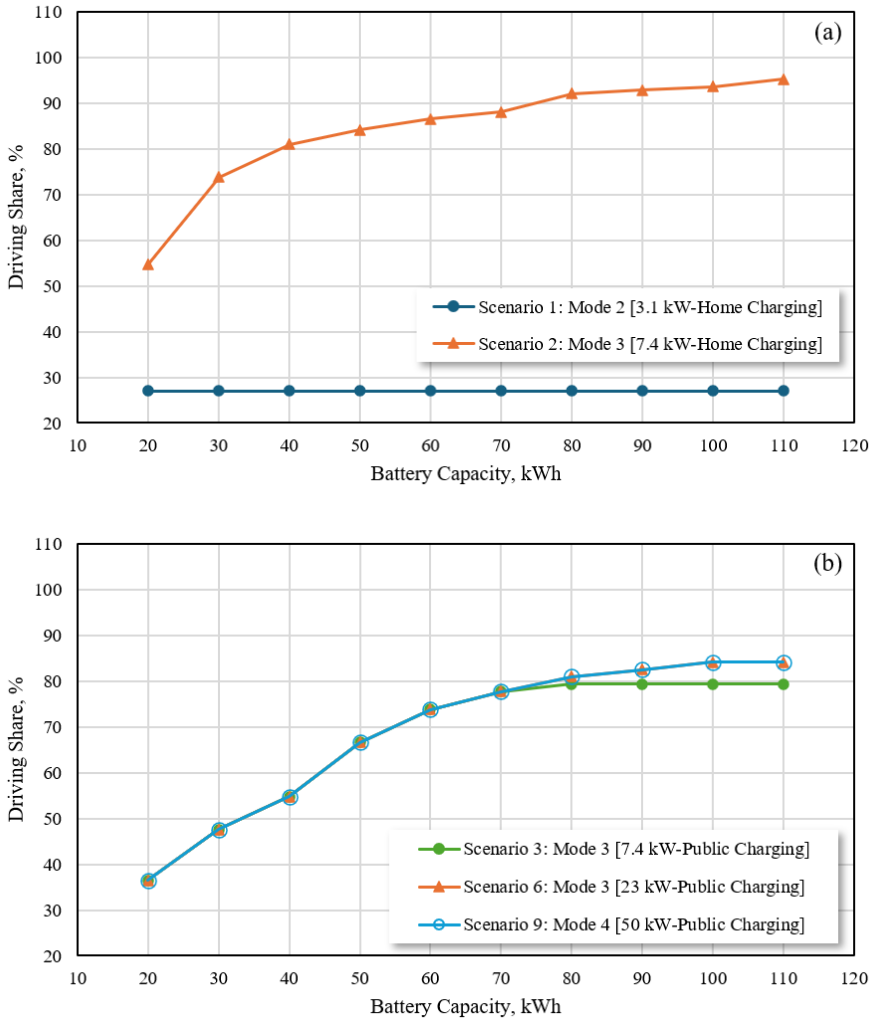


Figure 12. Driving share against battery capacity under the weekend driving scheme for the single-source charging approaches: (**a**) home-only charging (scenarios 1 and 2); (**b**) public-only charging (scenarios 3, 6 and 9).

The public approaches (Figure 12b) returned identical values from 20 kWh to 70 kWh (36.51% to 77.78%) and separated at 80 kWh, where scenario 3 reached 79.37% and held that value, while scenarios 6 and 9 continued to 84.13% at 100 kWh. Scenarios 6 and 9 were identical at every capacity. The benefit of higher public power is therefore confined to batteries above 70 kWh and to the step from 7.4 kW to 23 kW, which is the same conclusion reached under the weekday scheme but at a higher capacity threshold.

One weekend result has no weekday counterpart: the public approaches fall short of scenario 2 even at 50 kW, at 84.13% against 95.24%. Figure 13 explains why. Under scenario 2, every profile in Figure 13 falls into one of two categories: those that reach 100% at the start of the day, and those that cannot complete the day at all. For profiles that complete the day, the overnight charging period of at least 13 h at 7.4 kW provides sufficient energy to restore the battery to 100% before the next day. Consequently, the share of profiles satisfying the start-of-day condition is equal to the share that can complete the day.

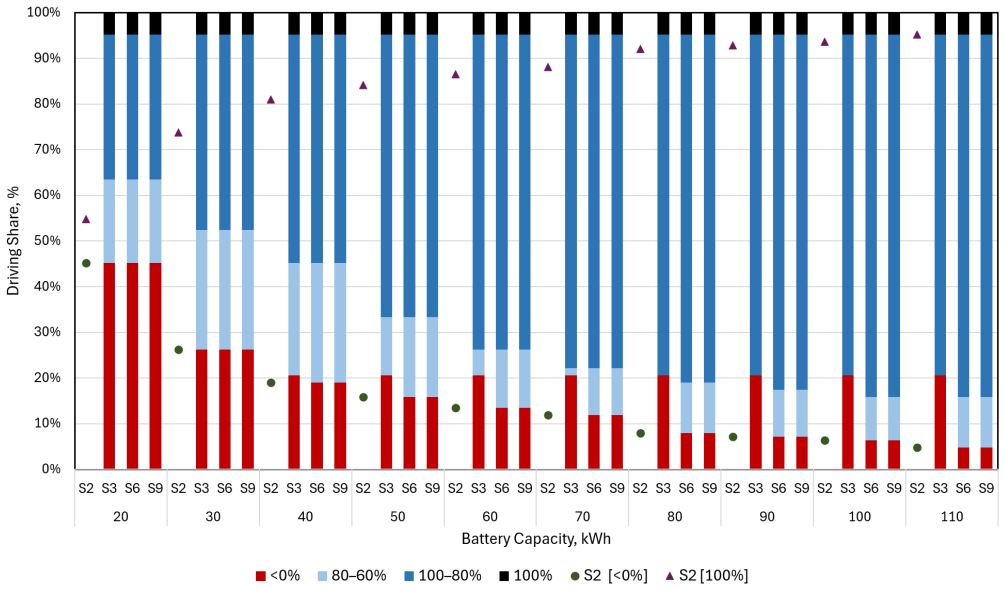


Figure 13. Distribution of the start-of-day state of charge across the 126 driving profiles under the weekend driving scheme, for scenarios 2, 3, 6 and 9 at each battery capacity. Profiles in the 100% and 100–80% bands satisfy the start-of-day condition. Profiles below 0% cannot complete the day at that capacity. Scenario 2 is shown as two markers because it produces no intermediate values.

Under scenarios 3, 6 and 9, a third category appears. These profiles complete the day but begin the next one with a state of charge between 80% and 60%, failing the start-of-day condition despite never breaching the 20% floor while driving. At 110 kWh this group comprises approximately 11% of the profiles under scenarios 6 and 9, the difference between their 84.13% driving share and the roughly 95% that complete the day. The group exists because no charging opportunity follows the last trip: the vehicle leaves the public place at most fully charged, drives home and remains there until morning, so the trip home must consume no more than 20% of the battery. Charging power cannot relieve this constraint, which is why scenarios 6 and 9 stop at 84.13% with a 200 kWh session available while scenario 2 reaches 95.24% at 7.4 kW. Drivers without home charging tend to rely on opportunistic charging at activity locations such as supermarkets and shopping centers rather than overnight [51]; the weekend results show that this pattern alone cannot satisfy the start-of-day condition for about 11% of profiles, whatever the charging power.

The weight of the two failure modes also differs between the public scenarios (Figure 13). At 110 kWh, approximately 21% of profiles cannot complete the day under scenario 3 against approximately 5% under scenarios 6 and 9, because a 4 h session at 7.4 kW

transfers 29.6 kWh while the same window at 23 kW transfers 92.0 kWh. Scenario 3 is therefore limited mainly by the session energy and scenarios 6 and 9 mainly by the absence of home charging, which is why raising the power resolves part of the gap and not the remainder.

Battery capacity raised the weekend driving share in every scenario except scenario 1, with the gains concentrated below 50 kWh in the combined approaches and below 70 kWh in the public-only approaches (Figure 14). Scenario 4 rose from 66.67% to 81.75% at 60 kWh and held that value, and scenario 5 rose from 80.95% to 99.21% at 100 kWh. The ranking within each panel was the same at every capacity and matches the weekday ordering: Mode-3 home charging highest, Mode-2 home charging second, and public charging alone lowest.

The weekend gains from adding a home connection were larger than the corresponding weekday gains in Figure 8 and decayed differently (Figure 14). At 20 kWh, adding a Mode-2 home connection (S3 → S4) raised the driving share from 36.51% to 66.67%, a gain of 30.16 percentage points, and adding a Mode-3 connection (S3 → S5) raised it to 80.95%, a gain of 44.44 points. At 110 kWh the same additions gave 2.38 and 19.84 points with public charging at 7.4 kW, and 3.97 and 15.87 points at 23 kW and 50 kW. The gain from a Mode-2 connection therefore falls almost to nothing as capacity grows, whereas the gain from a Mode-3 connection remains above 15 points across the whole range. Upgrading the home connection from 3.1 kW to 7.4 kW (S4 → S5, S7 → S8 and S10 → S11) gave 14.28 points at 20 kWh in all three panels, and 17.46 points at 110 kWh with public charging at 7.4 kW against 11.90 points at 23 kW and 50 kW. That upgrade also determines whether full coverage is reached: scenarios 8 and 11 admitted every recorded profile from 90 kWh onwards, while scenarios 7 and 10 reached only 88.10% at 110 kWh.

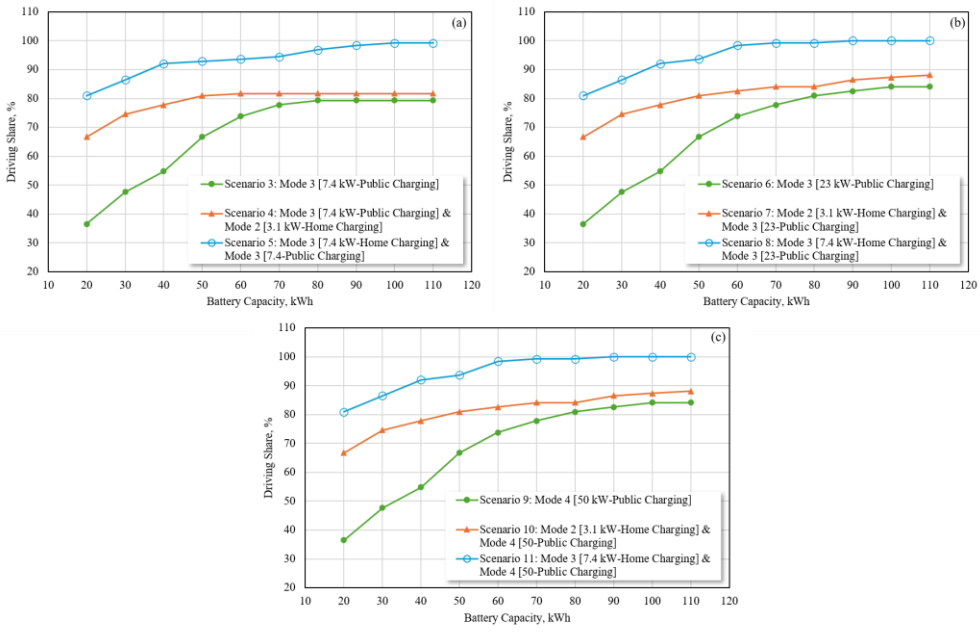


Figure 14. Driving share against battery capacity under the weekend driving scheme for the combined charging approaches, each compared with its public-only baseline: (**a**) public charging at 7.4 kW (scenarios 3, 4 and 5); (**b**) public charging at 23 kW (scenarios 6, 7 and 8); (**c**) public charging at 50 kW (scenarios 9, 10 and 11).

Raising the public charging power changed nothing below the capacity at which the 29.6 kWh session becomes binding (Figure 14), and that capacity depends on the home charging arrangement: scenarios 3, 6 and 9 were identical up to 70 kWh, scenarios 4, 7 and

10 up to 50 kWh, and scenarios 5, 8 and 11 up to 40 kWh. Above those capacities the increase to 23 kW gave at most 4.76 percentage points in the public-only approaches (S3 → S6), 6.35 points with a Mode-2 home connection (S4 → S7) and 4.77 points with a Mode-3 home connection (S5 → S8), and the further increase to 50 kW (S6 → S9, S7 → S10 and S8 → S11) gave nothing anywhere, panels (b) and (c) being identical throughout.

4.2.2. Overall Comparison of the Charging Scenarios

The eleven scenarios again reduce to five bands (Figure 15), defined by the same two features as under the weekday scheme (Figure 9). Scenarios 5, 8 and 11 form the highest band, reaching 80.95% at 20 kWh and 92.06% at 40 kWh, with scenarios 8 and 11 admitting every recorded profile from 90 kWh. Scenarios 4, 7, and 10 form the second band, at 66.67% at 20 kWh and between 81.75% and 88.10% at 110 kWh. Scenario 2 forms the third, scenarios 3, 6 and 9 the fourth, and scenario 1 the lowest at 26.98% throughout. Battery capacity separates the bands most strongly below 50 kWh, where the driving share spans 26.98% to 92.06%; above that capacity, the four upper bands converge towards a range of roughly 80% to 100%.

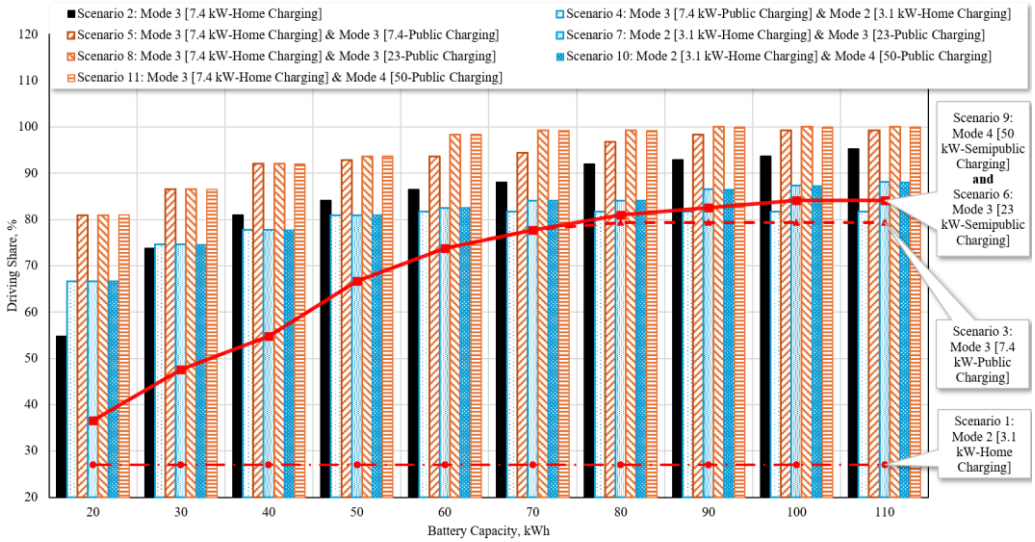


Figure 15. Driving share against battery capacity for all eleven charging scenarios under the weekend driving scheme.

The weekend scheme differs from the weekday scheme in one structural respect. In Figure 15, scenario 2 changes band as capacity grows, falling below the Mode-2 combined band at 20 and 30 kWh and rising above it from 40 kWh onwards, whereas under the weekday scheme the band order was fixed at every capacity. The reversal occurs because the two configurations are limited by different things. Scenario 2 is battery-limited: its unrestricted overnight session replaces the energy used during the day, so its driving share keeps rising as capacity grows. The Mode-2 combined band (S4, S7 and S10) is session-limited: the restricted two-hour home window and the public top-ups cap the energy that can be delivered, so it flattens from 60 kWh, at 81.75% for scenario 4 with public charging at 7.4 kW and at 88.10% for scenarios 7 and 10 at 23 kW and 50 kW. The choice between an unrestricted home connection (S2) and a restricted one supplemented by public charging (S4, S7 and S10) therefore depends on battery size, since the ranking reverses at 40 kWh.

4.2.3. Maximum Supported Driving Distance

The maximum daily driving distance attainable under each scenario is independent of the driving scheme, since it follows from the charging cycle and the eligibility conditions rather than from the recorded profiles. The values reported in Scheme 1 therefore apply unchanged, provided the vehicle is parked at home for at least 13 h, which holds for every weekend profile except one (10.75 h), and the differences between the two schemes reported in this section arise entirely from the distribution of daily distances in the weekday and weekend profiles and not from what the scenarios can support.

4.2.4. Benefit of Upgrading Between Charging Configurations

Table 7 reports the corresponding changes for the weekend scheme, calculated with Equation (5) in the same way as Table 5. The three largest increases in Table 7 again begin from scenario 1, each averaged over the ten battery capacities: 57.2 pp for upgrading the home connection to Mode-3 (S1 → S2), and 54.3 pp and 52.1 pp for combining the existing Mode-2 connection with public charging at 23 kW or 50 kW (S1 → S7 and S1 → S10) and at 7.4 kW (S1 → S4), respectively. As under the weekday scheme, these increases are large because the configuration being replaced admits so few profiles. On weekends, upgrading the home connection alone (S1 → S2) outperformed adding any public charging point to the restricted connection (S1 → S4, S1 → S7 and S1 → S10), including one rated at 50 kW, whereas on weekdays the 23 kW and 50 kW combinations were marginally ahead (73.1 pp against 72.9 pp). The weekend gains from scenario 1 are smaller than the weekday equivalents in Table 5 (57.2 pp against 72.9 pp) because the weekend configuration already admits a larger share of profiles (26.98% against 21.43%).

Table 7. Effect of upgrading charging on driving share for the weekend driving scheme.

Charging Approach		Upgrading Charging Mode		Upgrading Scenarios		Percentage Point Change in Mean Driving Share, 20–110 kWh [pp]	Effect (pp)
FROM	**TO**	**FROM**	**TO**	**FROM**	**TO**		
Single	Single	Mode-2 (3.1 kW) @ home	Mode-3 (7.4 kW) @ home	S1	S2	+57.2	↑ Large (≥10 pp)
		Mode-3 (7.4 kW) @ public	Mode-3 (23 kW) @ public	S3	S6	+1.4	↑ Marginal (1–5 pp)
			Mode-4 (50 kW) @ public	S3	S9	+1.4	↑ Marginal (1–5 pp)
		Mode-3 (23 kW) @ public	Mode-4 (50 kW) @ public	S6	S9	0.0	→ Not affected (0 pp)
Single	Combined	Mode-2 (3.1 kW) @ home	Mode-2 (3.1 kW) @ home + Mode-3 (7.4 kW) @ public	S1	S4	+52.1	↑ Large (≥10 pp)
			Mode-2 (3.1 kW) @ home + Mode-3 (23 kW) @ public	S1	S7	+54.3	↑ Large (≥10 pp)
			Mode-2 (3.1 kW) @ home + Mode-4 (50 kW) @ public	S1	S10	+54.3	↑ Large (≥10 pp)
		Mode-3 (7.4 kW) @ home	Mode-3 (7.4 kW) @ home +	S2	S5	+9.2	↑ Moderate (5–10 pp)

		Mode-3 (7.4 kW) @ public				
		Mode-3 (7.4 kW) @ home + Mode-3 (23 kW) @ public	S2	S8	+10.8	↑ Large (≥10 pp)
		Mode-3 (7.4 kW) @ home + Mode-4 (50 kW) @ public	S2	S11	+10.8	↑ Large (≥10 pp)
	Mode-3 (7.4 kW) @ public	Mode-2 (3.1 kW) @ home + Mode-3 (7.4 kW) @ public	S3	S4	+11.6	↑ Large (≥10 pp)
		Mode-3 (7.4 kW) @ home + Mode-3 (7.4 kW) @ public	S3	S5	+26.0	↑ Large (≥10 pp)
	Mode-3 (23 kW) @ public	Mode-2 (3.1 kW) @ home + Mode-3 (23 kW) @ public	S6	S7	+12.4	↑ Large (≥10 pp)
		Mode-3 (7.4 kW) @ home + Mode-3 (23 kW) @ public	S6	S8	+26.1	↑ Large (≥10 pp)
	Mode-4 (50 kW) @ public	Mode-2 (3.1 kW) @ home + Mode-4 (50 kW) @ public	S9	S10	+12.4	↑ Large (≥10 pp)
		Mode-3 (7.4 kW) @ home + Mode-4 (50 kW) @ public	S9	S11	+26.1	↑ Large (≥10 pp)
Combined Combined	Mode-2 (3.1 kW) @ home + Mode-3 (7.4 kW) @ public	Mode-3 (7.4 kW) @ home + Mode-3 (7.4 kW) @ public	S4	S5	+14.4	↑ Large (≥10 pp)
	Mode-2 (3.1 kW) @ home + Mode-3 (23 kW) @ public	Mode-3 (7.4 kW) @ home + Mode-3 (23 kW) @ public	S7	S8	+13.7	↑ Large (≥10 pp)
	Mode-2 (3.1 kW) @ home + Mode-4 (50 kW) @ public	Mode-3 (7.4 kW) @ home + Mode-4 (50 kW) @ public	S10	S11	+13.7	↑ Large (≥10 pp)
	Mode-2 (3.1 kW) @ home + Mode-3 (7.4 kW) @ public	Mode-2 (3.1 kW) @ home + Mode-3 (23 kW) @ public	S4	S7	+2.2	↑ Marginal (1–5 pp)
	Mode-2 (3.1 kW) @ home +	Mode-2 (3.1 kW) @ home +	S4	S10	+2.2	↑ Marginal (1–5 pp)

Mode-3 (7.4 kW) @ public	Mode-4 (50 kW) @ public				
Mode-2 (3.1 kW) @ home + Mode-3 (23 kW) @ public	Mode-2 (3.1 kW) @ home + Mode-4 (50 kW) @ public	S7	S10	0.0	→ Not affected (0 pp)
Mode-3 (7.4 kW) @ home + Mode-3 (7.4 kW) @ public	Mode-3 (7.4 kW) @ home + Mode-3 (23 kW) @ public	S5	S8	+1.6	↑ Marginal (1–5 pp)
Mode-3 (7.4 kW) @ home + Mode-3 (7.4 kW) @ public	Mode-3 (7.4 kW) @ home + Mode-4 (50 kW) @ public	S5	S11	+1.6	↑ Marginal (1–5 pp)
Mode-3 (7.4 kW) @ home + Mode-3 (23 kW) @ public	Mode-3 (7.4 kW) @ home + Mode-4 (50 kW) @ public	S8	S11	0.0	→ Not affected (0 pp)

The ordering of the upgrades in Table 7 is unchanged from Table 5 and most magnitudes are larger, although the upgrades that begin from scenario 1 and the additions of a Mode-2 home connection are smaller than their weekday counterparts. Adding a Mode-3 home connection to a public-only approach gave 26.0 pp at 7.4 kW (S3 → S5) and 26.1 pp at 23 kW and 50 kW (S6 → S8 and S9 → S11), on average across the ten battery capacities, against 21.3 pp and 20.2 pp on weekdays. Adding a Mode-2 home connection gave 11.6 pp (S3 → S4) and 12.4 pp (S6 → S7 and S9 → S10), so the Mode-3 connection again returned rather more than twice the Mode-2 connection. Upgrading an existing Mode-2 connection to Mode-3 within a combined approach gave 14.4 pp at 7.4 kW (S4 → S5) and 13.7 pp at the higher powers (S7 → S8 and S10 → S11), about three times the weekday values of 5.3 pp and 4.8 pp, and adding public charging to an existing Mode-3 home connection gave 9.2 pp (S2 → S5) and 10.8 pp (S2 → S8 and S2 → S11), about twice the weekday values of 4.8 pp and 5.0 pp. The weekend advantage was smaller where the home connection was being added rather than improved: a Mode-3 connection returned about 1.25 times its weekday gain, and a Mode-2 connection returned less than on weekdays, 11.6 pp and 12.4 pp against 16.0 pp and 15.4 pp. This may be associated with the session limit of the restricted connection, since the combined approach with Mode-2 home charging flattens from 60 kWh under the weekend scheme, at 81.75% with public charging at 7.4 kW and at 88.10% at 23 kW and 50 kW (Figure 14).

The contrast between the two upgrade types is sharper in Table 7 than in Table 5. Raising the public charging power saturates almost immediately, returning 1.4–2.2 pp between 7.4 kW and 23 kW (S3 → S6, S4 → S7 and S5 → S8) and nothing above 23 kW (S6 → S9, S7 → S10 and S8 → S11), again on average across the ten battery capacities, whereas adding or improving a charging location returned between 9.2 and 26.1 pp in every case. The least demanding upgrade in Table 7, the addition of a Mode-2 home connection using only a standard domestic socket-outlet (S3 → S4), returned 11.6 pp, roughly eight times more than raising the public power from 7.4 kW to 50 kW (S3 → S9).

4.2.5. Target and Elbow Capacity

Using the elbow capacity defined in Section 3, Figure 16 presents the elbow capacity and corresponding driving share for each charging scenario under the weekend driving scheme. Scenarios 5, 8, and 11 achieve the highest driving shares at their respective elbows,

ranging from 92.86% to 93.65%, with an elbow capacity of 50 kWh. Scenario 2 achieves 84.13% at 50 kWh, while scenarios 3, 6, and 9 achieve 77.78% at 70 kWh. Scenario 4 reaches its elbow at 60 kWh with an 81.75% driving share, which remains unchanged up to 110 kWh. These findings demonstrate that the charging configuration substantially influences both the elbow capacity and the driving share achieved at that capacity. In particular, combining Mode-3 home charging with workplace and public charging provides higher weekend driving-profile compatibility at comparatively moderate battery capacities.

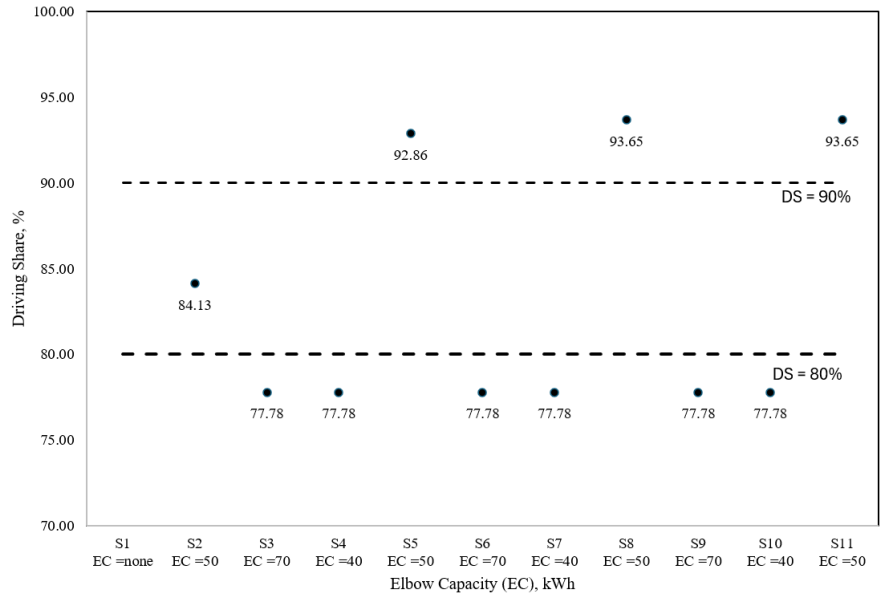


Figure 16. Weekend driving share achieved at the elbow capacity for each charging scenario. Dashed lines indicate the 80% and 90% driving-share targets.

Although the elbow capacity indicates where further increases in battery capacity produce diminishing improvements, it does not establish the minimum capacity required to achieve a specific driving-share target. To complement this assessment, Figure 17 presents the minimum battery capacities required to achieve weekend driving shares of 80%, 90%, and 100% under the eleven charging scenarios. Targets that could not be achieved within the investigated battery-capacity range of 20–110 kWh are reported as exceeding 110 kWh.

To achieve a driving share of 80% or above, the weekend scheme required a larger battery capacity in all scenarios, as shown in Figure 17, in comparison with the weekday scheme (Figure 11). The exceptions to this conclusion are S5, S8, and S11, owing to the charging mode and the available charging time at home. The smallest requirement was 20 kWh at the 80% target and 40 kWh at the 90% target, both obtained by scenarios 5, 8 and 11, against 20 kWh for both targets on weekdays; and 90 kWh at the 100% target, obtained by scenarios 8 and 11, against 60 kWh on weekdays. Failures are also more numerous. Two scenarios did not reach the 80% target at any capacity examined, seven did not reach 90%, and nine did not reach 100%. Raising the target from 80% to 90% doubled the requirement for scenarios 5, 8 and 11, from 20 kWh to 40 kWh, and for scenario 2, from 40 kWh to 80 kWh, and moved the remaining five beyond the investigated range. Raising it further to 100% added 50 kWh in scenarios 8 and 11 and exceeded the range in all other cases.

Improved charging reduced the required capacity at every target in Figure 17 where a comparison is available. At the 80% target, public charging alone at 23 kW (S6) required 80 kWh, adding a Mode-2 home connection (S7) reduced this to 50 kWh and adding a

Mode-3 connection (S8) to 20 kWh; home charging alone in Mode-3 (S2) required 40 kWh and adding public charging (S5, S8 and S11) reduced this to 20 kWh. At the 90% target, home charging alone (S2) required 80 kWh and adding public charging (S5, S8 and S11) halved this to 40 kWh. With higher public charging power (S9, S10, and S11), reaching a 100% driving share required a battery capacity greater than 110 kWh, except for S11, where the target could be achieved using 90 kWh. S11 is supported by home charging at 7.4 kW, whereas S10 is supported by home charging at 3.1 kW for two consecutive hours and S9 has no home charging.

Target driving share (%)	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11
80	> 110	40	> 110	50	20	80	50	20	80	50	20
90	> 110	80	> 110	> 110	40	> 110	> 110	40	> 110	> 110	40
100	> 110	> 110	> 110	> 110	> 110	> 110	> 110	90	> 110	> 110	90

Figure 17. Minimum battery capacity, in kWh, required to reach a target weekend driving share of 80%, 90% and 100% under each of the eleven charging scenarios. Entries marked as greater than 110 kWh indicate that the target was not reached at any capacity within the investigated range.

Comparing Figures 16 and 17 demonstrates that the elbow capacity and target-based minimum capacity provide complementary information. For example, scenarios 8 and 11 reach their elbow capacity at 50 kWh, achieving a 93.65% driving share, whereas achieving a 100% driving share requires 90 kWh. Therefore, additional battery capacity beyond the elbow may still be necessary when a higher driving-share target is specified, even though the incremental improvements fall below the five-percentage-point criterion.

Of the twenty-five upgrades listed in Table 8, six reduced the elbow capacity, twelve left it unchanged, three increased it, and four are not defined because they begin from scenario 1, whose curve is flat. The reductions were obtained only by adding a home connection to a public-only approach, at 42.9% for a Mode-2 connection (S3 → S4, S6 → S7 and S9 → S10) and 28.6% for a Mode-3 connection (S3 → S5, S6 → S8 and S9 → S11), corresponding to moves from 70 kWh to 40 kWh and to 50 kWh, respectively, at all three public powers.

Table 8. Percentage change in the elbow capacity resulting from each charging upgrade under the weekend driving scheme.

Charging Approach		Upgrading Charging Mode		Upgrading Scenarios		Change in Elbow Capacity [%]	Effect
FROM	TO	FROM	TO	FROM	TO		
Single	Single	Mode-2 (3.1 kW) @ home	Mode-3 (7.4 kW) @ home	S1	S2	NA	S1 has no elbow
		Mode-3 (7.4 kW) @ public	Mode-3 (23 kW) @ public	S3	S6	0.0%	→ Not affected
			Mode-4 (50 kW) @ public	S3	S9	0.0%	→ Not affected
		Mode-3 (23 kW) @ public	Mode-4 (50 kW) @ public	S6	S9	0.0%	→ Not affected
Single	Combined	Mode-2 (3.1 kW) @ home	Mode-2 (3.1 kW) @ home + Mode-3 (7.4 kW) @ public	S1	S4	NA	S1 has no elbow
			Mode-2 (3.1 kW) @ home + Mode-3 (23 kW) @ public	S1	S7	NA	S1 has no elbow

			Mode-2 (3.1 kW) @ home + Mode-4 (50 kW) @ public	S1	S10	NA	S1 has no elbow
		Mode-3 (7.4 kW) @ home	Mode-3 (7.4 kW) @ home + Mode-3 (7.4 kW) @ public	S2	S5	0.0%	→ Not affected
			Mode-3 (7.4 kW) @ home + Mode-3 (23 kW) @ public	S2	S8	0.0%	→ Not affected
			Mode-3 (7.4 kW) @ home + Mode-4 (50 kW) @ public	S2	S11	0.0%	→ Not affected
		Mode-3 (7.4 kW) @ public	Mode-2 (3.1 kW) @ home + Mode-3 (7.4 kW) @ public	S3	S4	−42.9%	↓ Large (>15%)
			Mode-3 (7.4 kW) @ home + Mode-3 (7.4 kW) @ public	S3	S5	−28.6%	↓ Large (>15%)
		Mode-3 (23 kW) @ public	Mode-2 (3.1 kW) @ home + Mode-3 (23 kW) @ public	S6	S7	−42.9%	↓ Large (>15%)
			Mode-3 (7.4 kW) @ home + Mode-3 (23 kW) @ public	S6	S8	−28.6%	↓ Large (>15%)
		Mode-4 (50 kW) @ public	Mode-2 (3.1 kW) @ home + Mode-4 (50 kW) @ public	S9	S10	−42.9%	↓ Large (>15%)
			Mode-3 (7.4 kW) @ home + Mode-4 (50 kW) @ public	S9	S11	−28.6%	↓ Large (>15%)
Combined	Combined	Mode-2 (3.1 kW) @ home + Mode-3 (7.4 kW) @ public	Mode-3 (7.4 kW) @ home + Mode-3 (7.4 kW) @ public	S4	S5	+25.0%	↑ Large (>15%)
		Mode-2 (3.1 kW) @ home + Mode-3 (23 kW) @ public	Mode-3 (7.4 kW) @ home + Mode-3 (23 kW) @ public	S7	S8	+25.0%	↑ Large (>15%)
		Mode-2 (3.1 kW) @ home + Mode-4 (50 kW) @ public	Mode-3 (7.4 kW) @ home + Mode-4 (50 kW) @ public	S10	S11	+25.0%	↑ Large (>15%)
		Mode-2 (3.1 kW) @ home + Mode-3 (7.4 kW) @ public	Mode-2 (3.1 kW) @ home + Mode-3 (23 kW) @ public	S4	S7	0.0%	→ Not affected
		Mode-2 (3.1 kW) @ home + Mode-3 (7.4 kW) @ public	Mode-2 (3.1 kW) @ home + Mode-4 (50 kW) @ public	S4	S10	0.0%	→ Not affected
		Mode-2 (3.1 kW) @ home + Mode-3 (23 kW) @ public	Mode-2 (3.1 kW) @ home + Mode-4 (50 kW) @ public	S7	S10	0.0%	→ Not affected
		Mode-3 (7.4 kW) @ home + Mode-3 (7.4 kW) @ public	Mode-3 (7.4 kW) @ home + Mode-3 (23 kW) @ public	S5	S8	0.0%	→ Not affected
		Mode-3 (7.4 kW) @ home + Mode-3 (7.4 kW) @ public	Mode-3 (7.4 kW) @ home + Mode-4 (50 kW) @ public	S5	S11	0.0%	→ Not affected

Mode-3 (7.4 kW) @ home + Mode-3 (23 kW) @ public	Mode-3 (7.4 kW) @ home + Mode-4 (50 kW) @ public	S8	S11	0.0%	→ Not affected

Providing a home charging opportunity is therefore the only upgrade that reduces the battery capacity a weekend driver needs, and this is the clearest difference from the weekday scheme (Table 6), in which upgrading an existing home connection also reduced it. Raising the public charging power did not change the elbow capacity anywhere in the table: the elbow remained at 70 kWh with public charging alone, at 40 kWh with a Mode-2 home connection (S4, S7 and S10) and at 50 kWh with a Mode-3 home connection (S5, S8 and S11), at every power from 7.4 kW to 50 kW. Adding public charging to an existing Mode-3 home connection (S2 → S5, S2 → S8 and S2 → S11) also left the elbow capacity unchanged at 50 kWh; its benefit appeared in the driving share instead, at 92.86% for scenario 5 versus 84.13% for scenario 2.

The three positive entries in Table 8 do not indicate a penalty. Scenario 4 reaches its elbow at 40 kWh with 77.78%, then rises only to 81.75% at 60 kWh and holds that value to 110 kWh, whereas scenario 5 reaches its elbow at 50 kWh with 92.86% and continues to 99.21% at 100 kWh. Upgrading the home connection extends the range over which capacity remains useful, so the higher elbow reflects a longer useful range and not a larger requirement.

4.2.6. Weekend Synthesis

The weekend scheme returns the same ordering of scenarios as the weekday scheme and the same conclusion about where investment is effective, but at consistently higher capacities and with larger gaps between the scenarios. Scenarios 5, 8 and 11 again form the highest band, reaching 80.95% at 20 kWh and 92.06% at 40 kWh (Figure 15), and scenarios 8 and 11 alone reach full coverage, at 90 kWh (Figure 16). Scenario 5 at 40 kWh is the most economical configuration for weekend mobility, reaching 92.06% with no charging point above 7.4 kW at either location, a driving share that scenario 2 did not reach below 80 kWh and that no public-only approach (S3, S6 and S9) reached at any capacity. This choice follows the 90% target in Figure 16; the elbow rule places scenario 5 at 50 kWh on weekends, where the additional 10 kWh adds only 0.8 percentage points. Where a driving share approaching 100% is required, scenario 8 at 60 kWh is the smallest configuration that suffices, at 98.41%, and this is the only point in the weekend results at which a public charging point above 7.4 kW earns its cost.

4.2.7. Comparison of the Two Driving Schemes

Three findings hold under both schemes and are supported by matched pairs of exhibits. The number of charging opportunities available to a driver governs the outcome more strongly than either the battery capacity or the semi-public or public charging power (Figures 9 and 14); the home charging arrangement determines the capacity required, and the semi-public or public charging power does not except for drivers with no home charging (S3, S6 and S9) (Tables 6 and 8); and no configuration in either scheme benefited from a semi-public or public charging point rated above 23 kW (Tables 5 and 7).

Three differences are material to infrastructure planning. First, every target requires a larger battery on weekends except the 80% target under scenarios 5, 8 and 11, which needs 20 kWh under both schemes (Figure 10 against Figure 16): 40 kWh rather than 20 kWh for a 90% driving share under scenarios 5, 8 and 11, and 90 kWh rather than 60 kWh for full coverage under scenarios 8 and 11. Second, upgrades made to a configuration that already includes home charging return two to three times more on weekends than on

weekdays (Table 5 against Table 7), whereas adding a home connection to public charging returns between 0.7 and 1.5 times its weekday gain. Third, the weekend results contain a ceiling that the weekday results do not (Figure 13): public charging alone cannot exceed 84.13% at any power, because no charging opportunity follows the last trip of the day and the journey home must therefore be completed from the state of charge held on leaving the public place. The same scenarios are recommended under both schemes, but the battery capacity that supports them is set by the weekend requirement. The dependence of both schemes on home charging aligns with the findings of Funke et al. [18], who found public charging to be needed as an alternative to home charging mainly in densely populated areas, while cautioning that such findings transfer between countries only to a limited extent. This is relevant in Oman, where current EV owners report that home charging is possible but public charging points are few, and where perceived infrastructure support is associated with a higher intention to adopt an EV [52].

5. Conclusions

This study examined whether current internal combustion engine vehicle drivers in Oman could complete their journeys using an electric vehicle (EV), and how this outcome varies with battery capacity and charging scenario. The state of charge (SoC) was calculated after each trip for 126 driving profiles under weekday and weekend driving schemes across eleven charging scenarios and battery capacities ranging from 20 kWh to 110 kWh. A driving profile was considered eligible if the SoC remained at or above 20% throughout every trip and at or above 80% at the start of each day. Each scenario combined home charging (Mode-2 at 3.1 kW or Mode-3 at 7.4 kW) with charging away from home at 7.4 kW, 23 kW, or 50 kW, or with no home charging. Charging away from home refers to semi-public charging at workplaces during weekdays and public charging at shopping centers or similar locations during weekends. The term ‘elbow capacity’ identifies the battery capacity beyond which increasing it does not increase the driving share in each sector. The main conclusions are as follows.

i. The charging arrangement determined the driving share more strongly than either battery capacity or charging power. Under both driving schemes, the eleven scenarios formed five groups, defined by the home charging arrangement and by the presence of a second charging location. Raising the charging power at the workplace or public place did not move any scenario from one group to another. Scenarios 5, 8 and 11, which combine Mode-3 home charging with workplace charging, reached a weekday driving share of 96.03% at 20 kWh. No single-source charging approach reached this value below 40 kWh.

ii. Mode-2 home charging alone did not support an EV transition at any battery capacity. The two-hour limit on Mode-2 charging in Oman restricts each home charging session to 6.2 kWh. Scenario 1 therefore remained at 21.43% under the weekday scheme and 26.98% under the weekend scheme across the whole capacity range, and supported a maximum daily driving distance of 26 km. Replacing the socket-outlet with a Mode-3 home charging point increased the weekday driving share to 66.67% at 20 kWh and to 99.21% from 60 kWh onwards.

iii. Increasing the charging power at the workplace or public place above 7.4 kW produced small gains, and increasing it above 23 kW produced none. Without home charging, raising the power from 7.4 kW to 23 kW (S3 → S6) increased the driving share by 1.3 pp under the weekday scheme and by 1.4 pp under the weekend scheme, both mean changes in percentage points across 20–110 kWh. Raising it further to 50 kW changed no driving share, target capacity or elbow capacity under either scheme. This result may be attributed to the session energy: a 4 h session at 7.4 kW already delivers 29.6 kWh, which exceeds the daily energy requirement of most recorded

profiles. The higher power affected the results only where this session limited the day. That occurred at five points. It extended the maximum daily driving distance above a 40 kWh battery capacity. It reduced the capacity required for the 100% weekday target from 90 kWh to 60 kWh. It moved the weekday elbow capacity with no home charging present (S3, S6 and S9) from 70 kWh at 7.4 kW to 90 kWh at 23 kW and 50 kW, where the curve continued to rise to 97.62% instead of stopping at 94.44%. Under the weekend scheme it decided the 80% target for public-only charging, which scenario 3 did not reach at any capacity examined while scenario 6 reached it at 80 kWh, and it raised the driving share of the Mode-2 home and public combinations (S4, S7 and S10) at 110 kWh from 81.75% at 7.4 kW to 88.10% at 23 kW and 50 kW.

iv. An additional charging opportunity reduced the battery capacity required. Adding Mode-3 home charging to workplace charging at 7.4 kW (S3 → S5) reduced the elbow capacity from 70 kWh to 30 kWh, a reduction of 57.1%. Under scenario 8, a 30 kWh battery supported a maximum daily driving distance of 202 km; the same distance required 60 kWh with Mode-3 home charging alone (S2). Adding a Mode-2 connection through a standard domestic socket-outlet to workplace-only charging (S3 → S4) increased the weekday driving share by 16.0 pp, a mean change in percentage points across 20–110 kWh. Raising the workplace charging power from 7.4 kW to 50 kW (S3 → S9) increased it by 1.3 pp.

v. The weekend driving scheme set the battery capacity requirement. Every driving-share target required a larger battery capacity under the weekend scheme than under the weekday scheme except the 80% driving-share target under scenarios 5, 8 and 11, which required 20 kWh under both schemes. For scenarios 5, 8, and 11, the 90% target required 40 kWh rather than 20 kWh. For scenarios 8 and 11, full coverage required 90 kWh rather than 60 kWh. Public charging alone did not exceed a driving share of 84.13% at any charging power. No charging opportunity followed the last trip of the day, so the trip home had to be completed from the SoC held on leaving the public place.

The preferred configuration depends on the target driving share. Across both the weekday and weekend schemes, a 40 kWh battery is sufficient to reach a 90% driving share, provided that Mode-3 charging is available at home, at the workplace, and at public destinations (scenario 5). It reached more than 99% under the weekday scheme and 92.06% under the weekend scheme, with no charging point rated above 7.4 kW at either location. For a target approaching 100%, scenario 8 with a 60 kWh battery reached 100% under the weekday scheme and 98.41% under the weekend scheme. Scenario 11 returned the same values as scenario 8 in every analysis. A 50 kW charging point at workplaces or shopping destinations is therefore not supported by the daily driving examined in this study.

These results suggest three priorities for charging infrastructure policy in Oman under the modeled assumptions. The first is dedicated Mode-3 home charging points, because the Mode-2 socket-outlet permitted for occasional use cannot provide daily charging. The second is AC charging rated between 7.4 kW and 23 kW at workplaces. The third is public AC charging at shopping and leisure destinations to support weekend driving.

The driving shares reported here describe technical feasibility under the modeled travel patterns, charging access, session limits and SoC criteria. They do not predict adoption rates, nor do they show that any configuration is economically superior. Future work should use logged driving data from a wider population and include long-distance and intercity travel, together with the role of DC fast charging along travel corridors. It should also determine the elbow capacity by weighing battery costs against charging infrastructure costs, and assess the grid impacts of home and daytime charging in Oman.

https://doi.org/10.3390/wevj17120629

Author Contributions: Conceptualization, A.A.-J. and A.Z.; Methodology, A.A.-J. and O.A.M.; Formal analysis, M.A.H. and A.Z.; Data curation, A.Z. and O.A.M.; Writing—original draft, M.A.H.; Writing—review & editing, A.A.-J.; Supervision, A.A.-J.; Project administration, A.A.-J. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare that they have no known financial or personal conflicts of interest that could have influenced the work reported in this study.

Nomenclature and Abbreviations

AC	Alternating Current
APSR	Authority for Public Services Regulation
BEVs	Battery Electric Vehicles
C	Usable (net) battery capacity, kWh
c_{size}	Vehicle power consumption, kWh/km
CC	Conductive Charging (CC)
CSO	Charging Station Operator
DC	Direct Current
DS	Driving Share, %
$d_{\Delta t}$	Traveling distance, km
E	Stored energy, kWh
E_{ch}	Energy regained after charging, kWh
E_{dis}	Energy remaining after discharging, kWh
EC	Elbow Capacity
EV	Electric Vehicle
EVSE	Electric Vehicle Supply Equipment (EVSE)
HEVs	Hybrid Electric Vehicles
IC-CPD	In-Cable Control and Protection Device
ICE	Internal Combustion Engine
ICEVs	Internal Combustion Engine Vehicles
IEC	International Electrotechnical Commission
MTCIT	Ministry of Transport, Communications and Information Technology
OBC	Onboard Charging
PHEVs	Plug-in Hybrid Electric Vehicles
P_{loc}	Charging power available at a given location, kW
SAE	Society of Automotive Engineers
SoC	State of Charge, %
t	Time, h
V2G	Vehicle-to-Grid
WPT	Wireless Power Transfer

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