EV Charging: Will Modular Architecture Be the Holy Grail?

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The transition to electric vehicles (EVs) is underway.

Supported by government policies, technological advancements, and evolving consumer preferences toward reducing carbon emissions, the EV market is set for substantial growth. According to our EV market model, the global EV passenger vehicle park is projected to see growth of ~28% CAGR, which would require >122 million charge points (CPs) by 2030. Besides the estimated growth, we are observing volatility in the market, mainly driven by fluctuating subsidies and the rollout of new technologies, e.g., battery capacity increases. As a result, the projected growth is not clearly predictable, especially with respect to time.

Need for scalable and flexible charging infrastructure.

Facing uncertainties in the speed of EV uptake, charge point operators (CPOs) must ensure that charging site capacity aligns flexibly with the expected growth. Building up infrastructure too fast might massively deteriorate utilization and profitability of CPOs, while underinvesting in their infrastructure expansion might, in the best case, result in missed opportunities and, in the worst case, stifle demand for EVs altogether. Scalable and flexible charging infrastructure solutions emerge as a strategic option offering CPOs the necessary balance between expanding infrastructure, securing sites, and maintaining high utilization rates to ensure economic viability in the long run.

Consequently, when designing a charging site's architecture, CPOs have a choice between different architectures considering the outlined aspects and the specific application. These two major charging site layouts are:

- **Stand-alone (the status quo)**
  Power electronics are positioned in each charging station.

- **Modular (the emerging trend)**
  Power electronics, thermal management, and switching matrix are centralized in one unit called the power unit, which dynamically assigns the power modules to distributed dispensers for each CP.

Key differences between stand-alone and modular architecture

While a monolithic stand-alone charger with integrated power electronics is the current technical standard, trends suggest a shift toward the modular power-unit/dispenser architecture in which the central power unit includes power electronics and a switching matrix connected to dispensers for greater scalability and flexibility *(see Exhibit 1)*.

Stand-alone architecture.

All components needed for DC charging and driver-EV interaction, e.g., power modules, active cooling, isolation monitors, charge controllers, and RFID readers, are merged into one monolithic housing of a stand-alone charger. Depending on the power level, the number and rating of integrated power modules and the dimensioning of electrical components differ.

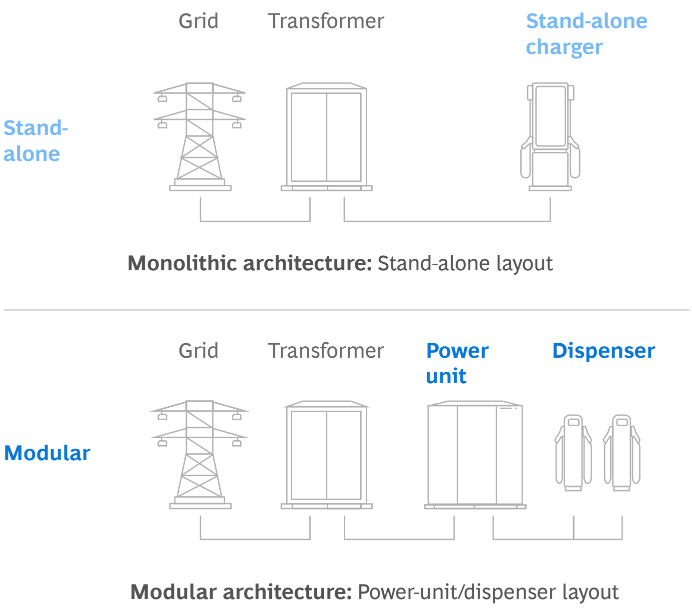
Modular architecture.

Power modules and their thermal management are externalized into a separate power unit that processes AC power supply into DC and provides a central DC power source to dispensers. For efficient operations, power modules are actively cooled. Both air and liquid cooling concepts are used. The power unit is designed modularly, typically ranging from 200 kW up to 2 MW. It can draw from both low- and medium-voltage AC networks. A so-called switching matrix consisting of DC breakers inside the power unit dynamically allocates power from the power modules mounted in the power unit to multiple dispensers via DC cables based on demand. As the dispensers are the sub-systems facing EV and driver, they include all components of a stand-alone charger that are not yet included in the power unit. Depending on power rating, components in the dispensers are dimensioned differently. Due to the absence of power modules, dispensers can be more compact than stand-alone chargers. They exist in different shapes that are often specialized to specific applications. With higher charging speeds, charging cables need cooling, e.g., by being connected to the power unit cooling system.

Exhibit 1

Similar components, different layout for stand-alone vs. modular architecture

EV charging infrastructure architecture



Key component

	Stand-alone	Power unit	Dispenser
Power modules	✓	✓	
HV relays	✓	✓	✓
Charging cables	✓		✓
Housing	✓	✓	✓
Active cooling (optional)	✓	✓	✓
Fans and filters	✓	✓	
AC contactors	✓	✓	
Power meters	✓		✓
Isolation monitors	✓		✓
Charge controller/PLC[1]	✓	✓	
Network components	✓	✓	
Payment terminal	✓		✓
RFID reader	✓		✓
Display	✓		✓

1. PLC = Power line communication
Source: EcoG and BCG analysis

Three archetypical use cases to compare stand-alone and modular architecture

To examine the ideal technical setup for CPOs based on required station design and expected growth, we will focus on three archetypical use cases that are most relevant for our comparative analysis. *(See Exhibit 2)*

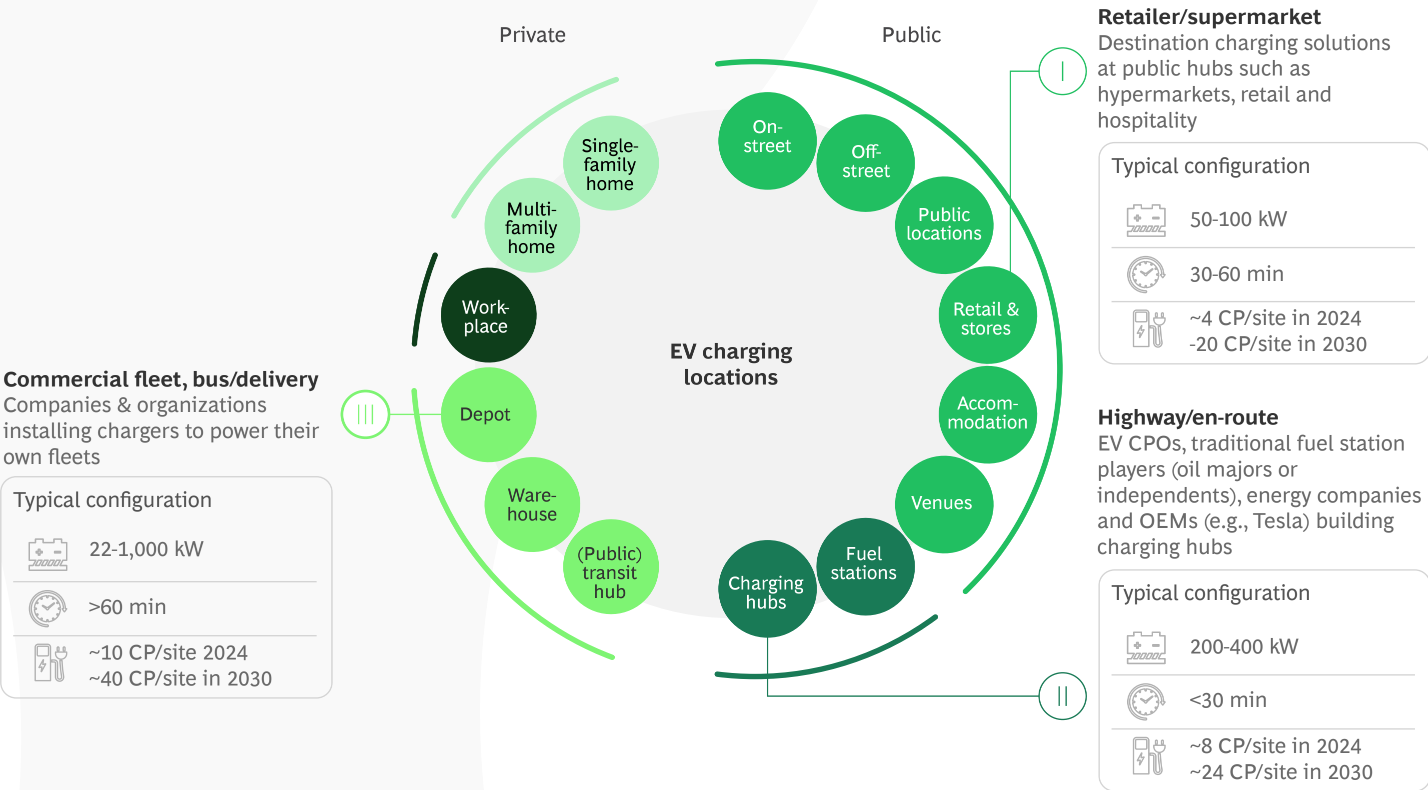
I **Semi-public or destination charging at retailers or supermarkets.** CPs located at shopping centers or supermarkets enhance customer convenience by enabling charging while shopping. These retail environments typically feature 50-100 kW chargers, which support 30-60 min charging sessions to align with the average consumer's shopping time. For these charging locations, we shall use a typical configuration of 4 CPs, each delivering 50 kW, as an example. We anticipate the site size to increase to 20 CPs of 50 kW by 2030.

II **Public charging at highways or en-route.** Charging sites along major driving corridors provided by traditional fuel stations, CPOs, and some EV manufacturers are crucial for long-distance EV travelers. Highway sites are equipped with powerful 200 to 400 kW HPC stations delivering a quick charge in under 30 minutes to minimize travel duration. Charging hubs along the highway are typically equipped with 8 HPCs of 200 kW at present, which we will use as an example for our comparison. We further project that the size of en-route locations will increase to 24 HPCs by 2030.

III **Depot charging of commercial bus or delivery fleets.** Commercial operators with substantial EV fleets, such as buses and delivery vans, rely on depot charging stations for streamlined charging management. These facilities are equipped with a wide range of chargers, from 22 kW units for overnight charging to potent 1 MW systems that facilitate quick turnarounds during operational hours. In the case of commercial fleets, we assume a typical depot charging site to combine a total of 10 CPs of different power levels from 50 kW to 200 kW. By 2030, the typical location size is projected to expand to 50 CPs of the same power levels.

Exhibit 2

Three use cases selected to compare charging site architectures



Source: EcoG and BCG analysis

Functionality advantage for modular architecture in majority of assessed criteria.

The comparison of stand-alone vs. modular architecture based on functional criteria and investment cost enables the identification of a tipping point. Focus use cases are mapped on specific site configurations to support CPOs in finding the optimum setup per location.

Key functional criteria for CPOs when planning a charging site:

Scalability. Potential for the charging site to grow with demand and maturing markets.

Warranty. Complexity of warranty processing, e.g., multiple suppliers or different power levels.

Outage rate. Total outage rate of charging points and reduction of system uptime, e.g., by malfunctions or damaged components.

Solution adaptability. Ability to customize the charging site's setup, e.g., power module and outlet position for individual customer solutions and requirements.

Ease of installation. Efforts to install charging infrastructure, including groundworks, foundation, and cabling.

Charging speed flexibility. Peak and simultaneous charging power achieved per outlet, including even blocked outlets.

Time-to-market. Duration from initial charging product idea to final customer solution.

Site integration. Fit of charging infrastructure into its environment, including energy efficiency, cooling, noise, filtration, and volume.

Product variety. Availability of products to fulfill customer demand.

Key investment cost factors for CPOs to prepare a site (excluding similar cost buckets for both architectures):

Product cost. Expenses associated with the charging hardware in 2024 and 2030, including bill of materials, assembly, testing, manufacturing, overhead, and OEM gross margin.

Installation and foundation cost. Expenses for building the foundation and installing the charger, including materials and working hours of construction company.

Simultaneity factor. Resulting CP availability, considering expected site utilization, charging speed based on initial battery level, and potential blockage by fully charged EVs.

Scalability. Stand-alone hardware typically offers up to two or four outlets, which ensures efficiency and low complexity but does not allow for flexible scaling. Increasing the number of CPs or the maximum power per CP of a site usually requires additional hardware. This means additional investment cost and space requirements. In contrast, the power-unit/dispenser layout is particularly convenient when it comes to scaling a site over time. Adding dispensers to electrify more parking lots or increasing the power of existing dispensers is less costly, which makes upgrades and staged investments easier. For CPOs, scalable architecture is crucial to collect real-life experience with a specific site — starting small and scaling with growing EV numbers. This is most relevant for en-route charging but is also highly important for depot charging. For retailers, importance is expected to rise significantly by 2030 as it is the use case with the highest expected growth rate.

Warranty. When it comes to supplier agreements, CPOs seek contracts that clearly define responsibilities for uptime and timely repair in case of error. Warranty processing is currently, as this is a new trend, still more complex for modular architecture than for the already established stand-alone architecture. Also, warranty tends to be more relevant for en-route and depot charging due to the higher frequency of charging processes compared to retailers.

Outage rate. The power unit as the central source of DC supply might also be the source of risk regarding uptime. However, a power unit can be equipped with technical redundancies leading to higher uptimes than with stand-alone chargers since component defects, e.g., malfunctioning power modules or damaged charging cables, can be covered. Maximum system availability is key for any charging site but crucial for en-route and depot charging to ensure mobility at any time. For retailers, we expect demand for high uptimes to increase by 2030.

Image generated by AI

Solution adaptability. Dispensers are easier to develop than complete stand-alone charging systems due to the separation of power electronics, thermal management, and switching matrix from the EV and driver-facing functions. Hence, customized solutions can be rolled out more quickly and with less effort. This allows brand-specific individual solutions of retailers and adaptations to local requirements of depot sites for charger designs to fit the space and context of the specific site. Highway sites usually require less individual adoption as many of the sites have fewer existing structural constraints.

Ease of installation. The installation of a stand-alone charger requires a solid foundation and AC cabling from the transformer, as well as transportation, handling, and mounting of the heavy hardware. For modular architecture, a foundation for the power unit is needed, along with the connection of the power unit to the AC supply. Dispensers can be built on a lighter foundation due to their lower footprint and weight. With an increasing number of electrified parking lots, easier installation leads to additional benefits. Ease of installation is most relevant for en-route charging and depot charging where high numbers of chargers are required.

Charging speed flexibility. Stand-alone chargers usually provide power to an average of two outlets. If both are in use, power and power modules are shared between two EVs, resulting in a speed cap. Moreover, fully charged or non-charging EVs that are not removed from the parking lot or are damaged can lead to outlet blockage. In such cases, stand-alone chargers are limited as power electronics cannot be utilized to the full extent. The power-unit/dispenser layout allows for a dynamic shift of power electronics to another unblocked outlet. For instance, when an EV is already slowing down its charging curve after reaching a state of charge (SoC) >80% or when there are free outlets, power can be redirected to dispensers in use. Thereby, charging speed allocation can be optimized across a modular site. Flexible charging speed is particularly crucial for sites with high power required in a short period of time, e.g., along the highway or at depot sites.

Time-to-market. In a market phase of high innovation speed and maturing regulatory frameworks, fast development of new products is required to serve demand and keep up with competition. The past has proven that stand-alone charger development projects typically require up to 2 years. The main reason for this is the high complexity of a very integrated system with numerous requirements, e.g., EMC, safety, regulations, payment, and connectivity. The separation of functions into power unit and dispensers positively affects development speed. While the power unit becomes a very grid-connected subsystem with a mix of electrical, thermal, and mechanical requirements, the dispensers ensure the user interface for the driver and the connectivity to the car. This eases up time-to-market for both subsystems, which could potentially be developed by two different companies with component-specific competence profiles. Time-to-market is most relevant for depot charging but also for retailers as development needs are expected for these use cases.

Site integration. Space constraints can create hurdles to electrify parking lots as ground is costly. For charging infrastructure, this should minimize footprint and integrate into the site space availability in the best possible manner. Dispensers consume significantly less space than stand-alone chargers and can fit into an existing site more easily. Even ceiling-mounted dispensers are possible, highlighting the clear advantage of modular architecture. This is especially relevant for depot charging to ensure enough space for commercial vehicles. Also, retailers with space-efficient site architecture will benefit from more parking lots for customers.

Product variety. As of today, more stand-alone hardware products are available in the European market. Hence, the available product variety for stand-alone hardware is larger than for power-unit/dispenser systems. Over time, we expect to observe a growth in model and solution variety for modular architecture. For CPOs a broader option space will improve purchasing conditions, quality, supply chain stability, and delivery times. This is most relevant for retailers with a high tendency towards individualization.

In summary, modular architecture offers numerous functional advantages for the analyzed criteria, making it an attractive alternative to stand-alone chargers in all three evaluated use cases. This is highlighted by 45% to 65% higher functionality scores, depending on the use case. Moreover, the advantage of power-unit/dispenser systems against stand-alone chargers is expected to further increase in the future, yielding 60% to 70% higher functionality scores by 2030 *(see Exhibit 3)*.

Exhibit 3

Modular architecture with higher functionality in most of criteria

Functional criteria	Evaluation (in '24 und '30) Stand-alone	Modular	Rationale for evaluation	Criteria importance (in '24 und '30) Retailer/ super-market	Highway/ en-route	Comm. fleet bus/ delivery	Rationale for criteria importance
Scalability	●○○○	●●●●	Staged investment and upgrades easier for modular architecture				Rising importance for retailers by 2030 as use case with highest expected growth rate
Warranty	●●●○	●●○○	Stand-alone less complex as typical model with established market and supply chain				Higher importance for en-route and depot due to higher utilization rates
Outage rate	●●●○	●●●●	Flexible power allocation and redundant systems in power unit				Crucial for en-route and depot to ensure mobility 24/7; increasing retailer uptime demand by 2030
Solution adaptability	●○○○	●●●○	Design and positioning of components more flexible for modular architecture				High importance for depot due to space constraints and for retailers due to branding
Ease of installation	●●●○	●●●●	Equal in cabling, simpler foundation for dispensers than for stand-alone hardware				Importance depending on use case size, expected to rise for all use cases by 2030
Charging speed flexibility	●●○○	●●●●	Speed cap for stand-alone chargers if all outlets occupied, more flexible allocation for dispensers				High importance for en-route and depot as high power required in short period of time
Time-to-market	●●○○	●●●●	Separation of power unit and dispenser means simplified products and less development time				Highest importance for depot and retailers due to expected development needs
Site integration	●●○○	●●●●	Smaller footprint for flexible dispenser design and hidden power units				Highest relevance for depot as commercial vehicles require space to be moved
Product variety	●●○○	●○○○	Number of available modular solutions growing, market picking up speed by 2030				Highest importance for retailers due to higher tendency towards individualization

Low ○○○○ ↔ ●●●● High   Low ○ ↔ ● High   ○ Updates '30 vs. '24

Source: EcoG and BCG analysis

Investment cost advantage of modular architecture for large-scale charging sites

Investment cost for retailer/ supermarket.

Comparing the investment need for both architectures in the assumed setup of 4 CP with 50 kW each reveals a cost delta of 27% (€7k) per CP favoring stand-alone (€23k per CP) over modular (€30k per CP). As the tipping point can be identified at approximately 6 CPs, only above-average dimensioned sites would benefit from lower cost at present with modular compared to stand-alone architecture. Moreover, the modularity of components within the modular architecture causes fluctuations in the total cost per CP for increasing location dimensions. Particularly, the cost of the additional power unit required from 12 CPs drives up the expenses for modular architecture, introducing an additional intersection of both cost curves at around 13 CPs. However, this will not result in a significant cost advantage for stand-alone. Therefore, we would still consider the de facto tipping point at which modular architecture becomes more cost-efficient for retail charging sites to be 6 CPs.

By 2030, the average site size and the cost for both layouts will change: For a typical site with 20 CPs at 50 kW, the power-unit/dispenser layout is expected to be 38% more cost-efficient (€13k per CP) versus stand-alone (€22k per CP). At this stage, the tipping point is expected to be approximately 4 CPs *(see Exhibit 4)*.

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Investment cost for highway/ en-route.

Based on our assumption of 8 CPs with 200 kW, the current cost delta amounts to 12% (€5k per CP) more for modular (€54k per CP) vs. stand-alone (€49k per CP). Both cost curves intersect multiple times due to additional required power units from 8 CP, 14 CP, and 20 CP, causing a cost per CP increase for the modular architecture. However, for 14 or more CPs, the cost delta in favor of stand-alone is negligible. Therefore, the effective tipping point from which modular is more cost-efficient than stand-alone for HPC hubs is currently at around 10 CPs.

In 2030, the cost delta for the assumed typical location size of 24 CPs with 200 kW is expected to change to 31% (€14k per CP) in favor of modular (€31k per CP) vs. stand-alone (€45k per CP). The tipping point will be at 3 CPs by then *(see Exhibit 4)*.

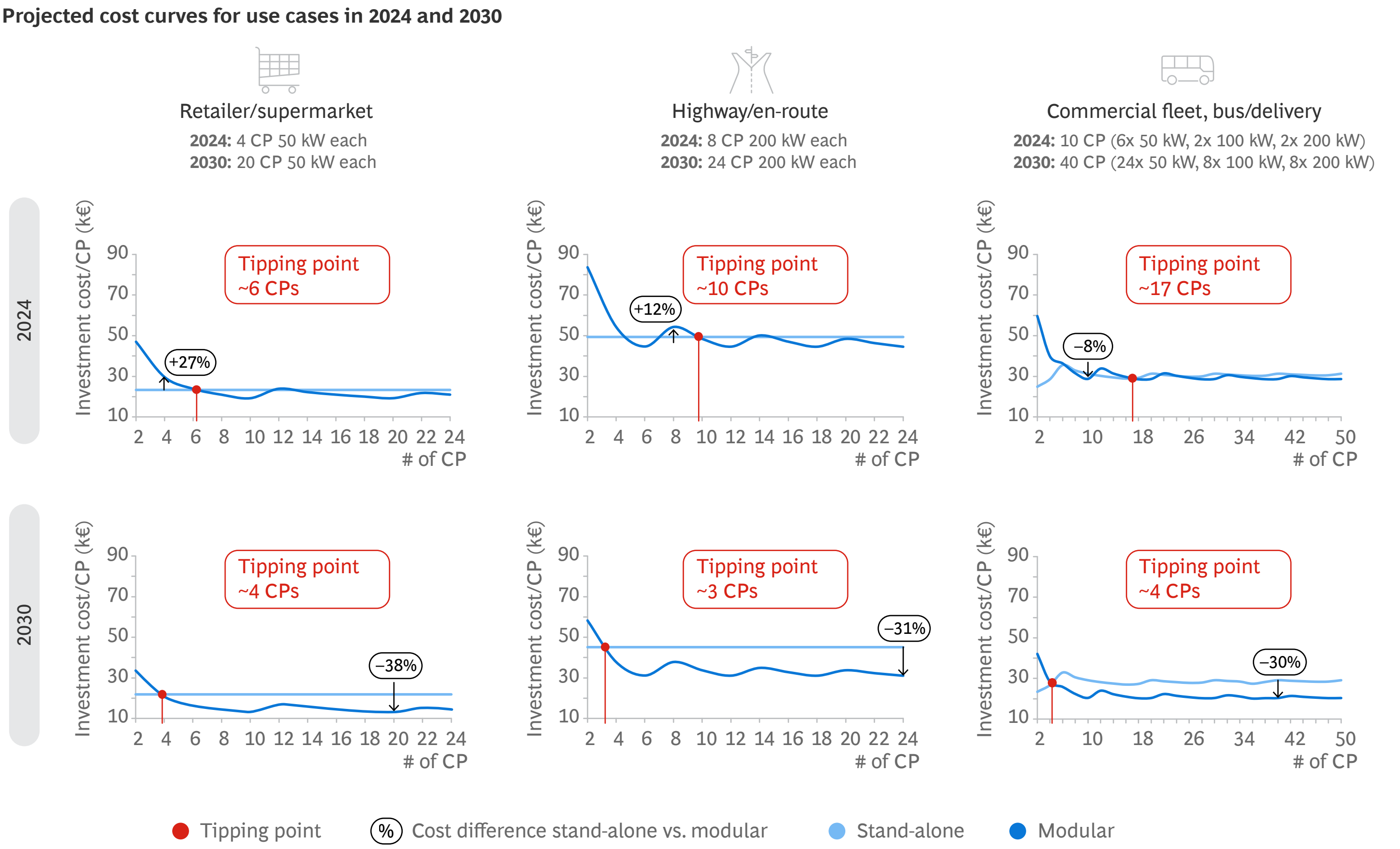
Investment cost for commercial fleet, bus/delivery.

In the case of commercial fleets, we assume a typical depot charging site to combine a total of 10 CPs of different power levels, e.g., 6x 50 kW, 2x 100 kW, and 2x 200 kW. Our analysis reveals a cost advantage of 8% (€2k) per CP for modular (€29k per CP) compared to stand-alone (€31k per CP) for the assumed site configuration. Due to the mixed setup of multiple CPs with different charging power, cost per CP fluctuates for both architectures, resulting in multiple cost curve intersections. Again, there is no relevant cost advantage for stand-alone for the intersection around 22 CP. As a result, the tipping point at present can be located at approximately 17 CPs.

Similarly, in 2030, when a total of 40 CPs with similar power level distribution is expected, the cost-benefit of modular (€20k per CP) vs. stand-alone (€29k per CP) is expected to rise to 30% (€9k per CP). The power-unit/dispenser layout will be more cost-efficient for any site size greater than the tipping point at 4 CPs as cost for modular architecture are expected to decrease much more than for stand-alone in the coming years *(see Exhibit 4)*.

Exhibit 4

Modular architecture most cost-efficient by 2030



Source: EcoG and BCG analysis

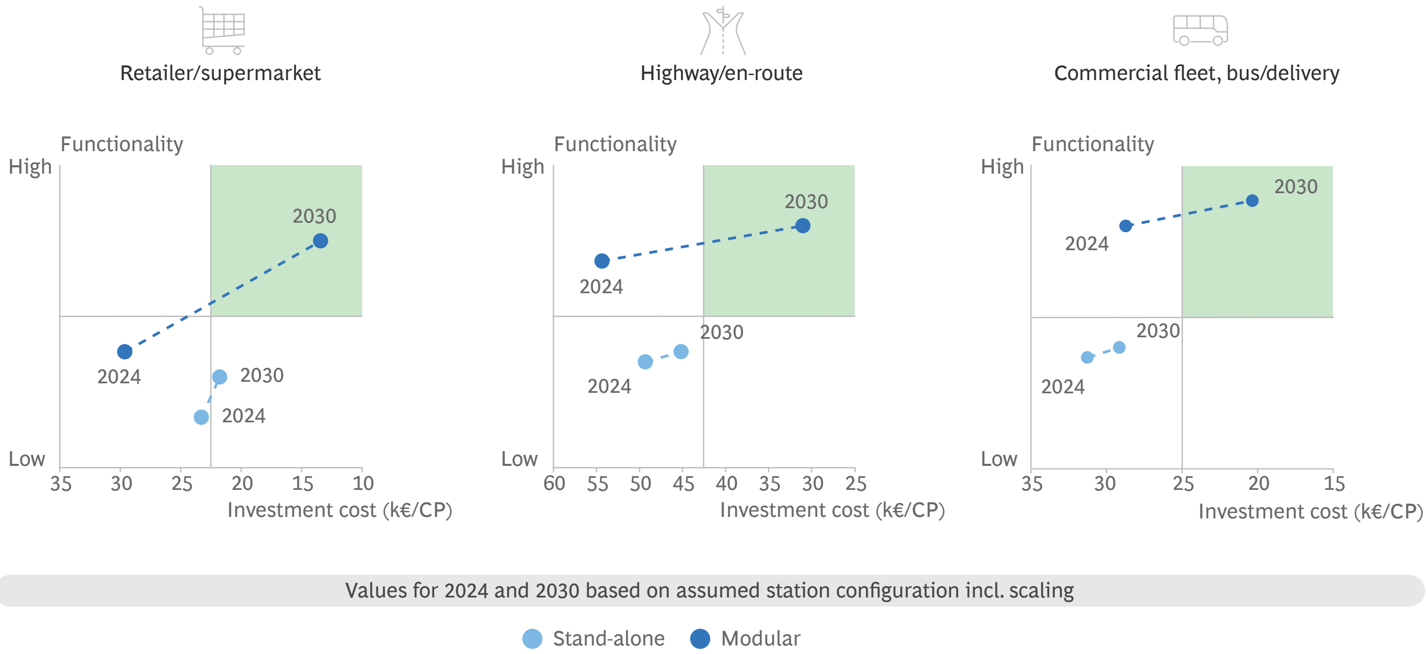
Modular architecture with higher functional value already today and lower investment costs by 2030

The comparison of both charging architectures shows that modular offers superior functionality across the analyzed criteria and is expected to increase its functional advantages further by 2030. Regarding investment cost, large-scale use cases and sites expecting future scaling can especially benefit from modular architecture. Depending on the location dimensions, modular can already be more cost-effective. *Exhibit 5* illustrates these trends, predicting that by 2030, modular systems will be more cost-efficient and functional for all three use cases in the assumed site setup.

Exhibit 5

Modular architecture with higher functional value already today and lower investment costs by 2030

Comparison of functionality score and investment cost by use case in 2024 and 2030



Source: EcoG and BCG analysis

CPOs should analyze each site case-by-case to identify the most suitable architectural solution

Prioritize modular architecture for large-scale use cases that expect further scaling.

As our analyses underscore, modular charging architecture is clearly beneficial for larger charging locations with 6 to 17 CPs at present. Moreover, sites with fewer CPs but highly fluctuating utilization rates or high variations in required power per CP, e.g., HPC parks or fleet charging sites, might already be equipped with power units and dispensers to benefit from the related functional advantages while being able to easily scale as soon as demand takes up. Consequently, for the above-mentioned or similar applications, CPOs should consider prioritizing modular instead of stand-alone architecture.

Keep focus on stand-alone architecture for small to medium-scale use cases requiring individual solutions.

Moreover, the assessment points out that stand-alone charging architecture is advantageous for smaller use cases requiring unique, tailored solutions. Our results indicate that for locations with fewer than 6 to 17 CPs at present, the cost-efficiency and simplicity of stand-alone systems make them the preferred choice. Small retail parking lots, supermarkets, and low-space areas in city centers particularly benefit from the integrated design and ease of installation of stand-alone chargers. These systems provide a straightforward solution, making them ideal for applications with stable, predictable demand and limited expansion plans. Therefore, CPOs should prioritize stand-alone architecture for small-scale projects where individualized charging solutions are essential.

Request and compare several available offers as cost is currently fluctuating.

The variability in market prices and supplier margins can significantly impact overall cost. By soliciting and analyzing various quotes, CPOs can identify the most cost-effective options and leverage competition to negotiate better terms. This approach ensures that they secure the best possible prices, maximizing cost-efficiency and profitability. Given the current fluctuations in market prices as well as the uncertainties on the exact tipping point, it is crucial for CPOs to request and compare multiple offers before making purchasing decisions, especially for sites with 6 to 17 CPs. By 2030, we expect the fluctuations to ease as market prices for modular architecture will decrease due to stronger competition and product efficiencies.

Despite the current market turbulences, the EV market will rise, driven by regulation, R&D, and consumer demand. As a result, the need for scalable and flexible charging infrastructure has never been greater. Our analysis demonstrated that modular architecture already offers significant functional benefits, and further advantages are expected by 2030. Several large European CPOs have already recognized this and are in the process of moving to power-unit/dispenser architectures.

Investment cost for modular architecture is currently higher than for stand-alone systems, depending on the specific location setup. However, the tipping point at which modular architecture becomes more cost-effective is already within reach for certain use cases, such as large HPC parks and depot charging sites with high power demand variations. By 2030, we anticipate additional players entering the modular segment, driving down market prices, and reducing the tipping points.

As a result, we expect modular architecture to become the holy grail for a variety of use cases. Moreover, the power-unit/dispenser layout could already be prioritized for sites expecting future growth. Therefore, CPOs should conduct a case-by-case examination to identify the optimal architectural solution that meets the functional and financial needs of each site. This approach will allow them to scale flexibly and keep up the pace of the evolving landscape of EV charging infrastructure.

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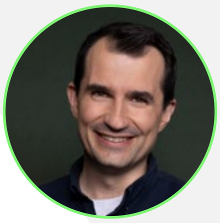

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