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Innovative EV Charging Infrastructure for European Transportation Electrification

MW charging hubs with battery energy storage and solid-state transformers for medium voltage grid integration

By Zian Qin, Sebastian Rivera, Haoyuan Yu, Frede Blaabjerg

The global race toward decarbonization has reached a transformative inflection point as electrification surges across the transportation sector in most of the world. No longer confined to passenger vehicles, electric mobility now spans trucks, ships, and even aircraft, driven by a confluence of environmental mandates, policy momentum, and technological innovation. Nowhere is this shift more pronounced than in Europe, where the Trans-European Transport Network (TEN-T) envisions a seamlessly connected, zero-emissions infrastructure backbone by mid of this century. At the heart of this revolution lies a new breed of ultra-fast charging technologies, electrified highways and maritime ports—each pushing the limits of energy delivery, grid integration, and power electronics. Yet, as the charging power scales from kilowatts to multi-megawatts, and as electric mobility moves from concept to logistics-critical reality, the challenges to the power grid—especially at the distribution level—are becoming clearly visible. This article explores the emerging architectures and innovations required to enable this new era of electric transport, from Megawatt Charging Systems (MCS) to medium-voltage grid integration with Solid State Transformers (SSTs) and Grid Forming Battery Energy Storage Systems (GFM-BESS) as key components.

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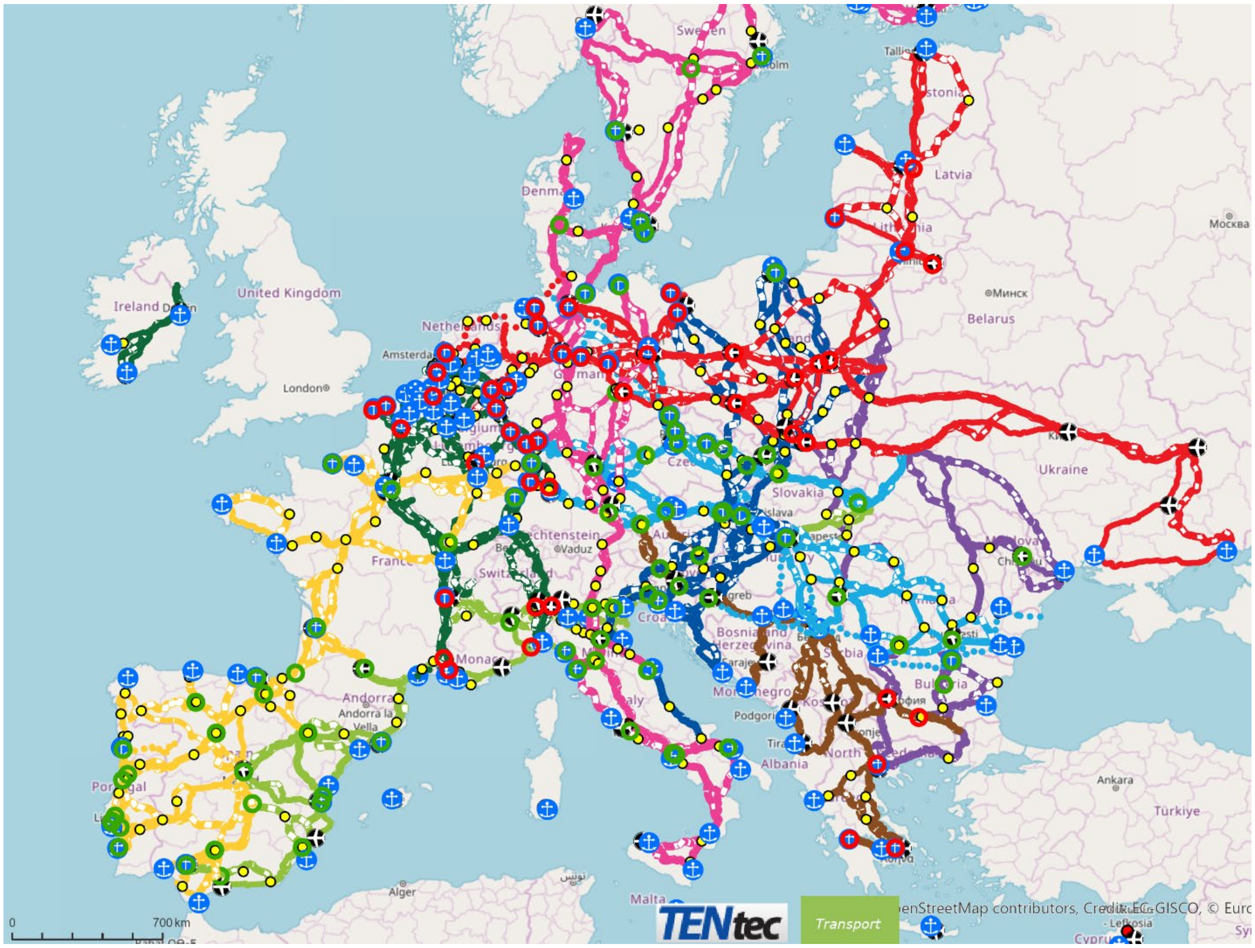


Figure 1 Trans-European Transport Network (TEN-T) Schematic Map of the European Transport Corridors. The regional transport networks are differentiated by colors. (Source: European Commission, DG MOVE, TENtec Information System, based on Reg. 2024/1679)

Section 1 Transportation network is being electrified in Europe

Electric vehicle charging today is no longer limited to passenger cars. The entire transportation sector is undergoing a profound transformation as electrification expands across all kinds of travel and transport. Europe has set an ambitious course through the development of the TEN-T; a comprehensive strategy designed to interconnect the continent and modernize its infrastructure to meet the demands of a sustainable future. The TEN-T initiative envisions a highly integrated and multimodal transport network, involving significant investments aimed at enhancing roadways, railways, inland waterways, and airports. The plan distinguishes between the core network, which prioritizes the most vital connections between major cities and logistics hubs and is targeted for completion by 2030, and the comprehensive network, which is intended to ensure connectivity across all EU regions and is scheduled for completion by 2050. A central objective of the TEN-T is the substantial reduction of greenhouse gas emissions from the transport sector, with railway lines across the network set to be fully electrified to minimize reliance on fossil fuels. Additionally, considerable attention is being directed toward equipping roads and ports with the infrastructure necessary to support electrified freight and passenger transportation. Heavy-duty vehicles, trucks, and maritime vessels are central to this shift. From 2025 onwards, legislation mandates that fast-charging stations capable of delivering at least 150 kilowatts of power must be installed at intervals of no more than 60 kilometers along major transport corridors to ensure reliable coverage. Looking ahead to 2030, these charging requirements will become even more demanding, with the expectation that ultra-fast charging stations with a minimum output of 350 kilowatts will be installed every 100 kilometers across the full extent of the European road network. Maritime infrastructure is also under transformation. By 2030, maritime ports that accommodate a minimum number of large passenger or container vessels will be required to provide shore-side electricity to reduce emissions from docked ships. (Source: AFIR, [Alternative fuels infrastructure: Council adopts new law for more recharging and refuelling stations across Europe - Consilium])

Section 2 Charging systems for the electric vehicles

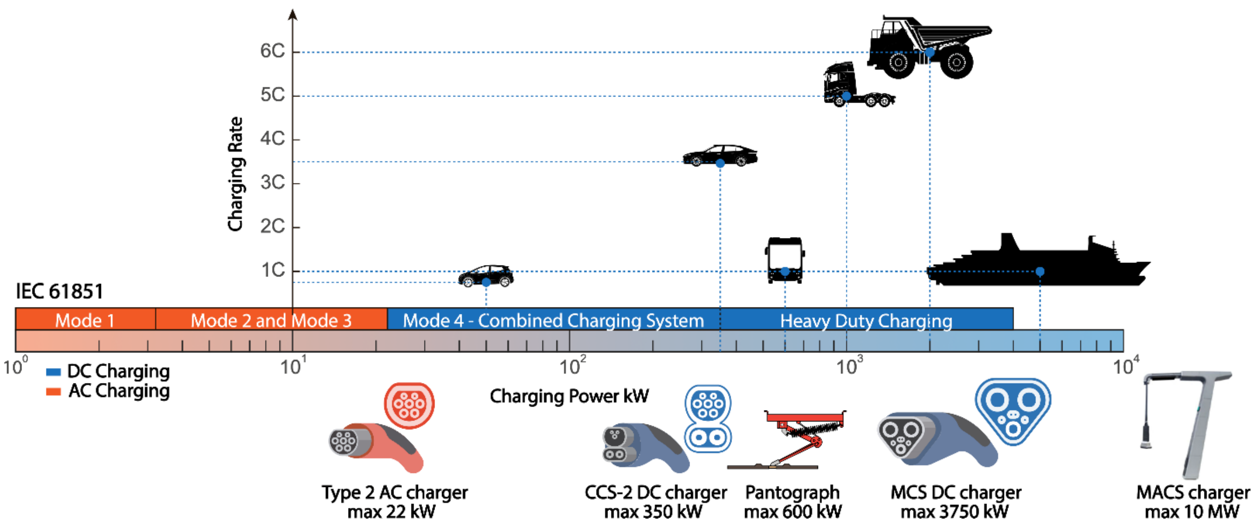


Figure 2 Electrified transportation and their charging systems. (*MACS: short of Machine Assisted Charging Systems*).

The Combined Charging System (CCS) has been adopted as the principal direct current (DC) fast-charging connector across Europe, forming a critical backbone of the continent's electric vehicle infrastructure. It supports charging power levels up to 350 kW, which serves as an initial pillar that can supply mid-range heavy duty trucks. Under ideal conditions, this level of power allows electric heavy-duty trucks to recover approximately 300 kms of driving range within the span of just one hour. Such capability has been pivotal in demonstrating the technical feasibility of electric freight transport for up to medium-range logistics. However, for long-haul trucking applications, where vehicles are expected to operate continuously over vast distances with minimal downtime, the current limitations of CCS pose a considerable operational challenge. Time spent charging on the road directly translates to decreased productivity, reduced vehicle utilization rates, and a corresponding increase in the total cost of ownership for fleet operators. Specifically, at 350 kilowatts, a full charge for a long-haul truck typically takes between two to three hours, which is viewed by the transport and logistics industry as unacceptably long due to the substantial opportunity cost associated with idling vehicles.

In response to this bottleneck, the industry has embarked on the development of next-generation ultra-fast charging technologies tailored to the unique requirements of heavy-duty commercial vehicles. The result is the Megawatt Charging System (MCS), a breakthrough charging solution engineered to provide the dramatically higher power levels necessary to support rapid turnaround times. MCS introduces a newly designed charging interface and connector capable of delivering up to 3.75 Megawatts of power, representing a tenfold increase over the CCS standard. This monumental jump in charging capability enables electric trucks to drastically reduce downtime by significantly shortening the duration of full battery recharging, potentially aligning charging breaks with mandated driver rest periods and thus preserving the high utilization rates essential for profitable logistics operations. The MCS initiative has been driven by a consortium of industry leaders, standardization bodies, and vehicle manufacturers, culminating in its formal integration into international regulatory frameworks. Specifically, MCS has been incorporated into the International Electrotechnical Commission's standards under IEC 61851-23-3, which governs high-power DC charging systems for electric road vehicles, with additional cross-references to IEC 61851-23-2 to ensure global interoperability and compliance.

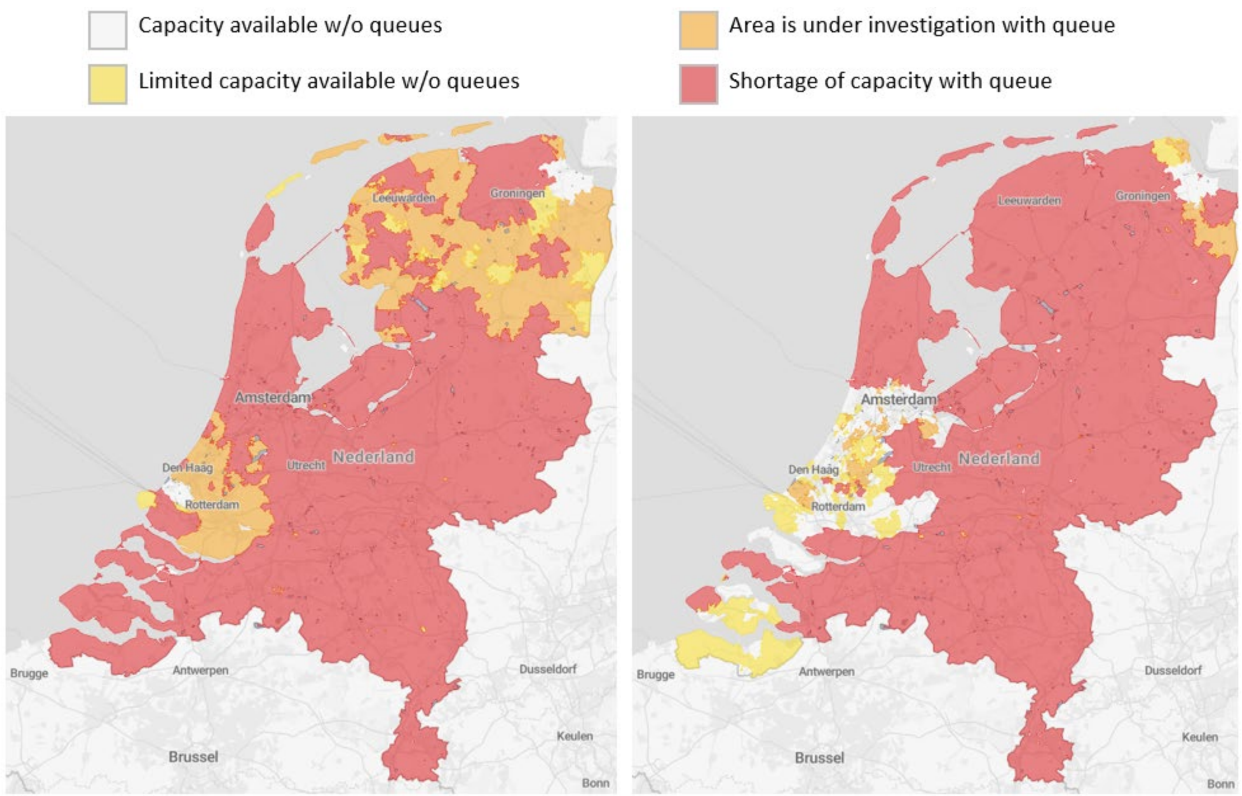
Individual companies have also pursued parallel paths to meet the urgent demand for faster charging solutions. Notably, Tesla has developed and deployed its own proprietary high-capacity charging architecture specifically designed for its electric long-haul trucks – Tesla Semi. Tesla's system similarly supports megawatt-level power delivery and seeks to offer comparable advantages in terms of reduced charging time and increased operational efficiency, though it currently remains distinct from the MCS standard and tailored to its specific vehicle platforms. Meanwhile, on the regulatory front in the United States, MCS has been officially incorporated into the SAE J3271_202503 standard, further cementing its status as a globally recognized solution for high-power electric vehicle charging.

The electrification of maritime transport, while equally critical to global emissions reduction targets, presents an additional set of challenges due to the sheer scale and energy requirements of large vessels. Unlike the relatively standardized landscape of road vehicle charging, the infrastructure for electric vessel charging remains highly fragmented and less mature. Nevertheless, innovation is rapidly taking place. Leading suppliers such as Zinus (NO) and PowerCon (DK) have developed pioneering solutions capable of delivering more than 1 MW of charging power to full electric and hybrid vessels. These systems are designed to accommodate a variety of vessel types and port conditions, offering automated connection mechanisms and robust energy transfer capabilities to meet the demanding needs of the shipping industry.

Section 3 Challenges to the future electric power grid

Subsection 3.1 Grid is getting congested

Most charging solutions sink power from the electric power grid, which basically serves as the backbone of modern energy distribution. It has a finite capacity that is increasingly being tested, particularly in many developed regions where infrastructure is nearing its operational limits. Much of the grid in these areas was constructed several decades ago, at a time when the demand for electricity was significantly lower and less complex. Over the years, while utilities have undertaken regular maintenance and incremental upgrades to maintain reliability and safety standards, these measures have not substantially expanded the overall capacity of the grid to meet today's growing and highly variable demands. The recent surge in electrification across multiple key sectors has further accelerated the pressure on grid infrastructure. In particular, the simultaneous integration of renewable energy sources such as solar and wind power, which feed intermittent generation into the grid, and the increasing proliferation of electric vehicles (EVs), which draw substantial amounts of energy during charging, are driving new and unprecedented demands for both energy consumption and generation management. The combined impact of these changes has exposed structural vulnerabilities in grid resilience and has heightened the urgency for more strategic grid modernization efforts.



(a) Consumption congestion (b) Generation congestion

Figure 3 Grid congestion of the Netherlands. (Source: Netbeheer Nederland)

A critical dimension of this strain is not simply the total amount of energy consumed but rather the dynamics of peak power demand, which places an acute stress on grid capacity. While the average energy usage may appear manageable, it is the short-duration spikes in electricity demand that create congestion and instability. For example, a study published in *Transportation Research Part D* (j.trd.2022.103564) in 2022 reported that the average utilization rate of public DC fast-charging stations in the United States was below 11%. This figure reveals a key challenge: although an individual fast charger can draw several hundred kilowatts of power during a vehicle charging session, the actual active charging period typically lasts less than an hour and is often followed by long stretches of idle time. This uneven and sporadic demand results in an extremely high peak-to-average power ratio. Such conditions significantly complicate the operation of electric grids, as infrastructure must be built to accommodate these rare but extreme peaks in demand, even if the overall energy throughput remains relatively low.

The situation is particularly visible in densely populated and highly industrialized regions where the grid is already operating near its technical limits. Fig. 3 provides an illustrative example of these challenges, focusing on the Netherlands, a country that has been a frontrunner in green energy transition to renewable energy and e-mobility, but also suffers from grid congestion issues. Fig. 3 highlights the transport capacity constraints faced by both consumer and supply parties within the Dutch utility grid. In regions marked in red, which represent areas experiencing severe congestion, any new customer or business requiring a connection with a capacity greater than 3×80 A is subject to extensive delays. It is currently estimated that in these congested zones, affected users must wait approximately 6~7 years before a new grid connection can be approved and installed. This reality underscores the severity of grid bottlenecks and the urgent need for innovative solutions, such as local energy storage, demand side management, and more robust grid planning, to accommodate the growing energy demands of electrified transport and decentralized energy production.

Subsection 3.2 Grid fee depends on the peak power and is rapidly increasing

Fast charging also introduces economic challenges for charging point operators. A critical aspect of the economic challenge arises from the structure of electricity tariffs, which are increasingly designed to reflect not just total energy consumption but also the magnitude and timing of the power demand. When an EV is charged, especially at a high-power DC fast charging station, the charging point operator typically incurs two key cost components:

1. Energy Fee (€/kWh) – This is paid to the energy supplier and is based on the quantity of electricity consumed during the charging session. This component is relatively straightforward and scales linearly with usage.
2. Grid Tariff (Grid Fee) – This is levied by the local Distribution System Operator (DSO) and is used to cover the cost of maintaining, operating, and expanding the grid infrastructure. Unlike the energy fee, the grid tariff often includes peak-based components, which are nonlinear and sensitive to the highest level of instantaneous demand registered during a billing period.

In countries like the Netherlands, where grid congestion is already a pressing issue, particularly in urban areas, DSOs have implemented increasingly granular and punitive grid tariffs for users with high peak loads. This reflects a broader trend in grid tariff design, which aims to internalize the cost of grid strain and incentivize users to adopt more grid-friendly load profiles. Table 1 illustrates this phenomenon with a breakdown of grid tariff categories from a Dutch DSO. The table shows a stepwise increase in monthly grid charges as the contracted peak capacity rises. These charges are not just marginal adjustments—they can dominate the overall operational expenses of a charging station, often eclipsing the energy costs themselves. Consequently, the economic viability of fast charging stations becomes heavily dependent on utilization rates. Underutilized stations with high contracted capacity suffer disproportionately high costs per kWh delivered.

Table 1. An example of grid fee in the Netherlands. LS: ≤ 1 kV; MS: > 1 kV, ≤ 20 kV;(Source: published data in 2025 from Stedin, a Dutch DSO)

Connection capacity	One-off connection fee (€)	Annual fee to maintain the connection (€)
> 175 kVA to 630 kVA via LS measurement	34002	1455
> 630 kVA to 1000 kVA via LS measurement	36000	
> 1000 kVA to 1750 kVA via MS measurement	58000	
> 1750 kVA to 5000 kVA	330000	3642

Contracted transport capacity	Transportation service			
	Fixed charge	Variable tariff		
	Transport per month (€)	kW contract per month per kW (€)	Double tariff per kWh (€)	Reactive power consumption per kVARh (€)
151 to 1500 kW	36.75	2.0250	0.0198	0.017
> 1500 kW	230	1.8958	0.0198	0.017

A quantitative assessment was conducted to evaluate the contribution of grid-related expenses to the total levelized cost of a high-power charging infrastructure. The findings, illustrated in Fig. 4, reveal that for a large-scale 3.5 MW charging station, grid transportation service fees account for approximately 18% of the annual levelized cost. These fees correspond to recurring operational expenses associated with the use of the distribution network, including peak-based charges levied by the DSO. In addition to the transportation tariff, grid connection costs—which include the capital investment required to establish a dedicated grid connection capable of supporting such high loads—represent a further 7% of the levelized cost, assuming a service life of 11.2 years. This service life is the estimated life of battery energy storage that will be integrated into the charging hub for grid fee reduction, and more elaboration will be given in the following sections. As this component is mainly a capitalized, one-time expenditure, its relative contribution diminishes with extended infrastructure lifetime.

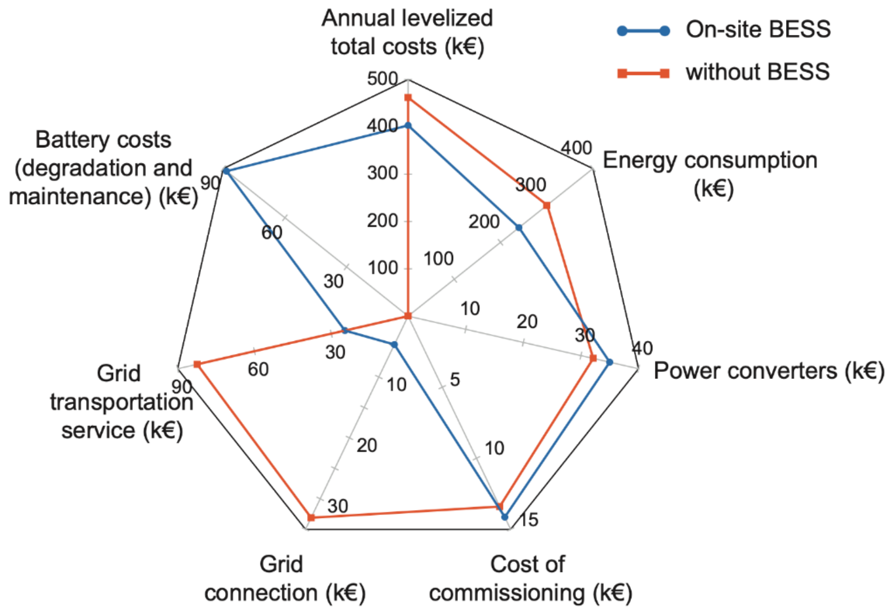


Figure 4 Annual levelized cost of a 3.5 MW charging station with and without BESS. The following assumptions are made for the study: the peak load is 3.5 MW. In the case without BESS, the grid connection is 3.5 MVA. In the case with BESS, the grid connection is 1 MVA, and a 2.5 MW/2.5MWh battery energy storage is connected. LFP battery is used. The electricity price is flexible. The lifetime of the battery is 11.2 years under the given load profile. (Source: the study is based on published data, where the load profile is from Fastned (NL), the grid fee is from Stedin (NL), the battery and converter cost are referring to several latest literature)

Overall, the combined share of grid-related expenses (transportation and connection) constitutes more than 20% of the total levelized cost, underscoring their critical influence on the economic viability of high-capacity charging stations. Moreover, given the current trajectory of increasing grid tariffs—driven by network congestion, reinforcement needs, and evolving tariff structures—this proportion is expected to rise in the coming years. As such, the grid fee burden represents not only a current financial challenge but also a growing risk to the scalability of fast charging infrastructure.

Section 4 Charging hub with batteries and MV grid integration based on Solid State Transformer

Given the substantial stress they represent, the current grid scenario hinges on the deployment of a vast fast charging network exclusively relying on AC power. The magnitude jump in energy and power requirements requires a different approach for megawatt charging networks. In this sense, a paradigm shift in layout and composition is expected. Additionally, such charging stations most likely include on-site energy storage elements and generation, aiming to flatten the grid-power consumption and reduce its dependence dramatically. Pairing these MW chargers with battery storage and generation units can bring more benefits than alleviating peak demand, optimizing grid usage, or even accelerating their roll-out of electric long haul.

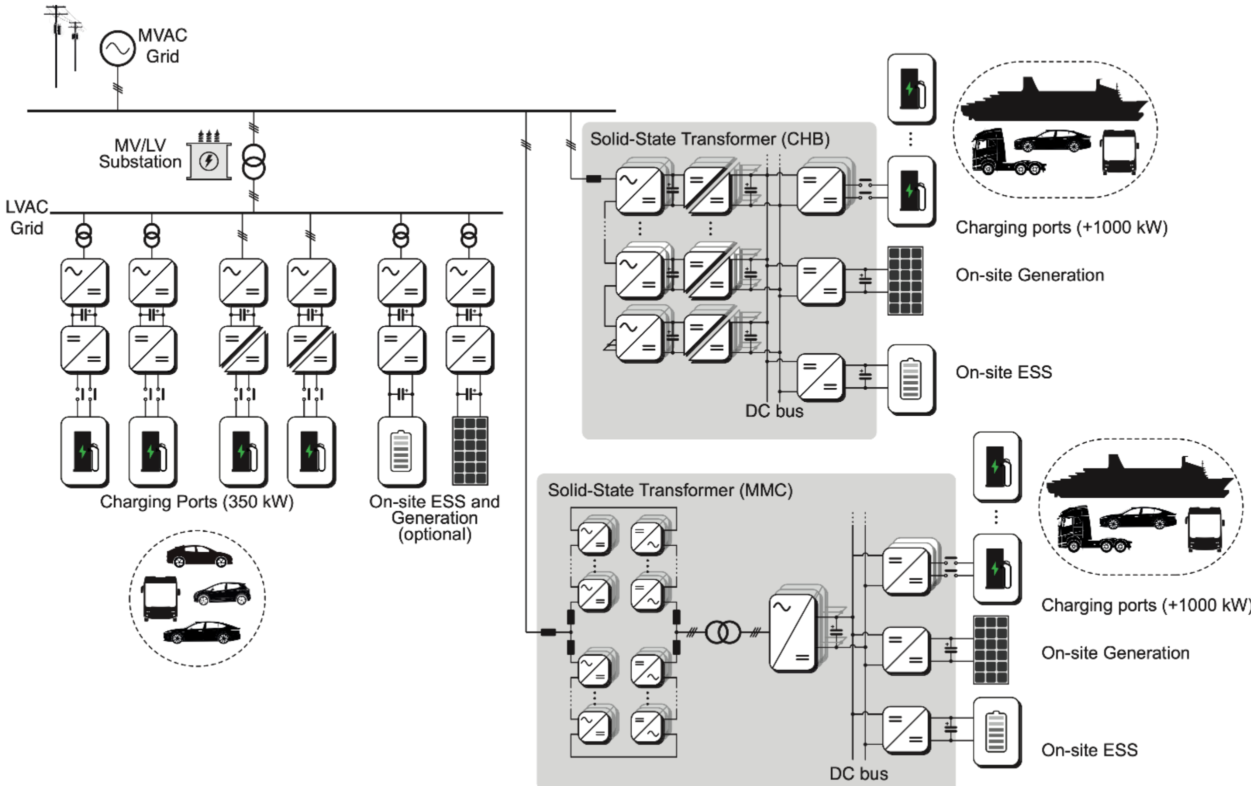


Figure 45 Simplified structure of the energy hub for Megawatt Charging Systems (MCS)

As displayed in Fig. 5, charging ports are typically connected using different setups, which vary based on factors like location and manufacturer. The figure shows that traditional charging stations with 350-kW ports usually connect to the medium-voltage (MV) AC grid through a dedicated link. A local substation then creates a low-voltage (LV) AC grid—typically in the 380–480 V range — which supplies power to the front-end converters. Then, since the batteries require power to be delivered at DC, a DC-DC converter performs battery voltage and current regulation. As displayed, each charging point is enabled by a dedicated power converter, with either low- or medium-frequency isolation besides some level of reconfiguration when interfacing with larger EVs or different voltage architectures. In some cases, the charging stations also include generation or storage units (through dedicated converters) to reduce grid power consumption.

Subsection 4.1 Energy storage integration for grid stress reduction

Energy storage integration can certainly reduce the peak grid power and thereby both grid stress and grid fee. Among all kinds of energy storage, batteries that can supply power at MW level and last for several hours are the most suitable, due to their scalability, fast response time, and deployment flexibility. Unlike other forms of energy storage (e.g., pumped hydro or compressed air), battery systems can be packaged in modular containers and placed in the charging hub without dependence on specific geographical features. However, battery systems, although they have experienced a significant price drop due to the booming of e-mobility in the past years, come with their own cost challenges. Capital costs remain relatively high, and trade-offs must be considered between battery size, power rating, and the capacity of the grid connection.

To give an idea about how much cost can be saved by battery energy storage integration, an optimal configuration is studied, focusing on minimizing the levelized cost of charging while considering both grid fees and energy storage costs. The results of this analysis, shown in Fig. 4, indicate that for a 3.5 MW charging hub, a battery system rated at 2.5 MW with 2.5 MWh of storage capacity offers the most cost-effective solution when combined with a reduced grid connection rated at just 1 MW. This configuration significantly lowers the required grid infrastructure, leading to a 75% reduction in grid fees. Additionally, the battery enables time-shifting of electricity consumption, allowing the station to charge the battery during off-peak hours when the electricity prices are lower and discharge it during peak demand periods. This load-shifting strategy results in an additional 20% reduction in the station's energy consumption expenses.

Despite the higher initial capital cost, integrating a battery energy storage system (BESS) into EV charging infrastructure results in a total cost of charging approximately 13% lower than a system relying solely on grid power. This cost reduction is achieved through mechanisms such as load shifting during off-peak hours, peak shaving to avoid high demand charges, and deferring expensive grid infrastructure upgrades—particularly beneficial in areas with limited grid capacity. In addition to economic savings, BESS enhances the grid stability, enables greater flexibility in response to dynamic electricity pricing schemes, and contributes to local energy resilience. Several European charging hubs already exemplify the benefits of this approach: Audi’s charging hubs in Nuremberg utilize second-life EV batteries for modular energy storage and high-power DC charging; the Energy Superhub Oxford combines lithium-ion and vanadium flow batteries with ultra-rapid charging, backed by a direct high-voltage grid connection; Connected Energy’s E-STOR systems, deployed at Allego sites in Belgium and Germany, repurpose second-life Renault batteries to support fast charging where grid constraints exist; and KREISEL’s CHIMERO chargers integrate BESS directly into charging hardware to deliver high output without burdening the local grid.

5Subsection 4.2 MV Grid integration with SST

As EVs demand faster charging, modularity has become essential. Most manufacturers now design chargers as a set of smaller power modules. These can be added or combined (like building blocks) to scale up power as needed. This makes charging stations flexible, future-ready, and capable of evolving with battery technology. Thereby, each power module typically includes galvanic isolation, ensuring safety, and allowing multiple EVs to charge at once from the same converter. By shifting the transformer operation to the medium-frequency range, both weight and volume are reduced. This is especially relevant to the European case.

Currently, most manufacturers use modules in the 25 to 125 kW range (average is 30 kW). An illustration of such an approach is presented in Fig. 6, where a high-power charger solution is depicted. It can be seen that how modern charging cabinets use these smaller modules to either split power across multiple EVs or combine power into a single MW-charger (like the upcoming Megwatt Charging System standard). However, for enabling future-proof MCS solutions, this approach needs some rethinking. For example, delivering 2 MW using 30 kW modules would require 67 units, making it excessive for practical, efficient design.

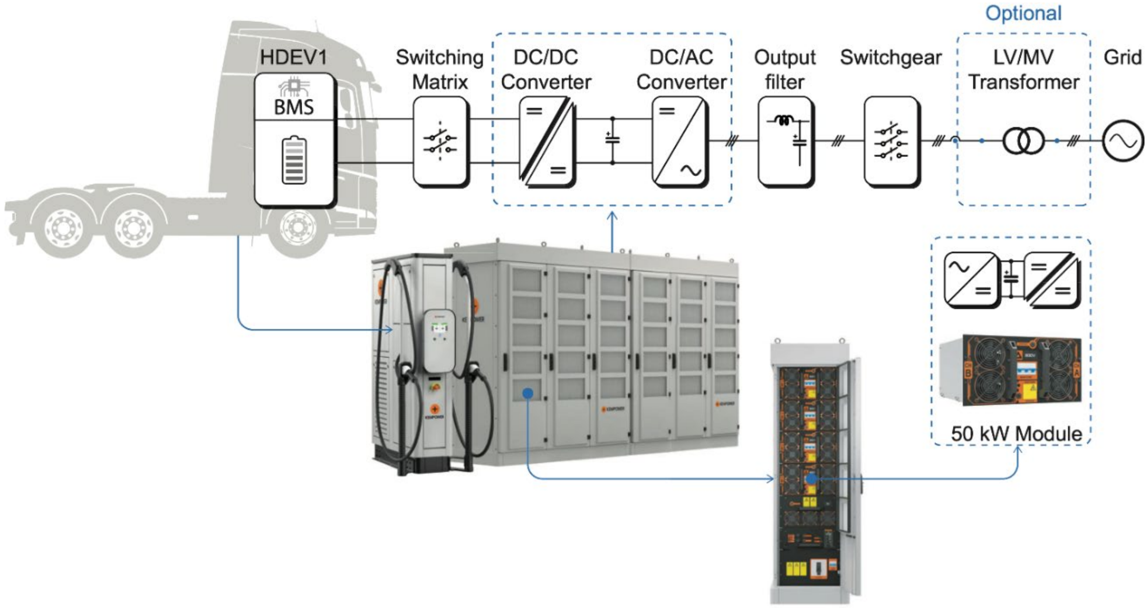


Figure 6 Simplified circuit structure of the Mega-watt charger for the EV trucks.

Moreover, nowadays most of these systems require LVAC input, which means they still need a local substation as described earlier. A new approach skips the traditional substation and connects chargers directly to an MV grid. This is enabled by solid-state transformers (SSTs), which can handle voltage conversion, isolation, and regulation—all in one compact unit. Over the last two decades, SST has evolved quickly and can offer interesting alternatives for conventional transformers in applications where space and weight are limited, or when sophisticated power flow capabilities are critical.

MCS charging solutions with SSTs offer several key advantages:

• Direct MV connection (no substation needed), leading to reduced current, improved power quality, reduced standard requirements, etc.

• High power output and flexible power routing

• Reconfigurability to charge one EV or many

• Scalable design with fewer modules compared to conventional systems

SSTs use medium-frequency isolation, allowing smart distribution of power depending on demand. For instance, they can focus all available power on one MW-class charger or divide it among several vehicles.

At system level, the SST approach also holds an interesting feature, which is the deployment of energy/power intensive applications at MVDC, besides the capability of decoupling power fluctuations between HVDC and LVDC. By enabling the direct integration of renewables (RES) and ESS at MVDC by an SST, interesting and rather unexplored benefits can be deployed in support of the congested AC grid. Horizontal power transfer links can be deployed in a radial AC structure, with direct integration of energy resources and storage. On the other hand, reinjecting energy from the transportation sector can be done more efficiently, since the recovered energy is already DC, hence it can be stored and used at the same voltage level. Also, the SST controllability eliminates overvoltage events caused by transformer impedances when the power is injected at distribution levels. As presented in Fig. 5, different deployments of this concept can be found, either based on the CHB- or MMC-structures. Several efforts pushing this technology have been reported, funded by the U.S. Department of Energy. For instance, a collaboration between national laboratories (NREL, Argonne, Oak Ridge) demonstrated the feasibility of enabling an SST-based multiport +1 MW charger directly connected to MVAC. On the other hand, Delta Electronics led another effort on designing and testing a high-efficiency, medium-voltage-input, SST-based 400-kW Extreme Fast Charger. Another aspect of the SST functionalities was explored by ABB and researchers from North Carolina State University. In this project, the focus was developing an intelligent, grid-friendly, modular fast charging system, with solid-state DC protection. Here, a low-cost SST was designed and built to reach 1 MW and validate the footprint reduction of this concept. Finally, EPRI along with Eaton and Tritium developed a behind-the-meter SST solution that enables the DC integration of chargers, aiming to reduce the grid impacts and operational costs of heavy-duty EV charging. All of these approaches were based on the CHB-SST structure in Fig. 5.

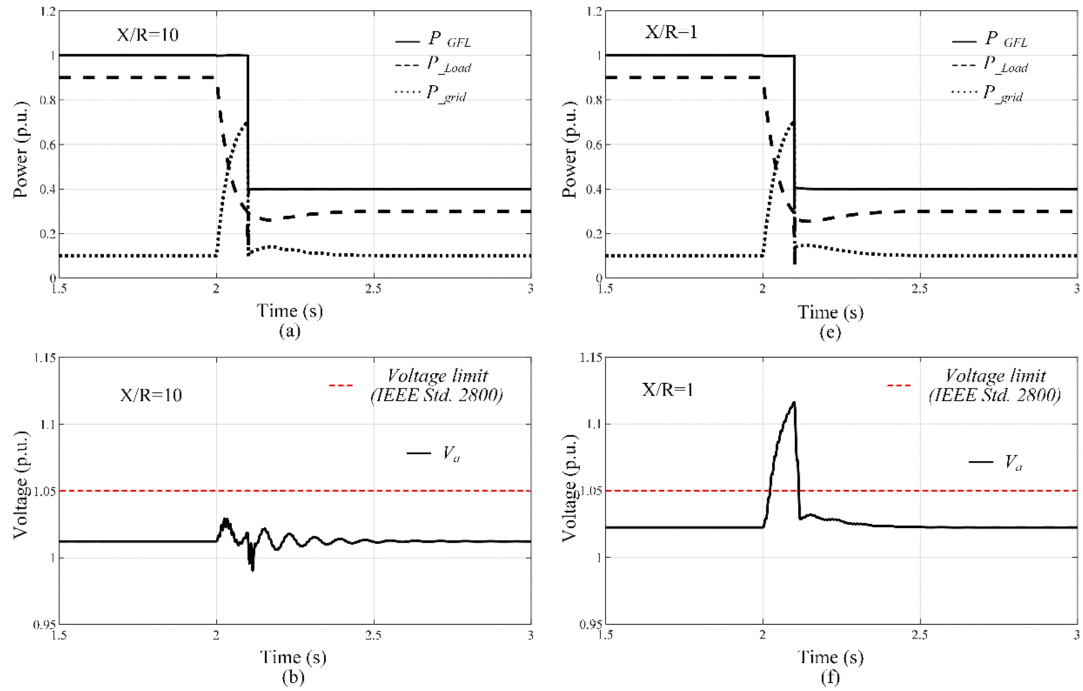
Section 5 Will the grid voltage still be stable?

Audi's high-power charging hub in Nuremberg offers a compelling example of how BESS can support peak shaving in fast EV charging environments. The facility integrates six 320 kW chargers, collectively backed by a 2.45 MWh battery system and a much lower grid connection at 200 kW. Despite such limited grid power, the station supports an average of 24 charging sessions per day, delivering roughly 800 kWh daily demonstrating how the on-site battery can handle most of the energy throughput. The operational data reveals significant untapped potential.

The BESS not only manages charging demand during peak periods but can also act as a dynamic energy buffer. It may absorb surplus generation from distributed energy resources such as residential solar, or provide supplementary energy to local consumers, alleviating the local grid congestion. Furthermore, its capabilities extend to supporting the voltage profile of the distribution grid, a task that becomes increasingly vital as electrification and decentralization progress.

In contrast to transmission networks, where changes in active power predominantly influence frequency, distribution grids behave differently. Their lower X/R ratios, typically less than 5, render them to be more resistive, making them more susceptible to voltage fluctuations from active power variations. Consequently, the role of the DSO will center on voltage regulation rather than frequency control. Incidents of voltage flicker caused by abrupt charging events are a direct manifestation of this challenge.

BESS in grid following control:



BESS in grid forming control:

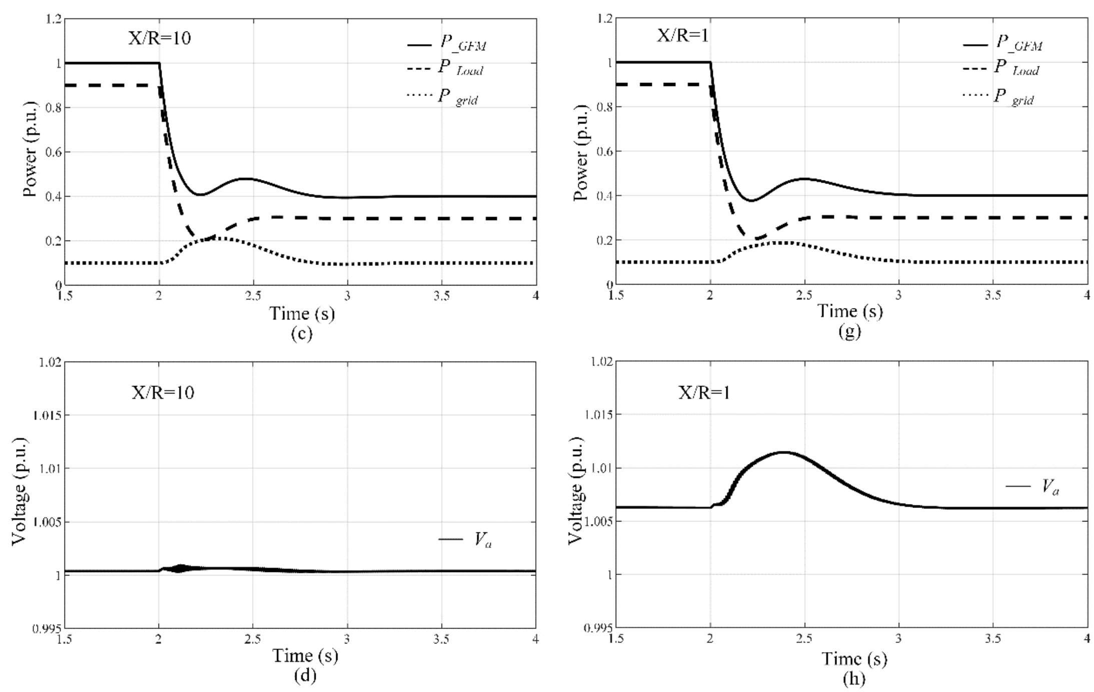


Figure 7 Impact of the charging hub on the grid voltage, with (a) (b) (e) (f) when the BESS is in grid following control, and (c) (d) (g) (h) when the BESS is in grid forming control. Where the grid short circuit power is 6.6 MW, 0.1 pu power is 200 kW. It shows that with grid following BESS, during charging load change, the grid power can easily exceed 200 kW for a short period of time. While with grid forming BESS, the grid power is much less influenced by the charging load change. This does not make a difference on voltage variation when X/R = 10, but triggers more than 10% overvoltage on the grid when X/R = 1 if BESS is in grid following rather than grid forming.

When a BESS is employed at a charging hub for reduced grid connection, it also introduces what is essentially a weak grid connection. For instance, in the Nuremberg case, assuming the grid has a nominal rating at 200 kW and a maximum permissible voltage drop of 3% on the cable connecting the substation and the charging hub, the required short circuit capacity of the grid connection must exceed 6.6 MW. If this grid serves only a single 200 kW load, the short circuit ratio (SCR) is 33—indicating a strong connection. However, in the charging hub, the grid is connected to a battery and six chargers. If the BESS delivers 1.8 MW to the chargers during high demand and meanwhile the grid is connected, the SCR drops to approximately 3.67. At such low SCR values, large voltage variations can happen during the charging load change, if the BESS is in grid following control, as shown in Fig. 7. It reveals that large power mismatch can happen between the BESS and the charging load during load change when the BESS is in grid following control. This power mismatch can create a significant grid voltage variation when the X/R ratio is low. With grid forming control, the BESS will actively maintain the grid voltage, and thereby the grid power is much less affected by the charging load change, and the grid voltage variation becomes negligible.

The well studied grid forming control, including the droop and virtual synchronous machine, however cannot be directly used. As they are both based on the assumption that the active power is strongly affected by grid voltage phase angle, while the reactive power is strongly affected by grid voltage magnitude, and the cross coupling is negligible. This is true when the X/R is high, typically for transmission grid (X/R > 10). The coupling however becomes much stronger when the X/R is low, which is the case in distribution network (X/R < 5). Therefore, tailored grid forming control has to be developed which can therefore truly help maintain the distribution network voltage.

Conclusions

The shift to electric transportation goes far beyond just replacing fuel with electricity—it demands new ways of delivering energy at scale. Fast charging, especially for heavy-duty vehicles, puts a serious strain on today's power grids. This is where charging hubs come in. By combining high-capacity chargers with battery energy storage, smart controls, and direct medium-voltage connections, these hubs can reduce peak loads, lower grid fees, and operate more efficiently—even in areas with limited grid capacity. They also enable smarter energy use by shifting charging to off-peak hours and supporting local grid stability. As we look to a future of fully electrified roads and ports, charging hubs are not just a convenience—they are a critical piece of infrastructure that makes large-scale electric mobility possible, practical, and sustainable. More storage in the grid will enable such systems to contribute to the overall grid operation.

For Further Reading

- Z. Qin, T.B. Soeiro, J. Dong, et al, "Chapter 9-Electric vehicle charging technology and its control," *Control of Power Electronic Converters and Systems*, Editor: F. Blaabjerg, Academic Press, vol. 4, pp. 241-307.

- L. Wang, Z. Qin, T. Slangen, P. Bauer and T. van Wijk, "Grid Impact of Electric Vehicle Fast Charging Stations: Trends, Standards, Issues and Mitigation Measures - An Overview," *IEEE Open J. of Power Electron.*, vol. 2, pp. 56-74, 2021.
- A. Ahmad, Z. Qin, T. Wijekoon, P. Bauer, "An overview on medium voltage grid integration of ultra-fast charging stations: Current status and future trends," IEEE Open Journal of the Industrial Electronics Society 3, 420-447, 2022.
- A. Ahmad, J. Meyboom, P. Bauer, Z. Qin, "Techno-economic analysis of energy storage systems integrated with ultra-fast charging stations: A dutch case study," eTransportation 24, 100411, 2025.
- S. Rivera, S. M. Goetz, S. Kouro, et al., "Charging Infrastructure and Grid Integration for Electromobility," in *Proceedings of the IEEE*, vol. 111, no. 4, pp. 371-396, April 2023
- S. Rivera, S. Kouro, S. Vazquez, et al, "Electric Vehicle Charging Infrastructure: From Grid to Battery," in IEEE Industrial Electronics Magazine, vol. 15, no. 2, pp. 37-51, June 2021.
- Audi charging hub: flexible, sustainable, convenient | audi.com
- News Center - Delta Demonstrates 400kW Solid State Transformer-based Extreme Fast EV Charger to Partners GM, DTE Energy, NextEnergy, American Center for Mobility and U.S. DOE - Delta
- High-Efficiency, Medium-Voltage Input, Solid-State, Transformer-Based 400-kW/1000-V/400-A Extreme Fast Charger for Electric Vehicles

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