CWIEME
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Whitepaper in partnership with PTR

Exploring the Synergy Between Transformers and EV Charging Infrastructure

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Glossary

CPO	Charge Point Operator
LCVs	Light Commercial Vehicles
EV	Electric Vehicle
EVSE	Electric Vehicle Supply Equipment
EVCI	Electric Vehicle Charging Infrastructure
OEM	Original Equipment Manufacturer
V2G	Vehicle to Grid
IRA	Inflation Reduction Act
NEVI	National Electric Vehicle Infrastructure
BEV	Battery Electric Vehicle
PHEV	Plug-in Hybrid Electric Vehicle
V2H	Vehicle to Home
EDSO	European Distribution System Operators' Association for Smart Grids
IPDS	Integrated Power Development Scheme
DERs	Distributed Energy Resources

1

Executive Summary

1. Executive Summary

The electrification of transportation has taken centre stage in the modern era, marking a profound shift toward sustainability in the automotive industry.

As the global demand for Electric Vehicles (EVs) continues to surge, the critical role of charging infrastructure cannot be overstated. In this whitepaper, titled "Exploring the Synergy Between Transformers and EV Charging Infrastructure", we embark on a comprehensive journey through the intricate nexus of EV adoption, charging infrastructure evolution, and the integration of smart charging solutions and V2G dynamics. This exploration will illuminate the pivotal role that advanced transformer technology plays in shaping the future of e-mobility and energy management.

This whitepaper provides a comprehensive overview of the global electric vehicle landscape and charging infrastructure. It presents insights into global EV adoption rates and projections, examines the growth trends and market dynamics of Electric Vehicle Supply Equipment (EVSE), and analyzes the market forces driving widespread EV charging adoption. It serves as a foundational understanding of the critical relationship between EVs and their charging ecosystem. It further explores various aspects of charging, including charging patterns and utilisation trends. It also highlights the role of smart charging in meeting energy needs and introduces the concept of V2G technology. V2G technology leverages electric vehicles to contribute to grid stability and balance. The paper underscores the transformative potential of smart charging and V2G dynamics, emphasizing their pivotal role in shaping the future of e-mobility and energy ecosystems.

Finally, we delve into the intricate effects of EVs on the power grid. It explores various challenges, including grid congestion, power quality issues, and the need for infrastructure upgrades, with a specific focus on transformers. Additionally, it highlights emerging transformer technologies and their role in addressing these challenges, while emphasizing the growing demand for advanced transformers due to the rising prevalence of EVs in the energy ecosystem.

2

EV and Charging Infrastructure Market Overview

2. EV and Charging Infrastructure Market Overview

The global automotive landscape is experiencing a profound transformation, with electric vehicles at the forefront of a sustainable future.

With their cutting-edge features, EVs provide an advanced and sustainable alternative to traditional internal combustion engine vehicles, playing a pivotal role in reducing emissions and fostering a cleaner environment. This paradigm shift is driven by a convergence of factors that include regulatory support, financial incentives, and environmental considerations.

The growth of the EV market is closely tied to charging infrastructure development. Collaborative efforts between charging station operators, governments, and utilities are expanding charging networks. Technological advancements, including fast-charging technology, have enhanced convenience. Charging infrastructure is fundamental to overcoming range anxiety and ensuring EVs' practicality and accessibility, further contributing to the sustainable transformation of transportation.

2.1. Global EV Adoption Rates and Projections

The traction gained by e-mobility is not merely a passing trend; it is a paradigm shift driven by a convergence of factors that promise to reshape the way we view transportation. One of the most significant catalysts behind the surge of electric vehicles is the regulatory environment. Governments worldwide have been crafting policies aimed at combating climate change and reducing emissions. These regulations set clear and ambitious goals, with many developed economies pledging to phase out the sale of new Internal Combustion Engine (ICE) vehicles by 2035. These measures not only provide certainty but also direction for the future of EVs, reinforcing the idea that electric vehicles are the future of mobility.

Government policies and incentives such as tax credits, rebates, and access to carpool lanes are playing a pivotal role in accelerating the adoption of electric vehicles. Governments are actively encouraging consumers to make the switch to EVs, and their efforts are producing tangible results. Global subsidies and incentives surpassed a remarkable USD 40 billion in 2022, making EVs more affordable and accessible to a broader range of consumers [1]. While some markets, like China, are gradually becoming self-sustaining, continued support in 2023 has further fueled the growth of the EV market. Venture capital investments in start-up firms developing EV and battery technologies have also boomed, reaching nearly USD 2.1 billion in 2022, up 30% relative to 2021, with investments increasing in batteries and critical materials.

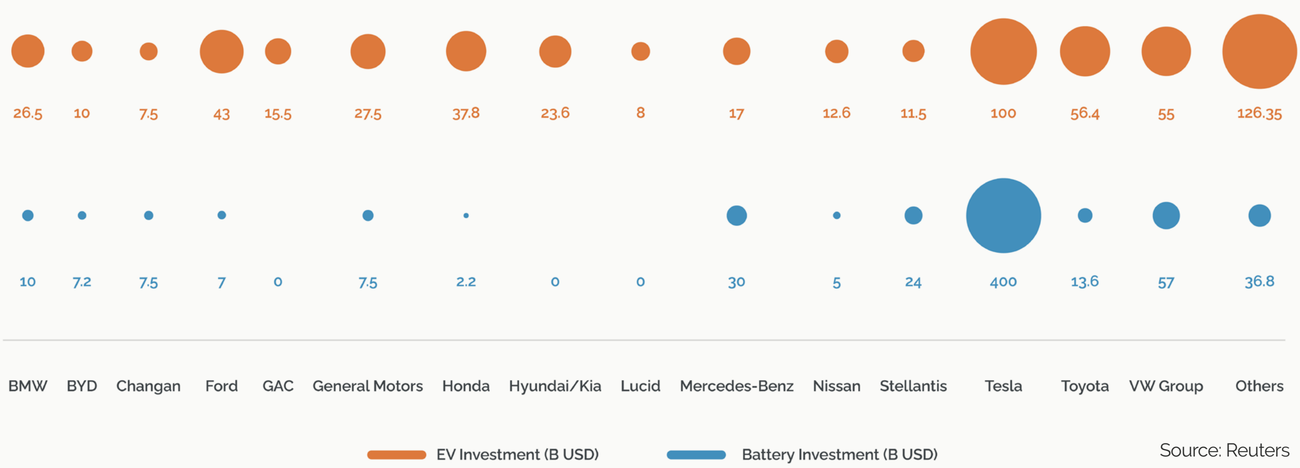


Figure 1: Planned EV and Battery Investments by Automotive OEMs [2]

Electric vehicles present a solution to the pressing societal and political urgency to decarbonise our world. In an era marked by fluctuating energy prices and heightened concerns about energy security, EVs offer a solution by reducing our dependency on fossil fuels. Automakers are not merely adapting to the evolving market; they are proactively driving the change. Many have unveiled plans to transition their entire fleets to electric within the next decade. This industry-wide pivot is not just a response to regulatory pressures but also a recognition of changing consumer preferences. Global automakers are making bold commitments to an electric future by investing nearly USD 1.2 trillion into EV production and battery facilities [2]. This massive investment underscores their belief in the viability and potential profitability of electric vehicles. As automakers pivot from internal combustion engines to electric propulsion, consumers can expect a widening array of electric vehicle options.

The global transition to EVs hit a milestone in 2022 with 10.4 million in annual EV sales, marking a substantial 60% increase compared to 2021. By the end of 2022, the total number of EVs sold globally reached 28 million. Among these, light-duty vehicles made up 99% of the total EV sales for the year, while the remaining 1% consisted of electric heavy-duty vehicles. When it comes to the type of electric vehicles, battery electric vehicles continued to dominate the market. They accounted for 72% of all EV sales in 2022 whereas PHEVs held a decreasing share, dropping from 30% in 2021 to 28% in 2022. This highlights the growing popularity of electric vehicles and the increasing preference for fully electric options over plug-in hybrids.

The EV market is shifting from a policy-driven market to a self-sustaining one due to rising customer demand. This shift is aided by decreasing critical mineral prices, expected to make EVs more affordable. This improved supply-demand balance is projected to boost global EV sales from 10.5 million in 2022 to 14 million in 2023, as forecasted by PTR's EV Charging Infrastructure analysis [3]. In 2022, despite economic challenges, the EV market grew due to global regulatory commitment to e-mobility. Many countries pledged to phase out the sales of new ICE vehicles or set ambitious electrification targets, providing certainty in the direction of the industry.

China retained its position as the global leader in the electric vehicle market, showcasing remarkable growth in 2022 and accounting for a substantial 59% of the total global sales. The country witnessed a surge in EV sales, reaching a staggering 6.2 million units, marking an impressive 82% increase compared to the previous year. This growth is supported by government initiatives, such as the extension of tax exemptions for new energy vehicles (NEVs) until 2027 and other subnational regulations that provide incentives for EV adoption.

Europe saw EV sales increase to 20% of total sales, reaching eight million EVs. Anticipated 20% growth in 2023, fueled by pre-orders and easing supply chain issues, will continue this upward trend. In the United States, EV sales saw a remarkable 48% increase in 2022, surpassing 1.1 million vehicles for the first time. The Inflation Reduction Act (IRA) program, in conjunction with state-level subsidies in the US, is expected to have a substantial impact on bolstering the presence of passenger EVs, with a target of reaching 32 million such EVs on the road by 2030. This marks a considerable upswing from the 2.4 million vehicles that were in circulation by the end of 2021. The program offers tax credits for both new and used EVs, spanning passenger and non-passenger vehicles, which will further stimulate the adoption of electric vehicles.

Source: PTR, EAFO

2022 2030

Figure 2: Vehicle electrification rates and EV incentives for leading e-mobility markets [3],[4]

2.2. EVSE Growth Trends & Market Dynamics

The growth of the electric vehicle market relies on expanding charging infrastructure, vital for overcoming range anxiety and making EVs practical. In advanced economies like the EU and the US, rapid infrastructure development is a collaborative effort by businesses, governments, and utilities. The global EV Charging Infrastructure (EVCI) market is set to grow at 22% CAGR (2022-2030) and reach the USD 30 billion value mark by 2030 [3].

The remarkable expansion of this charging infrastructure can be attributed to a confluence of key factors:

- The surge in the number of electric vehicles on the road has catalysed the proliferation of charging networks. In concerted efforts, charging station operators have collaborated with governments and utilities to establish an extensive web of strategically located charging points.
- The widespread deployment of high-power fast chargers, capable of delivering significant energy within remarkably short durations, has not only rendered long-distance EV travel more feasible but has also greatly enhanced the overall convenience of electric vehicle ownership.
- Collaboration and synergy within the electric vehicle ecosystem have also been pivotal in propelling the expansion of charging infrastructure. Automakers are closely coordinating with charging network operators to ensure that their vehicles are compatible with a variety of charging standards and networks, thus simplifying the consumer experience.
- Governments, too, have provided vital support, offering incentives and subsidies to incentivise the development and deployment of charging infrastructure.

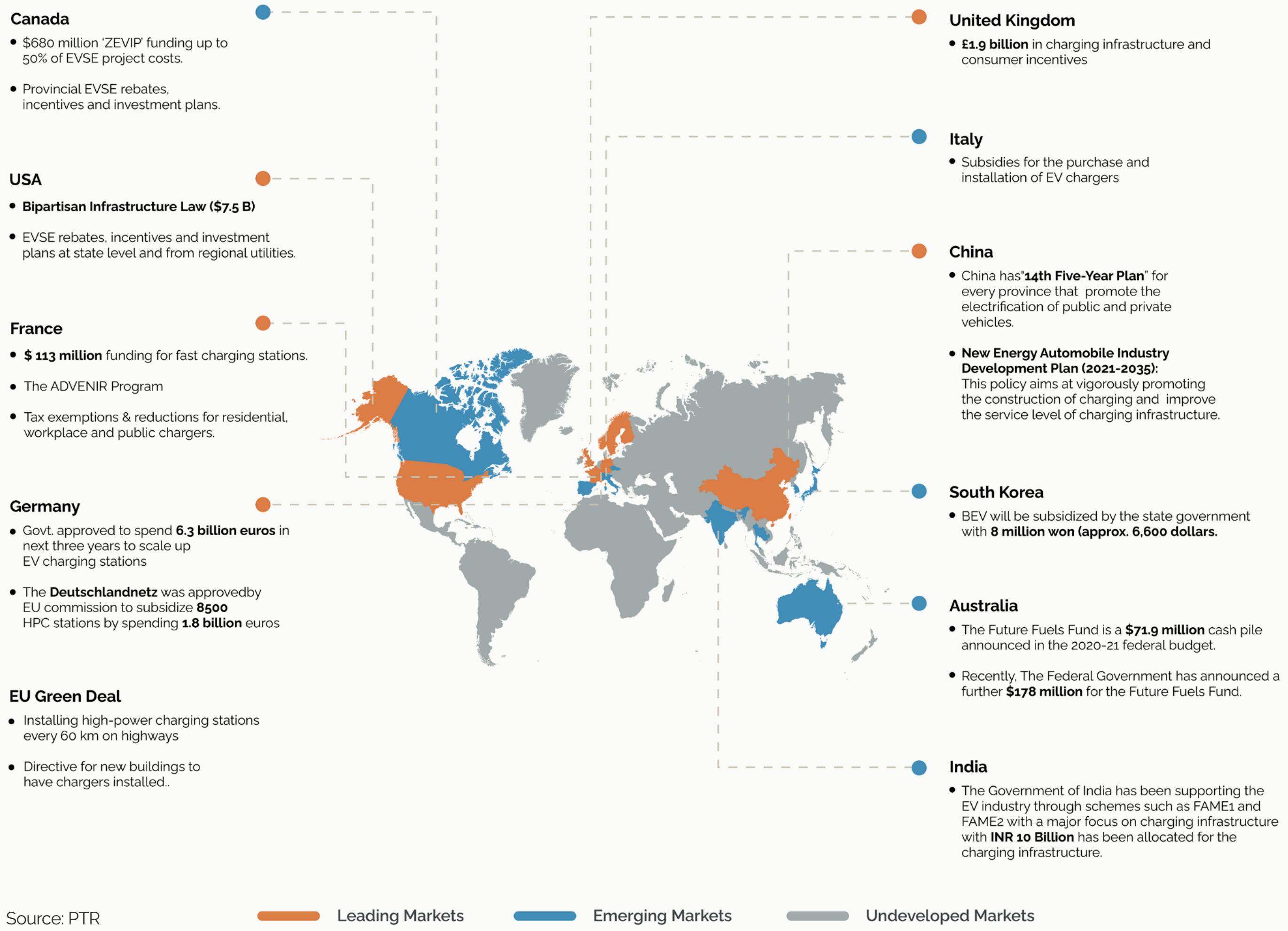


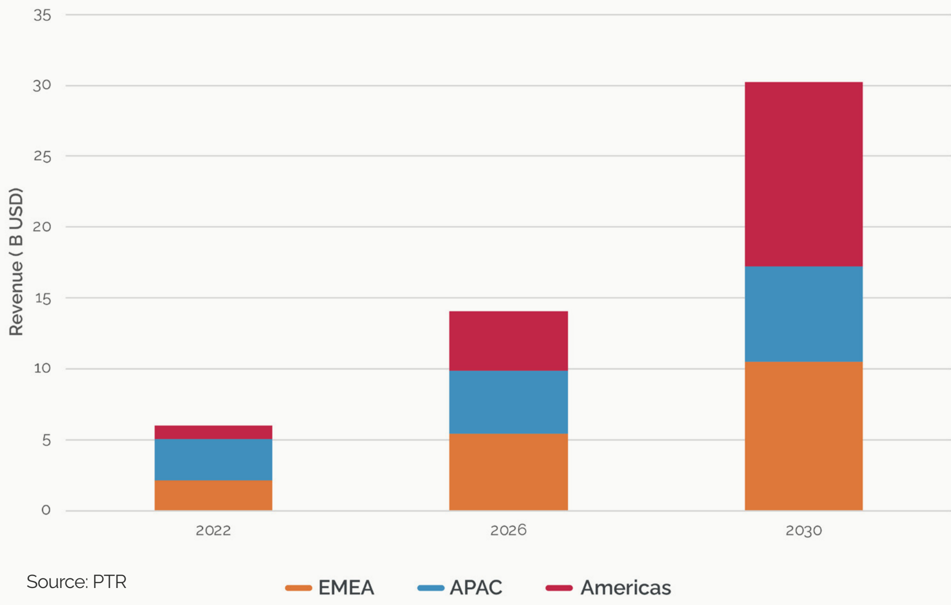
Figure 3: Global EVCI Policies, Incentives and Plans [3]

From 2018 to 2022, America's EV charging market showed remarkable growth, even in the face of economic challenges posed by the COVID-19 pandemic and grew by 32%. Looking ahead to 2023-2026, a substantial 38% growth is expected, as predicted by PTR's EV Chargers Market analysis [3]. The US, with government support like the Inflation Reduction Act (IRA) and National Electric Vehicle Infrastructure (NEVI) funding, is set to become the world's largest charging infrastructure market by 2030. Canada's 'Zero Emission Vehicle Infrastructure Program' (ZEVIP) extends to 2027 with USD 500 million in funding, targeting 50,000 chargers.

In the APAC region, the expansion of the EV chargers' market in the APAC region is driven by a combination of environmental, economic, technological, and policy factors. China's EV charging infrastructure market has experienced a significant surge due to supportive policies and grants. China leads the world in terms of the quantity of publicly accessible chargers, holding approximately 66% of all chargers globally in 2022. With a financial allocation of USD 125 million earmarked until March 2025, the FAME II scheme in India is set to channel these funds into the development of charging infrastructure. This strategic investment is aimed at bolstering India's electrification goals, with the target of achieving a 10% penetration of electric vehicles by 2025. South Korea targets 1.23 million charger installations for the anticipated 4.2 million EVs by 2030.

National funding and investments are playing a crucial role in increasing charging infrastructure in Europe. Germany plans to invest Euro 6.3 billion over three years, while the UK has multiple funding initiatives totaling up to $2.5 billion. The implementation of various European Green Deal regulations, such as the installation of fast chargers every 60km on the highway network, is expected to boost public confidence in the technology and alleviate range anxiety. The region is experiencing rapid growth in public charging infrastructure deployment reaching a $3 billion valuation by 2030 at a growth rate of 17% from 2022-2030.

Figure 4: Global EV Charging Infrastructure Market [3]



Source: PTR

The expanding electric vehicle charging infrastructure constitutes a foundational element of the broader EV ecosystem. It exemplifies the collective endeavors of governments, utilities, charging network operators, and automakers, all working collaboratively to facilitate a seamless and convenient transition to e-mobility for consumers. As the population of electric vehicles continues to soar, we can anticipate continued investments and innovations in charging infrastructure.

2.3. Market Forces Driving EV Charging Adoption

Electric vehicles have captured the imagination of consumers and policymakers alike as a crucial solution to reduce greenhouse gas emissions and combat climate change.

As the automotive industry undergoes a fundamental shift towards electrification, the adoption of electric vehicles and their charging infrastructure is being propelled by various market forces.

- Government policies and incentives promoting EV adoption with tax breaks, rebates, and infrastructure regulations.
- Private investments from CPOs, utilities, and OEMs funding extensive charging networks.
- Growing EV popularity is driving the demand for convenient charging solutions.
- Environmental consciousness encourages support for charging infrastructure.
- Advancements in charging technology and batteries dispel range anxiety.
- Renewable energy integration reduces costs and aligns with sustainability goals.
- Smart charging and V2G systems optimize energy use and enhance grid stability.

3

Smart Charging, V2G Dynamics, and Grid Integration

3. Smart Charging, V2G Dynamics, and Grid Integration

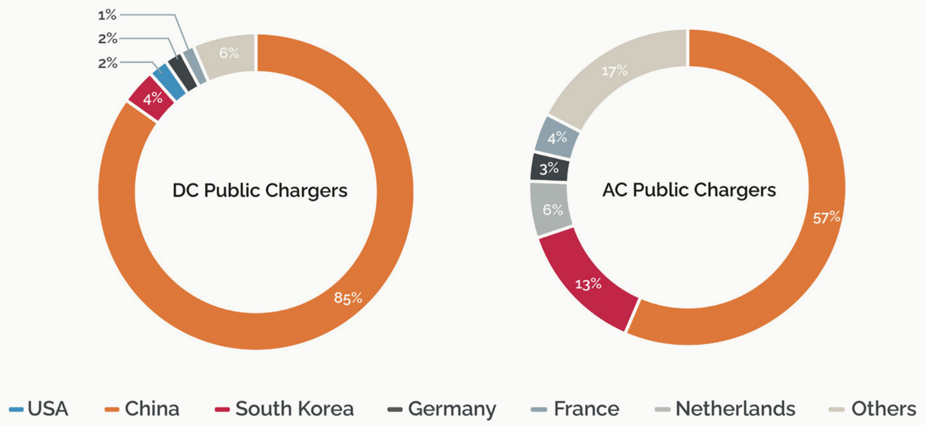
In the rapidly evolving landscape of EV technology, the synergy between smart charging, V2G dynamics, and grid integration has emerged as a pivotal point of discussion and innovation. In this section, we delve into the complex world of electric vehicle charging and its profound impact on the power grid, exploring the charging infrastructure landscape, charging patterns & utilization trends, meeting energy needs through EV charging, enabling smarter charging solutions, and the potential of V2G technology in harnessing EVs for grid balance. These interconnected aspects shed light on the dynamic relationship between EVs and the modern power grid.

3.1. Charging Infrastructure Landscape

In recent years, global electrification of transportation has rapidly expanded the EV charging infrastructure to accommodate the growing number of EVs and reduce carbon emissions. In 2022, there were 13.3 million charging points worldwide, with 2.8 million publicly accessible and 10.5 million privately owned. Residential charging constituted 60% of all points, followed by workplaces at 22%, destinations like hotels and shopping centers at 16%, and en-route charging at just 2%.

China, South Korea, the Netherlands, the USA, and the UK led AC public charging stations, emphasizing the global push for accessible charging networks. AC chargers dominate the market and will continue to do so, but DC chargers are rapidly growing, especially in depot, destination, and en-route charging. In 2022, DC chargers made up less than 12% of global installations but are expected to rise significantly, led by China, Germany, USA, France, and the UK. The electrification of heavy-duty vehicles will drive demand for ultra-fast chargers along urban corridors and highways. Despite substantial investments and support, challenges remain, including standardisation, grid infrastructure upgrades, and expanding charging coverage.

Figure 5: Countries leading the deployment of public charging infrastructure [3]



Source: PTR

The market is influenced by notable charger suppliers:

- In Germany, Mennekes, ABL Mobility, and Compleo Charging Solutions dominated the AC charging market, while ABB and Tesla led in the DC charging segment.
- In the United Kingdom, Podpoint, BP Pulse, and Ubitricity held substantial shares in the AC charging sector, while Tritium and BP Pulse made their presence known in the DC charging market. These suppliers played pivotal roles in shaping the charging infrastructure landscape, offering a wide array of charging solutions.
- In North America, ChargePoint emerged as a market leader, renowned for its extensive network of charging stations. Its presence was instrumental in expanding the accessibility of charging options across the region. ChargePoint maintained its influence in both the AC and DC charging sectors, ensuring a diverse and well-distributed network. Tesla, with its Supercharger DC network, continued to play a pivotal role in providing fast-charging solutions, contributing to the growth of the charging infrastructure. ABB, Tritium, and Delta also played significant roles, collectively contributing to the efficiency and reliability of the charging network.

Charging Patterns & Utilization Trends

Charging infrastructure is crucial for widespread electric vehicle adoption in various fleet applications. As of 2022, only a few businesses have transitioned to electric fleets, but this may change as discussions about phasing out gasoline and diesel continue.

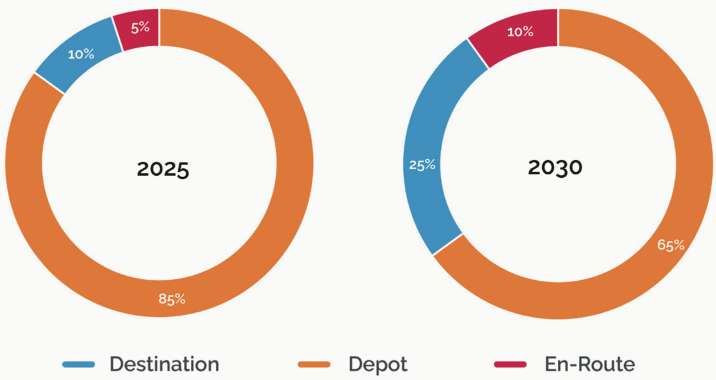
In the realm of public car charging, fast-charging stations are on the rise, especially along highways and in cities. These stations offer rapid DC charging, making long trips and daily commutes more convenient. Advanced payment and billing systems have improved user-friendliness, with mobile apps and contactless payments now common. Company cars often charge at home or work. Employers provide remote billing-enabled EV chargers at residences, monitoring vehicle usage and reimbursing charging costs. For those without home charging, workplace charging with AC chargers promotes EV adoption, especially for those lacking off-street parking.

Light commercial vehicles (LCVs) primarily rely on overnight AC charging due to their smaller battery packs. However, depending on their daily mileage, LCVs might require recharging during work hours, necessitating a combination of AC and DC charging. Public infrastructure offers similar trends in fast-charging accessibility and user-friendly payment options.

Bus charging infrastructure centers on depots, with overnight 30-50 kW cables or pantograph chargers and high-powered 150-350 kW chargers for quick daytime top-ups. Recent case studies suggest higher-powered chargers and top-down pantograph chargers along bus routes.

E-Truck registrations surged in 2021 and 2022, mainly for medium and heavy commercial vehicles over 3.5 tons. However, slow adoption is attributed to inadequate charging infrastructure. Winning over fleet managers requires public and private charging solutions. Specific needs depend on energy consumption and vehicle type. Depot charging suits single-shift trucks, while multi-shift or smaller battery trucks may need customer location charging. Long-haul operators depend on rapid charging solutions at gas stations or charging hubs, with at least 350 kW to 1 MW capacities in the future.

Figure 6: Electric Trucks Charging Behavior and Energy Requirements [3]



Source: PTR

While destination charging is expected to increase as logistics hubs install high-capacity chargers, depot charging will remain the predominant method of charging in the next decade. This evolving charging landscape is crucial for the broader electrification of commercial fleets, addressing unique requirements across company cars, LCVs, buses, and trucks. Public charging networks are continuously adapting to accommodate these trends, making EV adoption more accessible and convenient for various fleet applications.

Charging utilisation rates remain an intriguing aspect of this landscape. Residential charging stations currently have utilisation rates between 25-30%, indicating their regular use by homeowners. Public AC stations see utilisation rates in the range of 6-12%, suggesting that while public charging is available, it is not fully utilised. Public DC stations currently have utilisation rates between 4-8%, signifying the potential for growth in the fast-charging segment [3]. The charging infrastructure landscape continues to showcase the global commitment to supporting EV adoption through diverse charging solutions. The statistics highlight the significant strides made in building an accessible charging network, and the analysis underscores the importance of charging convenience and the role of various stakeholders in shaping this evolving landscape.

3.2. Meeting Energy Needs: The Charging Impact

The increasing adoption of EVs raises significant challenges for the energy sector, notably, how to meet the surging energy demand for EV charging while striving for a net-zero carbon footprint. The electric grid serves as the backbone for achieving a net-zero emissions future by facilitating the transition to clean and renewable energy sources. With the integration of EV charging into the grid, meticulous planning and infrastructure development are paramount.

Effective stakeholder collaboration: It is pivotal in addressing the widespread challenges posed by EV charging. Utilities, governments, automakers, and technology providers must work in synergy to develop standardized charging infrastructure, grid integration protocols, and regulatory frameworks that foster sustainable EV adoption. Collaborative efforts ensure that the grid can accommodate the increasing energy demand while minimizing disruptions.

Grid Resilience: EVs are not just energy consumers; they can also enhance grid resilience. Through bidirectional charging technology, EVs can function as mobile energy storage units, capable of supplying power back to the grid during peak demand or in emergencies. This V2G concept can help stabilise the grid, reduce the need for costly infrastructure upgrades, and enhance overall grid reliability, further reinforcing the importance of stakeholder collaboration in creating this innovative synergy.

Smart Charging: Managed charging systems play a pivotal role in optimizing EV charging and minimising grid strain. Smart charging infrastructure allows for the distribution of charging load across different times of the day, reducing the impact of simultaneous charging during peak hours. These systems enable utilities to implement time-of-use pricing and incentivize off-peak charging, further promoting grid stability. Additionally, understanding EV owners' charging behaviour can lead to a change in habits, contributing to more grid-friendly charging practices, thus seamlessly connecting managed charging with behavior modification. One of the most pressing concerns for grid operators is managing peak charging times and frequencies. Avoiding simultaneous high-demand charging events is essential to prevent grid overloads. Grid operators can employ predictive analytics to anticipate peak charging times and implement measures to redistribute charging loads to non-peak periods. This proactive approach is essential for grid stability and, importantly, relies on the data derived from understanding EV owners' charging behavior, underscoring the interconnectivity of grid management strategies.

Sustainable Grid Solutions: Integrating renewable energy sources into the grid is crucial for reducing carbon emissions associated with EV charging. Smart grid technologies can optimise the use of renewable energy by coordinating charging times with periods of high renewable generation. Furthermore, grid-scale battery storage systems can store excess renewable energy for later use, ensuring a constant supply of clean electricity for both EVs and other consumers. Demand response programs offer another dynamic solution to manage EV charging by providing incentives to consumers who adjust their charging schedules during periods of high demand. This not only helps alleviate grid stress but also reduces the need for costly infrastructure upgrades.

Meeting the energy needs for EV charging while striving for a net-zero carbon footprint requires a multifaceted approach that seamlessly integrates various elements. Together, they create a resilient and sustainable grid that supports the widespread adoption of electric vehicles and alleviates the burden on the grid.

3.3. Enabling Smarter Charging Solutions

The substantial growth in EV landscape has led to a parallel evolution in charging infrastructure, particularly with smart charging solutions. EVSE has transformed from basic cables to ultra-fast chargers with advanced communication features, improving charging speed, user experience, and grid management.

The first-generation 'dumb' chargers were simple, providing a fixed power output without remote management or cloud connectivity. Many residential and workplace charging stations still use these basic chargers. However, the surge in EV popularity has strained the grid, requiring significant investments in upgrades and expansion. To tackle these challenges, smart chargers with advanced software and communication capabilities have emerged. These chargers interact intelligently with the grid and the EV ecosystem, offering numerous benefits.

Grid Integration: Smart chargers can seamlessly integrate with the electrical grid, allowing for optimal utilisation of energy resources. They can adapt their charging speed and schedule based on real-time grid conditions, reducing the risk of overloading the grid during peak demand periods.

Demand Response: Smart charging is a key component of demand-side management strategies. It empowers users to control the timing and magnitude of charging power from the source to the EV. This flexibility enables users to shift their charging sessions to off-peak hours when electricity is less expensive or when the grid is under less strain. Utilities and market aggregators often offer incentives to users who participate in managed charging programs, helping to balance collective energy demand and optimise grid services.

Load Balancing: In locations with multiple chargers, smart charging solutions can effectively manage power demand to create an equilibrium across sites. By balancing energy distribution among chargers, smart chargers streamline the EV charging process without affecting the delivery of electricity to the site.

Cloud Connectivity: Smart chargers can upload data to the cloud and be managed remotely, enhancing convenience for users and operators. This remote management capability ensures that chargers can be monitored, updated, and maintained more efficiently.

While smart chargers offer numerous advantages, it's important to acknowledge that their increased connectivity and data exchange capabilities create potential vulnerabilities that cyber attackers can exploit. Therefore, as the adoption of smart charging continues to grow, cybersecurity measures must be a top priority to protect the integrity of the EVSE system. Smart charging solutions have emerged as a critical component of the electric vehicle ecosystem. Their ability to integrate with the grid, support demand response programs, balance energy distribution, and contribute to grid stability makes them indispensable in the transition to a sustainable and electrified transportation system. As electric vehicles continue to gain traction, the widespread adoption of smart chargers will be vital to meeting energy needs efficiently and responsibly while ensuring the longevity and reliability of our electrical grids.

3.4. V2G: Harnessing EV Potential for Grid Balance

In the ever-evolving landscape of renewable energy and EVs, innovations continue to reshape the way we interact with power grids and the environment. One such innovation that has been gaining traction in recent years is V2G charging. This technology takes the concept of smart charging to the next level by enabling the energy stored in EV batteries to be fed back into the grid. Smart charging solutions, often referred to as V2G or Vehicle-to-Home (V2H) technologies, facilitate precise control over charging times and power magnitudes. V2G and V2H technologies enable electric vehicles to not only consume energy but also serve as energy sources.

At its core, V2G charging is about more than just plugging in your electric vehicle to charge it. It empowers users and utilities to exert control over the charging process, including the timing, magnitude, and even the direction of power flow. This means that not only can you decide when your vehicle charges, but you can also allow energy to flow from your car's battery back into the grid when the energy system is under strain. This dynamic capability of V2G has the potential to revolutionize the energy market in several ways.

Balancing Supply and Demand: One of the most significant advantages of V2G technology is its ability to balance variations in energy production and consumption. EVs can act as short-term

storage devices for renewable energy sources like photovoltaics. They can charge during the day when the sun is shining, and then, during periods of high energy demand, they can release power back into the grid. This concept extends to V2H and Vehicle-to-Building (V2B) applications, where EVs become integral components of local energy management.

Grid Stability and Frequency Control: Beyond load-leveling and energy storage, V2G-enabled vehicles can participate in frequency control markets, effectively acting as reserve spinners to maintain grid stability. This is crucial to ensuring a reliable power supply, especially as renewable energy sources with variable outputs become more prevalent [6].

Sustainable Energy Solutions: V2G technology brings a host of benefits and considerations for various stakeholders in the energy ecosystem. For aggregators and energy retailers, V2G represents a new opportunity to offer sustainable energy solutions to their customers. It allows them to create products aligned with sustainability values while assisting customers in managing their energy bills more effectively. Additionally, V2G can enhance the utilisation of renewable energy resources, aligning with the global shift toward cleaner power sources.

Enhanced Visibility and Control: Transmission and distribution network service providers stand to gain significantly from V2G technology. While it involves some regulatory and infrastructure costs, V2G expands its visibility and control over the distribution grid. It enables them to balance supply and demand on an intra-day basis, provide crucial services like frequency control and voltage regulation, and defer costly network upgrades. Moreover, V2G enhances network security and fault recovery services, ultimately improving network planning.

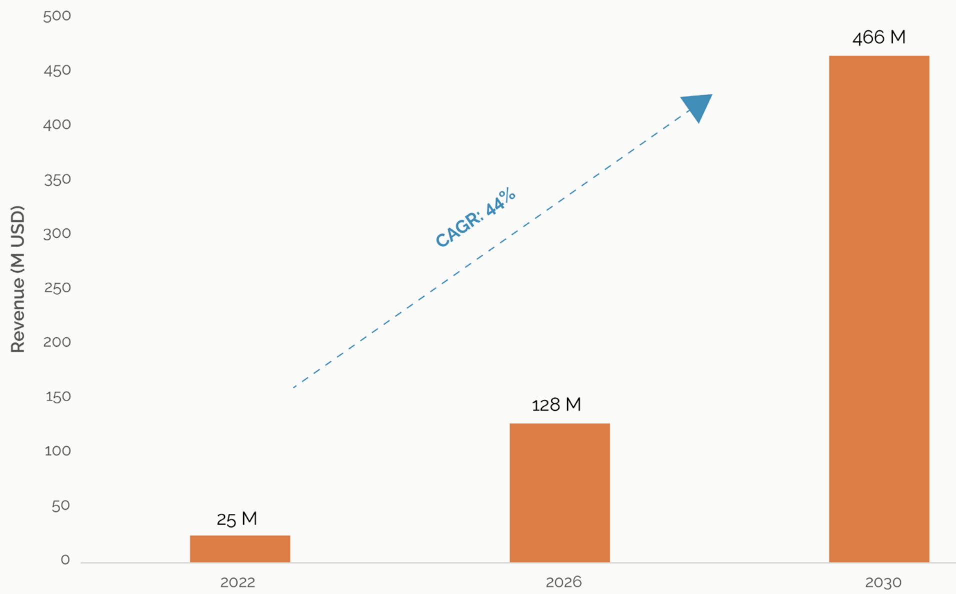
To make V2G a reality, electric vehicles must be identified and seamlessly connected to the power grid. This process is commonly known as 'plug & charge' and is based on the ISO 15118 standard, which regulates the automatic and secure data exchange between the vehicle and charger. By eliminating the need for RFID cards and mobile apps, this technology simplifies the charging process and ensures a smooth flow of power between EVs and the grid.

Overcoming Deployment Hurdles

Despite its potential, V2G deployment encounters several challenges that must be addressed for broader acceptance. Foremost among these is the cost of implementing V2G technology, notably the higher expense associated with DC chargers necessary for bidirectional power transfer compared to their AC counterparts. This cost factor restricts access to a select demographic, limiting the technology's outreach. Another significant obstacle pertains to the restricted availability of EV models equipped for bi-directional charging, which constrains the proliferation of V2G technology. Additionally, concerns surrounding battery life play a pivotal role in V2G adoption, given that EV batteries have a finite number of charge cycles. Users may be hesitant to engage in V2G practices unless the compensation outweighs potential losses resulting from accelerated battery wear. Addressing these issues is paramount to cultivating trust among EV owners.

To facilitate the flourishing of V2G, it is imperative to establish standardisation and robust communication protocols. This involves ensuring seamless two-way data flow between EVs, chargers, and the grid. Ongoing standardisation initiatives, such as ISO 15118 for CCS connectors, are currently in progress and are anticipated to ease the widespread integration of V2G technology. Presently, V2G projects are predominantly in the experimental phase, encompassing proof-of-concept trials and small-scale commercial endeavors. Nevertheless, V2G charging technology represents a promising avenue for energy management in a world increasingly reliant on electric vehicles and renewable energy sources. While there are hurdles to overcome, such as cost, EV compatibility, battery concerns, and standardisation, the potential benefits for grid stability, renewable energy integration, and stakeholder engagement make V2G a compelling proposition. As technology continues to advance, V2G can play a pivotal role in shaping the future of energy distribution and sustainability.

Figure 7: Global V2G Charger Market [3]



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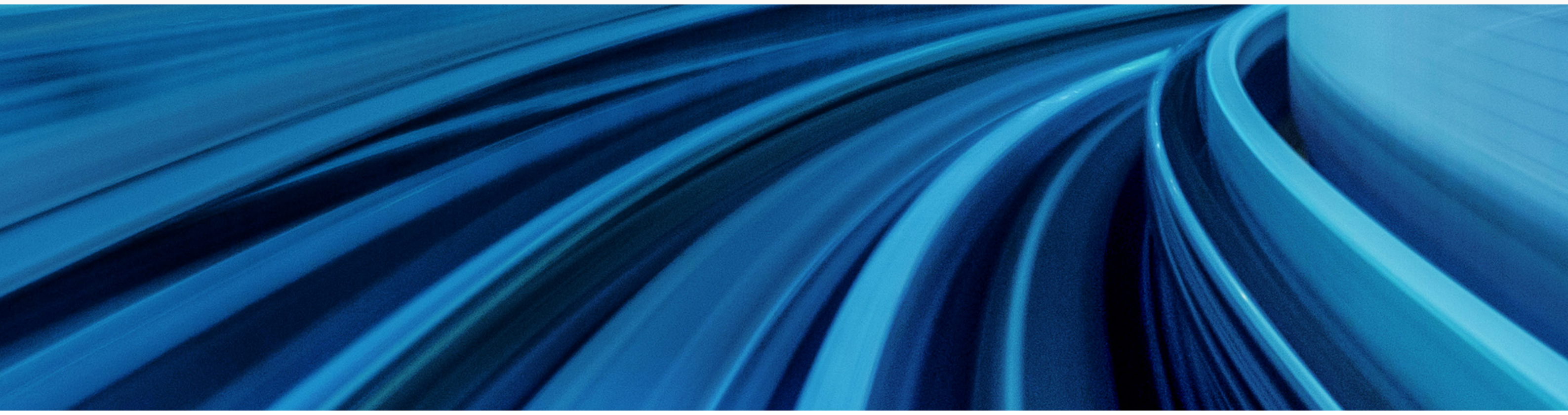


4

The Nexus between Transformers and EV Charging

4. The Nexus between Transformers and EV Charging

The exponential growth of EVs is reshaping the power grid landscape, posing challenges related to grid congestion, power quality, and transformer capacity. Expected high-demand charging patterns, characterised by a substantial and concentrated demand for electricity, especially during peak hours, strain aging infrastructure, thus necessitating upgrades. These patterns occur when a large number of EV owners plug in their vehicles for charging simultaneously, creating surges in electricity demand that can overwhelm the grid. Transformers play a pivotal role in enabling precise voltage regulation and supporting real-time monitoring. Transformer technologies, such as digital and dry-type transformers, offer solutions for grid optimisation and safety. Solid-state transformers (SSTs) facilitate V2G integration, contributing to grid stability and sustainability. Market trends indicate a thriving transformer market driven by EV adoption, digitalisation, and innovative technologies. These cutting-edge transformers are essential for a seamless transition to an EV-dominated future, ensuring a reliable, efficient, and sustainable energy ecosystem.

4.1. The Impact of Electric Vehicles on the Power Grid:

As the adoption of EVs accelerates, it brings forth a complex set of challenges for the power grid. EVs, due to their primary connection to the low-voltage distribution grid, exert a more direct impact on this grid, leading to localized challenges. This direct influence translates into immediate repercussions for the distribution transformer market, while the power transformer market feels the effects indirectly. Furthermore, the concentrated charging of EVs in specific regions, particularly during peak demand hours, places substantial stress on local distribution networks.

High power demand: One of the primary challenges posed by EVs is high power demand. Fast charging and the simultaneous charging of multiple EVs can draw a substantial amount of power from the grid within a short time frame. The existing grid infrastructure, particularly in older areas, may not be equipped to handle such high and concentrated loads, leading to voltage instability and potential equipment damage.

California, known for its high EV adoption rate, serves as a pertinent example of these challenges. As EV ownership soars, the state has grappled with grid issues, including voltage problems and the necessity for grid upgrades. Similarly, Nordic countries, despite their advanced infrastructure, have also had to implement grid management solutions to strike a balance between the increasing demand for EV charging and the available supply.

Charging patterns among EV owners represent another significant contributor to grid issues. Typically, individuals tend to charge their EVs when they return home from work, aligning with evening peak hours. This creates a concentrated demand during specific times, further intensifying the load fluctuations and voltage drops. This peak demand period necessitates additional power generation resources to prevent blackouts or burnouts. These EV charging habits primarily during nighttime also reduce the crucial cooling-off period for transformers. Transformers rely on this rest time to recover from the stresses of daytime operation. Prolonged operation without adequate cooling increases temperatures, accelerating wear and tear, and shortening operational lifespans. This, in turn, elevates the risk of overheating-related failures and necessitates more frequent maintenance and replacements. Therefore, the challenge here lies in finding a balance between the convenience of EV charging and the strain it puts on the grid during peak hours.

Load fluctuations: The sudden and substantial increases in power demand when multiple EVs charge simultaneously can lead to pronounced fluctuations in the grid's load. This impacts the crucial grid components such as transformers, additional stress leads to overheating, accelerated wear and tear, reduced operational lifespan, and even equipment failures. This, in turn, requires utilities to invest in expensive infrastructure upgrades to ensure grid reliability. Unfortunately, these expenses often translate into higher electricity bills for consumers.

The rising prevalence of EVs presents a complex interplay of power demand, charging patterns, and load fluctuations, necessitating innovative solutions to safeguard grid stability and affordability in the face of this transformative technology.

4.2. Grid Congestion and Power Quality Issues Stemming from Electric Vehicles

The rapid adoption of EVs presents the power grid with a different set of challenges.

Grid Congestion: Due to numerous EVs charging simultaneously, particularly during peak hours, one of the pressing concerns is grid congestion. This influx strains the distribution grid, which was originally designed for traditional energy consumption, resulting in a substantial surge in peak load. Consequently, areas with high EV concentrations often grapple with localised distribution overloads. In more severe instances, grid congestion can trigger operational inefficiencies, stress vital grid components, and introduce the potential for electricity supply interruptions, all of which compromise power supply reliability and necessitate costly repairs. Notably, the European Distribution System Operators' Association for Smart Grids (EDSO) highlights that scenarios marked by high EV penetration may witness distribution substations facing peak load increases of up to 25%, while transformers could contend with growth in loading of up to 35% [7].

Power quality: In addition to grid congestion, the introduction of EVs can also impact power quality, which refers to the stability and reliability of the voltage and frequency in the electrical system. These issues manifest as fluctuations, harmonic distortions, and disruptions to sensitive equipment. Power quality problems trigger flickering lights, malfunctioning devices, and even halt critical operations, disrupting daily life. Industries relying on precision machinery can suffer from decreased efficiency and increased maintenance costs due to power quality problems. Moreover, the integration of intermittent renewable energy sources can introduce harmonics and voltage variations into the grid, further destabilising power quality.

These power quality issues have a cascading effect, leading to voltage drops and stability problems. Regions with weaker distribution infrastructure are more vulnerable to voltage instability when sudden demand surges occur. This instability can result in damage to sensitive electronics in homes and businesses, causing disruptions and potential economic losses.

Fossil fuel dependency: Another significant issue emerges in the form of fossil fuel dependency. EV owners often charge their vehicles during evening peak demand periods when solar energy isn't readily available. This intensified demand for electricity during nighttime charging can inadvertently lead to a greater reliance on fossil fuel-based power plants. This unintended consequence threatens to undermine the core objectives of EV adoption, which include reducing greenhouse gas emissions and combating climate change. In essence, grid congestion during EV charging could inadvertently necessitate the use of fossil fuel-based power generation, running counter to the essence of transitioning to electric vehicles for a more sustainable future.

The widespread adoption of EVs poses multiple challenges for the power grid and addressing these issues is vital to ensure a smooth and sustainable transition to EVs, safeguarding power supply reliability and environmental objectives.

4.3. Transformers as Grid Enablers for EV Charging

The rapid expansion of electric vehicles is reshaping the power grid. However, the initial design of transformers and grid infrastructure did not anticipate the concentrated and erratic power demands associated with EV charging. Consequently, infrastructure upgrades are pivotal to efficiently accommodate this surging load.

Transformer Infrastructure Upgrade

Transformers, the backbone of the electrical grid, must be closely examined concerning their capacity, condition, and suitability to meet the escalating demands of EV chargers. The traditional transformers, operating at full capacity, often fall short of accommodating the augmented load brought about by EV charging. Consequently, the upgrade or replacement of these transformers with higher capacity units becomes imperative.

One striking example of capacity enhancement is occurring in India, where the government's "Integrated Power Development Scheme" (IPDS) is modernising the power distribution network. This initiative involves the replacement of smaller capacity transformers with higher capacity units to meet the growing energy demands [8]. As India's EV market expands, the need for such upgrades becomes increasingly evident, ensuring a stable and reliable electricity supply. Another example is from the Netherlands where utilities have upgraded transformers from 400 kVA to 630 kVA. The DOE report estimates approximately USD 1.1 trillion in investments are required to replace, expand, and upgrade the U.S. electrical grid through 2040 [9].

Moreover, in areas with a high concentration of EV charging stations, multiple distribution transformers can be operated in parallel to distribute the load effectively, thereby increasing the overall capacity of the distribution network.

Aged Transformer

The introduction of electric vehicles brings a multitude of load pattern variations that significantly heighten the vulnerability of aging transformers to breakdowns and failures, necessitating the urgent replacement of these vital components. According to a survey DOE released in 2015, a striking 70% of transformers surpass 25 years of operational life in the United States [9], it has become imperative to replace them, underscoring the critical importance of infrastructure modernisation. This proactive stance taken by utilities and organisations not only ensures grid reliability but also enhances overall efficiency.

Impact of Supply Chain Disruptions on Transformer Upgrades

A dependable and efficient supply chain for transformers plays a pivotal role in realising the objectives of EV adoption. The current disruptions in the global transformer supply chain, characterised by significant price increases and prolonged lead times, directly impede the affordability and practicality of upgrading EV charging infrastructure. This exacerbates the difficulties associated with replacing aging transformers, especially evident in the US distribution transformer market where the price of a 50kVA unit has surged by an astounding 900% since 2020. Lead times have also extended from mere weeks to several months or even up to two years. The situation is further compounded by shortages in electrical steel, which have quadrupled the waiting periods for distribution transformers. Given these formidable challenges, it becomes abundantly clear that a well-functioning transformer supply chain is not just desirable but imperative for the successful attainment of EV adoption targets.

Innovative Development

To address the challenges posed by EV charging, innovative developments in transformer design are underway. For example, harmonic mitigating transformers are being developed to combat issues like harmonic distortion. These transformers incorporate additional windings or components designed to filter out harmonics, reducing distortion and energy loss within the grid.

Furthermore, real-time monitoring systems are playing a pivotal role in continuously tracking transformer performance. This capability enables grid operators to swiftly identify issues, optimise transformer usage, and ensure grid stability. The integration of transformers into smart grid systems has revolutionised grid management, enabling precise load balancing and enhanced reliability.

Transformers are central to the electrification revolution driven by the widespread adoption of EVs. By upgrading transformers and optimizing their performance, we pave the way for creating a more efficient, resilient, and sustainable future for transportation and power distribution.

4.4. Emerging Transformer Technologies for EV Integration

The surge in electric vehicle adoption has spurred innovation in transformer technologies to cater to the unique demands of integrating EVs into power grids.

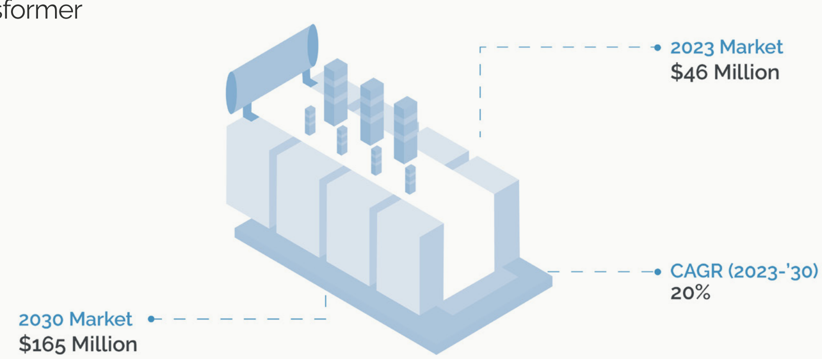
Digital Transformers for Enabling Smart Charging

Among these transformative technologies, digital transformers have emerged as a beacon of progress in power distribution systems. These transformers incorporate an array of additional sensors and focus on real-time monitoring that continuously collects data, enabling grid operators to closely observe the performance of the electrical network. This heightened monitoring capability empowers grid operators to make informed decisions regarding load management, grid stability, and the optimisation of EV charging. Ultimately, digital transformers stand as pillars of efficiency and resilience within evolving energy ecosystems.

Notably, the increasing presence of Distributed Energy Resources (DERs) and EVs is compelling utilities to shift from model-driven systems to data-driven ones at the distribution level, thus driving the market for digitalisation. The Covid pandemic has also contributed to the realisation of remote monitoring, control, and predictive maintenance. The need for digitalization of the grid network has been recognized and efforts are being made through smart grid and smart transformers adoption.

However, while the advantages are evident, certain aspects such as the lower unit price of conventional distribution transformers contribute to the perception that investing in digital distribution transformers may not be cost-effective compared to traditional alternatives. Taking these considerations into account, the digital transformer market is anticipated to maintain a relatively smaller market share in absolute terms when compared to the conventional transformer market.

Figure 8: Global Digital Distribution Transformer Market Projection (2023-2030) [10]



Source: PTR

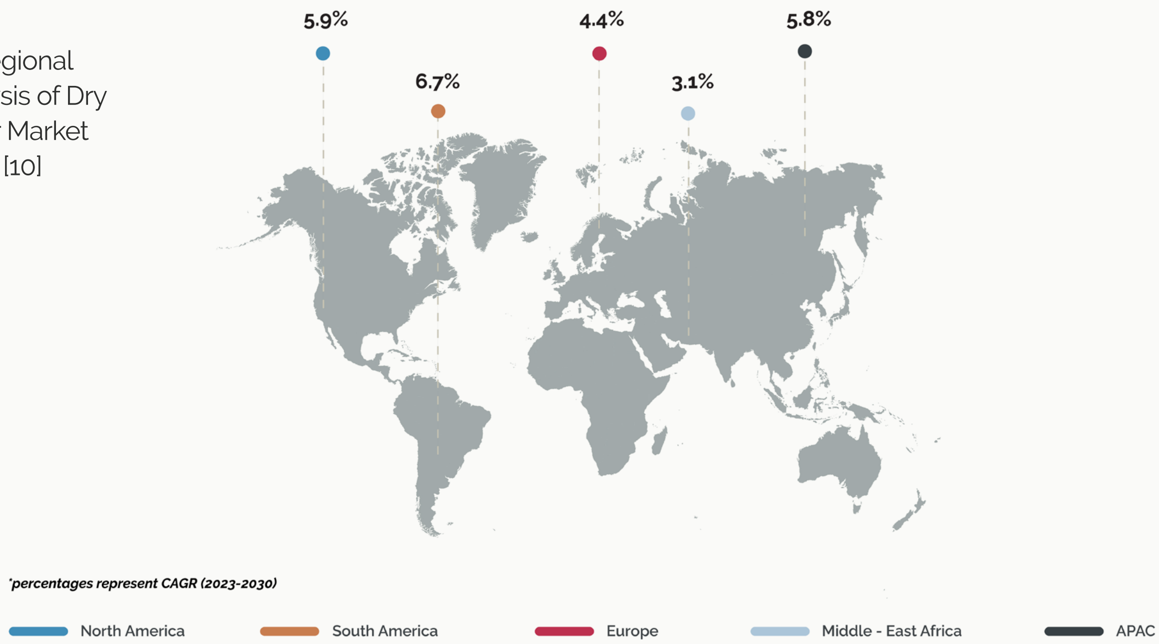
Interestingly, from PTR's Distribution Transformer Market Analysis, we see that North America is expected to exhibit the highest CAGR in the adoption of digital transformers, signaling a burgeoning recognition of their transformative potential in modernising power grids and ensuring their readiness for the EV-dominated future [10].

In the realm of industry players, major companies like Hitachi, Siemens, Schneider, and Eaton have already incorporated digital transformers into their product portfolios. Hitachi Energy leads the digital transformer market with a diverse product range [10]. Siemens Energy has also recently introduced a single face pole mounted dry type transformer in America which could be digitalised.

Dry-Type Transformers for Private Charging Applications

Dry-type transformers are another transformative technology that, although often perceived as more costly than oil-filled ones, come with a compelling advantage, primarily the absence of oil spillage risk and fire safety. This characteristic holds exceptional significance in the realm of EVs as it not only minimises the risk of environmental contamination but also bolsters safety for end-users. Notably, they are preferred in private charging stations, both residential and commercial, where safety and environmental concerns take precedence. The Netherlands has embraced dry-type transformers for private charging applications, simplifying the installation of home and workplace charging stations. According to the PTR's Distribution Transformer Market Analysis, the largest market for dry-type transformers is in China where more than half of the demand for dry-type transformers is coming from EV charging stations [10]. This adoption not only enhances convenience but also elevates safety standards for EV charging infrastructure.

Figure 9: Regional CAGR Analysis of Dry Transformer Market (2023-2030) [10]

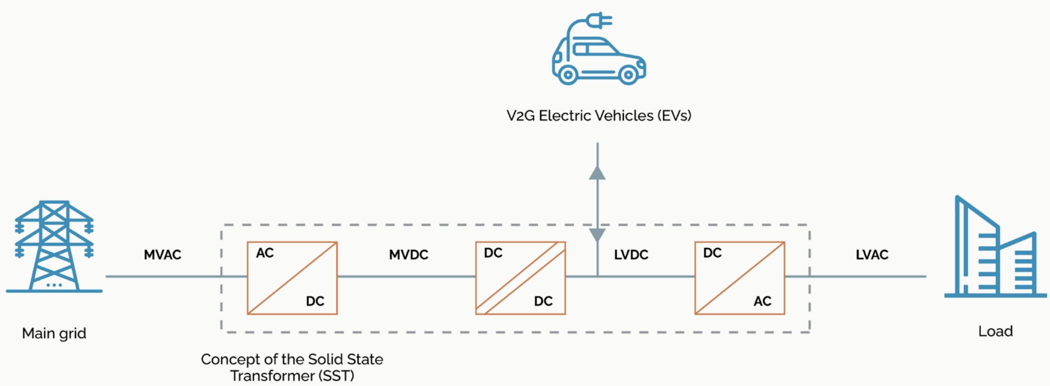


Source: PTR

Bidirectional Transformers (Solid-State) for Vehicle-to-Grid Integration

The rise of V2G technology necessitates the adoption of bidirectional transformers. V2G empowers EVs to not only consume electricity but also contribute excess energy back into the grid during periods of peak demand. SSTs emerge as key enablers in the integration of EVs into the power grid. Their ability to facilitate bidirectional power flow, efficiently converting AC to DC and vice versa, makes them pivotal in supporting V2G applications, where EVs can act as distributed energy resources, helping balance the grid and contributing to grid stability.

Figure 10: Bidirectional Power Flow of V2G



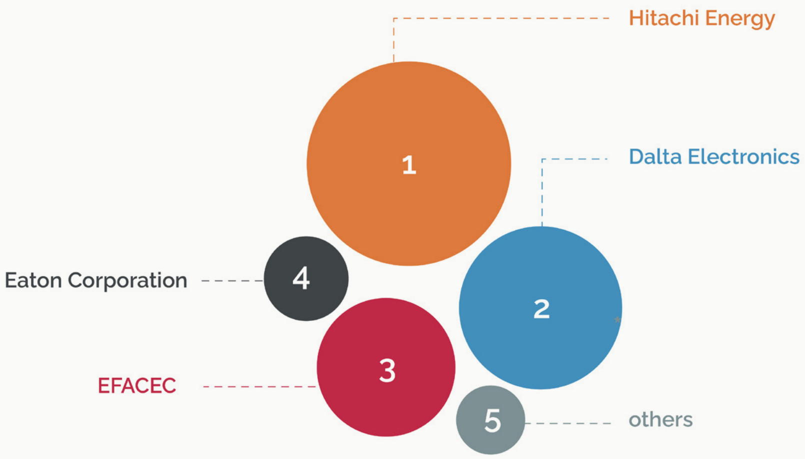
Source: PTR

SSTs are highly controllable, allowing for precise voltage and frequency regulation, which is crucial for managing the impact of large-scale EV charging on the grid. SSTs are modular and scalable, making it easier to adapt to the growing demand for EV charging infrastructure without requiring extensive grid upgrades. Overall, SSTs play a pivotal role in enhancing the reliability, efficiency, and sustainability of EV integration into our energy systems.

As SSTs are designed to operate seamlessly with both AC and DC power, they eliminate the need for separate inverters. This is significant for EVs because they primarily use DC power for charging their batteries. By connecting directly to the DC grid end of the transformer, SSTs bypass the need for an AC-to-DC inverter, reducing energy conversion losses and improving charging efficiency. In traditional charging systems, an AC-to-DC inverter is often employed, which adds complexity, cost, and energy losses to the charging process. SSTs streamline this process by providing a direct interface with the DC components of EV charging infrastructure.

As per PTR's Distribution Transformer Market Analysis the commercialization of SSTs is yet to happen, the top suppliers of SSTs based on their engagement in research and development are Hitachi Energy, Delta Electronics, EFACEC, and Eaton as shown below:

Figure 11: SST Suppliers Ranking [10]



*

General Electric (GE)	Laplace	Sungrow Power Supply Co. Ltd.	Huawei Digital Power Technologies Co. Ltd.
Hysosung Heavy Industries Co. Ltd	Huanyu Group Nanjing Co. Ltd	Premo	MMB Drives Ltd

* Top suppliers of SSTs have been determined based on their engagement in Research and Development **(R&D)** endeavors.

Source: PTR

5

Conclusion

The global EV landscape and charging infrastructure presented in this paper highlight the transformative potential of smart charging and V2G technologies. By intelligently managing EV charging patterns and utilising V2G capabilities, the burden on the power grid, grid congestion, and grid instability can be significantly reduced. These innovations not only facilitate the transition to clean energy but also empower e-mobility to play a pivotal role in shaping sustainable and resilient energy ecosystems for the future.

As EVs integrate into our power grids, innovative solutions become imperative to address load fluctuations and voltage stability. Demand response programs incentivise EV owners to charge during off-peak hours, reducing strain on grid equipment and thus improving grid stability. Simultaneously, grid upgrades, including capacity enhancement and advanced transformers tailored to EV charging demands, play a pivotal role in mitigating power quality issues. This presents growth opportunities for transformer manufacturers as there will be significant demand for transformers due to EV adoption. Primary research shows that transformer manufacturers specialising in the solar industry are pre-booked for the next 2 to 3 years. This competition for manufacturing resources underscores the critical need for advanced transformer technology and strategic planning to meet the demands of both sustainable energy generation and the growing EV market.

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