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Perspective

An Overview of Level 3 DC Fast Chargers: Technologies, Topologies, and Future Directions

Alan Yabin Hernández Ruiz [1], Susana Estefany De león Aldaco [1,*], Jesús Aguayo Alquicira [1,*], Mario Ponce Silva [1], Omar Rodríguez Benítez [1] and Eligio Flores Rodríguez [2]

[1] Centro Nacional de Investigación y Desarrollo Tecnológico (CENIDET), Tecnológico Nacional de Mexico, Cuernavaca 62490, Morelos, Mexico; m24ce024@cenidet.tecnm.mx (A.Y.H.R.); mario.ps@cenidet.tecnm.mx (M.P.S.); d19ce044@cenidet.tecnm.mx (O.R.B.)

[2] Laboratory of Electrical and Power Electronics, Tecnológico Nacional de Mexico, Instituto Tecnológico Superior de Irapuato, Irapuato 36821, Guanajuato, Mexico; eligio.fr@irapuato.tecnm.mx

* Correspondence: susana.da@cenidet.tecnm.mx (S.E.D.l.A.); jesus.aa@cenidet.tecnm.mx (J.A.A.)

Abstract

The increasing adoption of electric vehicles has driven the development of charging technologies that meet growing demands for power, efficiency, and grid compatibility. This review presents a comprehensive analysis of the EV charging ecosystem, covering Level 3 DC charging stations, power converter topologies, and the role of energy storage systems in supporting grid integration. Commercial solutions and academic prototypes are compared across key parameters such as voltage, current, power, efficiency, and communication protocols. The study highlights trends in charger architectures—including buck, boost, buck–boost, LLC resonant, and full-bridge configurations—while also addressing the integration of stationary storage as a buffer for fast charging stations. Special attention is given to wide-bandgap semiconductors like SiC and GaN, which enhance efficiency and thermal performance. A significant gap persists between the technical transparency of commercial systems and the ambiguity often observed in prototypes, highlighting the urgent need for standardized research reporting. Although converter efficiency is no longer a primary constraint, substantial challenges remain regarding infrastructure availability and the integration of storage with charging stations. This paper seeks to offer a comprehensive perspective on the design and deployment of smart, scalable, and energy-efficient charging systems, with particular emphasis on cascaded and bidirectional topologies, as well as hybrid storage solutions, which represent promising pathways for the advancement of future EV charging infrastructure.

Keywords: fast charger; EV; charger level 3; impact for EV; fast charger topologies

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1. Introduction

Today, the use of transportation is vitally important due to the constant need for mobility, which has always been a daily priority. This has led to the development of technologies that modernize or streamline the fulfillment of this need, the most popular being the conventional fossil fuel-powered automobile [1]. The constant need for mobility, coupled with global overpopulation, has led to a concerning level of greenhouse gas emissions. According to the national inventory of greenhouse gases and compounds, transportation was the largest emitter of CO_2, accounting for a significant contribution of emissions in 2019 (Figure 1) [2].

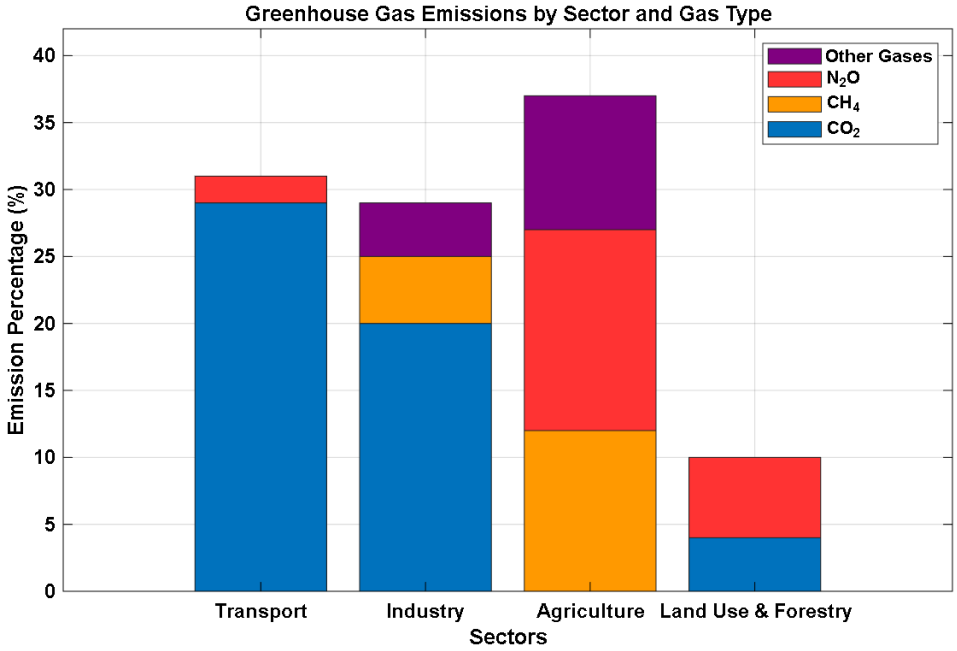


Figure 1. Greenhouse Gas emissions.

The continuous use of transportation in our daily lives raises growing concerns about energy efficiency and the use of energy technologies. To mitigate this environmental impact, along with the trend toward reducing dependence on fossil fuels, the development of functional and efficient electric vehicles began in 2010. This initiative aims to help reduce greenhouse gas emissions and promote the adoption of alternative energy sources to address mobility challenges.

However, the deployment of these technologies faces several challenges that hinder the widespread and rapid adoption of electric vehicles. These challenges include high maintenance costs, which stem from the vehicle's technical characteristics and its relatively short time on the market. Additionally, maintenance expenses remain inadequately addressed and are further exacerbated by the high charging rates for these vehicles [3].

Greenhouse gas emissions continue to be generated mainly through carbon dioxide emissions from two major sectors: industry and transportation, as illustrated in Figure 1. The energy sector is one of the primary polluters, making the integration of renewable energy sources a viable solution to mitigate future emissions. This approach also addresses other greenhouse gases, including methane and nitrous oxide [4].

The deployment of fast and ultra-fast charging stations not only enhances energy efficiency but also contributes to the reduction in greenhouse gas emissions. In 2015, emissions were reduced by 50% compared to the reference benchmark of that period. This outcome is consistent with the observed trajectory, as scenarios based on lower charging capacities or continued reliance on fossil fuels yield a less favorable cost–benefit ratio, expressed as the percentage of particles mitigated relative to those emitted. As shown in Figure 2, this relationship is projected to extend through 2050 [5].

The adoption of electromobility contributes to reducing climate change by decreasing dependence on internal combustion engines and facilitating integration with electricity grids powered by renewable sources. It also has positive effects on urban air quality by reducing pollutants such as nitrogen oxides, carbon monoxide, and fine particulate matter, which translates into health benefits for the population.

However, at the global level, the environmental balance is influenced by the carbon intensity of electricity generation and the management of the life cycle of lithium-ion batteries. In regions with a high share of renewable energy, electromobility achieves

significant reductions in emissions; in contrast, in countries whose energy matrix depends on coal or natural gas, its positive impact is more limited. Hence, the transition to cleaner electricity systems, together with the development of strategies for recycling and reusing critical materials, is essential to maximize the environmental benefits of electromobility on the world stage [6].

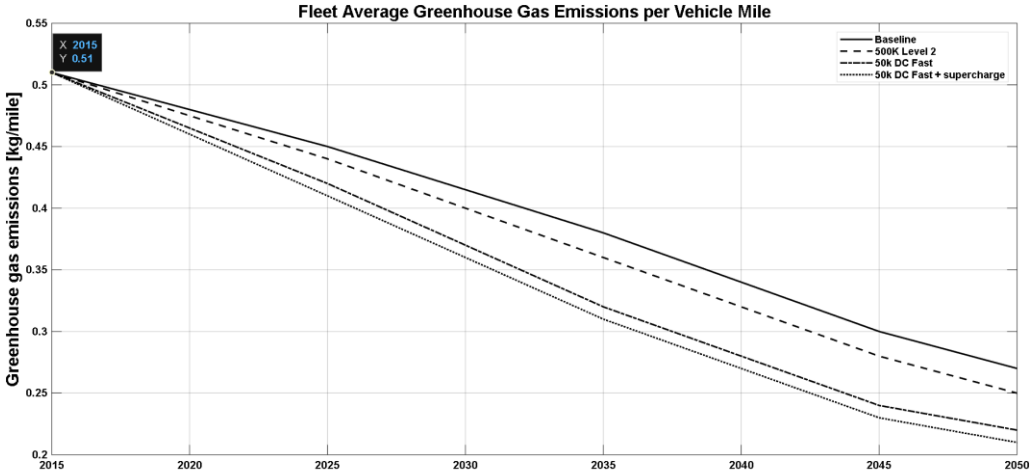


Figure 2. Fleet average greenhouse gas emissions per vehicle mile (Adapted from [5]).

Below is a structured review of information that extensively analyzes everything related to electric vehicle charging, with an emphasis on

- Power converters topologies
- The performance and characteristics of the various energy storage systems integrated in EVs,
- The design and deployment of commercial charging infrastructures
- A systematic examination of research prototypes proposed in the scientific literature.

This research is structured into five main sections. Section 1 introduces the context, objectives, and scope of the study. Section 2 examines the current state of electric vehicles, addressing their technological development, market penetration, and challenges, while Section 2.1 focuses specifically on battery technology, emphasizing advances in storage capacity, efficiency, charging times, and lifespan. Section 3 analyzes the electric vehicle charging infrastructure, with Section 3.1 highlighting the role of DC-DC power converters as key components for efficient, stable, and reliable fast-charging systems. Section 4 presents the results, synthesizing the main findings and relating them to the initial objectives. Finally, Section 5 provides the conclusions, summarizing the most significant contributions of this work and outlining directions for future research and technological progress in electromobility.

Systematic Review Methodology

For this study, various academic databases were consulted to collect documents that provide an overview of electric vehicles and their impact on the power grid. The research then focused on different types of direct current chargers for electric vehicles. Subsequently, the literature specifically related to Level 3 fast charging devices was examined to compare their key electrical parameters—such as rated power, output voltage, and operating current. This review also explored the current state of development of these chargers to establish a foundation for future charger design and their potential integration into everyday use.

The paper search followed a document-based approach, organizing publications from 2013 to 2024. Keywords used included: “fast charger,” “EV,” “Level 3 charger,” “impact of

EV," and "fast charger topologies." The documents were sourced from multiple databases and search engines, including IEEE Xplore, MDPI, and ScienceDirect, among others.

Inclusion and Exclusion Criteria

The inclusion criteria considered peer-reviewed articles, conference papers, and review papers that:

- Focus on EV fast charging systems, charger architectures, or power converter topologies.
- Provide technical or experimental contributions (simulation or prototype).

The exclusion criteria eliminated studies that:

- Did not directly address the central theme of fast charging.
- Were outside the publication years of interest.
- Were duplicated across databases.

Selection Process

The initial search returned a total of 7344 articles. After applying the exclusion criteria, 7074 articles were removed. The remaining 270 articles were thoroughly reviewed, and ultimately, 100 articles were selected for inclusion in the state-of-the-art analysis. A detailed summary of the selection process is shown in Figure 3, adapted from the PRISMA flow diagram.

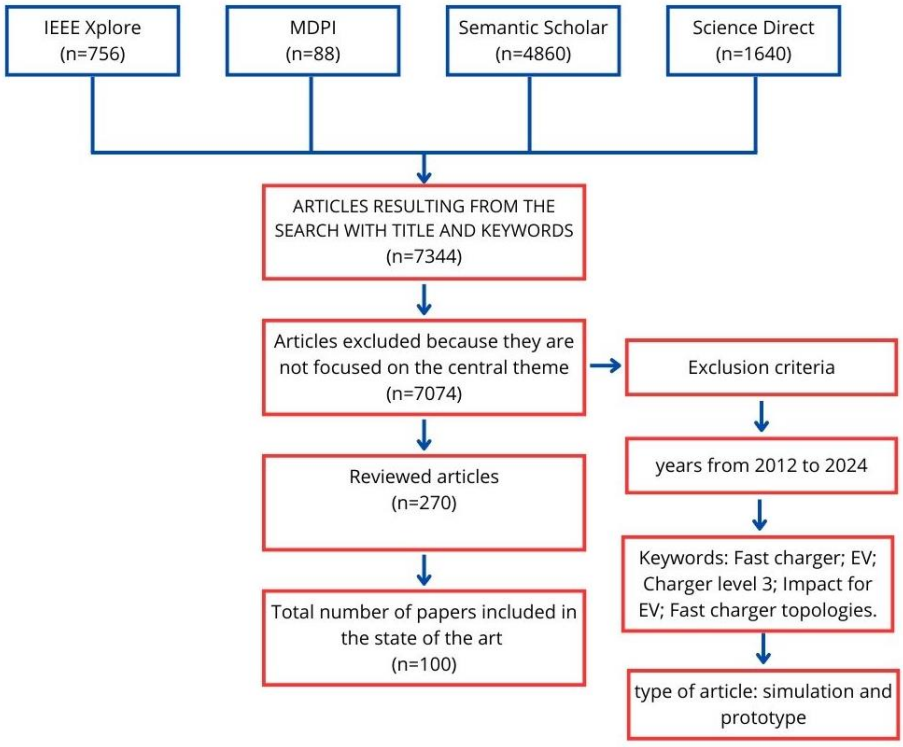


Figure 3. Systematic review methodology.

Once the papers were collected, they were categorized by publication year. This categorization allowed for the identification of trends over time. It facilitated the analysis of the devices proposed in the reviewed papers, enabling the detection of key patterns relevant to the study (Figure 4).

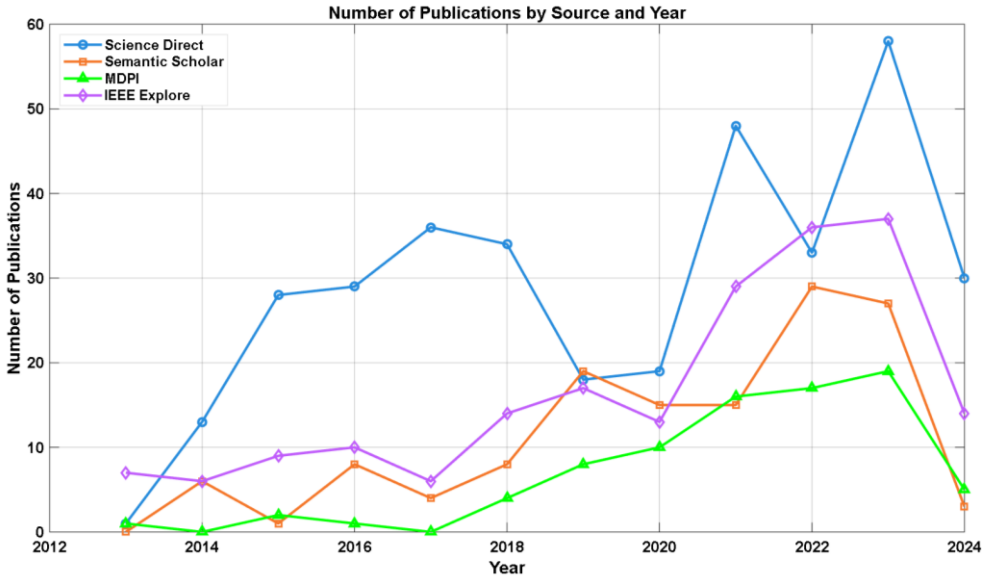


Figure 4. State-of-the-art publications.

2. Current State of Electric Vehicles

Today, automotive progress has a significant impact on everyday life, and the integration of eco-friendly vehicles into daily life is becoming increasingly common. This constitutes a substantial opportunity for sustainable development, encompassing ecological, economic, and social dimensions, which, when combined with proper implementation, can help establish and maintain standards in these areas. Regarding the implementation of electric vehicles (Figure 4), a standardization and ecological education protocol has been implemented to guide users in learning about and becoming interested in these vehicles [7].

The implementation of electric vehicles can be seen as a reality rather than as futuristic concepts depicted in science fiction films, fostering the idea of a future oriented toward their mass adoption. A clear example of this is Formula E, which represents the integration of electric vehicles into motor racing, providing a platform to demonstrate their efficiency, productivity, and versatility.

Until a few years ago, there was a conflict of interest due to a lack of information about the cost–benefit ratio of these vehicles, making their ecological efficiency questionable due to the use of batteries with polluting waste [8]. A critical factor influencing user adoption, particularly with respect to charging infrastructure, is the perceived charging speed. Whereas conventional Level 2 chargers typically require several hours to deliver a full charge, Level 3 fast-charging stations reduce this time to approximately 30 min, providing a driving range exceeding 300 km. This substantial improvement in charging convenience has a direct impact on user acceptance, as the ability to recharge rapidly makes electric vehicles more comparable to conventional internal combustion vehicles in terms of the refueling experience [9].

Thus, the deployment of Level 3 charging stations plays a key role in addressing one of the main barriers to adoption: charging time. By aligning technological advances in efficiency with infrastructure that prioritizes user convenience, electric vehicles become a more viable and attractive option for widespread use [10].

The massive change shown in Figure 5 will significantly impact the global electricity grid, as the growing demand for energy to charge EVs will require investments in infrastructure, smart grid technologies, and energy storage. Countries with closer deadlines are already integrating these vehicles into the grid (Figure 6). Solutions could be explored to mitigate challenges to grid stability, such as energy demand management and the incorpo-

ration of renewable sources, whose variability reinforces the need for robust planning and large-scale storage [11].

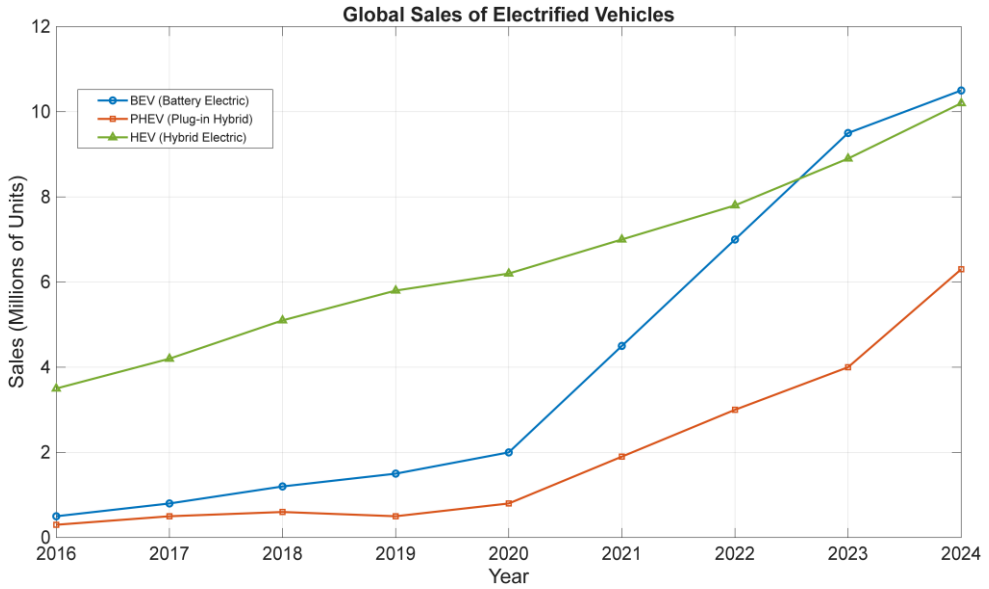


Figure 5. Global sales of electric vehicles.

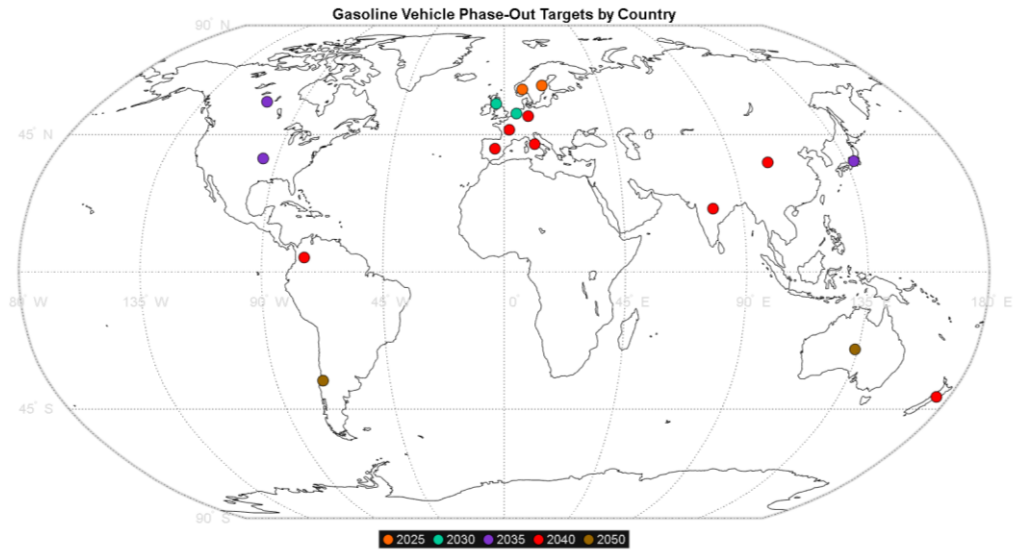


Figure 6. Future outlook for electromobility.

One of the major challenges is the variability in the electrical load introduced by electric vehicles. Electricity demand becomes less predictable, which could complicate grid planning and operation. Without proper management, this could lead to imbalances between energy supply and demand, affecting grid stability.

Another scientific aspect is wireless charging, which is implemented for the design of spaces and the practicality of vehicle recharging, using pressure plates on the floor to generate recharging via coils during a rest period without generating considerable energy losses in the form of heat. In addition, they can offer innovative solutions, such as the ability to act as distributed energy storage through technologies where vehicles return energy to the grid at times of high demand, helping to balance the load.

Wireless charging also adds flexibility in terms of space design and user convenience, with the added potential of being integrated into managed or V2G strategies. However, the challenge is particularly pronounced in the case of fast-charging stations, which concentrate

high energy demands in short periods. Clusters of such stations could significantly stress local grids, potentially leading to blackouts or requiring costly infrastructure upgrades.

Thus, comparing and implementing a mix of strategies—such as coordinated smart charging, time-of-use tariffs, and V2G—becomes essential to mitigate the impact of fast-charging adoption on the electrical grid and to ensure a sustainable transition to large-scale electromobility.

The mass adoption of electric vehicles faces significant challenges that go beyond a simple technological transition. One of the main challenges is the potential overload of the electrical grid. Electricity demand could increase significantly, testing the capacity of the current infrastructure to meet these new energy needs. This is particularly concerning in the case of fast-charging stations, which require large amounts of energy in short periods. The concentration of multiple fast-charging stations in specific areas could lead to demand spikes that the current electrical infrastructure is not prepared to handle, potentially resulting in blackouts or the need for costly upgrades to the electrical grid.

Another challenge is range anxiety, which refers to the concern that an EV will not have enough range to complete a trip without recharging. Despite improvements in battery range, this concern persists, especially in areas with insufficient charging infrastructure. The lack of fast-charging stations, coupled with the perception of long charging times, contributes to this anxiety, which discourages potential buyers.

2.1. Battery Technology

The energy industry in the field of energy efficiency is focused on two areas in terms of electromobility. One of these areas is focused on the development of energy storage technology through the design of lithium-ion batteries, due to their great capacity to establish a good relationship between power density and energy density parameters. This means that they have a balance between the large amount of energy they can store in a small space and how quickly they release that energy [12].

Table 1 shows that lead-acid batteries store very little energy and cannot withstand a large number of charge cycles. For this reason, the current trend favors the use of lithium-ion batteries. It is also noteworthy that nickel-cadmium batteries present a high self-discharge rate compared to the other technologies analyzed. This aspect is relevant, as it will later be used to illustrate the relationship between efficiency, battery size, and energy storage technologies [13].

Table 1. Technical characteristics of main battery types used for EV(Adapted from [14]).

Battery Technology	Specific Energy (Wh/kg)	Self-Discharge Coefficient (%/24 h)	Number of Recharging Cycles
Pb-acid	40	1	500
Ni-Cd	60	5	1350
NiMH	70	2	1350
Li-ion	125	1	1000
Na-NiCl	125	0	1000

This is why lithium-ion batteries are used on a large scale in applications such as electromobility. However, researchers are seeking to develop a new storage method focused on the implementation of supercapacitors. This technology implements double-layer devices with minimum values of 1 farad. Compared to lithium-ion batteries, these devices have a high energy density. However, their power density is very low. In simple terms, they store a large amount of energy but release it quickly [15]. Below is a Ragone plot (Figure 7) that illustrates the above [16].

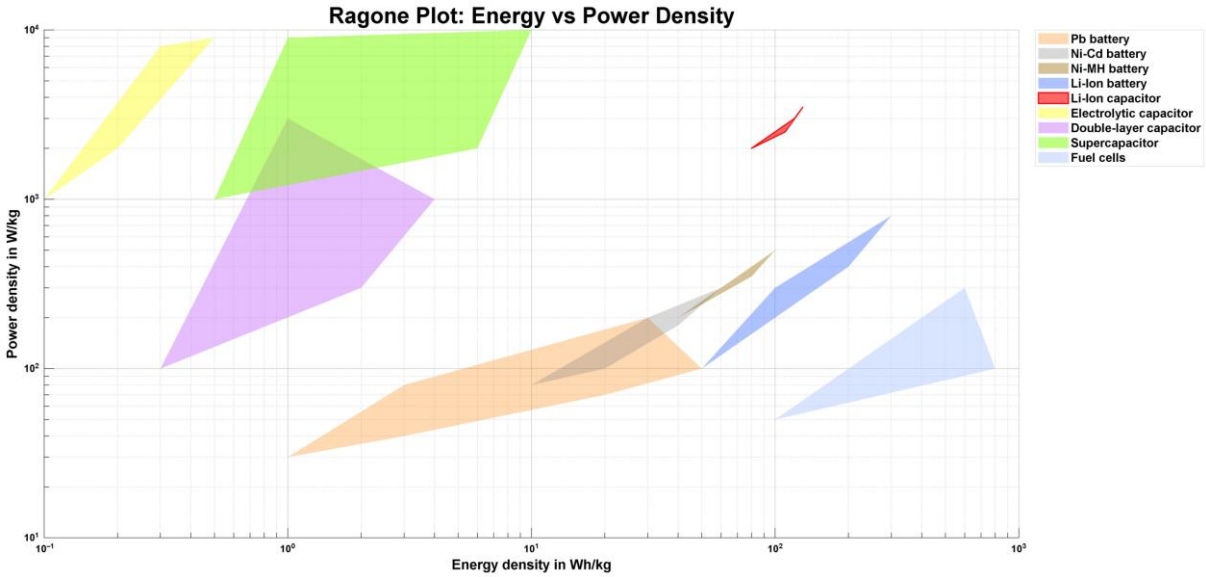


Figure 7. Ragone Plot: Energy vs. Power Density for Energy Storage Technologies.

Fuel cells are generally unsuitable for energy storage in electric vehicles due to their structural complexity and size. To achieve efficiency and provide a driving range comparable to that of batteries used in electric and hybrid vehicles, fuel cells would need to be significantly larger, posing considerable challenges in terms of packaging and integration.

2.1.1. Pouch Cell

Lithium-ion pouch cells (Figure 8) are characterized by their flexible and flat design, which allows for higher energy density per unit volume compared to cylindrical and prismatic formats. Encapsulation in multilayer polymer and aluminum foil makes them lighter and thinner, facilitating integration into compact designs and adaptation to diverse vehicle structures [17].

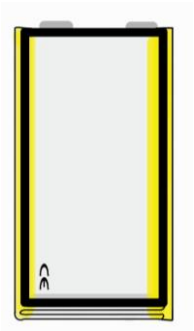


Figure 8. Pouch cell.

In electric vehicles, pouch cells are typically assembled into modules and then into battery packs installed in the vehicle's base, similar to cylindrical cells. This configuration contributes to optimal weight distribution, a lower center of gravity, and efficient use of structural space.

A major advantage of pouch cells is their larger surface area, which facilitates heat dissipation at the module or pack level through conduction or liquid cooling. This feature has encouraged adoption by manufacturers such as Hyundai, Kia, and General Motors, who value their lightweight nature and flexibility in pack design. These batteries can provide driving ranges above 400 km per charge, depending on system design and operating conditions [18].

Nonetheless, at the individual cell level, pouch cells are more sensitive to fast charging than cylindrical cells. Their structural characteristics can lead to localized thermal stress and accelerated degradation under high C-rate operation, underscoring the need for robust thermal management strategies.

2.1.2. Prism Cell

Prismatic lithium-ion batteries (Figure 9) have now become quite ubiquitous in electric vehicles, extremely flat and "rectangular" to take up as little space as possible inside the vehicle [17]. The fact that these cells have a rigid frame rather than the more common cylindrical shape is novel and not only adds strength but also facilitates heat removal. Inside, they are composed of stacked layers of active material and enable high capacity [18].

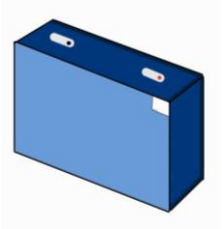


Figure 9. Prismatic cell.

Their design makes it easy to connect coolants such as liquids or special materials to help manage temperature when the battery is under load. They have an important advantage: they pack a lot of energy into a small volume, the perfect solution for electric cars intended to travel long distances [19]. They are also less susceptible to shock loads or vibrations and contribute to automotive safety on the road. On the other hand, they are more expensive and more difficult to manufacture, and if they fail, the consequences can be more severe due to the large amount of energy they handle. In addition, there have been reports that they can swell slightly if not used for long periods [20].

2.1.3. Cylindrical Cell

Cylindrical lithium-ion batteries (Figure 10) are constructed by winding layers of active materials, forming compact and efficient cells. These cells are connected in series-parallel configurations to achieve the required voltage and capacity levels. In vehicle applications, especially in electric cars, this type of battery is distributed along the floor of the vehicle, allowing for more efficient use of available space and helping to improve the center of gravity, thus optimizing the stability and dynamic performance of the car.



Figure 10. Cylindrical cell.

In addition, this uniform distribution of cells facilitates the implementation of more efficient cooling systems. Being located at the base of the vehicle, the batteries can have active or passive ventilation channels that allow the heat generated during charging,

discharging, or driving in demanding conditions to be dissipated. This not only extends the life of the cells but also prevents overheating, improving the safety and performance of the system [21].

Brands such as Tesla have adopted this approach in several of their models. For example, the Tesla Model S uses a battery pack composed of thousands of cylindrical cells distributed across the vehicle floor. This architecture has proven to be highly efficient in terms of both energy density and thermal management.

Cylindrical lithium-ion batteries focus on rolling the cells into small-scale layers, making series-parallel arrangements. These same batteries are distributed along the floor of the vehicle, making more efficient use of space. It should also be noted that this distribution of the battery arrangement promotes better cooling around the cells, as they are distributed throughout the base of the vehicle and have ventilation channels that cool the process of useful life and prevent overheating [21].

The development of technologies for electrical energy storage has a comprehensive market. Table 2 shows some types of packaging as part of a review of the current market.

Table 2. Comparison of commercial batteries in Electric Vehicles.

Ref.	Year	Battery Model	Chemical Composition	Capacity	Cells	Type
[21]	2009	BYD Tang (BYD, Shenzhen, China)	LFP	100–150 kWh	200	Pouch
[22]	2014	GM LMR prismatic (General Motors, MI, USA)	LMR	150 kWh	273	Prism
[23]	2020	Lucid Air 2170 (Samsung SDI, Yongin, South Korea)	NCA	113 kWh	6600	Cylinder
[24]	2022	Ford Mach-E (Ford, MI, USA)	NCM811	91 kWh	376	Pouch
[25]	2022	Tesla 4680 (Tesla, TX, USA)	NCM o NCA	82 kWh	4680	Cylinder
[26]	2022	Tesla/NMC (Tesla, NV, USA)	NMC	~55–82 kWh	108	Prism
[27]	2023	Nio ET7 (NIO, Hefei, China)	NMC	150 kWh	108	Pouch
[28]	2023	GM Ultium (Ultium Cells LLC, OH, USA)	NCMA	100 kWh	264	Pouch
[29]	2023	Nio ET7 (NIO, Hefei, China)	NMC	100 kWh	192	Prism
[30]	2023	Nio ET7(NIO, Hefei, China)	NMC + LFP	75 kWh	118	Prism
[31]	2023	BYD Blade (BYD, Qinghai, China)	LFP	82–100 kWh	230	Prism
[32]	2023	BMW NEUE KLASSE (BMW, Debrecen, Munich, Hungary and Germany)	NMC	105 kWh	4680	Cylinder
[33]	2023	Tesla 2170 (Tesla, NV, USA)	NCA	60–82 kWh	2170	Cylinder
[34]	2024	Hyundai loniq (Hyundai, Ulsan, South Korea)	LFP	77 kWh	360	Pouch
[35]	2025	Porsche 18650 (Panasonic, Kadoma, Japan)	NCA	93 kWh	396	Cylinder

As can be seen in the table, battery packs are grouped according to their year of implementation. Recently, there has been research and development into models based on cylindrical batteries. The main characteristic of this assumption is that their packs have more cells compared to prismatic or pouch-type batteries. This is because the structure of the cell grouping allows for better placement and distribution of the cells throughout the electric vehicle, improving cooling and efficiency compared to the rest.

3. EV Charging Infrastructure

Currently, there are four main types of charging systems for electric vehicles, categorized into levels. Each level specifies a type of charging categorized by the power it supplies and the time it takes to charge. Levels 1 and 2, based on low power, are designed to focus on alternating current, which, for level 1, provides a charging power of 1.44 kW to 1.92 kW, with an estimated charging time of 11 to 36 h. Level 2 provides a charging power of 3.1 kW to 19.2 kW, with a charging time of 2 to 6 h. The following modules focus directly on direct current, dedicating them to higher power for a faster charging time. Level 3 covers a charging power range of 50 to 350 kW, achieving charging times of 30 min. Finally, Level 4, dedicated to super-fast charging, handles power values in the ranges above 350 kW, giving charging times of 10 min (Table 3) [4].

Table 3. Comparison of the characteristics of EV charging infrastructure levels.

	Level 1 (AC)	Level 2 (AC)	Level 3 (DC)	Level 4 (DC)
Recharge time	11–36 h	2–6 h	30 min	10 min
Energy consumed	16–50 kWh	16–30 kWh	20–50 kWh	50–160 kWh
Connection protocols	SAE J1772	SAE J1772	CCS, CHAdeMO	CCS, CHAdeMO
Voltage (V)	120	240	200–1000	Up to 1000
Current (A)	12–16	16–80	100–400	300–500

From a comparative perspective, each level entails distinct implications for both the electrical grid and the end users. Level 1 and Level 2 chargers exert relatively low stress on the grid due to their limited power demand, making them easier to integrate into residential and commercial settings. However, their long charging times may discourage users who prioritize convenience and fast turnaround. Level 3 chargers represent a balance, offering fast charging suitable for public stations while still imposing significant but manageable peaks on the grid. In contrast, Level 4 chargers provide the highest convenience for users—recharging in minutes—but also generate extremely high, concentrated loads that can challenge local grid stability and often require costly infrastructure upgrades, such as reinforced substations or dedicated energy storage systems.

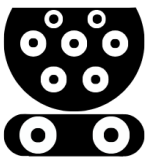
Therefore, while fast and ultra-fast charging are essential to support mass adoption by reducing range anxiety, their deployment must be accompanied by grid management strategies such as demand response, smart charging, and integration of renewable energy sources to mitigate their impact. This trade-off highlights the importance of balancing user convenience with the technical and economic feasibility of grid operation.

Now, ways are being sought to implement the use of renewable energies in the recharging of electric vehicles, taking advantage of technological advances in energy use for a high-energy-consuming device like an electric vehicle. The scientific community is currently focusing on the use of technologies to enhance the service of electric vehicles by implementing artificial intelligence that utilizes neural networks to intelligently charge the electric vehicle's battery, thereby mitigating grid overload [36]. It is important to clarify that from this section onwards, the information will focus on fast and ultra-fast charging stations, due to the trend and adoption of electric vehicles.

The use of electric vehicles has increased. However, two current crises—overpopulation and the energy crisis—are hindering their full adoption. This situation represents a significant shift in the way energy is consumed and managed, generating both positive and negative impacts. One of the main challenges is the rising energy demand, particularly when a large number of electric vehicles are charged simultaneously during peak hours. Such circumstances could overload the existing electrical infrastructure, which in many cases was not originally designed to accommodate these additional demand peaks.

This raises environmental concerns, as batteries contain hazardous materials that require safe recycling processes. The mass adoption of EV, while crucial for sustainable mobility, requires careful planning to avoid overloading the electrical grid and to ensure that infrastructure, policies, and technology evolve in harmony. Table 4 provides a summary of the points mentioned.

Table 4. Comparison of the characteristics of connection protocols for EVs.

	CHAdeMO	**Tesla Supercharger**	**CCS**
Connection type	DC	DC	AC/DC
Maximum load capacity	Up to 400 kW	Up to 250 kW	Up to 350 kW
Maximum current	Up to 400 A	Up to 423 A	Up to 500 A
Voltage standards	200–1000 V	480 V	200–1000 V
Communication protocol	Control Area Network	Only Tesla	Power Line Communication
Manufacturers	Nissan, Mitsubishi, Kia	Tesla	BMW, Audi, Ford, Hyundai
Connection port diagram			

The comparative analysis presented in Table 5 evidences the technological evolution of commercial fast and ultra-fast charging stations over the last decade. Early systems, operating in the 100–500 V range with power levels near 50 kW, achieved efficiencies around 90%, establishing the foundation for standardized protocols such as CHAdeMO. From 2017 onwards, significant progress has been observed in both voltage and current handling capabilities, with chargers reaching 150–350 kW while maintaining efficiencies consistently above 94%.

Table 5. Comparative analysis of commercial charging stations focused on fast and ultra-fast charging.

Ref.	**Year**	**Voltage (V)**	**Current (A)**	**Power (kW)**	**Efficiency (%)**	**Protocol**
[37]	2011	100–500	120	50	90	CHAdeMO
[38]	2017	200–500	125	50	95	CCS, CHAdeMO
[39]	2019	50–500	125	50	94	CCS, CHAdeMO
[40]	2020	500	200	100	95	CCS1,CHAdeMO
[41]	2021	150–950	120	60	94	CCS1,CHAdeMO
[42]	2021	170–940	50–400	150	93	CHAdeMO
[43]	2021	920	200–500	350	98.5	CCS2,CHAdeMO
[44]	2021	200–1000	375	150	94	CCS, CHAdeMO
[45]	2022	920	188	75	95	CCS ½, CHAdeMO
[46]	2022	50–920	200	100	95	CCS1,CHAdeMO
[47]	2022	50–410	330	135	91	Supercharger
[48]	2023	200–1000	250–500	2000	94	CCS, CHAdeMO
[49]	2023	150–950	500	350	95	CHAdeMO
[50]	2023	150	500	350	96	CCS, CHAdeMO
[51]	2023	150–1000	350	350	95	CCS, CHAdeMO
[52]	2024	150–920	325	130	97	CCS ½, CHAdeMO
[53]	2024	150–950	380–500	350	94	CCS ½, CHAdeMO
[54]	2024	200–920	500	350	96	CCS2, CHAdeMO
[55]	2024	500	-	6.6	-	CCS
[56]	2024	200–1000	350	350	97	CHAdeMO

Recent implementations (2021–2024) extend the operating voltage up to 1000 V and current ratings exceeding 500 A, enabling charging powers of 250–350 kW. These platforms demonstrate peak efficiencies close to 98%, consolidating the use of wide-bandgap semiconductors and advanced thermal management strategies. Furthermore, the adoption of CCS (Types 1 and 2) as the dominant protocol reflects the trend toward interoperability and harmonization of standards in high-power applications.

In summary, the data in Table 5 illustrate a clear trajectory toward higher charging power, shorter charging times, and improved system efficiency. The commercial state-of-the-art has converged on architectures capable of reliably delivering more than 300 kW at efficiencies above 95%, confirming the maturity of fast-charging technology for large-scale deployment in EV infrastructure.

3.1. DC-DC Power Converters

3.1.1. Buck Converter

The Buck converter is a popular topology for the initial conversion stage or auxiliary power supplies in fast charging stations. Our inverter is original; its operating principle consists of switching a high-frequency switch, then transferring energy through an inductor to the output, where a capacitor filters the output voltage [57]. Figure 11 shows a schematic diagram of a buck converter highlighting the current flow.

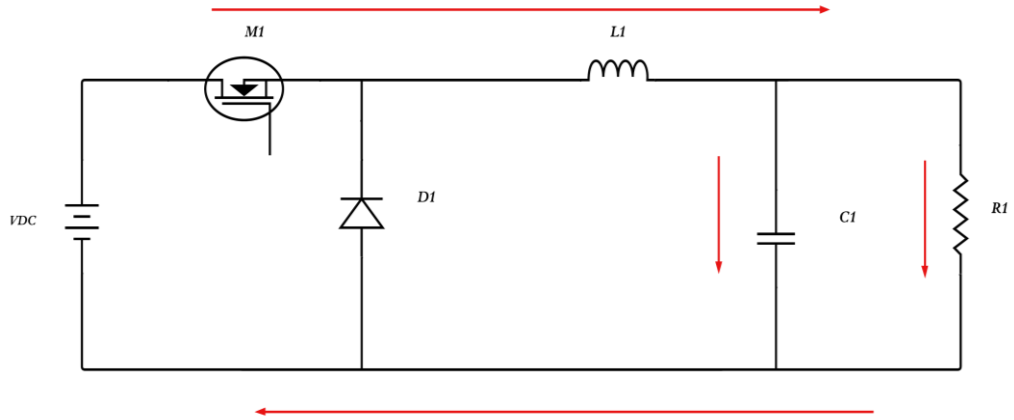


Figure 11. Buck converter.

In fast charging, this converter is used to generate intermediate control voltages, control higher power levels, or as part of the charge control system by acting as a constant voltage or current parameter [58]. Wideband semiconductors, such as silicon carbide, can be used to achieve an efficiency level and to minimize switching losses, which is necessary when aiming for high-frequency operation. From a design perspective, the trade-offs are well established: low duty ratios at high step-down ratios lead to increased current ripple, requiring larger inductors or higher switching frequencies [59]. Wide-bandgap semiconductors, particularly SiC MOSFETs, enable switching frequencies above 100–200 kHz, improving transient response and reducing passive component size. Efficiencies above 95% are typical in isolated auxiliary stages, while system-level implementations reach 90–94% depending on loading and cooling constraints [60].

3.1.2. Boost Converter

This power converter focuses on raising the electrical parameters, specifically the voltage at its output, by utilizing a switch that increases the voltage values by applying a DC bus. This process injects more voltage than it receives [61]. It accumulates energy in an inductor during the switch-on time and transfers it to the output when the switch turns

off [62]. To ensure fast response and precise regulation during fast charging, pulse width modulation techniques and digital control strategies are used. Figure 12 shows a schematic diagram of a boost converter highlighting the current flow.

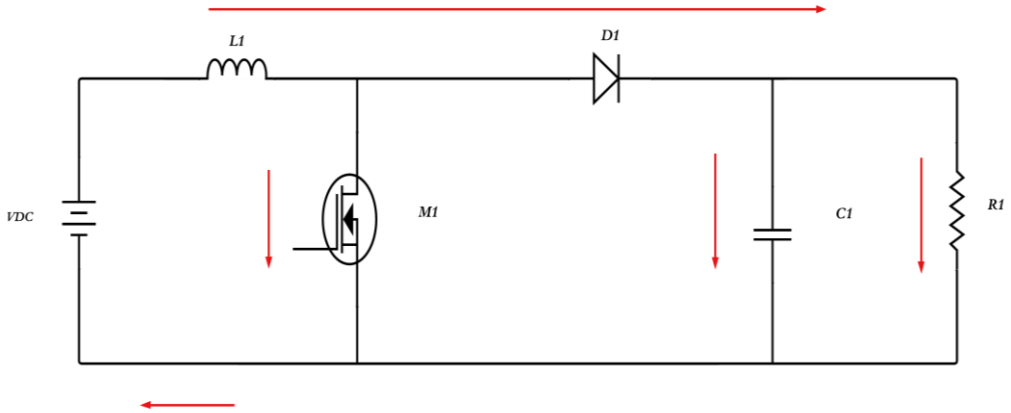


Figure 12. Boost converter.

Design compromises include managing high peak currents in the switch and diode, especially at high duty cycles, which lead to increased conduction and switching losses. Digital control strategies with PWM and current-mode control are often adopted to maintain fast response. In high-power EV chargers, operating frequencies typically fall within 50–150 kHz, balancing efficiency and magnetic design. Efficiencies up to 97–98% are reported in experimental setups using SiC devices. Thermal management becomes critical due to current stress, which can be mitigated by interleaving multiple boost phases [63]. It should be noted that this type of converter is most commonly used in high-power applications, such as fast vehicle charging, where it is employed in different branches to expand its range of tolerances to electrical variables.

An analysis of Tables 5 and 6 shows that the percentages in prototypes remain within a certain margin of error. However, when compared with commercial topologies, a significant change in the variables is observed [64].

3.1.3. Buck-Boost Converter

The Buck–Boost converter is a versatile topology that allows operation in step-down or step-up modes depending on the difference between the input voltage and the battery's required voltage. This flexibility makes it an ideal solution for adapting to dual 400 V and 800 V architectures, common in modern platforms such as those from Hyundai and Porsche [65]. Figure 13 shows a schematic diagram of a buck-boost converter highlighting the current flow.

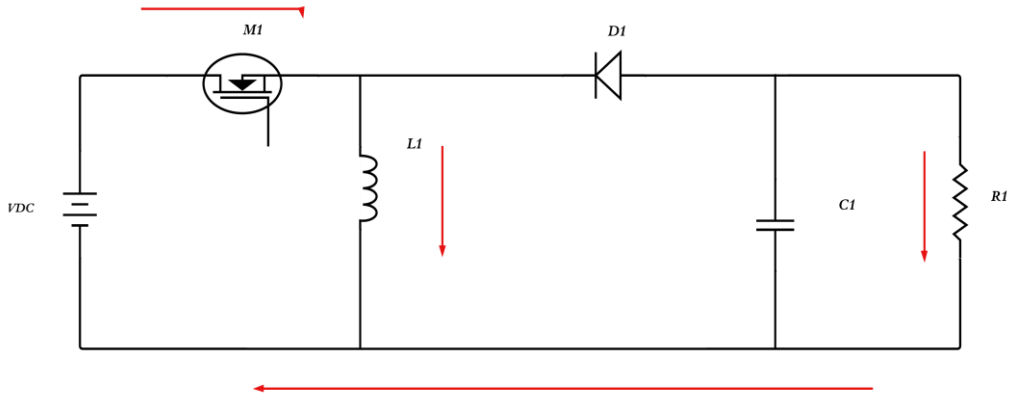


Figure 13. Buck-boost converter.

Unlike exclusively Buck or Boost converters, the bidirectional Buck–Boost topology allows both battery charging and discharging, contributing to smart grid functions such as load balancing or peak management. Efficiency trade-offs include increased conduction losses due to additional active devices compared with pure buck or boost stages. However, the integration of SiC MOSFETs allows switching frequencies above 100 kHz, enabling higher power density. Typical designs include multi-phase interleaving to reduce current ripple and improve thermal performance. Control strategies such as dual-loop nonlinear control enhance stability under fast load transients, which is crucial in fast-charging scenarios [66]. Reported efficiencies range between 95 and 97% across wide input/output voltage variations [67]. In addition, multi-branch implementation improves thermal performance and reduces current ripple, while nonlinear control techniques such as double-loop control ensure stability and fast dynamic response to load changes [68].

3.1.4. Resonant Converter

Resonant converters (Figure 14) are power models used to work at low power levels due to their high operating frequencies. By achieving a high operating frequency, low power is obtained. Resonant converters are characterized by their low switching loss despite their high frequency [69]. Another feature of this device is that by implementing a few elements, it considerably reduces the weight and temperature of the device, significantly reducing both thermal and conversion losses in the system [70]. Efficiency trade-offs are linked to the operation point: when the switching frequency deviates significantly from resonance, circulating currents increase, leading to higher conduction losses and reduced efficiency. For this reason, careful selection of the quality factor, magnetizing-to-resonant inductance ratio, and switching frequency margin is critical. Typical designs aim for factor quality values between 0.5 and 1.0 to balance efficiency, voltage gain range, and load regulation capability [71].

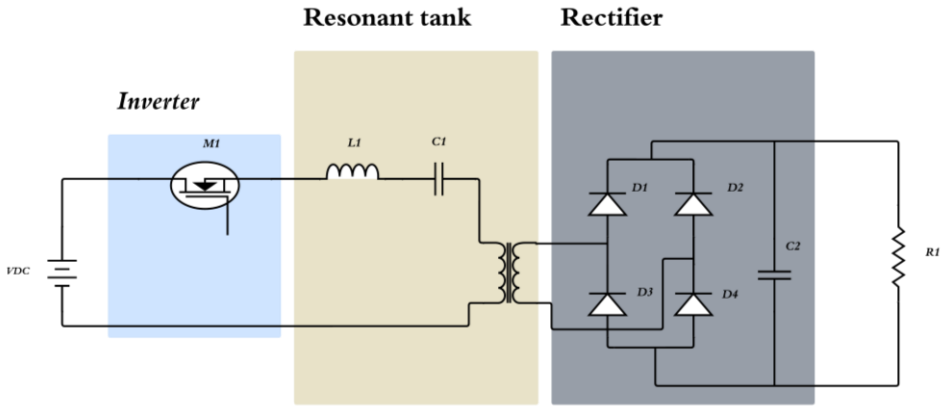


Figure 14. Resonant converter.

In fast-charging applications, the LLC converter achieves peak efficiencies of 96–98% with SiC MOSFETs, even under wide input ranges. Thermal management is simplified by the reduced switching losses, though designers must mitigate transformer parasitic losses and ensure robust control under light-load conditions where ZVS may be lost. To address this, digital control schemes and adaptive frequency modulation strategies are frequently implemented, improving transient response and extending the ZVS region [72].

3.1.5. Half-Bridge Converter

The half-bridge topology (Figure 15) is widely used in medium-power isolated resonant converters, especially in onboard chargers for EV and plug-in hybrids. This converter consists of two switches in series, the midpoint of which is connected to a resonant circuit

commonly consisting of a magnetizing inductor, a series inductor, and a capacitor. This tank is connected to an isolation transformer that adjusts the voltage level to the battery [71]. The half-bridge converter is further optimized by using silicon carbide material, which can alleviate pulse current oversaturation, as the modeling of semiconductor components is better due to its characteristics [73].

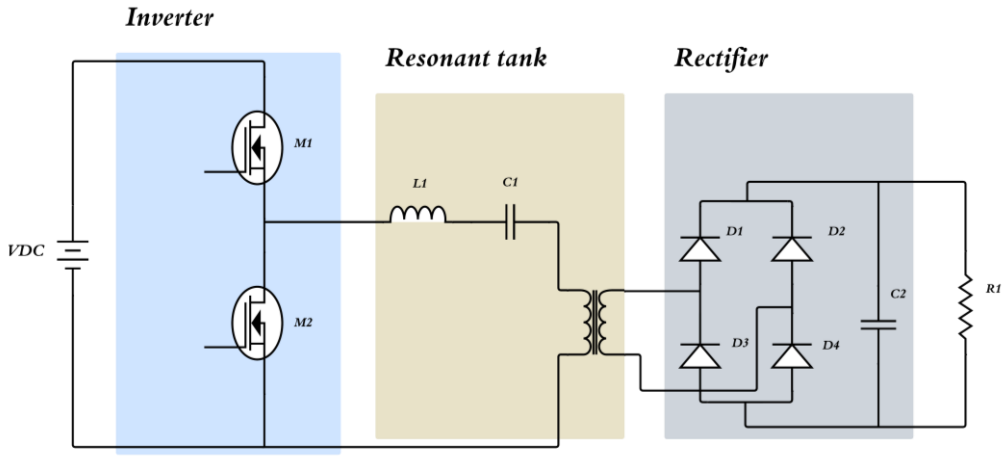


Figure 15. Half bridge converter.

With the integration of wide-bandgap semiconductors, switching frequencies between 100 and 300 kHz are achievable, supporting high power density and compact magnetics.

Efficiency values typically exceed 95% in experimental OBC prototypes, with optimized designs reaching 96–97%. The trade-offs involve limited output power capability compared to full-bridge structures, since only half of the DC-link voltage is effectively utilized across the transformer. In addition, careful design of the DC-link capacitors and balancing mechanisms is necessary to avoid midpoint voltage drift. Despite these limitations, half-bridge converters remain attractive for compact designs where cost, reduced device stress, and EMI performance are critical [74]. This topology also minimizes electromagnetic noise, improves component lifespan, and allows for more compact and lightweight designs, which is key in embedded applications.

3.1.6. Full Bridge Converter

This is an expanded version for higher power applications, such as fast charging stations over 20 kW, even reaching configurations above 150 kW in three-phase systems. In this design, four switches form an H-bridge that symmetrically feeds the resonant tank and transformer, generating an alternating signal with greater amplitude and symmetry, which improves power control and energy transfer [75].

Like the half-bridge, it operates with variable frequency modulation but has the additional advantage of being compatible with phase shift modulation. This technique extends the ZVS range, especially under partial load conditions, further reducing energy losses [76]. In addition, it allows for greater granularity in the control of the power delivered, which is essential to meet the fast-changing requirements of multiple types of batteries. Thanks to its high efficiency, which exceeds 95%, this topology has become one of the most reliable for modern EV fast charging stations.

At present, the implementation process remains unclear, and only a comparative assessment of certain topologies is available, with further ambiguity introduced by the existence of a functional prototype device. Typical design parameters include switching frequencies in the range of 50–200 kHz for high-power modules, with SiC MOSFETs enabling operation toward the upper end of this spectrum. Reported efficiencies exceed

95%, with state-of-the-art implementations achieving 96–98% in commercial fast-charging stations. The trade-offs include higher circulating currents when operating far from resonance and increased complexity in thermal management [77]. However, the benefits of high scalability, efficiency, and robust control make the full-bridge converter the dominant topology for high-power isolated DC/DC conversion in modern EV fast charging stations (Figure 16) [78].

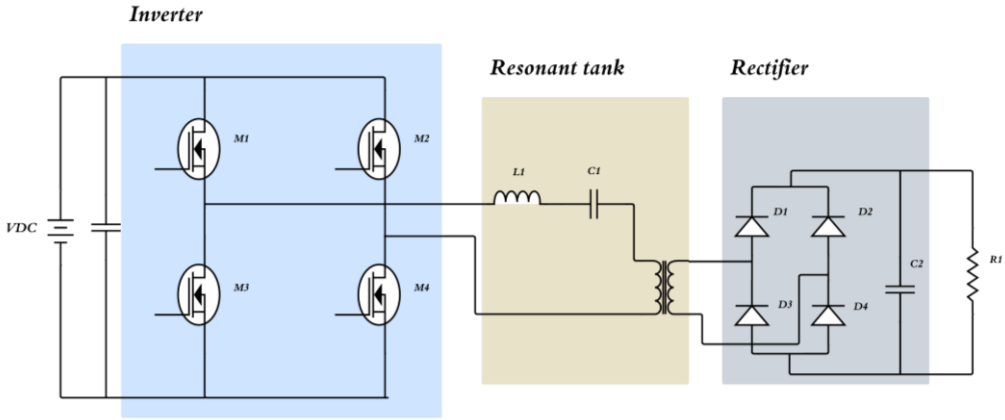


Figure 16. Full bridge converter.

3.1.7. Multilevel Converter

Multilevel converters (Figure 17) have emerged as an attractive alternative in fast-charging applications for EV, as they enable operation at high voltages and significant power levels while maintaining high efficiency and reducing electrical stress on the semiconductors. As is well known and as highlighted in the description of the previously discussed converters, the semiconductors required to achieve fast-charging stages with nominal ratings of around 50 kW demand specialized devices, since conventional MOSFETs would not withstand the current peaks caused by switching. Unlike conventional two-level converters, multilevel architectures split the DC-link voltage into multiple intermediate levels, thereby reducing the blocking voltage of each switch and, consequently, both switching and conduction losses. These characteristics enable the use of lower-voltage devices with improved dynamic performance and reduced cooling requirements, while also allowing for the design of more compact filters due to the higher effective frequency of switching harmonics [79].

At the same time, these converters have become a consolidated solution in high-power applications, as they allow for the combination of different topologies in configurations that distribute electrical demands across multiple conversion stages, typically arranged in parallel or modular operation. This approach reduces the voltage stress on each semiconductor, improves loss distribution, and facilitates the use of more compact filters. A key strategy in such architectures is the use of operating modes that ensure the natural balancing of voltages in the DC-link buses, thereby eliminating the need for additional circuits or complex control loops to equalize the intermediate capacitors. In this way, one of the main historical limitations of multilevel topologies is overcome, offering simpler control, improved robustness, and higher efficiency in large-scale power conversion systems [80].

Recent advances have gone beyond the traditional neutral-point-clamped and flying capacitor topologies. A notable development is the PEC converter topology (Figure 18), which combines modularity, scalability, and enhanced voltage balancing capabilities. This architecture integrates multiple E-Cells in a compact arrangement, enabling operation at medium- and high-voltage levels with improved efficiency and simplified control. Unlike conventional modular multilevel converters, the PEC structure naturally balances capacitor

voltages and reduces the number of bulky passive components, thus lowering system volume and cost. Furthermore, its compatibility with advanced digital control strategies, such as model predictive and adaptive modulation techniques, makes it highly suitable for high-power applications, including EV fast charging [81].

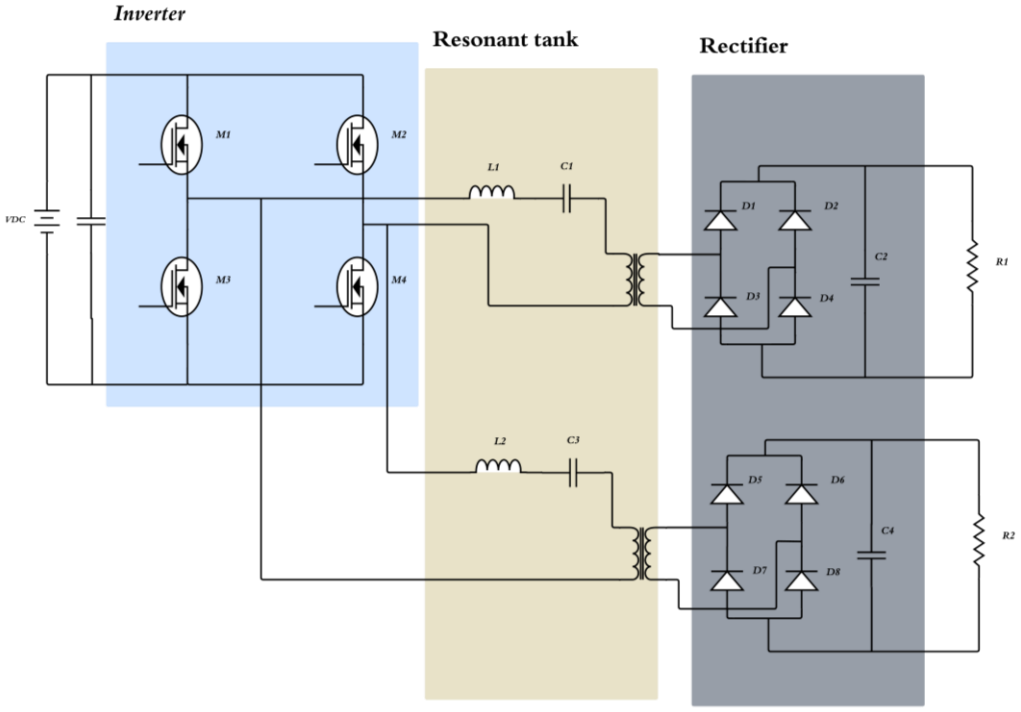


Figure 17. LLC Multilevel converter.

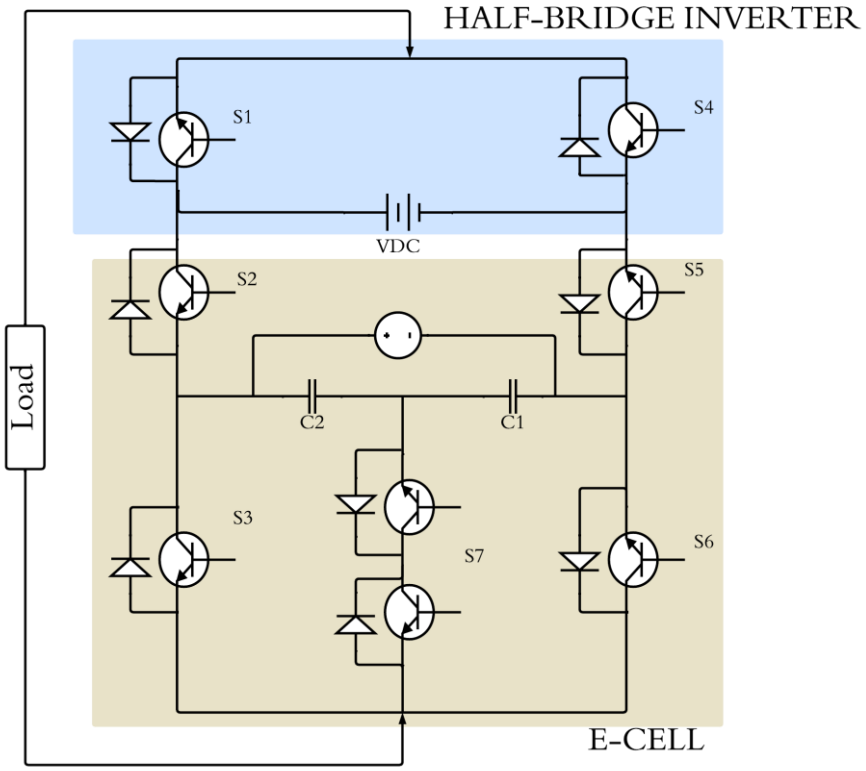


Figure 18. Packed E-Cell converter.

Table 6. Comparative Analysis of Literature on the Design and Simulation of Fast Charging Stations for Electric Vehicles.

Ref.	Year	Voltage (V)	Current (A)	Power (kW)	Efficiency (%)	Architecture	Protocol	Design
[82]	2013	390	66	25	95	HPFC	-	Prototype
[83]	2014	320	6.28	2.1	92	FBD	-	Simulation
[84]	2017	220	13.5	3	93.1	PFC	Plug in	Prototype
[85]	2017	380	132	50	94	-	CHAdeMO	Prototype
[86]	2018	700	22	15	96	spo2LB6		Prototype
[87]	2018	277	-	80	-	G2V	J2894	Simulation
[88]	2018	400	150	-	90	LLC	-	Prototype
[89]	2019	200	20	4	94	SST	CCS	Prototype
[90]	2019	500	300	150	-	P2P	-	Simulation
[91]	2019	800	6	4.6	-	PFC	CHAdeMO	Simulation
[92]	2019	310	30	1.5	96.4	LLC	-	Prototype
[91]	2019	800	24	3.6		PFC	-	Simulation
[55]	2019	100	-	15	-	Boost	-	Prototype
[93]	2020	48	12	1.5	90	Buck	-	Prototype
[94]	2020	400	-	3.6	95	LLC	-	Simulation
[95]	2020	400	12.5	15	94	Buck	-	Simulation
[96]	2021	240	18.8	4.5	98.6	2LB6	CCS	Prototype
[55]	2021	400	-	5	-	2LB6	CCS	Prototype
[97]	2021	230	14	3	80	-	Plug in	Prototype
[98]	2021	220	27	6	-	G2V	-	-
[99]	2023	230	16	3.6	-	V2H	-	-

A general principle of operation in multilevel converters can be expressed by the state equation governing the inductor current in terms of the applied switching states.

$$L\frac{di_L}{dt} = V_{dc}m(t) - v_0(t)$$

where L is the filter inductance, V_{dc} is the total DC-Link voltage, $m(t)$ is the modulation function that determines the instantaneous voltage level applied by the multilevel structure, and $v_0(t)$ is the output voltage across the load. This equation highlights how multilevel converters regulate energy transfer by distributing the DC-link voltage across multiple intermediate levels. As a result, each semiconductor device experiences reduced voltage stress, switching and conduction losses are minimized, and the effective switching frequency is increased, leading to higher efficiency, simplified filtering requirements, and enhanced dynamic performance in fast-charging applications.

4. Results

Today, fast charging devices for EVs are considered new technologies that are still in the improvement stage. Currently, there are different variants of devices. Below is a comparative table of the characteristics shared by the various types of charging devices.

The absence of standardized criteria for evaluating and reporting fast charging technologies. Addressing this gap will require the development of clear benchmarking frameworks to enable consistent and meaningful comparisons between emerging designs and established products. Encouragingly, both sectors are moving in the same direction—toward more compact, efficient, and powerful systems—thanks in part to the growing use of wide-bandgap semiconductors like SiC and GaN and the adoption of high-performance topologies such as the full-bridge resonant converter. Table 6 provides a comparative analysis of the power converter designs used in electric vehicle charging proposed in the literature.

By analyzing the data presented in the table, several key observations can be made. In terms of topology development, there is a clear trend among authors toward multilevel topologies, primarily because they can handle high electrical variables more efficiently, making them particularly suitable for fast and ultra-fast charging applications. For instance, topologies such as 2LB6 demonstrate excellent performance, with efficiencies consistently exceeding 96%. In contrast, simpler topologies like LLC or buck converters face significant limitations in achieving high power levels. While they may be easier to implement, their power capacity is generally restricted, with buck converters typically reaching only around 1.5 kW. As a result, they are less favorable for the development of power converters aimed at electric vehicle charging, especially in the context of high-power applications.

In reviewing the literature, numerous prototypes proposed by users can be observed, due to the fact that years ago, there was a need to work with energy efficiency in the field of electric vehicle charging. There are multiple papers describing the processes and detailing the electrical variables of the same designs, establishing the importance of using multilevel topologies associated with power converters used in the design of charging stations, where the main objective is to find a balance between the robustness of the components and stable usage characteristics. It is important to clarify that in the search for information and the designs proposed in papers, there is a significant bias in the information, which is clearly evident in the development of the table.

5. Conclusions

A comparative analysis of commercial fast charging solutions and prototype systems currently under academic investigation reveals notable differences in both technical attributes and development maturity. Commercial chargers today typically present well-established specifications—such as output voltage, rated current, delivered power, and efficiency—with most exceeding 90% efficiency. This reflects a high level of technological refinement and adherence to industrial standards.

On the other hand, many of the prototypes found in the literature bring forward promising innovations in architecture and design, including LLC resonant converters, bidirectional buck-boost topologies, solid-state transformers, and other advanced configurations. However, these experimental systems often lack detailed technical data. Key parameters like communication protocols, power ratings, and efficiency figures are frequently omitted or vaguely reported, making it difficult to compare them with commercially deployed systems directly.

To bridge this gap, future academic work should adopt standardized reporting practices aligned with those used in the commercial sector. At a minimum, prototypes should consistently include specifications such as rated power, efficiency under different load conditions, supported voltage and current ranges, and communication protocol compatibility. Clear disclosure of these parameters would enable meaningful benchmarking across different designs and facilitate a more objective assessment of their potential for commercialization. Establishing such standards in academic reporting will not only improve the comparability of research outcomes but also accelerate the transfer of innovative topologies—such as resonant, bidirectional, or multilevel architectures—into industrial practice.

Synthesis

This paper adopts a descriptive and technical perspective to examine the assembly and operation of different fast-charging topologies, with particular emphasis on cascade and bidirectional designs.

A review of scientific journals reveals a bias in the information depending on the authors and publications. This is largely due to the lack of general standardization in how

circuit designs are documented, specifically regarding the level of detail provided. From a structured perspective, when presenting results, authors should report all the variables that a power converter can generate. At present, however, many focus only on output variables and highlight efficiency metrics without explaining how the converter develops and performs across its multiple stages.

Our goal is to support the advancement of a smart, scalable, and energy-efficient charging infrastructure that can keep pace with the accelerating adoption of electric vehicles. Although energy efficiency has improved significantly and is no longer the primary barrier, critical challenges remain, particularly the limited availability of charging stations and the need for seamless integration with the power grid. Addressing these issues is essential to ensure the sustainable growth of electromobility. While several commercial fast-charging solutions are already available, their large-scale deployment and accessibility are still constrained, underscoring the importance of coordinated efforts in infrastructure planning, standardization, and grid compatibility.

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Nomenclature

kW	Kilowatt
h	Hours
V	Volt
A	Ampere
Hz	Hertz
kWh	Kilowatt-hour
AC	Alternating Current
DC	Direct Current
J2894	Wireless Power Transfer for Light-Duty Plug-In Vehicles
CCS	Combined Charging System
CHAdeMO	Charge de Move
PSBC	Power Supply and Battery Charger
EV	Electric Vehicle
2LB6	Two-Level-Based Six
V2H	Vehicle-to-Home
PFC	Power Factor Correction
SST	Solid-State Transformer
G2V	Grid-to-Vehicle
P2P	Peer-to-Peer
HPFC	High Power Factor Correction

TLB	Two-Level Bridge
CMM	Current Mode Control
DCM	Discontinuous Conduction Mode
LLC	LLC Resonant Converter
SiC	Silicon Carbide (Wide Bandgap Semiconductor)
GaN	Gallium Nitride (Wide Bandgap Semiconductor)
Pb-acid	Lead-Acid
Ni-Cd	Nickel-Cadmium
NiMH	Nickel-Metal Hydride
Li-ion	Lithium-Ion
Na-NiCl	Sodium-Nickel-Chloride
LFP	Lithium Iron Phosphate
LMR	Lithium-Manganese-Rich
NCA	Nickel-Cobalt-Aluminum
NCM811	Nickel-Cobalt-Manganese (8-1-1 ratio)
NCM/NMC	Nickel-Cobalt-Manganese
NCMA	Nickel-Cobalt-Manganese-Aluminum
PEC	Packed E-Cell
MOSFETs	Metal Oxide Semiconductor Field Effect Transistor
OBC	On-Board Charger
EMI	Electromagnetic Interference
ZVS	Zero Voltage Switching

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