The Path to Global Interoperability: Evaluating IEC 62196 and NACS as Solutions to the Fragmentation of Electric Vehicle Charging Standards

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Abstract

As electric vehicle (EV) adoption continues to increase worldwide, differences among charging standards remain a major obstacle to widespread adoption. The absence of a unified charging protocol. In their stead, a handful of competing charging standards have emerged on the market, namely Combined Charging System, the first and foremost fast-charging standard for electric vehicles (EVs) introduced in Japan in 2010 (CHAdeMO), and the North American Charging Standard (NACS) of the Tesla corporation.

This paper proposes a concept called the Universal Converter, a smart adapter that helps electric vehicles and charging stations with different charging standards work together.

Based on the reviewed literature, this paper concludes that achieving global interoperability will require both standardized hardware and compatible communication protocols. The proposed Universal Converter is presented as a conceptual solution that could bridge existing charging standards without requiring immediate replacement of current infrastructure.

Introduction

Along with the rapid growth of EV usage, the issue that constantly emerges pertains to the lack of compliance with universal standards of charging by manufacturers. For instance, Combined Charging System (CCS), representing the innovative DC fast-charging standard for EVs, was created in Japan in 2010 as CHAdeMO (Combined High-power AC/DC Charger), and NACS, introduced by Tesla, have different structures and functions, as well as means of communicating with vehicles (NIST, 2022; IEEE Access, 2023; Energy Reports, 2020).

Such problems inevitably bring about some disadvantages when it comes to regions where charging stations are not numerous. Thereby, people tend to be less inclined to buy new automobiles and travel long distances due to the risk associated with incompatibility with their EVs. It is crucial to achieve interoperability between various types of charging systems (NIST, 2022; IEA, 2023; World Electric Vehicle Journal, 2024).

A universal plug will facilitate convenience in everyday life. People won't have to stockpile adapters and plan trips around particular plug types. It will be convenient and available, just like fueling a gas car anywhere. Standardizing will also increase trust, decrease confusion for first-time EV users, and speed up the transition process (NIST, 2022; Batteries, 2025; IEA, 2023).

The market for EVs is expanding rapidly. By 2024, EVs will account for 22% of all car sales worldwide compared to only three percent five years ago. That same year, China's EV sales will reach 11.3 million units. There is still growing interest in EVs in the US, with 20% of prospective customers considering purchasing one. With increasing numbers of EVs entering people's daily lives, charging will become more frequent. However, many users still face problems with different plug types, confusing station arrangements, and incompatible stations (IEA, 2023; World Electric Vehicle Journal, 2024).

Public charging reliability is only 78%, meaning one in five charging attempts fails. The U.S. has just 3,200 DC fast chargers compared to one million gasoline pumps. Surveys show that one in three EV drivers has experienced charging failure, and 60% of non-EV owners cite charging inconvenience as a major barrier (NIST, 2022; IEA, 2023; Batteries, 2025).

This is precisely the rationale behind the increasing relevance of the idea of a universal charger, like the USB-C plug. An example of such an upcoming contender is IEC Standard 62196. This can facilitate easy, cheap, and standardized charging (NIST, 2022; IEEE Access, 2023; Batteries, 2025).

Fragmentation still exists because each group creates its own infrastructure. There are certain charging stations built specifically for particular brand cars. The same situation applies to firms working in this area; they have already established their own infrastructures, which might not necessarily be compatible with those developed by others. There is also the issue of different standards in different countries and different software used by cars and charging stations. Creating all these into one will involve very expensive improvements, something that most people will be deterred from doing. To avoid the difficulty of forcing one global plug standard, this paper suggests another solution: a Universal Converter. This is a smart device that acts as both a physical adapter and a communication translator. It uses the structure of IEC 62196 and software that can convert different communication systems. This allows different EVs and chargers to work together without companies needing to replace their existing equipment.

Literature Review

How Interoperability Can Be Achieved

The absence of a universal plug is a problem already noticed many times in the process of using electric cars and serves as one of the significant barriers on the path towards implementation. Interface compatibility is important in this case because it eliminates technical issues and allows for charging an electric car anywhere. At present, all firms utilize different technologies for charging electric cars and cannot charge at stations or from other sources of power supply. There is no doubt that the absence of common standards will cause confusion and problems when building infrastructure.

Several studies indicate that automakers are gradually adopting common charging systems. While the IEA (2023) focuses on industry collaboration, Batteries (2025) argues that hardware standardization alone is insufficient unless communication protocols are also standardized. Together, these studies suggest that interoperability depends on both physical and software compatibility.

But interoperability involves something beyond the collaboration between carmakers. Government agencies, enterprises, and technical experts have to cooperate in establishing common standards. Common standards must be established both for physical connections and communication protocols in order to make EV charging as easy as plugging in a phone charger. Coordination is necessary between policy-makers and industries in order for this to occur.

As stated by NIST, there isn't any industry consensus either on the hardware or the software. Different manufacturing companies use different connectors, communication protocols, and safety standards. Upgrading the existing infrastructure requires huge amounts of money, and corporations are unwilling to lose what they've already invested. This is why fragmentation persists. Consequently, current literature reveals a major gap: while automakers are attempting to compromise on physical plug shapes on a regional scale, the underlying software communication barriers remain unaddressed. Relying on static, passive plastic adapters is insufficient due to protocol mismatches. Therefore, what is required is a shift in focus away from corporate consensus, towards developing an active, intelligent universal converter capable of bridging disparate hardware and software ecosystems simultaneously.

Methodology

The methodology of qualitative literature review is used in the research. Peer-reviewed scientific journals, government reports, and international standards documents are selected as sources of data due to the information about the charging standards and interoperability of electric vehicles contained in them. The comparison of information collected from the sources is performed for the purpose of identifying similarities, discrepancies between charging standards and proposed solutions by authors. No new experiments and data were collected. IEEE Access (Acharige et al., 2023); Energy Reports (Alam et al., 2020); Batteries (Memon & Rossi, 2025); NIST report (2022); and IEA report (2023).

In the context of this research, the main focus of the current literature review will be the comparison of the architecture of CCS, CHADEMO, NACS, and IEC 62196 Type 2 charging stations and their differences that will influence interoperability of EVs worldwide. The technical specifications, information protocol, voltage, and regional discrepancies will be compared (IEEE Access, 2023; Renewable & Sustainable Energy Reviews, 2021).

Finally, government and manufacturer policies as well as case studies will be analyzed in order to understand how it can be possible to integrate these disjoint standards. As a result, the necessary obstacles towards EV charge station compatibility will be determined, the existing approaches for addressing this problem will be assessed, and a universal standard will be created. This standard will then be applied in developing and analyzing a design framework for Universal Converter. The proposed solution will be analyzed along two key dimensions: (1) Hardware Interoperability (pin-mapping of pins in CCS, NACS, and IEC 62196) and (2) Software Compatibility (real-time conversion of communication protocols). The design will be assessed based on hardware and software, as well as international cooperation aspects (NIST, 2022; IEA, 2023).

Because this study relies on external data, it cannot independently verify technical claims such as thermal failure points of third-party adapters. (General methodological note — no citation needed).

Discussion

The diversity of standards adopted across different countries when it comes to charging electric vehicles affects the ecosystem negatively. Although there is a tendency to adopt NACS among the U.S. manufacturers of electric vehicles, this solution still will not address the question of compatibility of chargers on a global basis. Thus, the adoption of NACS is likely to lead to even greater fragmentation as international collaboration in this area is currently absent. Therefore, a new strategy is needed to find an effective solution. The reviewed literature suggests that improving interoperability requires more than selecting one connector type. Successful charging also depends on communication between the vehicle and charging station, meaning both hardware and software compatibility must be considered together (NIST, 2022; IEA, 2023; IEEE Access, 2023).

As soon as a universal plug is introduced, people using electric vehicles will have a uniform experience when it comes to recharging their vehicles. Such a plug needs to be compatible with current and future charging points, allow for fast charging, and be accepted internationally. The best choice in this case seems to be the standard IEC 62196, which, however, needs to be supplemented with some communication software (NIST, 2022; Batteries, 2025; IEEE Access, 2023).

There are several problems in the existing system. For instance, a European driver who uses a Type 2 connector plug cannot connect a vehicle to a U.S. Type 1 cable, despite the two being part of the IEC 62196 group of standards. The above scenario implies that hardware standardization should be coupled with software standardization.

The adoption of a universal plug would make owning EVs convenient, cut down the cost of production, and enable governments to set up their charging stations easily. Besides, such an innovation would facilitate smart-charging management, uniform safety standards, and consistent EV performance within different regions. According to NIST (2022), interoperability is necessary for incorporating EVs into national and international energy networks.

According to research published by IEEE Access in 2023, standardization will lead to savings in infrastructure redundancy. The International Energy Agency (IEA) reported in 2025 that standardization has already led to a 20% rise in ultra-fast charging products. Europe's AFIR directive illustrates the impact of a global standard on governments' ability to expand infrastructure, guaranteeing high-power charging every 60 kilometers. Instead of waiting for governments and companies to agree on one universal plug, another solution is possible: a Universal Converter. This is not just a simple plastic adapter. It must be a smart device that includes both hardware and software. It acts as a physical connection between chargers and also uses small computer chips (microcontrollers) to translate communication between systems. The hardware part of the Universal Converter is based on the IEC 62196 Type 2 design because it already works well with many charging systems. Since NACS is common in the United States and CCS is more common in Europe, the Universal Converter acts as a physical bridge between these systems. It allows electricity to safely pass between different plug types using a secure locking connector system. Even if plugs match, charging will not work if the car and charger cannot communicate. Different systems, like Tesla chargers and CCS chargers, use different communication languages. The Universal Converter solves this problem by using a built-in chip that translates these messages in real time. It reads the communication from the car (such as ISO 15118) and converts it into a format that the charging station understands, such as DIN 70121 or Tesla's system.

In the end, cooperation between companies, governments, and industries is still important to create a charging system that works for all electric vehicles (NIST, 2022; IEA, 2023; Renewable & Sustainable Energy Reviews, 2021).

- Work with both existing and future stations
- Support fast charging
- Be accepted globally

IEC 62196 meets many of these requirements, but software alignment is equally important. Without unified communication protocols, even identical plugs may fail to charge *(NIST, 2022; IEC 62196; IEEE Access, 2023).*

If governments, automakers, and charging providers work together, EV charging can become simple, universal, and accessible, benefiting drivers and the planet *(NIST, 2022; IEA, 2023; Batteries, 2025).*

Comparison of Major EV Charging Standards (Letter-Size Friendly)

Standard	Main Regions	Connector Design	Max Charging Speed	Interoperability	Key Limitation
CCS	Europe, North America	Large	Up to ~350 kW (DC)	Moderate	Bulky; Tesla requires an adapter
CHAdeMO	Japan	Largeround	Up to ~400 kW (newer versions)	Low	Limited adoption outside Japan
NACS (Tesla)	United States	Small, compact	Up to ~250+ kW	Moderate (U.S.-focused)	Not globally standardized
IEC 62196 (Type 2)	Europe (global framework)	Medium	AC & DC supported	High	Requires global adoption

Table 1 - Demonstrates an extensive comparison of global electric vehicle charger standards, which highlights the regions dominated by them, their respective connector specifications, maximum rates of charge, and other logistical limitations that come with the CCS, CHAdeMO, NACS, and IEC 62196 (Type 2) chargers.

Key to Colomum interoperability

- ease with which various EV manufacturers will be able to utilize that charge standard without using adapters, specialized applications, or restricted network access.
- Thus:
- High – applies to most vehicles and chargers in that particular area
- Medium – applies to many, but not all (may require adapters or have restrictions)
- Low – only applicable to a few select vehicles or networks (IEEE Access, 2023; Batteries, 2025; Energy Reports, 2020).

Conclusion

The development of electric vehicles has a significant impact on mobility. However, it may be difficult to charge them. There are numerous electric vehicle standards, including the CCS standard, NACS, and CHAdeMO standards. This makes the procedure rather complicated, particularly for developing nations. Although IEC 62196 and the NACS standard offered by Tesla are examples of tackling the problem, it seems impossible to achieve a universal standard. Consequently, the following research question can be asked: This review examined how differences among EV charging standards affect global interoperability and explored what a universal charging solution could look like. Hence, the principal aim of the paper is to determine a universal plug and software that would allow all electric cars to communicate with any charger across the globe (World Electric Vehicle Journal, 2024; NIST, 2022; IEEE Access, 2023).

It is necessary to establish a universal standard for charging electric vehicles as they become increasingly popular. In addition to having several benefits compared to conventional automobiles, such as positive effects on the environment and sustainability, electric cars cannot develop due to diverse charging standards adopted by various firms. Furthermore, every charger requires a specific plug, which adds to the complexity of the situation (IEA, 2023; Batteries, 2025; Renewable & Sustainable Energy Reviews, 2021).

Future developments in EV charging should focus on both hardware compatibility and communication standards. Although achieving a single global charging connector may take many years, improving interoperability through standardized communication protocols and conceptual solutions such as the proposed Universal Converter could make charging more accessible for drivers worldwide (IEA, 2023; NIST, 2022; IEEE Access, 2023; Batteries, 2025).

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