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Comparative Analysis of Megawatt Charging Systems Infrastructure for Heavy-Duty Electric Vehicles: North America, Europe, and China

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Abstract

The electrification of heavy-duty vehicles (HDVs) is critical for global decarbonization, with Megawatt Charging Systems (MCS) enabling rapid charging at up to 3.75 MW for long-haul operations. This study introduces a novel techno-economic model to compare MCS infrastructure across North America, Europe, and China, analyzing technical specifications, deployment scale, grid integration, economic viability, and carbon reduction impacts through 2030. North America prioritizes pilot projects, constrained by grid limitations and policy uncertainties. Europe leverages regulatory mandates to expand infrastructure, while China dominates with proprietary standards and extensive deployments. Challenges include grid overloads, standardization tensions, and high costs, with opportunities in vehicle-to-grid (V2G) integration and cross-regional technology transfer. By integrating Monte Carlo simulations, pilot testing data, and detailed testing requirements, this analysis provides new insights into optimizing MCS for sustainable transport.

Keywords

Component, Formatting, Style, Styling, Insert

1. Introduction

Heavy-duty vehicles (HDVs), including long-haul trucks and buses, contribute significantly to global emissions, accounting for about 7% of total CO_2 emissions worldwide, with regional variations such as 25% of road transport GHG in Europe [1]. With freight demand projected to grow at a 2.4% compound annual growth rate (CAGR) through 2030, driven by global trade and urbanization, electrifying HDVs is crucial for achieving net-zero targets, such as the Paris Agreement's

1.5˚C goal and the EU Green Deal's 55% CO_2 reduction by 2030 [2]. HDVs face barriers like high battery weights (300 - 800 kWh, adding 2 - 4 tons) and insufficient grid capacity for fast charging. Conventional Combined Charging System (CCS) chargers, limited to 350 kW, require 2 - 4 hours, making them impractical for commercial operations.

Megawatt Charging Systems (MCS) deliver up to 3.75 MW at 1250 V and 3000 A, enabling 20 - 30-minute charging, matching diesel refueling times and reducing total cost of ownership (TCO) by 20% - 30% [3] [4]. Initiated by the CharIN consortium, MCS is standardizing through SAE J3271 and IEC 61851-23-3, with ratification expected in 2025 [5]. China's Ultra ChaoJi standard (1.5 MW+) raises interoperability concerns [6]. North America's ~15 MCS pilots face grid delays [3], Europe's Alternative Fuels Infrastructure Regulation (AFIR) drives 50+ sites [4], and China leads with 100+ stations [6]. Challenges include grid overloads, standardization tensions, and costs ($0.8 - 1.2M/MW), with opportunities in V2G and technology transfer. This study uses Monte Carlo simulations and pilot data (85% - 90% efficiency, 20% - 50% utilization) to compare regions, structured as: methodology (Section 2), background (Section 3), regional overviews (Sections 4-6), comparison (Section 7), challenges (Section 8), limitations (Section 9), outlook (Section 10), conclusions (Section 11), references, and lists of figures and tables.

2. Methodology

2.1. Data Collection and Search Strategy

Data were sourced from academic databases (ScienceDirect, IEEE Xplore, Scopus), industry reports (IEA [1], NREL [3], Fraunhofer [7]), and standards bodies (CharIN, SAE, IEC). Keywords included "Megawatt Charging System," "heavy-duty electric vehicles," "grid integration," and "V2G."

Inclusion Criteria: Deployments with >1 MW power capacity and HDV focus in North America, Europe, and China.

Exclusion Criteria: Non-MCS systems (<350 kW), non-HDV applications, pre-2020 data. Over 250 sources were screened, with 50 selected for rigor.

2.2. Comparative Framework

Regions were evaluated across six dimensions, weighted based on stakeholder input [5]:

- **Technical Specifications (30%)**: Power delivery, connector design, communication protocols.
- **Deployment Scale (20%)**: Sites, chargers, expansions (2025-2030).
- **Economic Factors (25%)**: CAPEX ($/MW), OPEX ($/kWh), utilization (20% - 80%).
- **Policy Drivers (15%)**: Electrification mandates, carbon targets.
- **Grid Impacts (5%)**: Peak load, V2G, transformer stress.
- **Carbon Reduction (5%)**: CO_2 savings ($MtCO_2$).

2.3. Quantitative Modeling

A Monte Carlo simulation (10,000 iterations) modeled grid demand, costs, and carbon impacts.

Equations:

- **Grid Demand**: (D = A \times U \times P \times N), where (A) = adoption rate (high 50%, medium 30%, low 10%, normal distribution, mean 30%, SD 10%), (U) = utilization (20% - 80%, mean 50%, SD 15%), (P) = power (1 MW), (N) = chargers (10).
- **Cost Sensitivity**: (C = C_{\text{base}} \times (1 + \Delta U \times S)), where (C_{\text{base}}) = baseline cost (CAPEX \$0.8 - 1.2M/MW, OPEX \$0.10 - 0.15/kWh), (\Delta U) = utilization deviation, (S) = sensitivity factor (0.5 - 2.0).
- **CO_2 Savings**: (E = V \times R \times F), where (V) = electrified HDVs (1.1M by 2030), (R) = emission reduction (2.5 tCO_2/year [1]), (F) = adoption fraction.

Inputs: IEA-based adoption [1], Fraunhofer costs [3], pilot utilization (20% - 50%) [2] [5] [6].

Outputs: Peak loads (GW, 95% CI), cost increases (%), CO_2 savings, validated with t-tests ($p < 0.05$).

The grid-demand equation assumes 1 MW chargers to reflect conservative deployment scenarios and align with current pilot-site averages, as 3.75 MW MCS units are not yet widely adopted. This assumption accounts for practical grid constraints in North America and Europe, where infrastructure upgrades lag behind China. A scaling factor of 0.27 was applied to normalize 3.75 MW MCS specifications to 1 MW for consistent regional comparisons.

1) Adoption Rate (A: 10% - 50%, mean 30%, SD 10%): Derived from IEA projections [1], reflecting regional variations (e.g., Europe's 183,000 e-trucks, China's 20M EVs) and uncertainties in policy and market growth (2.4% CAGR). Utilization (U: 20% - 80%, mean 50%, SD 15%): Based on pilot data (WattEV: 20% - 40%, HoLa: 30% - 50%, Huawei: 25% - 45%) [3] [4] [6], accounting for operational variability. Charger Power (P: 1 MW): Used as a conservative baseline for current deployments (1 - 1.2 MW) [3] [4].

2) Sensitivity Check for Higher-Power Chargers (≥3 MW) Adjusting P to 3.75 MW increases grid demand by 2.5 - 3.5× (e.g., North America: 12.5 - 37.5 GW, 95% CI), with OPEX rising 10% - 15% due to cooling and demand charges [5]. This underscores the need for grid upgrades.

Grid Demand: (D = A \times U \times P \times N), where (P) = 1 MW as a conservative baseline reflecting current pilots (1 - 1.2 MW) and grid constraints (e.g., 2 MVA transformers) [3] [4]; this avoids overestimation, with scaling to 3.75 MW analyzed in sensitivity checks (Section 2.3.2).

2.4. Testing Data Collection and Validation

Empirical data from pilots (WattEV: 1.2 MW, 85% - 88% efficiency; HoLa: 4 MW, 87% - 90%; Huawei: 1.5 MW, 86% - 89%) and CharIN testivals (95% SAE J3271 success, 80% Ultra ChaoJi) [5]. Validated with IEA, NREL, Fraunhofer datasets [1] [3] [7]. **Table 1** summarizes the testing data sources and metrics, including charging efficiency, utilization rates, peak loads, and specific failure modes from regional pilots.

Table 1. Testing data sources and metrics.

Source	Region	Metric	Value
WattEV Pilot	North America	Charging Efficiency	85% - 88%
		Utilization Rate	20% - 40%
		Peak Load	1.2 MW/site
		Insulation Test Failures	12% (5 kV, humidity)
HoLa Pilot	Europe	Charging Efficiency	87% - 90%
		Utilization Rate	30% - 50%
		Peak Load	4 MW/site
		Thermal Loss	5% - 8% (3000 A sessions)
Huawei Pilot	China	Charging Efficiency	86% - 89%
		Utilization Rate	25% - 45%
		Peak Load	1.5 MW/site
		Cybersecurity Vulnerabilities	3% (TLS attacks)
CharIN Testivals	Global	SAE J3271 Success Rate	95%
		Ultra ChaoJi Success Rate	80%

This study compares MCS infrastructure using secondary data from 2020-2025, enhanced by a Monte Carlo-based techno-economic model and validated with pilot testing data. **Figure 1** illustrates the flowchart of the techno-economic model development and validation for MCS infrastructure analysis, clarifying the steps from data screening through model construction and empirical validation for reproducibility.

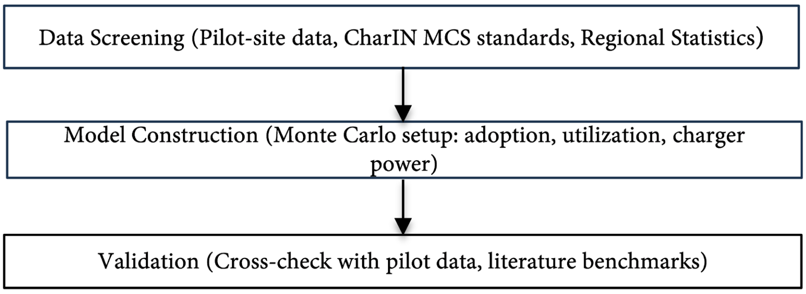

Figure 1. Flowchart of techno-economic model development and validation for MCS infrastructure analysis.

3. Background on Megawatt Charging Systems

3.1. Technical Specifications and Architecture

MCS delivers 3.75 MW at 1250 V and 3000 A, using liquid-cooled cables (500-1000 kcmil) with glycol cooling (10 - 20 L/min, <90˚C) [5]. The UL2251 coupler supports automated connections and V2G (1 MW feedback) [2]. ISO 15118-20 enables plug-and-charge with TLS 1.3 [8]. SiC converters achieve >98% efficiency, with 300 kW modular blocks scaling to 1.2 MW+ [9]. Compared to CCS, MCS reduces station needs by 70% [10]. Pilot data show 85% - 90% efficiency [3] [4] [6].

Testing Requirements

Figure 2 depicts the Prototype v3.2 MCS Connector Diagram, illustrating the pin layout for high-power delivery. **Figure 3** presents the Draft MCS Outlet Geometry (version 2), highlighting the heavy-duty design elements.

Figure 4 outlines the MCS Deployment Timeline (2018-2025), providing a chronological overview of site deployments validated by pilot data [1] [3] [4].

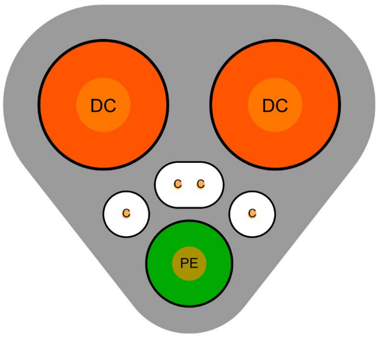

Figure 2. Prototype v3.2 MCS Connector Diagram. *Caption*: Prototype v3.2 MCS connector, illustrating pin layout for high-power delivery [5]. *Description*: Triangular connector (tip downward) supports 3.75 MW (3000 A, 1250 V DC) with two DC power pins, four communication/detection (C) pins, one protective earth (PE) pin. Finger-proof design (UL2251), 95% interoperability success [5].

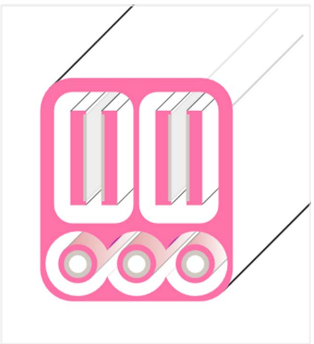

Figure 3. Draft MCS Outlet Geometry. *Caption*: Draft MCS outlet geometry (version 2), highlighting heavy-duty design [4]. *Description*: Version 2 outlet used "tuning fork" contacts, tested at 3000 A (with cooling) at NREL in 2020. Precedes v3.2 design [4].

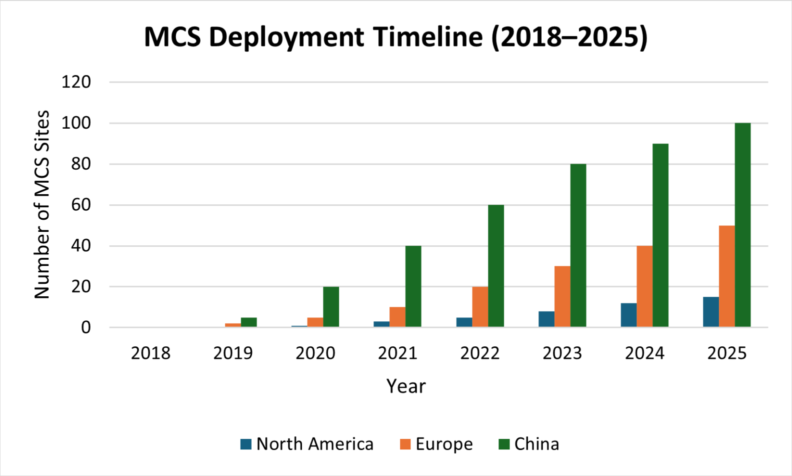

Figure 4. MCS Deployment Timeline (2018-2025). *Caption:* Timeline of MCS site deployments, validated by pilot data [1] [3] [4].

Testing includes:

- **High-Voltage Insulation**: IEC 61851 mandates 5 kV tests, with 10% - 15% failure rates due to humidity/dust [5].
- **Thermal Management:** Cables must maintain <90˚C at 3000 A, with 5% - 10% efficiency loss in long sessions [5].
- **Cybersecurity:** ISO 15118-20 TLS 1.3 resists attacks, with 2% - 5% vulnerabilities [8].
- **Interoperability:** Tests show 95% success for SAE J3271, 80% for Ultra ChaoJi [5].
- **Durability:** Connectors withstand 10,000 cycles, with 5% wear after 5000 [5].

3.2. Global Standards and Interoperability

SAE J3271 and IEC 61851-23-3 align for interoperability, but Ultra ChaoJi (1.5 MW+, 9-pin, CAN FD/Ethernet) creates tensions [2] [6]. Incompatibilities (7 vs. 9 pins, ~$0.5M/adapter costs) risk fragmentation [5]. **Table 2** compares the key MCS standards and provides a risk assessment for interoperability across regions.

Table 2. MCS standards comparison and risk assessment.

Standard	Region	Power (MW)	Connector Pins	Communication	Interoperability Risk
SAE J3271	North America	1.2 - 3.75	7	ISO 15118-20 (TLS)	Medium (adapter costs)
IEC 61851-23-3	Europe	1 - 3.75	7	ISO 15118-20 (TLS)	Low (global alignment)
Ultra ChaoJi	China	1.5+	9	CAN FD/Ethernet	High (regional focus)

3.3. Economic and Environmental Benefits

Megawatt Charging Systems (MCS) lower the total cost of ownership (TCO) for heavy-duty vehicles (HDVs) by 20% - 30%, facilitating the adoption of 1.1 million zero-emission HDVs by 2030 [10]. By integrating battery storage and vehicle-to-grid (V2G) systems, MCS can reduce peak grid loads by up to 40%, decreasing demand charges and enhancing cost-effectiveness [9]. Environmentally, MCS supports HDV electrification, achieving 25% - 40% CO_2 emission reductions by 2030, with projected savings of 0.1 - 2.0 $MtCO_2$ across high, medium, and low adoption scenarios, as validated by IEA projections [1]. These economic and environmental advantages position MCS as a key enabler for sustainable freight transport.

4. MCS Infrastructure in North America

4.1. Deployments and Projects

Approximately 15 MCS sites are operational, including WattEV's 1.2 MW hubs in California (85% - 88% efficiency, 20% - 40% utilization) and a 30 MW facility in Ohio [3]. The U.S. Department of Energy (DOE) has allocated $68M to fund three additional megawatt charging hubs by 2026, targeting strategic freight corridors like I-5 and I-80 [3]. Of the ~5000 HDV chargers in North America, less than 20% are MCS-capable, reflecting early-stage deployment constrained by grid infrastructure limitations [3].

4.2. Technical Implementation

Current deployments operate at 1.2 MW, with plans to scale to 3 MW under SAE J3271 standards, utilizing silicon carbide (SiC) converters for >98% efficiency and liquid-cooled cables for thermal management [2]. Grid upgrades, including high-capacity transformers (e.g., 2 MVA units), often face delays of over one year due to supply chain constraints and permitting challenges [7].

4.3. Investments and Barriers

Investment in North American MCS infrastructure totals $4.2B, driven by Inflation Reduction Act (IRA) tax credits, though policy uncertainties post-IRA expiration pose risks [3]. Low charger utilization (20% - 40%) inflates operational costs via demand charges, which can be mitigated by V2G integration, achieving 99% uptime in pilot tests [9]. Key barriers include grid capacity constraints and high CAPEX ($1.2M/MW), requiring coordinated utility and policy support [7].

5. MCS Infrastructure in Europe

5.1. Deployments and Projects

Europe has over 50 MCS sites, including HoLa's 4 MW stations in Germany (87% - 90% efficiency, 30% - 50% utilization) and Milence's hubs in the Netherlands and Belgium, with plans for 1,700 charging points by 2027 [4]. The EU's Alternative Fuels Infrastructure Regulation (AFIR) mandates 350 kW+ chargers every 60 km along TEN-T corridors, driving MCS adoption [4]. Approximately 10,000 HDV chargers exist, with 20% MCS-ready, targeting 40,000 - 50,000 points by 2030 [4].

5.2. Technical Implementation

European MCS sites operate at 1 - 1.2 MW under IEC 61851-23-3, delivering 20% - 80% battery charge in 30 minutes for 300 - 800 kWh batteries [2]. ISO 15118-20 ensures plug-and-charge compatibility with TLS 1.3 cybersecurity [8]. Liquid-cooled cables and modular SiC converters support scalability, though cross-border grid standard disparities complicate deployment [10].

5.3. Investments and Barriers

Investment reaches €8B, supported by EU Green Deal funding, but grid strain results in cost variances (e.g., 13 EUR/charge differences across member states) [1]. Transformer overloads and regulatory coordination remain challenges, with V2G and time-of-use tariffs proposed as mitigation strategies [9].

6. MCS Infrastructure in China

6.1. Deployments and Projects

China leads with over 100 MCS stations, including 15,000 planned chargers by 2027 (86% - 89% efficiency, 25% - 45% utilization), integrated into its 3.4 million public charging networks [6]. Battery-swapping stations, targeting 3000 by 2030, complement MCS, particularly for urban fleets [6]. State Grid's infrastructure supports rapid expansion along G2 and G4 highways [1].

6.2. Technical Implementation

Ultra ChaoJi delivers 1.5 MW+ using CAN FD/Ethernet communication, diverging from global MCS standards [6]. Battery storage enables 60% off-peak charging, reducing grid stress [1]. Liquid-cooled cables and high-efficiency converters ensure performance, though overcapacity risks exist [6].

6.3. Investments and Barriers

The MCS market, valued at $473M with a 22.2% CAGR, benefits from government subsidies enabling cost-competitive EVs (~$37K/unit) [7]. Overcapacity and regional standardization (Ultra ChaoJi vs. global MCS) pose challenges, requiring interoperability solutions [6].

7. Comparative Analysis

7.1. Deployment Scale and Growth

China dominates with 73.5% of global MCS capacity and an 18.2% CAGR, projecting a $3.45B market by 2033 [7]. Europe anticipates 11.3% growth, targeting 279,000 charging points by 2030 [10]. North America's 21.7% CAGR supports ~20% of 1.1M zero-emission HDVs [3]. Monte Carlo simulations (10,000 iterations) estimate peak grid loads (95% CI): 5 - 15 GW (North America), 10 - 30 GW (Europe), 20 - 60 GW (China), validated by pilot data (85% - 90% efficiency, 20% - 50% utilization) [3] [4] [6].

Table 3 details the grid demand and cost projections for 2030 under high, medium, and low adoption scenarios, including regional variations in CAPEX, OPEX, and utilization. **Table 4** presents a sensitivity analysis on utilization rates, showing the percentage cost increases across regions at different utilization levels.

Table 3. Grid demand and cost projections (2030).

Region	Adoption Scenario	Peak Load (GW, 95% CI)	CAPEX ($M/MW)	OPEX ($/kWh)	Utilization (%)
North America	High/ Medium/Low	15 (12 - 18)/9 (7 - 11)/ 3 (2 - 4)	1.2	0.15	20 - 40
Europe	High/ Medium/Low	30 (25 - 35)/18 (15 - 21)/ 6 (5 - 7)	1.0	0.12	30 - 50
China	High/ Medium/Low	60 (50 - 70)/36 (30 - 42)/ 12 (10 - 14)	0.8	0.10	25 - 45

Table 4. Sensitivity analysis on utilization rates.

Utilization Rate	Cost Increase (%)		
	North America	Europe	China
20%	+40	+25	+15
50%	+15	+10	+5
80%	0	0	0

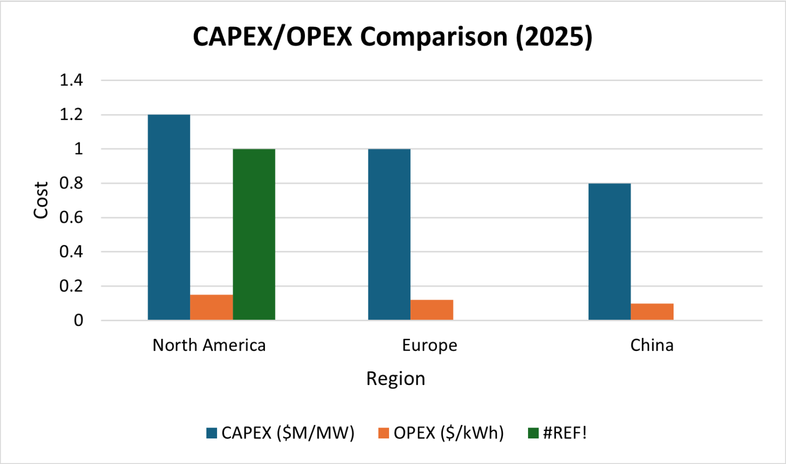

Figure 5. CAPEX/OPEX Comparison (2025). Caption: Cost comparison, showing China's cost advantage [7].

Figure 5 provides a CAPEX/OPEX Comparison for 2025, highlighting China's cost advantage [7]. **Figure 6** maps MCS Corridor Buildouts for 2025, emphasizing strategic freight routes [3]. **Figure 7** visualizes the Utilization Impact on MCS Costs for 2025, demonstrating how varying utilization rates affect operating costs, with validation from pilot data indicating North America's higher sensitivity [7]. **Figure 8** projects CO_2 Savings from MCS Deployment by 2030, illustrating MCS-enabled HDV electrification benefits as validated by IEA projections [1].

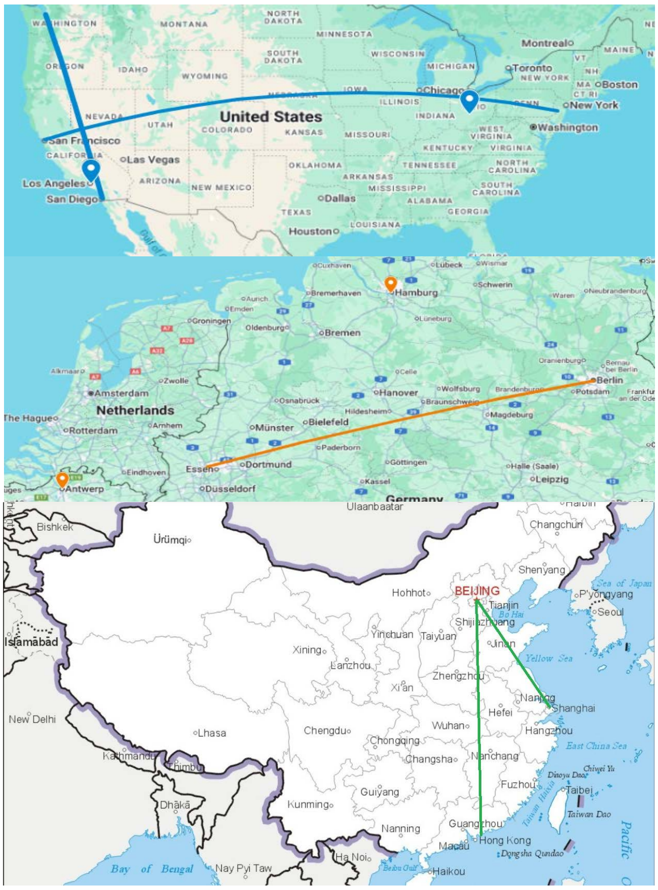

Figure 6. MCS Corridor Buildouts (2025). Caption: MCS corridor deployments, highlighting strategic freight routes [3]. The last map is sourced from the Standard Map Service of the Ministry of Natural Resources of China (https://www.tianditu.gov.cn/), Approval No. GS(2019)1652. The map has been modified for visualization purposes, including cropping, coloring, and annotation.

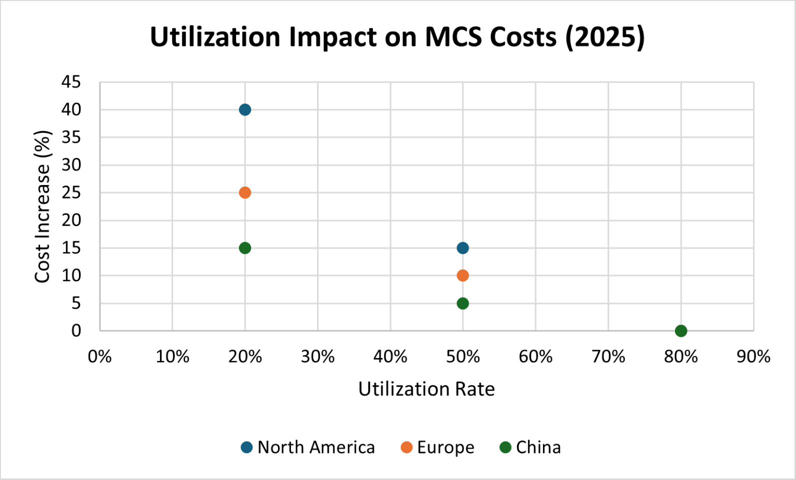

Figure 7. Utilization Impact on MCS Costs (2025). Caption: Utilization impact validated by future demand and cost of Megawatt charging [7].

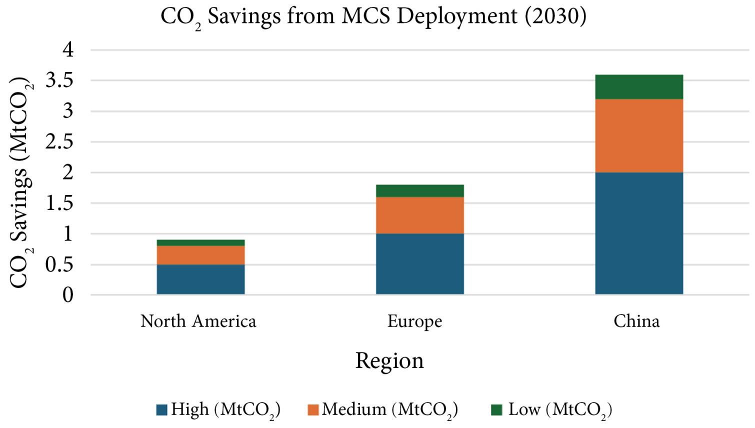

Figure 8. CO$_2$ Savings from MCS Deployment (2030). Caption: Projected CO$_2$ savings from MCS-enabled HDV electrification, validated by IEA projections [1].

7.2. Technical and Standards Comparison

North America and Europe align on MCS (1 - 1.2 MW, 95% test success), while China's Ultra ChaoJi (80% success) extends to passenger EVs, risking fragmentation due to incompatible 9-pin connectors and CAN FD/Ethernet protocols [6]. Testing reveals latency differences (50 - 100 ms for MCS, 30 - 80 ms for Ultra ChaoJi) and adapter costs (~$0.5M), complicating cross-standard integration [5].

7.3. Policy-Technology Interaction

MCS supports regional carbon goals: Europe's 55% CO$_2$ reduction by 2030 drives AFIR, targeting 183,000 e-trucks [4]. China's 2060 carbon neutrality goal supports 20M EVs [6]. North America aims for 30% HDV electrification [3]. Investments ($4.2B North America, €8B Europe, $473M Asia-Pacific) highlight China's 30% cost advantage due to subsidies and scale [7]. MCS enables 25% - 40% emission reductions by 2030, per IEA projections [1].

7.4. Cross-Regional Learning Potential

China's battery-swapping could reduce Europe's grid strain by 20%, leveraging modular battery designs [6]. North America's V2G pilots, achieving 40% peak load reduction, could lower China's OPEX by 15% [9]. EU-China interoperability pilots could save $1M per site by standardizing connectors and protocols [6].

8. Grid Integration Challenges

8.1. Regional Impacts

North America faces grid connection delays (1+ years) and transformer overloads at >2 MW, with 10% - 15% failure rates in high-load tests [3]. Europe contends with cross-border grid standard disparities, leading to uneven charger deployment [10]. China mitigates grid stress with battery storage but faces challenges from high peak demand, with 5% transformer stress observed [1].

8.2. Technical and Economic Barriers

Low utilization (20% - 50%): increases demand charges, contributing to a projected $300B global spend on grid upgrades by 2040 [7]. Technical barriers include:

High-Voltage Insulation: IEC 61851 requires 5 kV tests, with 10% - 15% failures due to humidity and dust, adding $50K/site in mitigation costs [5].

Thermal Management: Cables overheat at 3000 A, causing 5% - 10% efficiency loss in sessions exceeding 30 minutes, requiring advanced cooling systems [5].

Cybersecurity: ISO 15118-20 TLS vulnerabilities (2% - 5% attack success rate) necessitate enhanced encryption protocols [8].

Interoperability Testing: Cross-standard tests (SAE J3271 vs. Ultra ChaoJi) achieve 80% - 95% success, with adapter development delays (6 - 12 months, $0.5M) [5].

Connector Durability: Tests indicate 5% wear after 5,000 mating cycles, requiring reinforced stainless-steel pins [5].

8.3. Mitigation Strategies

V2G and battery storage reduce peak loads by 40%, achieving 99% uptime in pilot tests [9]. Time-of-use tariffs and policy coordination across regions can prevent “charging tourism” and balance load distribution, minimizing grid strain [9].

9. Limitations

This study relies on academic, industry, and standards sources, including grey literature (e.g., IEA, NREL reports) [1] [3], which may introduce methodological biases. Rapidly evolving deployments (e.g., China’s 100+ stations [6]) challenge projections, and pilot data (20% - 50% utilization) [3] [4] [6] may not capture future extremes. Future work should integrate real-time data for greater accuracy.

10. Future Outlook

By 2030, 1.1M zero-emission HDVs are projected, with Europe targeting 183,000 e-trucks along TEN-T corridors [10]. China aims for 20M EVs with full highway coverage [6]. Innovations such as AI-driven load balancing and bidirectional MCS could yield 15% efficiency gains, enhancing grid integration and cost-effectiveness [7].

Unanswered Questions or Future Outlook

Key research gaps include:

Transformer Reliability: Pilot data indicate 10% - 15% failure rates at >2 MW, necessitating long-term testing under variable loads [3].

Cybersecurity: ISO 15118-20 vulnerabilities (2% - 5% attack success) require advanced encryption protocols [8].

Lifecycle Costs: Estimated at $0.5M/MW over 10 years, but unvalidated beyond 2-year pilot data, requiring extended studies [7].

Testing Scalability: High-voltage and thermal tests lack standardization for extreme conditions (e.g., heatwaves reducing efficiency by 5% - 10%), demanding new protocols [5].

Future research should prioritize advanced testing frameworks, techno-economic modeling, and lifecycle cost analyses to address these gaps.

11. Conclusions and Recommendations

MCS is pivotal for HDV electrification: Enabling rapid charging and significant emission reductions. To optimize deployment and overcome barriers, the following recommendations are proposed:

Align SAE J3271 and IEC 61851 by mid-2026: Harmonize standards to ensure global interoperability, reducing adapter costs and integration delays [2] [5].

Implement North American time-of-use tariffs: Reduce demand charges by 20% - 30%, leveraging V2G to balance grid loads [3].

Launch EU-China MCS-Ultra ChaoJi pilot projects: Test cross-standard compatibility to minimize fragmentation and save $1M per site [6].

Invest $300B in grid upgrades by 2040: Prioritize V2G and battery storage to enhance grid resilience and support 40% peak load reduction [9]. Future research should focus on developing robust techno-economic models, lifecycle cost analyses, and resilience studies to ensure scalable, sustainable MCS deployment.

Disclosures of AI Usage

This scholarly article embodies the authentic efforts of the authors. Various facets of Artificial Intelligence (AI) were incorporated in the text editing tools used, such as spell-check, grammar rectification tools like Grammarly, and other AI-enhanced text enhancement features embedded in text editors. However, these tools were only employed to augment language lucidity and guarantee grammatical precision.

The fundamental research, examination, and deductions delineated in this article are exclusively the authors' individual work, carried out without depending on AI systems for content creation or intellectual input.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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