IMPLEMENTATION OF EVFCS ON HIGHWAYS: STUDIES AND LESSONS FROM AN R&D PROJECT

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ABSTRACT

The global energy transition and the ad- vent of clean mobility are unequivocal realities. This work addresses these themes pragmatically, examining the studies, challenges, and considerations inherent in the implementation of Electric Vehicle Fast Charging Stations (EVFCS). Pioneering EVFCS face multifaceted challenges, including: optimal siting, usability forecast- ing, technical configuration of individual stations, grid impact assessments, usage projections, and investment return analyses, among others. Based on a real-world case study conducted in Southern Brazil, this paper discusses the main factors and comprehensive studies developed for the deployment of EVFCS. Consequently, the principal contributions herein constitute an evalua- tion of the research, practical experiences, operational difficulties, and results obtained from a dedicated Re- search and Development (R&D) project.

Keywords: Energy transition; Fast charging infras-tructure; Grid integration; CO2 reduction; R&D project.

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INTRODUCTION

The global energy transition represents a paradigm shift in transportation systems, driven by the impera- tive to reduce atmospheric pollution, diversify energy sources, and decrease CO2 emissions. This transforma- tion is particularly critical in the transportation sector, which accounts for approximately 33% of global green- house gas emissions [1]. In Brazil, this percentage is even more significant, with road transport contributing 71% of the sector's total emissions, making mobility de- carbonization an urgent priority for achieving national climate targets [2]. Electric mobility has emerged as a technically viable and environmentally sustainable solution to the challenges associated with fossil fuel consumption in transportation [3].

The Brazilian electric vehicle market has experi- enced exponential growth, with an 80% increase in adoption during the pandemic period, reflecting grow- ing environmental awareness and the search for sus- tainable alternatives [3]. Government initiatives such as the Mover Program (Green and Innovative Mo- bility) have accelerated this transition through fiscal incentives and investments exceeding R$ 19 billion in financial credits until 2028.

However, the expansion of the electric vehicle fleet is intrinsically dependent on the development of ade- quate charging infrastructure, particularly Fast Charg- ing Stations (EVFCS). The implementation of these stations faces multiple interdisciplinary challenges en- compassing technical, economic, regulatory, and op- erational aspects. Recent studies indicate that more than 50% of consumers still hesitate to adopt electric vehicles due to insufficient charging infrastructure, while approximately 20% of charging attempts at pub- lic stations fail due to reliability issues [2].

The technical challenges for EVFCS implementation include: optimal allocation considering traffic flow pat- terns and grid capacity; proper sizing of power elec- tronics components; mitigation of power quality issues such as voltage sags, harmonic distortions, and phase unbalance; and thermal management of high-power charging systems [4]. Economic obstacles involve high capital expenditure for grid connection and equipment, operational costs dominated by demand charges, and uncertain return on investment due to evolving usage patterns [5].

The Brazilian energy context adds additional layers of complexity. Although the national grid is predomi- nantly renewable (with hydroelectric power represent- ing approximately 65% of the matrix), regional limi- tations in transmission and distribution infrastructure require significant investments to support the growing demand for electric vehicle charging [?]. Furthermore, the geographical vastness of the country necessitates careful planning of charging station deployment to avoid creating connectivity gaps between urban cen- ters.

This study aims to address these challenges through a comprehensive analysis based on empirical data from a real-world Research and Development (R&D) project implemented in southern

Brazil, as shown in Fig. 1.

The research employs a multidisciplinary approach that integrates: optimal allocation methodologies for EVFCS with distributed energy resources; advanced load modeling and generation potential assessment; comprehensive electrical studies evaluating grid im- pacts and power quality; economic viability analysis under different business models; and development of energy management strategies for optimized operation [6], [7], [8].

Figure 1: Geographical distribution of EVFCS in the Mercosur Route project [9].

EVFCS ALLOCATION AND DERS EVALUATION

Several scientific studies, alongside site visits and further research, were conducted for the selection and evaluation of candidate locations to host Electric Ve- hicle Fast Charging Stations (EVFCS). A methodology was developed and applied to determine the optimal placement of Fast Charging Stations (FCS) along an 832 km stretch of highway in southern Brazil, which previously lacked any charging infrastructure. Utiliz- ing a Genetic Algorithm, the study evaluated existing establishments, such as gas stations and shopping centers, based on three primary criteria: daily vehicle traffic flow, population of the nearest city, and the level of service offered by the location. The key finding was the determination that eleven stations would be required to cover the route, adhering to a maximum inter-station distance of 100 km, resulting in a final average spacing of 79.7 km. The significant advantage of this methodology is its capacity to optimize resource allocation by minimizing the number of required sta- tions while simultaneously maximizing the utility of the selected sites, in addition to reducing investment costs by leveraging pre-existing infrastructure [10].

Other studies encompassing broader technical, so- cioeconomic, and wind and photovoltaic generation potential factors were also conducted [6]. Thus, in [11] a methodology was proposed to evaluate and hierarchically rank candidate locations for the installa- tion of an“EVFCS microgrid.” This innovative concept integrates a charging station with on-site renewable energy generation (photovoltaic solar and wind). Using the Analytic Hierarchy Process (AHP), the study ranked 29 candidate points along the “Mercosul Route” based on 12 distinct criteria, ranging from vehicle flux and so-cioeconomic data to specific solar and wind generation potential. The results indicated that the highest-ranked locations were situated on the segment between Porto Alegre and Torres, which excelled in nearly all eval- uated criteria. The advantage of this approach is its ability to manage complex, multi-criteria decisions in a structured manner, offering a clear ranking that aids in investment optimization and promotes the creation of a more sustainable and resilient charging infrastructure. The availability of renewable generation for integra- tion with EVFCS was also a subject of initial studies. A technical survey was conducted to identify the es- sential criteria for assessing small-scale wind gener- ation potential, aimed at supporting projects such as renewable-powered electric vehicle charging stations. The work details crucial parameters, including wind speed distribution, wind power density, terrain rough- ness, and altitude. A case study was performed on the coast of Rio Grande do Sul, which concluded that the region possesses highly favorable conditions for wind energy harnessing, with average wind speeds predom- inantly above 5 m/s, low terrain roughness, and high wind power density, exceeding 400 W/m2 in more than half of the area. The primary advantage of this study is that it provides a simplified and consolidated guide for use in future feasibility analyses, promoting the integration of clean energy into new applications and offering specific, valuable data for project development in the coastal region of Rio Grande do Sul [7].

EVFCS LOAD MODELING AND DER GENERATION

In the absence of a consolidated usage history for EVFCS, several studies have been developed to pre- dict usage patterns, estimate future scenarios and de- mands, and evaluate potential on-site energy genera- tion capabilities. A refined model is proposed to ac- curately estimate the charging duration of various EV models, addressing the limitations of generalized ap- proaches that often lead to station sizing inaccuracies. The model incorporates specific battery characteristics of each vehicle, charger power output, and critically, the stochastic nature of the initial and final State of Charge (SoC). Utilizing a comprehensive database of 73 EV models available in the Brazilian market and employing Monte Carlo simulations to emulate vehicle arrival patterns, the model computes charging times on an individual basis, accounting for the char- acteristic reduction in charging rate above 80% SoC. Model validation demonstrated strong agreement be- tween calculated charging durations and manufacturer specifications, while revealing substantial variability in charging times: for identical vehicle models, charging duration exhibited a range of 39 to 112 minutes. The primary contribution of this methodology is its capacity to generate realistic estimates, serving as an essential tool for precise EVFCS dimensioning, queue management optimization, and accurate electrical grid demand forecasting [12].

The research presented in [13] focuses on predict- ing the saturation threshold of EVFCS infrastructure, specifically identifying the point at which queue forma- tion becomes operationally critical as EV market pen- etration increases. The methodological framework em- ploys a three-stage stochastic operation model incor- porating: (1) Monte Carlo simulation of driver behav- ior patterns (including range anxiety considerations), (2) traffic flow modeling, and (3) station operation simulation. Applied to an actual highway corridor in southern Brazil, the investigation utilized quantile anal- ysis (deciles) to assess queue formation probabilities across varying EV adoption scenarios (0.1% to 30% market penetration). Results demonstrated that the reference infrastructure configuration (a station with three charging units) would maintain adequate service levels up to 10% EV market penetration, beyond which queue formation would become frequent. Severe sat- uration conditions were predicted to occur at penetration rates between 20% and 30%. This approach provides grid operators and planners with a proactive planning tool to identify infrastructure limitations and schedule capacity expansions prior to service quality degradation.

Complementary research examines the impact of charging demand uncertainty on both operational plan- ning and business model viability for EVFCS instal- lations [14]. The study compares two distinct con- figurations: a conventional charging station (without integrated generation) and a microgrid implementation incorporating DERs and BESS. Through a stochastic model generating multiple load profile scenarios cou- pled with an optimization framework minimizing oper- ational expenditures, the research developed a pricing model incorporating both fixed infrastructure costs and variable operational expenses. Results indicated that while the microgrid configuration significantly reduced energy procurement costs (through reduced grid de- pendence), it incurred approximately fivefold higher availability costs due to substantial capital investment requirements. This economic structure renders the mi- crogrid business model particularly vulnerable under low-utilization scenarios where high fixed costs may lead to financial losses. This analysis provides valuable insights into the fundamental trade-off between opera- tional efficiency and financial risk exposure, offering a realistic assessment of different EVFCS business model viability in uncertain market conditions [14].

Focusing specifically on microgrid operation, the in- vestigation in [15] developed a comprehensive method- ology to evaluate the energy self-sufficiency of a high- way charging microgrid integrating photovoltaic gen- eration, wind generation, and BESS capacity. Using the HOMER software platform for energy generation mod- eling and polynomial trend analysis for EV fleet growth projections in the Brazilian market, the study quanti- fied the microgrid's capacity to meet evolving charging demands over time. Results indicated that while the microgrid could generate approximately 7,000 kWh monthly (sufficient for 175 full charges of 40 kWh each) and achieve high autonomy levels under current con- ditions, this capacity would become inadequate with increasing EV adoption rates. By 2027, the system would only be capable of serving 2.15% of the EVs projected to transit through the location. This research provides a dynamic modeling framework to quantify the sustainability of charging microgrids, demonstrat- ing how localized generation can mitigate grid impact while emphasizing the necessity of strategic planning for future capacity expansions.

ELECTRICAL STUDIES - IMPACTS AND ENERGY QUALITY

The integration of EVFCS and/or microgrids into existing electrical systems presents significant chal- lenges, necessitating specific technical studies. In [16], the electrical impacts of integrating an EV charging mi- crogrid into an existing distribution network in south- ern Brazil were investigated through simulation. The modeled microgrid comprised a fast charger, photo- voltaic and wind generation, and a BESS. The study conducted 365-day simulations using OpenDSS soft- ware, comparing feeder performance with and without the microgrid. Results indicated that the microgrid connection caused no negative impacts on the elec- trical network, maintaining voltage levels and per- centage losses virtually unchanged. A key advantage demonstrated was the microgrid’s high energy self- sufficiency, consuming an average of only 73.77 kWh from the grid daily, while internally generating and con- suming 263 kWh. Furthermore, the maximum power demanded from the grid (82.5 kW) was lower than the total simultaneous charging capacity (93 kW), high- lighting the consistent support from local generation and BESS in alleviating grid load. No feeder failures were observed, as the additional load from a single EVFCS was not substantial.

Conversely, focusing on operational EVFCS at a high- demand charging station, the study in [4] analyzed power quality at a functioning FCS using actual mea- sured field data. The research installed a power quality analyzer on a 60 kW DC / 44 kVA AC charger in Eldorado do Sul, Brazil, collecting data during April 2024 and selecting a high-demand day for detailed analysis. Results showed that voltage levels and net- work frequency remained within acceptable limits even during intensive operation, with Total Voltage Har- monic Distortion THDV reaching a maximum of 2.63%.

However, Total Current Harmonic Distortion THDI exhibited elevated values, with peaks of 22.24% (Phase A), 29.90% (Phase B), and 23.52% (Phase C), suggest- ing a significant source of harmonic distortion. The primary advantage of this work is the use of field- measured data, which provides greater realism to the analysis. The study infers that the high current distor- tion in Phase B may be attributed to a 9 kWp pho- tovoltaic system connected to this phase, highlighting the importance of investigating and mitigating harmon- ics generated by renewable energy integration with charging infrastructure. It is important to note that elevated THDI values were observed with chargers idle, meaning at low current. Nevertheless, in future EVFCS expansions, additional studies and potentially harmonic mitigation methods may be required.

ECONOMICAL STUDIES

Although conducted within an R&D framework with allocated funding, it remains crucial to develop models and evaluate the economic feasibility of an EVFCS. In [5], a methodology for the economic assessment of EVFCS operation on highways is elaborated, analyzing two distinct locations in Rio Grande do Sul: one in a high-traffic area and another in a less congested region. Utilizing demand projections based on EV fleet growth and the Net Present Value (NPV) method to calculate investment returns, the results underscored the critical importance of location. The station in the metropolitan area exhibited an estimated payback pe- riod of less than 4 years, whereas the station in the lower traffic location would require at least 6 years to recover the initial investment. The analysis also indicated that the busier station would rapidly reach its maximum capacity, highlighting the necessity for continuous planning for future expansions.

Meanwhile, [17] conducts a feasibility analysis by evaluating different infrastructure configurations, ranging from a simple charger to a complete microgrid with solar generation, wind generation, and BESS. The study estimated generation and consumption scenar- ios and applied the NPV method to determine the investment payback period for each configuration. The results demonstrated that, even under an optimistic scenario of exponential EV fleet growth, the payback period for the complete microgrid would be 8 to 9 years, while a simpler configuration with a charger and photovoltaic system would achieve return in 5 years. The research concludes that although storage systems offer operational benefits, their high initial cost signif- icantly prolongs the financial return, suggesting that a phased investment approach — starting with the charger and photovoltaic generation — is the most prudent strategy for investors.

STRATEGIES OF ENERGY MANAGEMENT

The deployment of a microgrid, beyond its energy and sustainability benefits, introduces demands for sophisticated management and control strategies. In [18], energy management is centered on an optimiza- tion algorithm for the dispatch of a BESS. The pri- mary method involves formulating a "preference index" based on a Time-of-Use (ToU) energy tariff. This index guides the management system, signaling the prefer- ence to charge the BESS during low-tariff periods and discharge it to meet EV charging demand during high- tariff periods. The procedure is modeled as a Mixed- Integer Linear Programming (MILP) optimization prob- lem, with an objective function to maximize the charge and discharge rates of the BESS weighted by the pref- erence index, resulting in reduced operational costs.

Building on these studies, a very similar management procedure is described, also formulated as a MILP optimization problem to control the dispatch of a BESS. The method begins with the modeling of microgrid components, estimating renewable generation profiles (solar and wind) using the Homer software and EV charging scenarios via Monte Carlo Simulation. The core procedure is the application of an objective func- tion that maximizes BESS dispatch based on a price preference index. The optimization is then solved using the AMPL language and the CPLEX solver, considering a one-year horizon with 5-minute intervals and respect- ing operational constraints such as energy balance, BESS SoC limits, and energy exchange capacity with the grid. The objective function aims to maximize BESS utilization during periods of highest economic advan- tage, resulting in optimized dispatch that balances local generation, storage, and grid energy purchases to minimize costs [19], [20].

With the advancement of research, new proposals and more dynamic and efficient strategies have been proposed. [21] presents a Rule-Based Energy Manage- ment System (RBEMS). The procedure is based on three forecasting models that feed the decision system: photovoltaic generation is predicted by an Artificial Neural Network (ANN); wind generation is estimated by a parametric model based on the theoretical power curve of the turbine; and EV consumption is forecasted by a Monte Carlo Simulation generating the worst- case daily demand scenario. Based on these forecasts, the RBEMS executes a set of predefined rules every 15 minutes, making decisions to charge/discharge the BESS or interact with the grid based on energy tar- iffs, battery SoC, and the balance between generation and consumption, prioritizing renewable energy self- consumption. The method also includes a stochastic analysis to quantify the financial impact of forecasting errors, offering insights into the system's robustness.

To complement this work, [8] details an optimization- based energy management method that explicitly con- siders BESS degradation. The procedure begins with input modeling: renewable generation profiles are es- timated from physical-mathematical models fed by me- teorological forecast data from an API; EV charging profiles are generated from statistical analysis of a historical database of actual charging events. The core of the method is the formulation of a MILP optimiza- tion problem, whose objective function is to minimize total operational cost. This cost comprises the cost of energy purchased from the grid and the cost of battery degradation per charge/discharge cycle, calculated by a wear cost function. The algorithm then determines the optimal BESS dispatch for the next day, balancing immediate energy tariff costs with long-term battery wear costs.

EVFCS OPERATIONAL DATA AND LEARNINGS

The deployment and operation of the 11 EVFCS within the R&D project have yielded invaluable real- world data and profound practical learnings that ex- tend far beyond the quantitative metrics of energy consumption and usage patterns. This section syn- thesizes these operational results with the significant implementation challenges encountered, providing a holistic view of the current state of EV infrastructure deployment in the Brazilian context [9]. The analysis of charging events reveals a consistent usage profile characteristic of highway corridors. Charging dura- tion confirms that the majority of users utilize the 60 kW DC chargers for sessions between 20 to 40 minutes, aligning with the expected behavior for top- up charging during medium to long-distance trips. This is further corroborated by the energy consumed per session, which typically ranges from 15 to 30 kWh, sufficient to add a significant range to most EVs. The concentration of connection times during the afternoon and early evening underscores the stations' role in supporting travel that combines daily commutes with intercity journeys. Furthermore, the analysis of poten- tial queuing events–where a new session starts within 5 minutes of a previous one–revealed critical congestion points, with the Pelotas station showing a rate of 30%, indicating high demand that occasionally exceeds the available capacity of a single DC charger [9].

However, the journey to acquiring this data was fraught with hurdles that highlight the immaturity of the EV ecosystem in the region. A significant non- technical challenge was the difficulty in securing host locations. Commercial establishments were often re- luctant to cede parking spaces due to concerns over business disruption during installation, perceived li- abilities, and a lack of immediate, clear economic benefits. This underscores the necessity of developing a compelling value proposition for hosts, extending beyond simple revenue sharing to include increased customer dwell time and attraction of a high-income demographic.

On the technical front, the project highlighted the critical importance of grid connection specifications. For high-power stations, a standard commercial meter- ing system is inadequate. The project learned that an indirect metering system via instrument transformers (CTs and VTs) is mandatory for accurate measure- ment and compliance with utility regulations for high- capacity connections. Furthermore, communication in- frastructure proved to be a linchpin for reliable opera- tion. The dependency on a single cellular network for data transmission to the cloud management platform was identified as a risk; a more robust design requires a primary link (e.g., fiber optic) with a cellular modem as a mandatory backup to ensure continuous monitoring, remote diagnostics, and payment processing.

The logistical landscape presented its own set of challenges. Unpredictably long lead times were experi- enced for critical path items, including the delivery and installation of power transformers by the utility and the manufacturing and shipping of the charging hardware itself. These delays, often exacerbated by global supply chain issues and the lingering effects of the COVID- 19 pandemic, require incorporating significant buffers into project timelines and developing strong contin- gency plans.

Perhaps the most persistent operational challenge stems from the technological immaturity and lack of a localized support ecosystem. The scarcity of spe- cialized technical expertise for high-power charging systems meant that routine maintenance, firmware up- dates, and troubleshooting required dedicated travel from central teams, leading to longer station down- times. This was compounded by the recent availability and reliability of components; the project served as a real-world beta test, often being the first to identify the need for firmware updates, component replacements, and hardware revisions. This experience emphasizes that pioneering projects must account not only for capital expenditure but also for the high operational cost of maintaining a nascent and evolving technology. The parallel challenge of a lack of a dedicated electro- mobility team within the local distribution utility often led to knowledge gaps and slower response times for connection approvals and technical support, highlight- ing the need for proactive engagement and training with utility partners.

The operational data confirms that the deployed infrastructure is effectively serving a growing and en- gaged user base, enabling longer journeys and reduc- ing range anxiety. However, the learnings from this R&D project paint a clear picture: the major barriers to mass deployment are no longer primarily technological but are rooted in economic viability, logistical planning, ecosystem development, and regulatory alignment. Fu- ture expansions must prioritize strategies that miti- gate these identified challenges, such as redundant communication designs, pre-established local service partnerships, proactive utility engagement, and robust project management that accounts for extended lead times.

CONCLUSIONS AND FUTURE STUDIES

This study has provided an overview of the chal- lenges of deploying EVFCS in south of Brazil, drawing on real-world operational data. The adoption of EVs in Brazil is experiencing exponential growth, a trend that has significantly accelerated since 2020. This surge is fueled by increasing consumer confidence, a growing model portfolio, and a broader societal acceptance of electromobility. Although the absolute number of electrified vehicles (including both pure electric and hybrids) remains modest compared to global leaders, nearing 1 million units, the market demonstrates im- mense potential [3]. The analysis of highway charging patterns confirms a corresponding rise in demand for public EVFCS, particularly along corridors with high traffic flow. The research also reinforces the potent synergy between DERs and EVs, a combination proven to be economically advantageous and environmentally sustainable, forming a cornerstone for a clean energy future.

However, the journey towards a robust charging net- work is not without its obstacles. The initial implemen- tation phase faced significant hurdles, primarily due to the technological immaturity of the ecosystem and a natural hesitation during the early stages of market popularization. Challenges such as securing host loca- tions, ensuring reliable internet and cellular commu- nication for station management in remote areas, and navigating extended lead times for equipment and grid connections were critical learning points. While these barriers are now being progressively overcome, they underscore the necessity of strategic planning, robust project management, and proactive engagement with all stakeholders, including utilities, host businesses, and governments.

Looking ahead, this work opens several promising avenues for future research. Based on the identi- fied challenges and opportunities, subsequent studies should focus on the economic and technical viability of V2G applications, particularly in residential/commer- cial settings such as condominiums. Another direction is the development of the second-life battery market and its integration with energy storage systems, which can support the grid while reducing the overall costs associated with EVs. Additionally, the creation of in- novative business models and management strategies for the emerging used EV market in Brazil deserves further exploration. Finally, the design, optimization, and operation of EVFCS microgrids are a key research pathway to improve local resilience and sustainability.

The ongoing deployment of more EVFCS remains a priority. Future engineering challenges will involve not only increasing the number of stations to avoid congestion and create a comprehensive, non-sparse network but also deploying units with even higher power capacities (150-350 kW) to meet the demands of next-generation EV and reduce charging times further.

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