

A Complete Analysis of the Various Techniques Used in Charging Battery Electric Vehicles

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Abstract - The accelerated global transformation into sustainable transport has fueled an explosive advancement in Battery Electric Vehicles (BEVs). The large-scale penetration of BEVs is fundamentally dependent on the availability of a reliable, available, and energy efficient charging system. In this paper, a comprehensive review and detailed comparative survey of the various charging technologies currently available or under development for BEVs is carried out. Operational principles, the infrastructure requirements, and challenges related to grid interaction of the three systems, namely the conductive charging, wireless power transfer (WPT) and battery swap mechanisms are classified and compared against one another. This study reveals that each charging technique has its own unique trade-offs in terms of the charging rate, the ease of use, power conversion efficiency and the infrastructure costs. Conductive charging is still dominant because of its high-power conversion efficiency and well-established infrastructure. However, extremely high direct current (DC) technologies create problems of grid stability and heat dissipation. In comparison, inductive and capacitive wireless charging are promising technologies as they are very user friendly and also capable of enabling the dynamic charging, but air-gap power transfer has efficiency losses. Finally, this study also identifies how integrating BEV to Grid (V2G) technologies and solar charging stations could also enhance the performance of future charging stations. The survey is intended to give a broad over view of all available EV charging technologies to the researchers, policy makers and automotive engineers for future research in electric vehicle charging environment.

Key Words: Battery Electric Vehicles, Conductive Charging, Wireless Power Transfer, Vehicle-to-Grid, Fast Charging Infrastructure

1. INTRODUCTION

There is a revolutionary transition being carried out across the global transportation sector. This transition is driven by the imminent necessity to lower greenhouse gas emissions as well as reduce society's reliance on scarce fossil fuels. Leading this movement towards this transition are Battery Electric Vehicles (BEVs) that provide clean, efficient, and state-of-the-art technology to traditional Internal Combustion Engine (ICE) vehicles. With

government policies mandating emissions regulations and subsidizing zero-emission vehicles across the globe, the automobile industry has seen an explosion of BEVs produced and purchased by the public. The success of electric mobility, however, is intrinsically related to the rapid growth of equally sophisticated electric vehicle charging infrastructure.

Unlike ICE vehicles which have the advantage of over a century old and world-standard refueling infrastructure, BEVs utilize a network of electric charging systems that is continuously developing and evolving. The objective is to be able to charge a vehicle in a time that is competitive to refueling a traditional ICE vehicle while maintaining the stability of the grid and optimizing power transfer efficiency while extending the longevity of on board battery systems. To accomplish this, new charging techniques are in the development process; from low power domestic AC charging systems to ultra-fast DC chargers providing megawatt power transfer. On the other hand, the boundaries of the "charging station" concept are also being redefined through the utilization of dynamic wireless power transfer, automatic battery swapping, and two-way flow of power from the vehicle to the grid (Vehicle-to-Grid). Given the increasing demand for electricity that will accompany higher numbers of BEVs on the road, peak loads placed on local utility grids are increasing tremendously. Consequently, smart charging procedures, Energy Storage Systems (ESS), and Renewable Energy (RE) Sources must be utilized. This review aims to examine these various technologies by performing a descriptive comparative survey highlighting their respective specifications, economic viability and potential future.

1.1 Background

Electric vehicle charging has its roots in the very early lead-acid battery chargers of the 20th century which were highly inefficient and took days to charge a battery. The era of modern BEV charging is the result of the development of high-energy-density lithium-ion batteries requiring complex charging patterns for optimal lifespan and safety. Early modern charging consisted primarily of Level 1 and Level 2 AC charging which employs the on-board rectifier of the EV to convert utility AC voltage to battery DC voltage. While adequate for the overnight charging occurring at residences these systems were not suitable for

extended-distance driving resulting in the popular problem of "range anxiety". The demand for charging in under 1-hour at stations led to the development of DCFC (DC Fast Charging) stations. By moving the AC-to-DC conversion outside the vehicle to be performed at the DCFC station, charging times were dramatically reduced to a matter of minutes as the system could deliver high voltage DC directly to the battery pack. Parallel research explored contactless power transfer. Contactless, or wireless, charging is often based on near-field transfer of energy by means of magnetic resonance. The current landscape is now a complicated matrix of all three types of technology supported by dynamic international communication and safety standards.

1.2 Problem Statement

In spite of these technological strides in electrification, current BEV charging infrastructure is bottlenecked by deep technological and operational constraints. The widespread adoption of ultra-fast DC chargers induces heavy harmonic distortion and voltage fluctuations within local distribution grids during peak usage times. In contrast, although wirelessly charging presents ultimate ergonomic ease and in-motion charging capability, its system spatial constraints and lower energy transfer efficiency, as opposed to conductive charging, represent significant challenges. More importantly, a gap exists for standardized and comparative frameworks to quantify and evaluate the overall performance of these contrasting technologies in terms of energy efficiency, cost and infrastructure.

2. LITERATURE REVIEW

The scholarly discussion around electric vehicle charging technologies has exploded, demonstrating the numerous hurdles inherent in connecting millions of high capacity mobile energy storage systems with the existing grid. A significant portion of the literature details the fundamental separation between onboard AC charging and offboard DC fast charging. Limitations of onboard chargers have been extensively researched with a universal acknowledgement of the constraints placed on charging power by weight, volume and thermal limits. As a result, the mechanics of Level 1 and Level 2 AC chargers have been well documented, noting their applicability for extended residential or work parking but their general inadequacy for constant, long distance, vehicular travel.

Responding to the physical limitations of AC charging, there has been a massive push to investigate the implementation of high power DC fast charging topologies. Numerous articles detail complex power electronic architectures for offboard stations with focused analyses of the performance of modular multi-level converters and high frequency isolation transformers. The consensus of these articles points to the fact that while DC fast charging allows

for eighty percent battery charge within minutes, it introduces immense thermal stress on lithium-ion cells thereby degrading battery life and has severe negative consequences for grid impact. Uncoordinated fast charging results in dramatic voltage sags, phase imbalances and frequency deviations; requiring the implementation of coordinated intelligent charging algorithms.

In parallel with wired EV charging, wireless power transfer has become another focal point for numerous researchers with its promise of eliminating physical connection with minimal safety concerns for high voltage systems. A vast portion of the literature separates wireless power transfer between near field inductive and capacitive coupling, with some theoretical explorations of far field microwave and laser charging. Far field charging systems are significantly less prevalent in the literature due to their current inefficiency but inductive power transfer, working on Faraday's Law of Electromagnetic Induction, is consistently researched. Most studies of inductive charging involve modeling the magnetic flux linkage between primary ground pad and secondary vehicle pad, analyzing the efficiency loss from misalignment, or researching the optimal compensation circuit design necessary to minimize the circulatory reactive power. The implementation of dynamic wireless charging systems, for the ongoing charging of a vehicle while moving across the roadway, has been presented as the solution to EV range anxiety, though many economic articles highlight the immense cost of updating roads to allow for dynamic charging.

Another significant trend in EV charging research is that of bidirectional charging through the concept of Vehicle-to-Grid (V2G) charging. Numerous studies demonstrate the capabilities of BEV fleets to act as Distributed Energy Resources capable of fulfilling essential grid support services, such as peak shaving, load leveling and frequency regulation. While the technology is shown to significantly improve grid stability and allow for higher renewable energy integration, most research points to socio-technical limitations of the concept, primarily the detrimental effect of constant micro-cycling on battery lifespan and the owner's unwillingness to surrender vehicle control.

The technology of battery swapping has also been thoroughly analyzed as a charging alternative. Operational models, pilot programs, and robotic swapping station mechanic systems have been detailed in the literature, along with the inherent difficulties in the logistical requirements of central battery storage. While battery swapping has been proven to be a vastly quicker method of refueling, many sources confirm that the lack of a standardized battery in current vehicle designs prevents widespread implementation.

In closing, much recent literature has focused on pairing the grid with renewable energy sources, specifically solar, as an energy source for EV charging stations. The benefits

highlighted within these studies are increased grid stability, assured zero-emission operation from well-to-wheel and reduced overall operational costs. Stationary battery storage, charged via the solar canopies during daytime peak production and utilized to charge BEVs overnight, is commonly presented as part of these charging stations. These studies demonstrate an improvement in operational cost while still highlighting the capital cost issues associated with stationary energy storage.

2.1. Research Gaps

- Limited long-term empirical data exists to quantify the total life-cycle costs and actual battery degradation effect of a sustained ultra-fast DC charging compared to a dynamic wireless power transfer under diverse environments.
- Grid impact models have often abstracted charging technology, providing no emulation of the combined, multiplied effect of ongoing V2G, Megawatt-level conductive charging and renewables operation on micro-grids localized within a region.
- Clear benchmarks defining the interoperability and electromagnetic interference of a dynamic inductive charging system as a function of different vehicle chassis height have not yet been established nor sufficiently studied.
- There is a lack of published work investigating techno-economic optimization of stationary, second-life battery storage solely for peak shaving in distributed, solar powered, off-grid charging stations.

2.2. Objectives

- To analyze and categorize on the basis of basic operating principles, power electronics topologies and performance parameters for currently used charging technologies of BEVs.
- To perform a comparative study among conducted, wireless and battery swapping topologies based on energy transfer efficiency, infrastructure needs and ease of user access.
- To evaluate major consequences of different charging topologies on utility grid stability, in terms of power quality, harmonic distortions and peak load management.
- To investigate emerging concepts in EV charging, with emphasis on V2G integration, renewable energy operated charging hubs, etc.

3. METHODOLOGY

In order to conduct a comprehensive, objective, and systematic synthesis of contemporary EV charging technologies, a systematic review methodology has been employed in this study. The study's framework is designed to systematically identify, screen, analyze, and synthesize technical literature, industry reports, and standardization

documents concerning BEV charging infrastructure. The methodology at its core involves a layered search strategy across major academic databases (IEEE Xplore, ScienceDirect, SpringerLink, and MDPI's open-access repositories) with the core search string built using targeted Boolean operators as follows: ("Electric Vehicle" OR "BEV") AND ("Charging Technologies" OR "Conductive Charging" OR "Wireless Power Transfer" OR "Vehicle-to-Grid").

After the first wave of data collection which resulted in an overwhelming corpus of data, stringent inclusion and exclusion criteria had to be imposed in order to filter down the selected data to relevant and high-quality content. Only peer-reviewed journal articles, extended conference papers and official white papers published by renowned international standards bodies (SAE, IEC, IEEE, etc.) within the past decade were included in the review. This restriction with regard to the publication time frame is meant to cover the contemporary technological paradigms, specifically the adoption of ultra-fast charging and advanced semiconductors in power converters. Works focusing solely on internal battery chemistry or works written in non-English were excluded.



Fig 1. Systematic Review methodology for EV Charging Technologies

After an initial automated screening, the collected data was manually assessed by examining the content of abstracts and conclusions to ensure that the studies at hand provided quantitative measures of charging efficiency, grid impact or economic feasibility, and were not just conceptualized or speculative. Data was then extracted from the selected literature using a standardized data extraction protocol that included the type of converter topologies employed, power levels, efficiencies, operating frequency (in case of wireless solutions) and documented grid distortions.

In order to build up the comprehensive comparative survey, the data extracted was categorized into three groups: conductive charging (AC and DC), wireless power transfer (static and dynamic), and alternative refueling strategies (battery swap). All technologies under each of these categories were analyzed in terms of several standard performance indicators: peak power, overall efficiency (from grid to battery), capital costs, space requirements and the level of automation required.

In addition to this, a thematic analysis was conducted for the qualitative data related to grid integration and smart charging policies. Power quality mitigation techniques and architectures, such as the implementation of active front end converters or decentralized energy storage, have been analyzed. This framework, by combining quantitative data with thematic qualitative analysis, forms a comprehensive model not only of the individual technologies but also their impact and potential inter-operation within an entire sustainable transport infrastructure and smart grid.

4. SURVEY OF EV CHARGING TECHNOLOGIES

The realm of BEV charging technologies is fundamentally divided between conductive and non-conductive (wireless) charging. Each possesses its unique set of architectural advantages and limitations. Conductive charging is a physical link between the EVSE and the EV, which is currently the dominant form worldwide. Conductive charging can further be categorized as Alternating Current (AC) or Direct Current (DC) charging. AC charging is generally broken down into Level 1 and Level 2, where Level 1 is achieved by standard household outlets (120V), outputting relatively little power (generally under 2kW). Level 2 charging uses 240V (or sometimes 400V) sources and can output from 3.3kW up to 22kW. In AC charging the power is conditioned by a device on board the EV, called the OBC, where it is then rectified from AC to DC power. The limit of the OBC is primarily dictated by its size, the heat that can be dissipated from it, and as a result the maximum amount of AC power that can be fed into it. For this reason AC charging can take between 4 and 15 hours depending on battery size. Direct Current Fast Charging (DCFC) circumvents the onboard limitation by providing an off board, high-powered connection. The AC is then rectified to DC at the DCFC station itself, allowing the power

electronics to be as large and powerful as they need to be and the battery is interfaced directly with the battery management system of the EV. The most common DCFC standards are from 50kW to 350kW with the use of multi-level converters and high frequency transformers, with the most recent charging stations expanding to 1MW+ charging stations which are intended for use on heavy duty vehicles. The disadvantage of DCFC is the large spikes in grid demand that the vehicles cause due to the extremely high amount of power drawn at one moment. Often, stationary battery storage is required at a charging station to store power from the grid when demand is low and supply it to the car at the required peak power levels.

Wireless Power Transfer (WPT) circumvents electrical connectors entirely, which provides unprecedented convenience and extreme durability especially in adverse environmental conditions such as heavy snow or rain. Inductive power transfer is the most mature WPT technology available today, relying on magnetic resonance and is operated by passing an alternating current through a transmitter coil (typically 85 kHz, according to the SAE J2954 standard), mounted on the ground, to induce a current in a secondary receiver coil located beneath the vehicle. The efficiency of the WPT is directly tied to two main parameters: coupling coefficient (k) and quality factor (Q). As long as the alignment between the coils and air gap is maintained at an ideal level, stationary WPT systems can achieve efficiencies in excess of 90%, compared to the conductive charging efficiency of over 95%. A dynamic WPT system exists in the form of charging an EV as it drives over an array of segmented coils laid in the road, theoretically reducing the required on-board battery capacity, but is extremely difficult and expensive to implement due to the vast scale of roadway infrastructure renovation and grid integration that would be required.

Table 1. Summary of various charging technologies

Technology Type	Power Level	Typical Efficiency	User Convenience	Infrastructure Cost	Grid Impact
AC Conductive (L1/L2)	1.4 kW - 22 kW	90-95%	Low (Cable handling)	Low	Low (Distributed)
DC Fast Charging (L3)	50 kW - 350+ kW	92-97%	Medium (Heavy cables)	High	High (Peak spikes)
Static Inductive WPT	3.3 kW - 22 kW	85-92%	High (Automated)	Medium-High	Low-Medium
Dynamic WPT	Variable	80-85%	Very High (In-motion)	Extremely High	Medium
Battery Swapping	N/A (Mechanical)	Grid-dependent	Very High (< 5 mins)	Very High	Low (Off-peak charging)

Lastly, battery swapping is a different method of getting electricity into the vehicle altogether. In battery swapping,

instead of waiting for electrons to replenish a dead battery pack, automated stations remove the dead battery and replace it with a fully charged one in less than five minutes. This technology takes the electrical charging constraint out of the EV and into a charging station. Since charging batteries is no longer time critical for the EV, the station can take a long time to charge all its dead batteries overnight at off-peak times, essentially balancing the grid load. The problem, however, is standardizing battery size, thermal interface and connection type between many fiercely competitive automotive manufacturers is nearly impossible and so this technology is very localized in its application.

5. RESULTS AND DISCUSSIONS

It is clear from the comparative survey that there is no charging solution that will fix all problems inherent in electric mobility, instead the correct answer depends heavily on the application, location and behavior. The survey states that AC conductive charging is clearly the most economic and widely used solution for residential and office charging. The high total efficiency for energy transfer and low infrastructure capital outlay that this solution offers ensures it will form the back bone of electric vehicle charging for the foreseen future. From the graphs, it is evident however that for travelling between cities or the running of commercial fleets, DCFC must play a key role. There must be an argument made however concerning the engineering compromise when discussing DCFC; as power levels go up to the 350kW mark and towards the Megawatt level, the thermal losses through the cable and converters grow significantly, liquid cooling is required in the cables which dramatically increases maintenance and mechanical costs. Furthermore, the local grid impact of groups of DCFC's results in the deterioration of power quality shown by the large voltage sags and harmonics produced, proving it is not sustainable to have completely unfettered high power charging, without some form of intervention through the smart grid.

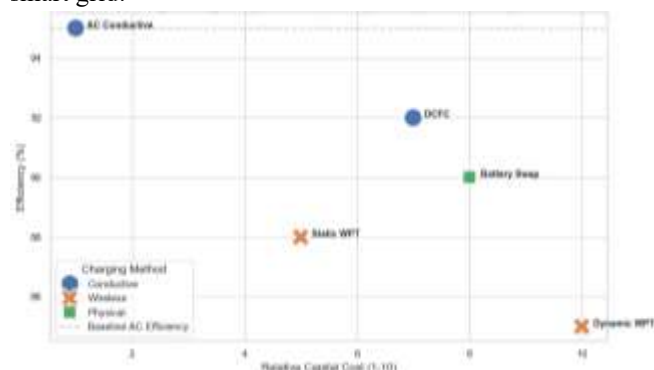


Fig 2. Efficiency vs Capital cost outlay

When looking at the Wireless Power Transfer technology, one can see it is an application of an idea that is slowly moving from theoretical to actual, from a "wow factor" to commercial feasibility. Although, the benefits to user convenience and automatic charging cannot be overstated,

the graph again shows a 3%-8% deficit in overall efficiency when compared to a direct conductive method due to losses through the air gap. As argued by the paper the solution to this magnetic flux leakage requires complicated resonant topologies and Wide band gap semiconductors, which subsequently increase the capital cost per kW. Dynamic WPT is again the most polarizing answer in the paper; providing the nirvana of endless range, the huge amount of capital required for a full overhaul of the infrastructure makes its deployment only viable in a closed loop system such as public transport networks.

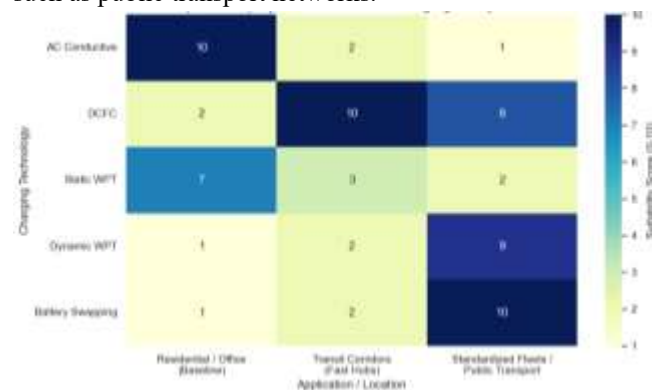


Fig 3. Optimal Deployment: A Stratified Charging Ecosystem

It seems the conclusion to be drawn from this is that there will be a convergence of technologies in the coming years; The sheer grunt required from DCFC should be combined with smart load management from V2G technology and the robustness offered by integrated solar plus storage systems. Battery swapping although incredibly successful in niche and defined areas (like a standardized fleet of vehicles), cannot really be compared for mainstream consumers, owing to closed systems.

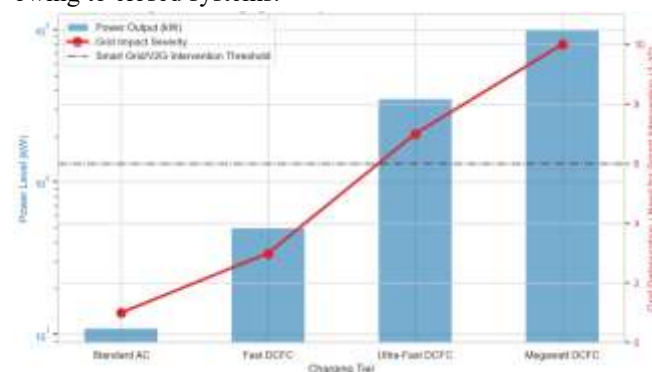


Fig 4. High Power Charging: Grid Impact and Need for smart Grids

6. CONCLUSION

The electrification of the automotive industry is the cornerstone of the worldwide pursuit for sustainability, but it cannot exist in isolation without efficient charging infrastructure that underpins this transformation. This literature and comparative survey has introduced and compared the wide spectrum of BEV charging technology in all its operational strengths and system weaknesses.

Conductive AC and DC charging are established technologies that forms the core of EV charging. They are energy efficient and rapid when it comes to replenishing EV batteries but often at the expense of grid instability and user effort. The alternative, wireless power transfer systems, especially magnetic resonance inductive charging, is an automatic and efficient technology. It has the potential to redefine user experience with EVs, but currently faces issues such as air-gap power losses and the high cost of installation. As the ownership of EVs grows at a faster rate than expected, the concept of solely pushing out higher kilowatt should shift towards harmonizing with the existing electrical grid. As this survey have demonstrated, EV charging is no longer solely about 'higher kilowatt', rather it is about 'smarter integration'. Decentralized smart charging protocols, V2G systems, renewable integrated microgrids must be implemented so as to handle the huge burden on the grid from electric fleets, and the successful deployment of a mix-and-match but well-coordinated charging infrastructure system will eventually enable the realization of universal electric mobility.

REFERENCES

- [1] Acharige, S. S. G., Haque, M. E., Arif, M. T., Hosseinzadeh, N., Hasan, K. N., & Oo, A. M. T. (2023). Review of Electric Vehicle Charging Technologies, Standards, Architectures, and Converter Configurations. *IEEE Access*, 11, 41218–41255. <https://doi.org/10.1109/access.2023.3267164>
- [2] Al-Amin, Burton, C., Shoeb, M., Ferdous, S., & Shafiullah, G. (2023). Impact of EV Charger on the Utility Grid and Reactive Power Operation of EV. 2023 International Conference on Sustainable Technology and Engineering (i-COSTE), 1–6. <https://doi.org/10.1109/icoste60462.2023.10500810>
- [3] Alshareef, S. M., & Morsi, W. G. (2017). Impact of fast charging stations on the voltage flicker in the electric power distribution systems. 2017 IEEE Electrical Power and Energy Conference (EPEC). <https://doi.org/10.1109/epec.2017.8286226>
- [4] Bai, S., Zhu, Y., Li, T., Zhang, Y., Wu, L., Geng, D., & Li, B. (2022). Overview of Electric Vehicle Charging Standards. 2022 IEEE/IAS Industrial and Commercial Power System Asia (I&CPS Asia), 700–705. <https://doi.org/10.1109/icpsasia55496.2022.9949844>
- [5] George, R., Vaidyanathan, S., & Deepa, K. (2019). Ev Charging Station Locator With Slot Booking System. 2019 2nd International Conference on Power and Embedded Drive Control (ICPEDC), 342–348. <https://doi.org/10.1109/icpedc47771.2019.9036610>
- [6] Goldstein, H. (2022). What V2G Tells Us About EVs and the Grid: Vehicle-to-grid technology adds another layer of complexity to the electric-vehicle transition. *IEEE Spectrum*, 59, 2–2. <https://doi.org/10.1109/mspec.2022.9852404>
- [7] Patil, B. P., Doodhwal, P., Kumar, P., Dudhawal, R. K., & Khonje, A. (2024). Smart Algorithm for Wireless EV Charging. 2024 4th International Conference on Emerging Frontiers in Electrical and Electronic Technologies (ICEFEET), 1–6. <https://doi.org/10.1109/icefeet64463.2024.10866513>
- [8] Petreus, D., Patarau, T., Etz, R., & Cirstea, M. (2021). Renewable energy EV charging station. 2021 International Aegean Conference on Electrical Machines and Power Electronics (ACEMP) & 2021 International Conference on Optimization of Electrical and Electronic Equipment (OPTIM), 28–33. <https://doi.org/10.1109/optimacemp50812.2021.9590053>
- [9] Rani, S. L., & Raju, V. V. R. (2022). V2G and G2V Technology in Micro-Grid Using Bidirectional Charger: A Review. 2022 Second International Conference on Power, Control and Computing Technologies (ICPC2T), 1–5. <https://doi.org/10.1109/icpc2t53885.2022.9777085>
- [10] Samanchuen, T., Jirasereamornkul, K., Ekkaravarodome, C., & Singhavilai, T. (2019). A Review of Wireless Power Transfer for Electric Vehicles: Technologies and Standards. 2019 4th Technology Innovation Management and Engineering Science International Conference (TIMES-iCON), 1–5. <https://doi.org/10.1109/timesicon47539.2019.9024667>
- [11] Tur, M., & Apaydin, E. (2022). Optimization Of Electric Vehicle Charging Stations. 2022 Global Energy Conference (GEC), 197–201. <https://doi.org/10.1109/gec55014.2022.9987046>
- [12] Xue, Z., Liu, W., Liu, C., & Chau, K. T. (2025). Critical Review of Wireless Charging Technologies for Electric Vehicles. *World Electric Vehicle Journal*, 16, 65. <https://doi.org/10.3390/wevj16020065>
- [13] Zhu, X., Mather, B., & Mishra, P. (2020). Grid Impact Analysis of Heavy-Duty Electric Vehicle Charging Stations. 2020 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT), 1–5. <https://doi.org/10.1109/isgt45199.2020.9087651>