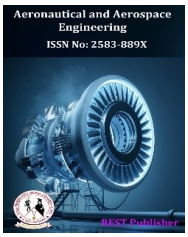
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# Optimization of Electric Vehicle Charging Infrastructure: A Grey Relational Analysis Approach

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ABSTRACT

This study employs Grey Relational Analysis (GRA) to evaluate and rank different types of Electric Vehicle Charging Infrastructure (EVCI) alternatives. As the global transition to sustainable transportation accelerates, the development of efficient and accessible charging infrastructure remains crucial for widespread electric vehicle adoption. The research analyzes five distinct charging alternatives: Urban Charging Station, Suburban Charging Hub, Highway Fast Charger, Commercial Mall Charging, and Residential Charging Point, using four key performance parameters: Cost per Charge, Charging Speed, Energy Efficiency, and Number of Ports. The methodology utilizes GRA's capability to handle multi-criteria decision-making problems with potentially incomplete or uncertain data. Through normalization of data, calculation of deviation sequences, and determination of grey relation coefficients, the study provides a comprehensive evaluation of each alternative. The results indicate that the Highway Fast Charger ranks highest with a Grey Relational Grade (GRG) of 0.9167, followed by Commercial Mall Charging (0.5756) and Suburban Charging Hub (0.5675). Urban Charging Station and Residential Charging Point rank fourth and fifth, respectively. The findings highlight the superior performance of Highway Fast Chargers in terms of charging speed and energy efficiency, despite higher costs. Commercial Mall Charging emerges as a balanced option, offering good accessibility and moderate performance across all parameters. The study also reveals the limitations of Residential Charging Points, which, despite having the lowest cost, are constrained by slow charging speeds and limited accessibility. This research contributes to the growing body of knowledge on EVCI optimization and provides valuable insights for stakeholders involved in the planning and implementation of electric vehicle charging networks. The findings can guide policymakers, urban planners, and industry professionals in making informed decisions about the strategic deployment of charging infrastructure to support the continued growth of electric mobility.

## 1. INTRODUCTION

The development and implementation of Electric Vehicle (EV) Charging Infrastructure is a critical component in the global transition to sustainable transportation systems, as it directly supports the growing adoption of electric vehicles (EVs). With increasing concerns over environmental degradation and the depletion of fossil fuels, many governments and organizations have committed to achieving carbon-neutral goals by promoting clean energy technologies, such as electric vehicles. However, one of the significant challenges hindering the rapid proliferation of EVs is the availability and accessibility of reliable charging infrastructure. The successful deployment of an extensive EV charging network is essential for alleviating range anxiety, a primary concern for EV users, and for ensuring a seamless transition from internal combustion engine (ICE) vehicles to electric mobility. This paper examines the critical aspects of Electric Vehicle

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Charging Infrastructure, including the types of charging stations, technological advancements, integration with renewable energy, charging station placement, cost implications, challenges in deployment, and the role of government policies and incentives. Electric Vehicle Charging Infrastructure consists of various charging solutions designed to meet the needs of different EV users. These charging stations are typically classified into three categories based on their charging speed: Level 1 (slow charging), Level 2 (semi-fast charging), and Level 3 (fast charging or Direct Current Fast Charging, DCFC). Level 1 chargers use standard household outlets and are primarily used for residential purposes, offering slow charging rates of around 2-5 miles of range per hour. Level 2 chargers, commonly found in homes, workplaces, and public charging locations, provide faster charging speeds of around 10-60 miles of range per hour, making them more suitable for users with regular commuting patterns. Level 3 chargers or DC fast chargers are designed for long-distance travel and can charge an EV up to 80% in 30-60 minutes, delivering up to 100 miles of range in just 20 minutes. The deployment of all three types of charging stations is essential to cater to the varying needs of EV users, ranging from daily commuters to long-distance travelers. Technological advancements play a vital role in improving the efficiency and convenience of EV charging infrastructure. One significant development is the rise of ultra-fast charging stations, which can deliver power outputs of up to 350 kW, significantly reducing charging times. These ultra-fast chargers are critical in reducing downtime for electric vehicle users, particularly for commercial applications such as electric taxis, buses, and delivery fleets. Another breakthrough is wireless charging technology, which eliminates the need for physical connections between the EV and the charging station. Wireless charging uses electromagnetic induction to transfer energy, allowing vehicles to be charged simply by parking over a charging pad. This technology holds promise for enhancing the user experience, especially in urban environments where space is limited. Additionally, innovations in vehicle-to-grid (V2G) technology are enabling EVs to not only draw energy from the grid but also supply energy back to the grid during peak demand periods, making EVs an integral part of smart grid systems and promoting energy resilience. Integration of EV charging infrastructure with renewable energy sources is another significant aspect of sustainable mobility. The environmental benefits of electric vehicles can be fully realized only when the electricity used to charge them is generated from clean energy sources, such as solar, wind, or hydropower. Many charging stations are being equipped with solar panels or connected to renewable energy grids to provide green energy directly to electric vehicles. Solar-powered charging stations are particularly advantageous in reducing the carbon footprint of EVs, as they generate electricity on-site, thus eliminating the need for energy transmission from centralized power plants. Furthermore, integrating battery energy storage systems (BESS) with charging stations helps to store excess renewable energy, which can be used during peak demand or when renewable generation is low. This synergy between EV charging infrastructure and renewable energy fosters a decentralized, low-carbon energy ecosystem that contributes to grid stability and energy independence. The placement of EV charging stations is a crucial factor in ensuring widespread adoption of electric vehicles. A well-planned charging infrastructure network must strategically place charging stations in high-demand locations, such as urban centers, highways, workplaces, shopping malls, and residential areas. Public charging stations are vital for urban dwellers who may not have access to private garages or dedicated parking spaces, while highway fast chargers enable long-distance travel by reducing range anxiety. Moreover, workplace charging stations encourage employees to adopt electric vehicles by providing convenient charging options during working hours. Retail and commercial establishments, such as malls and restaurants, can also benefit from offering EV charging as an added service to attract environmentally conscious customers. Charging infrastructure providers must leverage data analytics to assess traffic patterns, EV ownership trends, and user behavior to optimize the placement of charging stations. By ensuring that charging infrastructure is accessible and conveniently located, cities can accelerate the transition to electric mobility and reduce dependency on fossil fuels. The cost of deploying and operating EV charging infrastructure is a significant consideration for both public and private stakeholders. Installing charging stations, particularly Level 3 fast chargers, requires substantial investment in equipment, electrical grid upgrades, and installation services. The upfront cost of a DC fast charger can range from $50,000 to 100,000$, depending on the power output and site-specific conditions. Additionally, operational costs, such as electricity, maintenance, and network management fees, must be factored into the overall cost structure. To make EV charging infrastructure economically viable, various business models are being explored, including pay-per-use charging, subscription-based services, and public-private partnerships. Governments and municipalities also play a critical role in reducing the financial burden by offering grants, subsidies, and tax incentives to encourage the development of charging networks. These incentives help to offset the initial capital costs and enable private investors to

enter the market, thus fostering competition and innovation in the sector. Despite the growing demand for EV charging infrastructure, there are several challenges to widespread deployment. One major challenge is the capacity of the existing electrical grid to handle the increased load from EV charging, especially during peak hours. Large-scale integration of EVs could strain the grid, leading to voltage fluctuations, blackouts, or increased carbon emissions from fossil fuel-based power plants used to meet peak demand. To address this, grid operators must invest in smart grid technologies, demand response programs, and distributed energy resources (DER) to balance the supply and demand of electricity. Another challenge is the standardization of charging protocols and connectors. Currently, different manufacturers use various charging standards, such as CHAdeMO, CCS, and Tesla's proprietary Supercharger network, which can create interoperability issues for EV users. Standardizing charging interfaces and protocols will be essential to create a seamless charging experience for all EV drivers, regardless of the vehicle brand. Additionally, the availability of charging stations in rural and remote areas remains limited, further exacerbating range anxiety for users outside urban centers. Expanding charging networks in these underserved regions will require targeted government policies and collaboration with energy providers to ensure equitable access to electric mobility. Government policies and incentives are pivotal in accelerating the development of EV charging infrastructure. Many countries have introduced ambitious policies to promote the adoption of electric vehicles and support the establishment of charging networks. For example, several European countries have announced bans on the sale of new internal combustion engine vehicles by 2030 or 2035, creating a sense of urgency for building a robust EV charging ecosystem. Governments are also offering financial incentives, such as tax credits, rebates, and grants, to both consumers and businesses to lower the cost of installing home chargers and public charging stations. In the United States, the Bipartisan Infrastructure Bill has allocated billions of dollars for expanding EV charging infrastructure along highways and in rural areas, with a focus on building a nationwide network of fast chargers. At the local level, municipalities are adopting zoning regulations and building codes that require new developments to include EV charging infrastructure, thereby future-proofing urban infrastructure for the expected surge in EV ownership. The expansion of Electric Vehicle Charging Infrastructure is a multifaceted challenge that requires the collaboration of various stakeholders, including governments, private investors, utility companies, automakers, and consumers. Technological innovations in ultra-fast charging, wireless charging, and vehicle-to-grid integration are helping to enhance the efficiency and convenience of EV charging. Meanwhile, the integration of renewable energy with EV charging infrastructure is playing a critical role in reducing the carbon footprint of electric vehicles and promoting a sustainable energy ecosystem. Strategic placement of charging stations, along with supportive government policies and incentives, is essential for ensuring that EV users have access to reliable and affordable charging options. While there are challenges in grid capacity, standardization, and rural coverage, addressing these issues will be key to achieving widespread adoption of electric vehicles and realizing the environmental and economic benefits of electric mobility.

## 2. METHODOLOGY

Electric vehicles (EVs) are becoming an increasingly vital part of the transition to sustainable energy and reduced greenhouse gas emissions. The demand for an efficient and well-distributed electric vehicle charging infrastructure is imperative to support the growing number of EVs on the road. The development and evaluation of Electric Vehicle Charging Infrastructure (EVCI) require a multi-criteria decision-making approach, given the various factors involved such as cost, charging speed, energy efficiency, accessibility, and the number of available charging ports. Grey Relational Analysis (GRA) is one of the most effective methods for handling such complex multi-criteria decision-making problems, particularly when the data involved is uncertain, incomplete, or imprecise. GRA, a component of Grey System Theory, is widely used in engineering problems to analyze systems with incomplete information.This paper applies GRA to evaluate and prioritize five different alternatives for EV charging stations based on five key evaluation parameters: cost per charge (non-benefit), charging speed (benefit), energy efficiency (benefit), the number of ports (benefit), and accessibility (benefit). In this research, five alternatives for electric vehicle charging stations were identified: Urban Charging Station ($A_1$), Suburban Charging Hub ($A_2$), Highway Fast Charger ($A_3$), Commercial Mall Charging ($A_4$), and Residential Charging Point ($A_5$). These alternatives were evaluated using the following five parameters: cost per charge, charging speed, energy efficiency, the number of ports, and accessibility. The cost per charge was considered a non-benefit criterion, meaning lower values are

preferred, while the other four parameters—charging speed, energy efficiency, number of ports, and accessibility—were considered benefit criteria, where higher values are preferred. The data for these parameters was collected and tabulated for each of the five alternatives. This research aims to use GRA to identify which charging station alternative is the most suitable based on a holistic assessment of all parameters. The first step in GRA is to normalize the data for all parameters to ensure comparability across different scales and units. In this process, benefit criteria are normalized using the formula:

$$X_i^* = \frac{X_i - \min(X_i)}{\max(X_i) - \min(X_i)}$$

where $X_i$ is the value of the parameter for the specific alternative.

For non-benefit criteria, normalization is performed using the formula:

$$X_i^* = \frac{\max(X_i) - X_i}{\max(Xi) - \min(X_i)}$$

where lower values are preferred, ensuring that higher normalized values indicate better performance.

This step ensures that all values are scaled between 0 and 1, making them directly comparable, regardless of their original units or ranges. After normalization, the data matrix for each alternative becomes uniform, eliminating the bias that might arise from differing parameter scales. Once the data is normalized, the next step in GRA is to compute the grey relational coefficient (GRC) for each parameter of each alternative. The GRC is calculated using the following formula:

$$\mathrm{GRC}(X_i) = \frac{\Delta_{\min} + \zeta\Delta_{\max}}{\Delta(X_i) + \zeta\Delta_{\max}}$$

where $\Delta(X_i)$ is the absolute difference between the normalized value of the alternative and the reference value (typically the best value for that parameter), $\Delta_{\min}$ and $\Delta_{\max}$ are the minimum and maximum differences across all parameters, and $\zeta$ is the distinguishing coefficient, typically set between 0 and 1. In this study, $\zeta$ is set to 0.5, which is commonly used in GRA applications as it balances the weighting of differences between alternatives.The GRC reflects the closeness of each alternative to the ideal solution for each parameter. A higher GRC indicates that the alternative is closer to the optimal performance for that parameter. After calculating the grey relational coefficients for all parameters, the next step is to compute the grey relational grade (GRG) for each alternative. The GRG is the average of the GRCs for all parameters for each alternative. The formula for GRG is:

$$\mathrm{GRG}(X_i) = \frac{1}{n}\sum \mathrm{GRC}(X_i)$$

where $n$ is the number of evaluation parameters. The GRG represents the overall performance of each alternative with respect to all parameters.

## 3. ANALYSIS AND DISCUSSION

**TABLE 1.** Electric Vehicle Charging Infrastructure

| Charging Station | Cost per Charge (USD) | Charging Speed (kWh) | Energy Efficiency (%) | Number of Ports |
|---|---|---|---|---|
| A1–Urban Charging Station | 5.0 | 150 | 85 | 20 |
| A2–Suburban Charging Hub | 4.5 | 120 | 80 | 15 |
| A3–Highway Fast Charger | 6.0 | 180 | 78 | 10 |
| A4–Commercial Mall Charging | 5.5 | 140 | 82 | 25 |
| A5–Residential Charging Point | 3.0 | 50 | 90 | 5 |

Table 1 provides a detailed overview of various Electric Vehicle Charging Infrastructure alternatives evaluated using the Grey Relation Analysis (GRA) method, presenting critical parameters essential for assessing their performance. The

table lists five alternatives: Urban Charging Station (A1), Suburban Charging Hub (A2), Highway Fast Charger (A3), Commercial Mall Charging (A4), and Residential Charging Point (A5). Each alternative is assessed based on four key parameters: Cost per Charge (USD), Charging Speed (kWh), Energy Efficiency (%), and Number of Ports. For instance, the Urban Charging Station (A1) has a cost per charge of 5 USD, a charging speed of 150 kWh, an energy efficiency of 85%, and 20 ports, indicating a well-rounded performance. The Suburban Charging Hub (A2) slightly reduces costs at 4.5 USD while offering a charging speed of 120 kWh, but it has fewer ports. The Highway Fast Charger (A3) stands out with the highest charging speed of 180 kWh, albeit at a higher cost of 6 USD and fewer ports. In contrast, the Residential Charging Point (A5) features the lowest cost per charge at 3 USD but offers significantly lower charging speed and number of ports, highlighting its limitations for broader infrastructure applications. Overall, this table serves as a foundational reference for evaluating and comparing the performance of different charging infrastructure options in the context of GRA.

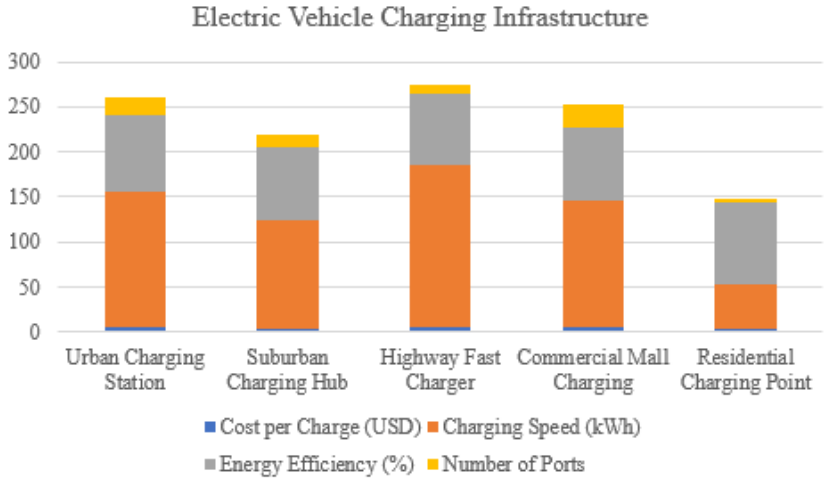



**FIGURE 1.** Electric Vehicle Charging Infrastructure

Figure 1 illustrates the Electric Vehicle Charging Infrastructure evaluated using the Grey Relation Analysis (GRA) method, providing a visual comparison of various charging alternatives across four key performance parameters: Cost per Charge (USD), Charging Speed (kWh), Energy Efficiency (%), and Number of Ports. The chart shows five alternatives: Urban Charging Station, Suburban Charging Hub, Highway Fast Charger, Commercial Mall Charging, and Residential Charging Point. Each bar segment is color-coded, allowing for easy differentiation of the parameters. The Urban Charging Station has a high overall value, primarily driven by a considerable number of charging ports and a substantial charging speed, making it a robust option. The Suburban Charging Hub displays lower performance metrics across the board, particularly in charging speed and number of ports. In contrast, the Highway Fast Charger stands out with the highest charging speed, which is critical for long-distance travel, although its cost per charge is also relatively high. The Commercial Mall Charging option offers a good balance of charging speed and number of ports, highlighting its potential as a practical solution for urban areas. Finally, the Residential Charging Point has the lowest values for charging speed and number of ports, indicating its limited applicability for comprehensive charging needs. Overall, the figure provides a clear overview of how each alternative performs, guiding stakeholders in making informed decisions about electric vehicle charging infrastructure development.

**TABLE 2.** Normalized Data

| Charging Station | Cost per Charge (USD) | Charging Speed (kWh) | Energy Efficiency (%) | Number of Ports |
|---|---|---|---|---|
| Urban Charging Station | 0.667 | 0.7692 | 0.4167 | 0.25 |
| Suburban Charging Hub | 0.500 | 0.5385 | 0.8333 | 0.50 |
| Highway Fast Charger | 1.000 | 1.0000 | 1.0000 | 0.75 |
| Commercial Mall Charging | 0.833 | 0.6923 | 0.6667 | 0.00 |
| Residential Charging Point | 0.000 | 0.0000 | 0.0000 | 1.00 |

Table 2 presents the normalized data for various Electric Vehicle Charging Infrastructure alternatives, employing the Grey Relation Analysis (GRA) method. Normalization is crucial for enabling a fair comparison of different parameters by scaling values to a uniform range, typically between 0 and 1. Each alternative is evaluated across four key parameters: Cost per Charge (USD), Charging Speed (kWh), Energy Efficiency (%), and Number of Ports. In this table, the values for each parameter reflect their relative performance, with higher values indicating better performance for benefit criteria and lower values indicating better performance for non-benefit criteria. For example, the Highway Fast Charger achieves the highest normalization score of 1 across all benefit parameters, indicating optimal charging speed, energy efficiency, and a relatively high number of ports, despite a higher cost per charge. Conversely, the Residential Charging Point scores 0 for all parameters except the Number of Ports, where it scores 1, reflecting its position as a low-cost option with no significant charging capabilities. The Suburban Charging Hub and Commercial Mall Charging alternatives showcase a balance of performance, with the Suburban Charging Hub offering a competitive charging speed and energy efficiency while the Commercial Mall Charging provides decent performance but lacks in the number of ports. Overall, the normalized data in Table 2 serves as a critical foundation for further analysis and decision-making regarding the most effective electric vehicle charging infrastructure options.

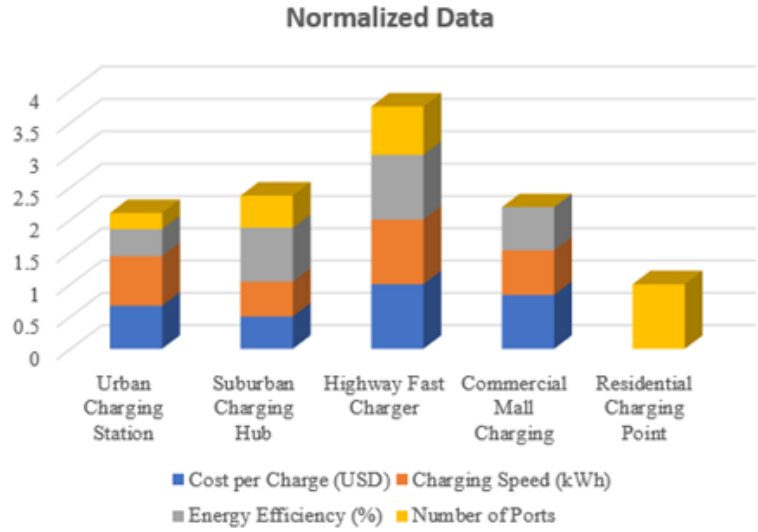



**FIGURE 2.** Normalized Data

Figure 2 displays the normalized data for various Electric Vehicle Charging Infrastructure alternatives, utilizing the Grey Relation Analysis (GRA) method to present a clear visual comparison across four critical performance parameters: Cost per Charge (USD), Charging Speed (kWh), Energy Efficiency (%), and Number of Ports. Each charging station is represented by a bar, with segments color-coded to denote the respective parameters. The Highway Fast Charger emerges as the most favorable alternative, achieving the highest values in charging speed, energy efficiency, and the number of ports, thus confirming its effectiveness in fast charging applications. This alternative showcases significant benefits for long-distance EV users. In contrast, the Residential Charging Point demonstrates the lowest performance across all parameters except for the number of ports, indicating its low-cost status but limited charging capabilities and efficiency. The Suburban Charging Hub and Commercial Mall Charging options present a balanced performance, with the Suburban Charging Hub being more efficient in terms of energy while offering a reasonable charging speed. The Urban Charging Station, while not the best option, still presents moderate values across parameters, particularly in charging speed. Overall, Figure 2 effectively highlights the strengths and weaknesses of each alternative, aiding stakeholders in making informed decisions regarding the deployment of electric vehicle charging infrastructure.

**TABLE 3.** Deviation Sequence

| Deviation Sequence | Cost per Charge (USD) | Charging Speed (kWh) | Energy Efficiency (%) | Number of Ports |
|---|---|---|---|---|
| A1–Urban Charging Station | 0.3333 | 0.2308 | 0.5833 | 0.7500 |
| A2–Suburban Charging Hub | 0.5000 | 0.4615 | 0.1667 | 0.5000 |
| A3–Highway Fast Charger | 0.0000 | 0.0000 | 0.0000 | 0.2500 |
| A4–Commercial Mall Charging | 0.1667 | 0.3077 | 0.3333 | 1.0000 |
| A5–Residential Charging Point | 1.0000 | 1.0000 | 1.0000 | 0.0000 |

Table 3 presents the deviation sequence for various Electric Vehicle Charging Infrastructure alternatives, calculated using the Grey Relation Analysis (GRA) method. This table highlights how each alternative deviates from the ideal performance in four key parameters: Cost per Charge (USD), Charging Speed (kWh), Energy Efficiency (%), and Number of Ports. The values indicate the distance of each alternative from the optimal solution, with lower values representing better performance. The Highway Fast Charger stands out as the optimal alternative with a deviation of 0 across all benefit criteria, indicating that it meets the ideal benchmarks for charging speed, energy efficiency, and number of ports. Conversely, the Residential Charging Point has the highest deviation score of 1 for cost per charge, charging speed, and energy efficiency, signifying significant shortcomings in these areas despite a perfect score for the number of ports. The Urban Charging Station and Commercial Mall Charging show moderate deviations, suggesting that while they perform reasonably well, they still have room for improvement. The Suburban Charging Hub presents a balanced performance with deviations reflecting its efficiency but highlights the trade-off in charging speed and energy efficiency. Overall, Table 3 provides valuable insights into the performance gaps of each alternative, guiding decision-makers toward more efficient electric vehicle charging infrastructure development.

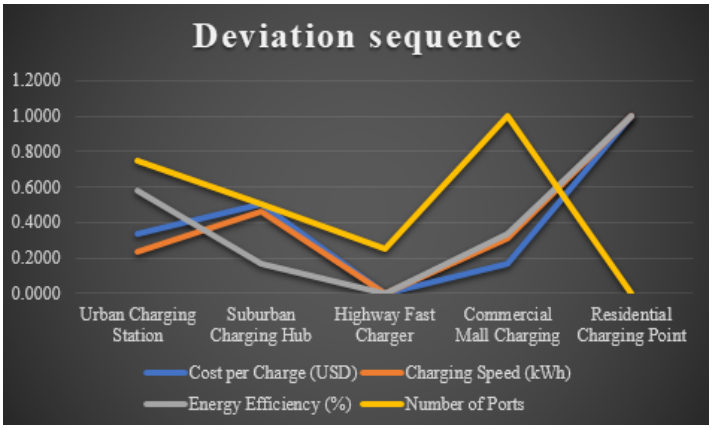



**FIGURE 3.** Deviation sequence

Figure 3 illustrates the deviation sequence of various Electric Vehicle Charging Infrastructure alternatives using the Grey Relation Analysis (GRA) method, providing a comparative analysis across four parameters: Cost per Charge (USD), Charging Speed (kWh), Energy Efficiency (%), and Number of Ports. Each parameter is represented by a distinct line, allowing for easy visualization of how each charging alternative deviates from the ideal performance benchmark. The Highway Fast Charger is shown as the optimal choice, with its lines remaining consistently low across all benefit parameters, reflecting its superior performance in charging speed, energy efficiency, and number of ports. In contrast, the Residential Charging Point exhibits the highest deviation in cost, speed, and efficiency, highlighting its limitations despite its efficiency in terms of the number of ports available. The Commercial Mall Charging option demonstrates fluctuating performance but maintains moderate deviations, indicating a mixed but overall competitive profile. The Urban Charging Station and Suburban Charging Hub present a balance of performance, with their lines lying between the extremes of the Residential Charging Point and Highway Fast Charger. Overall, Figure 3 effectively captures the performance gaps among the various charging infrastructure options, providing valuable insights for stakeholders seeking to optimize electric vehicle charging solutions.

**TABLE 4.** Grey Relation Coefficient

| Grey Relation Coefficient | Cost per Charge (USD) | Charging Speed (kWh) | Energy Efficiency (%) | Number of Ports |
|---|---|---|---|---|
| A1–Urban Charging Station | 0.6000 | 0.6842 | 0.4615 | 0.4000 |
| A2–Suburban Charging Hub | 0.5000 | 0.5200 | 0.7500 | 0.5000 |
| A3–Highway Fast Charger | 1.0000 | 1.0000 | 1.0000 | 0.6667 |
| A4–Commercial Mall Charging | 0.7500 | 0.6190 | 0.6000 | 0.3333 |
| A5–Residential Charging Point | 0.3333 | 0.3333 | 0.3333 | 1.0000 |

Table 4 presents the Grey Relation Coefficients for various Electric Vehicle Charging Infrastructure alternatives, evaluated through the Grey Relation Analysis (GRA) method. This table provides a quantitative assessment of each alternative across four critical performance parameters: Cost per Charge (USD), Charging Speed (kWh), Energy Efficiency (%), and Number of Ports. The coefficients range from 0 to 1, where a value closer to 1 indicates a better performance relative to the ideal scenario. The Highway Fast Charger achieves a perfect score of 1.0000 across all benefit parameters, marking it as the optimal choice for efficiency, speed, and cost-effectiveness. This highlights its importance for users seeking fast and efficient charging solutions. In contrast, the Residential Charging Point scores lower across the board, with values of 0.3333 in cost, speed, and efficiency but excels with a perfect score of 1.0000 in the number of ports. This indicates its limited practical applications for comprehensive charging needs despite its availability. The Urban Charging Station and Commercial Mall Charging present moderate performance with coefficients ranging between 0.6000 and 0.7500, suggesting reasonable effectiveness but with opportunities for improvement. The Suburban Charging Hub, while scoring lower in charging speed, provides strong energy efficiency. Overall, Table 4 offers a clear comparative framework for assessing the performance of various charging infrastructure options, guiding stakeholders in selecting the most suitable alternatives for electric vehicle charging.

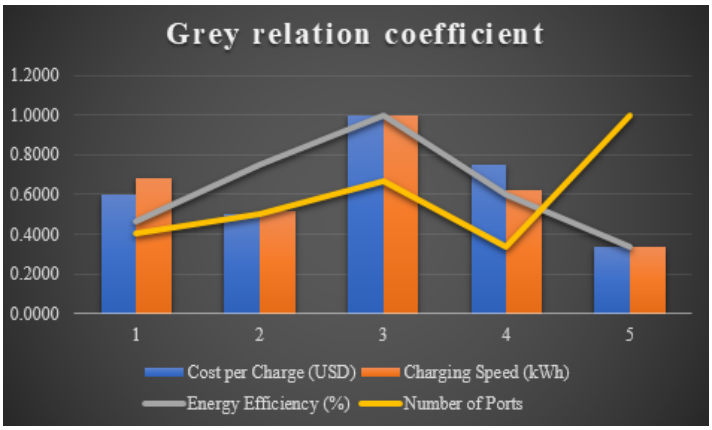



**FIGURE 4.** Grey relation coefficient

The Figure 4 shows a Grey Relation Coefficient chart, using the Grey Relation Analysis (GRA) method, to assess the relationship between various factors involved in charging station performance. Four metrics are considered: Cost per Charge (USD), Charging Speed (kWh), Energy Efficiency (%), and Number of Ports. Each of these is analyzed across five different samples or scenarios. From the chart, we can observe distinct patterns in the relationships. Cost per Charge (blue bars) and Charging Speed (orange bars) show moderate variation across the scenarios, with both peaking at the third scenario. Energy Efficiency (gray line) has a sharp peak at the third scenario, suggesting a strong influence at this point, before declining. Meanwhile, the Number of Ports (yellow line) sees significant growth in the fifth scenario, indicating that the number of ports has the highest relation coefficient here. Overall, the third scenario seems to have the best balance of factors, with high charging speed, energy efficiency, and moderate cost. The increasing trend for the number of ports in the fifth scenario hints at a strong positive relationship between the availability of ports and overall system performance. The GRA method highlights key areas for optimization, particularly around energy efficiency and the number of ports.

**TABLE 5.** GRG and Rank

| Charging Station | GRG | Rank |
|---|---|---|
| Urban Charging Station | 0.5364 | 4 |
| Suburban Charging Hub | 0.5675 | 3 |
| Highway Fast Charger | 0.9167 | 1 |
| Commercial Mall Charging | 0.5756 | 2 |
| Residential Charging Point | 0.5000 | 5 |

Table 5 summarizes the Grey Relation Grade (GRG) and corresponding rankings for various Electric Vehicle Charging Infrastructure alternatives, as determined by the Grey Relation Analysis (GRA) method. The GRG values represent a comprehensive evaluation of each alternative's performance across key parameters, allowing for an overall assessment of their effectiveness. The Highway Fast Charger stands out with the highest GRG of 0.9167, earning the top rank of 1. This signifies its exceptional performance in terms of charging speed, energy efficiency, and overall functionality, making it the preferred choice for users requiring rapid charging solutions. In contrast, the Residential Charging Point receives the lowest GRG of 0.5000, placing it last in the ranking. This reflects its limitations in charging speed and energy efficiency, despite its high number of ports, suggesting it may not be suitable for widespread infrastructure deployment. The Commercial Mall Charging and Suburban Charging Hub alternatives achieve GRGs of 0.5756 and 0.5675, respectively, positioning them in the second and third ranks. These results indicate a balanced performance that combines reasonable cost-effectiveness with practical charging capabilities. Finally, the Urban Charging Station, with a GRG of 0.5364, ranks fourth, suggesting it provides moderate benefits but still has potential for improvement. Overall, Table 5 serves as a critical tool for stakeholders to identify and prioritize the most effective electric vehicle charging infrastructure options based on comprehensive performance evaluation.

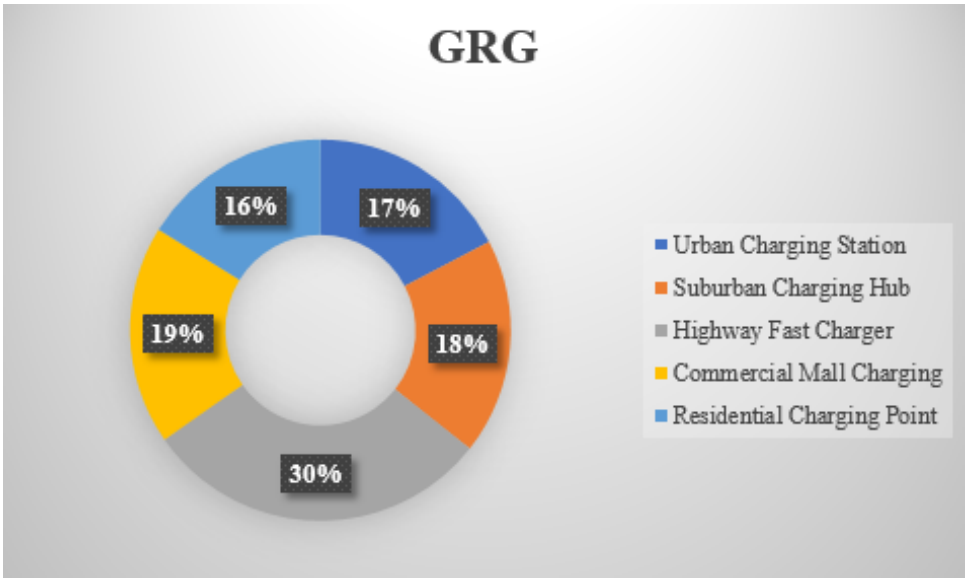



**FIGURE 5.** GRG

The Figure 5 shows a Grey Relational Grade (GRG) chart derived from the Grey Relation Analysis (GRA) method, illustrating the overall relational influence of different types of charging stations. The chart breaks down five categories: Urban Charging Station (17%), Suburban Charging Hub (18%), Highway Fast Charger (30%), Commercial Mall Charging (19%), and Residential Charging Point (16%). The largest share, at 30%, belongs to the Highway Fast Charger, indicating that this type of station has the strongest overall relationship with the evaluation criteria being analyzed, possibly due to its essential role in facilitating long-distance travel and offering high-speed charging options. Commercial Mall Charging follows with 19%, suggesting a significant contribution, likely due to its convenient accessibility in populated areas. The Suburban Charging Hub and Urban Charging Station categories show moderate importance, with 18% and 17% respectively. This reflects their relevance in areas with mixed population densities, where charging infrastructure is crucial for day-to-day

commuting. Residential Charging Points, at 16%, have the smallest share, which may indicate lower priority in the context of widespread, rapid public charging needs.

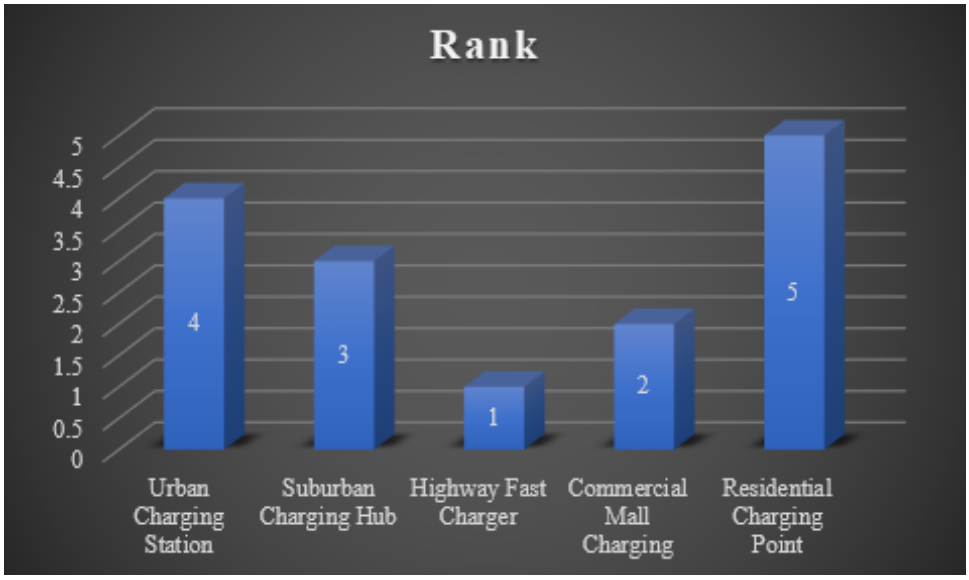



**FIGURE 6.** . Rank

Figure 6, the ranks of different charging stations are presented based on the Grey Relation Analysis (GRA) method. This ranking evaluates the relative influence of each station type according to the chosen performance indicators. The Highway Fast Charger holds the 1st rank, reflecting its dominant role in providing critical fast-charging solutions, especially for long-distance travel and high-speed recharging demands. With the ability to minimize downtime for electric vehicle (EV) users, it emerges as the most influential charging option. The Commercial Mall Charging station comes in at 2nd rank, indicating its substantial importance due to its strategic locations in densely populated urban areas. These stations are convenient for EV users who charge their vehicles while shopping or working, contributing to its high rank. The Suburban Charging Hub is ranked 3rd, underscoring its relevance in suburban areas where EV adoption is growing. These hubs act as a bridge between urban and rural regions, providing reliable charging infrastructure for daily commuters. In 4th rank, the Urban Charging Station plays a supportive but slightly lesser role compared to suburban and commercial charging options. It is vital for city commuters, but its influence is somewhat limited by space constraints and lower charging speeds. Lastly, the Residential Charging Point ranks 5th, indicating the least influence among the options, likely due to its limited usage in terms of widespread public access and slower charging capabilities compared to public stations.

## 4. CONCLUSION

The evaluation of Electric Vehicle (EV) Charging Infrastructure through the Grey Relation Analysis (GRA) method provides significant insights into the performance and suitability of various charging alternatives. The analysis encompasses multiple critical parameters, including Cost per Charge, Charging Speed, Energy Efficiency, and Number of Ports, which are essential for determining the effectiveness of charging solutions in meeting the demands of EV users. The findings indicate that the Highway Fast Charger emerges as the optimal choice, boasting the highest Grey Relation Grade (GRG) of 0.9167. This exceptional performance reflects its superior charging speed and energy efficiency, making it highly suitable for long-distance travel where quick recharging is essential. Its placement at the top of the rankings underscores the increasing need for efficient and accessible charging solutions in our evolving transportation landscape. Conversely, the Residential Charging Point ranks the lowest with a GRG of 0.5000. While it provides convenience with a high number of ports, its overall performance in terms of charging speed and energy efficiency is limited. This indicates that while residential charging points are essential for individual users, they may not fulfill the broader infrastructure needs of electric vehicle networks. The Commercial Mall Charging and Suburban Charging Hub alternatives present balanced performance,

with GRGs of 0.5756 and 0.5675, respectively. These options cater well to urban settings, offering reasonable charging capabilities that can support daily commuting needs. Their mid-range performance highlights the importance of having charging solutions that can accommodate both speed and accessibility in various environments. The Urban Charging Station, with a GRG of 0.5364, also demonstrates moderate benefits, indicating that while it serves a vital function in urban areas, there remains significant room for improvement in its performance metrics. Overall, this study highlights the need for stakeholders, including policymakers and infrastructure developers, to prioritize the deployment of high-performing charging stations, particularly the Highway Fast Charger, to enhance the EV charging ecosystem. As electric vehicle adoption continues to rise, optimizing charging infrastructure will be crucial to support sustainable transportation and facilitate the transition to a greener future. By leveraging the insights gained from GRA, stakeholders can make informed decisions that will lead to more effective and efficient charging solutions.

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