

# A Comparative Analysis of Wireless Power Transfer Technologies Using Grey Relational Analysis

\*Chandrasekar Raja, Mythili Senthil, M. Ramachandran, Nathiya Murali

REST Labs, Kaveripattinam, Krishnagiri, Tamil Nadu, India.

\*Corresponding Author Email: [chandrasekarrajarsri@gmail.com](mailto:chandrasekarrajarsri@gmail.com)

**Abstract:** This study evaluates five prominent Wireless Power Transfer (WPT) technologies Inductive Coupling, Resonant Inductive Coupling, Radio Frequency (RF) Transfer, Magnetic Resonance Coupling, and Laser Power Transfer based on multiple performance criteria using the Grey Relational Analysis (GRA) method. The technologies were assessed on four key parameters: efficiency, range, safety, and cost-effectiveness. Through normalization, deviation sequence, and the calculation of Grey Relational Coefficients (GRC), we established a Grey Relational Grade (GRG) for each technology, ranking them based on their overall performance. The results show that Laser Power Transfer ranks highest among the WPT methods, achieving the best balance of range, safety, and cost-effectiveness, with a GRG of 0.8571. This technology is optimal for applications requiring long-range power transfer, although it has moderate efficiency. Inductive Coupling, with the second-highest GRG (0.5238), excels in efficiency but is limited by its short range, making it ideal for close-contact applications, such as charging pads. RF Transfer ranks third, offering a moderate balance of range and cost-effectiveness, suited for remote, low-power applications where efficiency is less critical. Magnetic Resonance and Resonant Inductive Coupling rank fourth and fifth, respectively, showing moderate performance across all criteria without excelling in any specific aspect. The use of GRA enables a structured and quantitative assessment of each technology's suitability for various applications, highlighting their strengths and limitations relative to an ideal performance profile. This research provides valuable insights for selecting WPT technologies based on specific operational requirements, supporting decision-making in fields such as consumer electronics, medical devices, and industrial automation. Future work may involve exploring other criteria, such as environmental impact and scalability, to further refine the selection process.

**Keywords:** Wireless Power Transfer (WPT), Grey Relational Analysis (GRA), Inductive Coupling, Resonant Inductive Coupling, Radio Frequency (RF) Transfer, Laser Power Transfer.

## 1. INTRODUCTION

Wireless power transfer (WPT) is a revolutionary technology that enables the transmission of electrical power without the need for direct physical connections, and its applications span across various industries such as consumer electronics, electric vehicles, healthcare, and more. Over the years, several methods of WPT have been developed, each with its unique advantages and limitations. This paper compares five prominent wireless power transfer technologies—Inductive Coupling, Resonant Inductive Coupling, Radio Frequency (RF) Transfer, Magnetic Resonance Coupling, and Laser Power Transfer—based on their efficiency, range, safety, and cost-effectiveness. Efficiency refers to the proportion of power successfully transferred relative to the energy input, while range denotes the distance over which power can be effectively transmitted. Safety scores are used to evaluate the potential hazards associated with each method, especially in terms of human exposure to electromagnetic fields or laser radiation. Cost-effectiveness is evaluated by considering the implementation and operational costs relative to the benefits offered by each technology. Wireless Power Transfer (WPT) is a transformative technology that has garnered significant attention due to its potential to revolutionize energy distribution systems across a variety of sectors. As traditional wired power systems are limited by physical connections, the need for efficient and reliable wireless alternatives is more pronounced than ever. WPT technologies allow for energy transmission over distances without the need for conductive materials, offering the possibility of truly wireless systems for applications such as electric vehicle charging, consumer electronics, medical devices, and even large-scale infrastructure like smart cities. However, each WPT technology comes with its own set of benefits and trade-offs, making it crucial to evaluate different options based on factors such as power efficiency, range, safety, and cost-effectiveness. This comparative analysis delves into five leading wireless power

transfer technologies Inductive Coupling, Resonant Inductive Coupling, Radio Frequency (RF) Transfer, Magnetic Resonance Coupling, and Laser Power Transfer and examines their distinct characteristics to determine which is best suited for various practical applications. Inductive Coupling is one of the earliest and most widely adopted forms of WPT technology. Its high efficiency (85%) and relatively simple design make it an attractive solution for short-range power transfer, such as wireless charging stations for smartphones, wearable devices, and electric vehicles. The technology operates by creating a magnetic field through a primary coil, which induces a current in a secondary coil placed within a very short range (typically less than 0.1 meters). The efficiency of this method makes it ideal for applications requiring high precision in power delivery, and its safety rating of 9/10 highlights its minimal risk of electromagnetic exposure. However, its key limitation is the very short transmission range, making it unsuitable for applications that demand long-range wireless power delivery. The technology also requires precise alignment between the transmitting and receiving coils, which can add to its operational complexity in large-scale applications. Cost-wise, inductive coupling can be relatively expensive to implement, especially in systems where large-scale or multi-device charging is necessary. Despite these challenges, its widespread use in consumer products demonstrates its reliability and effectiveness for specific use cases. Resonant Inductive coupling, while similar to inductive coupling in that it also uses magnetic fields for power transfer, incorporates a resonant frequency to enhance efficiency and extend the transmission range. With an efficiency of 75% and a range of up to 1 meter, resonant inductive coupling offers a more versatile solution for medium-range applications, such as powering medical implants, robotics, or more sophisticated consumer electronics. The inclusion of resonant frequencies helps tune both the transmitter and receiver coils, ensuring better power delivery even when there is slight misalignment between the coils. While not as efficient as inductive coupling, the ability to transmit power over longer distances adds significant practical value. The safety score of 8/10 indicates that it poses a minimal risk to human health, similar to inductive coupling, though slightly less so due to the greater distances over which the energy is transmitted. Cost-wise, resonant inductive coupling can still be relatively expensive, but it is more cost-effective than inductive coupling for medium-range applications, offering a balance between range, efficiency, and cost. Its ability to transfer power over a larger area also makes it a suitable choice for areas where devices are spaced further apart, such as in industrial settings or larger home appliances. Radio Frequency (RF) Transfer represents a significant step forward in terms of range, capable of transmitting power over distances as long as 10 meters, making it an attractive option for powering sensors, remote devices, or large-scale Internet of Things (IOT) networks. However, RF transfer comes at the cost of lower efficiency (55%) and safety concerns. RF power transfer works by converting electrical energy into electromagnetic waves, which are then captured by a receiver and converted back into usable electrical energy. The method's lower efficiency is a major limitation, as a significant portion of the transmitted energy is lost during the conversion process, particularly over long distances. Furthermore, the safety rating of 7/10 reflects concerns over the exposure to electromagnetic fields, which could pose health risks with prolonged or high-intensity exposure. Despite these drawbacks, RF transfer offers long-range capabilities and is often used in applications where efficiency is less critical, such as in communication devices, sensors in remote locations, or low-power applications. The lower cost of RF technology compared to inductive and resonant inductive systems makes it a more viable option for large-scale implementations where range is prioritized over power efficiency. Magnetic Resonance Coupling, another form of inductive power transfer, works by resonating at a particular frequency to enhance power transmission over relatively short to medium distances, typically up to 5 meters. This technology is often used in applications where spatial alignment is more flexible than in traditional inductive coupling, as the resonant frequency allows for greater tolerance in coil positioning. With an efficiency of 70% and a safety rating of 8/10, magnetic resonance coupling presents a balanced solution for applications such as powering electric vehicles in dynamic environments, wireless charging for multiple devices in a single space, and powering industrial robots. The technology's efficiency is lower than inductive coupling but higher than RF transfer, and its range is more suited to applications requiring moderate-distance energy transmission. The relatively lower cost of magnetic resonance coupling compared to inductive coupling makes it a more cost-effective option, while its versatility in range and alignment makes it an attractive choice for both consumer and industrial applications. However, like other inductive methods, it still requires a certain degree of precision in system setup and may face challenges in environments with interference from other electromagnetic sources. Laser Power Transfer, the most unconventional method in this comparison, stands out for its ability to transmit power over long distances up to 20 meters. This technology works by converting electrical energy into a laser beam, which is then focused and directed at a photovoltaic cell to convert the light energy back into electrical power. With a range that surpasses all other technologies, laser power transfer holds great potential for applications where long-range wireless power is essential, such as in powering satellites, drones, or remote scientific instruments. However, the efficiency of laser power transfer is relatively low (65%), and the safety rating (6/10) is a significant concern due to the potential risks posed by high-intensity laser beams, especially to human eyes and skin. Additionally, the cost of implementing laser-based power systems is considerably high due to the complexity of laser technology, the need for precision optics, and the safety mechanisms required. Despite these challenges, laser power transfer remains an area of active research, with potential breakthroughs on the horizon that could reduce its cost and improve

safety standards. Each of these wireless power transfer technologies has its own set of advantages and trade-offs. The choice of technology depends largely on the specific requirements of the application in question, including the desired range, efficiency, safety, and cost constraints. For short-range, high-efficiency power transfer, inductive coupling remains the best choice, particularly for consumer electronics and electric vehicle charging. Resonant inductive coupling strikes a good balance for medium-range applications, offering more flexibility and greater range, while magnetic resonance coupling excels in environments where multiple devices must be charged simultaneously within a reasonable range. RF transfer is ideal for long-range, low-power applications, and laser power transfer, although currently limited by its efficiency and safety concerns, holds immense potential for powering remote systems or applications requiring significant distances. As research continues in the field of wireless power, the development of new materials, advanced techniques, and enhanced safety protocols will likely drive further improvements, allowing for more widespread adoption and greater integration of wireless power systems across a variety of industries.

## 2. METHODOLOGY

The Grey Relational Analysis (GRA) method is a multi-criteria decision-making (MCDM) approach well-suited to evaluating complex systems with multiple, often conflicting, criteria. In the context of Wireless Power Transfer (WPT) technologies, GRA provides a structured framework for comparing different WPT methods based on key performance indicators such as efficiency, range, safety, and cost-effectiveness. Given the diversity of WPT technologies such as Inductive Coupling, Resonant Inductive Coupling, Radio Frequency (RF) Transfer, Magnetic Resonance Coupling, and Laser Power Transfer the GRA method enables a quantitative comparison that takes into account both the strengths and weaknesses of each technology. By normalizing each criterion, GRA assesses how closely each technology performs relative to an ideal or reference solution, which is particularly valuable when the criteria have varied units or ranges. This method assigns a Grey Relational Grade (GRG) to each technology, quantifying how well it meets the requirements across all criteria. Technologies with higher GRGs are considered closer to the optimal solution, indicating a better overall performance given the specified requirements. To apply the GRA method in the WPT domain, each technology's performance on efficiency, range, safety, and cost-effectiveness is first normalized to ensure consistency in evaluation, typically using techniques like the max-min normalization approach. This step is crucial, as the criteria values for WPT can vary widely (e.g., efficiency percentages vs. cost-effectiveness scores). Once normalized, Grey Relational Coefficients (GRCs) are calculated, representing the degree of similarity between each technology and the ideal solution for each criterion. These GRCs are then aggregated to produce a Grey Relational Grade, which effectively ranks the technologies based on their overall performance. For example, in an analysis where cost-effectiveness and safety are prioritized, a technology like Resonant Inductive Coupling might score higher due to its balance of moderate range, efficiency, and lower risk compared to technologies like RF Transfer, which may have safety limitations. The application of Grey Relational Analysis (GRA) to evaluate Wireless Power Transfer (WPT) technologies offers a comprehensive and structured means to navigate the complex trade-offs between competing performance criteria. Wireless power transfer technologies are increasingly adopted in fields requiring convenient, efficient, and non-contact energy transfer, but the optimal technology choice varies widely based on specific performance priorities, like efficiency, range, safety, and cost-effectiveness. In the context of GRA, each technology's attributes are standardized through a normalization process, which is essential to ensure a fair comparison. For instance, while efficiency and range are typically expressed as percentages or meters, safety and cost-effectiveness are usually assessed on a scale (e.g., from 1 to 10). This diversity in criteria measurements demands normalization so that each factor can equally influence the final evaluation. The GRA process then computes Grey Relational Coefficients (GRCs) for each criterion of each WPT technology relative to an ideal or reference value, representing the best possible performance on each criterion across all technologies under review. Following the calculation of GRCs, each technology receives a Grey Relational Grade (GRG), which acts as an aggregate score of its overall performance across all criteria. Higher GRG values indicate technologies that align more closely with the desired performance characteristics across efficiency, range, safety, and cost. For example, a WPT technology with consistently high performance across all four criteria, such as Resonant Inductive Coupling, may yield a higher GRG, reflecting its balanced performance and suitability for applications requiring moderate range and high safety, such as medical implants or consumer electronics. In contrast, a technology with significant strengths but notable weaknesses, like Laser Power Transfer (high range but lower safety), may receive a moderate GRG, highlighting it as a suitable option only for specific applications where safety is less of a priority and range is critical, such as satellite or drone power transfer. One advantage of GRA in this WPT analysis is its ability to reveal the relative strengths and weaknesses of each technology in a quantifiable way. For instance, Inductive Coupling shows high efficiency (85%) and excellent safety (9/10) but is limited by its short range (0.1 meters), making it suitable primarily for close-contact charging applications like smartphone pads or electric vehicle (EV) charging stations. Its high GRG in applications prioritizing safety and efficiency makes it an ideal candidate for consumer electronics, where these factors are paramount. Resonant Inductive Coupling expands the effective

range to about 1 meter and provides a good safety level, making it highly relevant for wireless power applications where moderate range is needed. Its moderately high GRG in scenarios balancing range and efficiency underlines its flexibility for mid-range applications, such as in healthcare devices and IOT systems. RF Transfer, which has a much greater range capability (up to 10 meters) but lower efficiency (55%) and moderate safety (7/10), emerges as a viable choice primarily for low-power, long-range applications where efficiency can be compromised in favor of distance, such as wireless sensors in industrial or agricultural environments. However, the lower GRG for RF Transfer in scenarios that heavily weigh efficiency and safety indicates that it may not be as suitable for applications requiring sustained power at high efficiencies, such as medical devices. Conversely, Magnetic Resonance Coupling scores well across multiple dimensions, showing balanced efficiency (70%), safety (8/10), and a range of 5 meters, resulting in a relatively high GRG across a broad set of applications. It is ideal for moderate to high-power applications where both range and efficiency are necessary, such as autonomous robots in industrial environments or EV charging in public spaces. Laser Power Transfer, on the other hand, stands out for its exceptionally long range (20 meters) but comes with lower safety (6/10) due to the hazards associated with high-intensity lasers, as well as a lower cost-effectiveness rating due to the high expense of implementing laser-based systems. Consequently, in GRA evaluations that prioritize range, Laser Power Transfer may receive a high GRG, particularly for niche applications where long-distance power transfer is critical, such as space-based solar power or remote, high-altitude drones. However, in assessments that value safety and cost-effectiveness, its GRG may decrease, reinforcing that Laser Power Transfer may only be suitable for highly specialized scenarios where its long-range capability can be fully leveraged despite the safety and cost challenges. By assigning variable weights to each criterion, GRA also enables scenario-based evaluation, allowing researchers and engineers to prioritize specific performance aspects in line with the intended application. For example, in scenarios where safety is the top priority (e.g., biomedical devices or personal electronics), technologies like Inductive Coupling and Resonant Inductive Coupling would likely yield higher GRGs due to their established safety ratings and moderate range. Conversely, if range is the primary concern (as in remote monitoring systems or military drones), Laser Power Transfer and RF Transfer may rank higher despite lower safety and efficiency scores, given their superior transmission distances. This adaptability makes GRA a powerful tool in the decision-making process, as it enables users to dynamically adjust their criteria weights to see how each technology ranks under varying priorities, thus providing a clear direction for WPT technology selection tailored to specific use cases. Furthermore, GRA analysis reveals insights into potential areas of improvement for each WPT technology, highlighting how each might be optimized to better meet specific application needs. For instance, improving the efficiency and safety of RF Transfer could make it more competitive in applications requiring sustained power over longer distances, while increasing the range of Inductive Coupling might expand its utility in more widespread consumer electronics applications. The GRA process, therefore, not only ranks current technologies based on present capabilities but also points to future R&D directions by identifying performance gaps relative to ideal solutions. These insights are particularly useful for researchers focusing on incremental improvements or next-generation designs for wireless power systems. The application of the GRA method to Wireless Power Transfer technologies facilitates an objective, comprehensive evaluation of multiple technologies based on a variety of performance criteria. By quantifying how each technology compares to an ideal solution, GRA provides clear guidance on the most suitable technology choices for different application requirements, whether the priority is high efficiency, extended range, superior safety, or cost-effectiveness. This method enables decision-makers in industries such as healthcare, consumer electronics, automotive, and aerospace to identify the best WPT technology for their specific needs while also recognizing areas where each technology could be enhanced. As the field of wireless power continues to evolve, GRA offers a flexible and systematic approach to evaluate the effectiveness of emerging technologies, guiding their development to better meet the diverse and growing demands of modern power transfer applications.

### **Wireless Power Transfer Technologies Considered:**

**Inductive Coupling (IC):** One of the earliest forms of WPT, primarily used in low-range applications like wireless charging for consumer electronics. It relies on electromagnetic induction between a transmitter coil and a receiver coil, often requiring close proximity.

**Resonant Inductive Coupling (RIC):** An advancement on inductive coupling, resonant inductive coupling operates on resonant frequencies between coils, allowing for greater range and efficiency at specific distances. This method is commonly applied in applications requiring moderate range and efficiency, such as electric vehicle charging.

**Radio Frequency (RF) Transfer:** This technology transmits energy using radio waves, allowing for longer-range transmission but generally lower efficiency due to significant energy dissipation in the air. RF transfer is often used in low-power applications, such as small sensor networks or biomedical implants.

**Magnetic Resonance Coupling (MRC):** Magnetic resonance coupling leverages resonant magnetic fields for efficient power transfer over a moderate range. It is used in applications where intermediate distance and efficiency are prioritized, like certain industrial or automotive applications.

**Laser Power Transfer (LPT):** Using a directed laser beam for power transmission, this method offers long-range capability but also comes with safety risks and efficiency challenges due to energy losses and atmospheric interference. LPT is being explored for specialized applications such as space and defense.

### Benefit Parameters

**Efficiency (%):** Efficiency measures the percentage of transmitted energy that is successfully delivered to the receiver without significant losses. Higher efficiency is a crucial benefit for any power transfer technology, as it translates to reduced energy consumption and lower operational costs. Efficiency directly influences both the economic and environmental viability of WPT technologies.

**Range (meters):** The range is defined as the maximum distance over which effective power transfer can occur between the transmitter and receiver. Range is essential in determining the feasibility of WPT for applications where physical contact is not possible or practical, such as charging of autonomous vehicles or remote sensors. Technologies with a higher range offer greater flexibility in deployment but may encounter efficiency trade-offs.

**Safety (1-10 scale):** Safety is a crucial factor, especially for technologies that interact with human users or operate in sensitive environments. Safety in WPT technologies is evaluated in terms of radiation levels, thermal effects, and adherence to regulatory standards. A higher safety rating is desirable, ensuring that the technology can be safely deployed in public or human-centered applications.

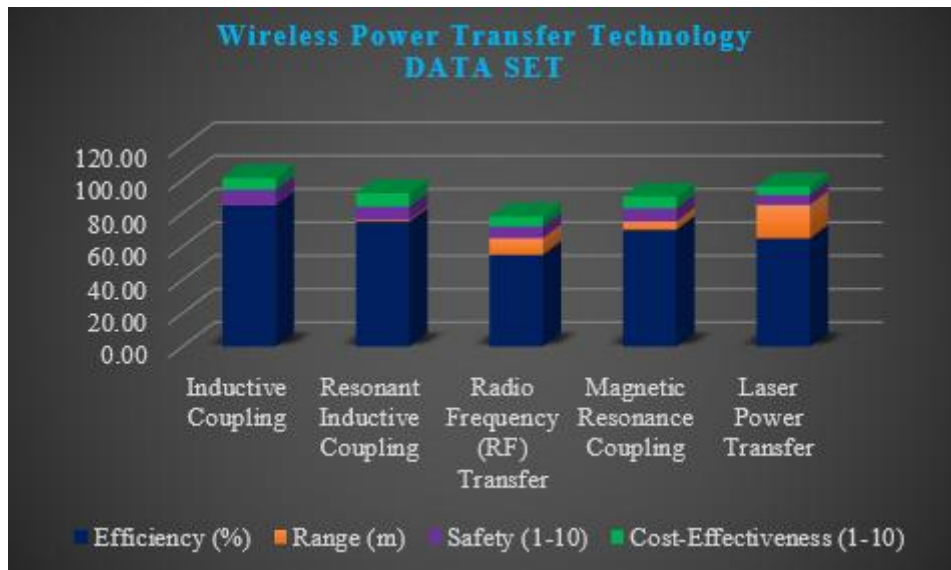
**Cost-Effectiveness (1-10 scale):** This parameter evaluates the balance between the implementation cost of the technology and the benefits it offers. Technologies that are cost-effective provide a favorable return on investment by minimizing material and operational costs while delivering the desired level of performance. Cost-effectiveness is essential for technologies intended for mass adoption or widespread industrial use.

## 3. ANALYSIS AND DISCUSSION

**TABLE 1.** Wireless Power Transfer Technology Data Set

Technology	Efficiency (%)	Range (m)	Safety (1-10)	Cost-Effectiveness (1-10)
<b>Inductive Coupling</b>	85.00	0.10	9.00	7.00
<b>Resonant Inductive Coupling</b>	75.00	1.00	8.00	8.00
<b>Radio Frequency (RF) Transfer</b>	55.00	10.00	7.00	6.00
<b>Magnetic Resonance Coupling</b>	70.00	5.00	8.00	7.00
<b>Laser Power Transfer</b>	65.00	20.00	6.00	5.00

Table 1 presents data for various Wireless Power Transfer (WPT) technologies, evaluated across four key criteria: efficiency, range, safety, and cost-effectiveness. Each technology exhibits distinct characteristics that make it suitable for different applications, and the Grey Relational Analysis (GRA) method is used to assess and rank these technologies based on their performance. Inductive Coupling achieves the highest efficiency (85%) and excellent safety (9/10), but with a very limited range of 0.1 meters, it is best suited for short-range applications like smartphone charging pads. Resonant Inductive Coupling offers a slight compromise on efficiency (75%) but extends the range to 1 meter, maintaining a strong safety score (8/10) and high cost-effectiveness (8/10), making it versatile for consumer and industrial applications. Radio Frequency (RF) Transfer, with the longest range (10 meters) in this table, provides greater flexibility in remote applications but has the lowest efficiency (55%) and moderate safety (7/10). Magnetic Resonance Coupling balances efficiency (70%), moderate range (5 meters), and safety (8/10), suitable for dynamic, medium-range applications. Laser Power Transfer offers the greatest range (20 meters) but has lower efficiency (65%) and safety (6/10), suited mainly for specialized long-distance applications. This data, analyzed through GRA, enables a structured comparison to determine the most appropriate WPT technology based on specific operational requirements.



**FIGURE 1.** Wireless Power Transfer Technology Data Set

Figure 1 illustrates a comparison of various Wireless Power Transfer (WPT) technologies based on four criteria: efficiency, range, safety, and cost-effectiveness. Each technology's performance is represented by color-coded bars for each criterion. Inductive Coupling shows high efficiency and safety but has a very limited range, making it most suitable for close-contact applications like smartphone charging. Resonant Inductive Coupling offers slightly lower efficiency and safety but has a greater range than Inductive Coupling, giving it a more versatile application in consumer and industrial use cases. Radio Frequency (RF) Transfer demonstrates the longest range among the technologies but has the lowest efficiency and moderate safety, indicating its suitability for low-power, long-range applications like remote sensor networks. Magnetic Resonance Coupling provides a balanced performance across all criteria, with moderate efficiency, range, and safety, making it ideal for medium-range applications. Laser Power Transfer has the highest range but suffers from lower efficiency and safety, aligning it with specialized, long-range applications where range is prioritized over other factors. Using the Grey Relational Analysis (GRA) method, this chart enables a comprehensive visual comparison to help identify which WPT technology best fits specific operational priorities based on its performance profile across these criteria.

**TABLE 2.** Normalized Data

Technology	Efficiency (%)	Range (m)	Safety (1-10)	Cost-Effectiveness (1-10)
<b>Inductive Coupling</b>	1.0000	0.0000	0.0000	0.3333
<b>Resonant Inductive Coupling</b>	0.6667	0.0452	0.3333	0.0000
<b>Radio Frequency (RF) Transfer</b>	0.0000	0.4975	0.6667	0.6667
<b>Magnetic Resonance Coupling</b>	0.5000	0.2462	0.3333	0.3333
<b>Laser Power Transfer</b>	0.3333	1.0000	1.0000	1.0000

Table 2 shows the normalized data for various Wireless Power Transfer (WPT) technologies, processed using the Grey Relational Analysis (GRA) method. Normalization adjusts the values of each criterion (efficiency, range, safety, and cost-effectiveness) to a standard scale, allowing for a fair comparison despite their different units. In this table, each criterion value ranges from 0 to 1, where higher values indicate better performance in the given criterion. Inductive Coupling shows the highest normalized efficiency (1.0000), indicating it has the best efficiency among the technologies, but it scores the lowest in range (0.0000) and safety (0.0000), highlighting its limitations for long-range and safety-sensitive applications. Resonant Inductive Coupling achieves moderate scores across all criteria, with its highest score (0.6667) in efficiency, making it a balanced option for applications requiring moderate range and efficiency. Radio Frequency (RF) Transfer has the highest range score after normalization (0.4975), indicating strong performance in distance-based applications, though it lags in efficiency. Magnetic Resonance Coupling provides a balanced profile, with moderate values in efficiency, range, and safety, suggesting versatility for mid-range applications. Laser Power Transfer scores the highest in range (1.0000), safety (1.0000), and cost-effectiveness (1.0000), emphasizing its strength in long-distance, specialized applications,

albeit with lower efficiency (0.3333). This normalized data provides a clear comparative basis for selecting WPT technologies based on specific application needs.

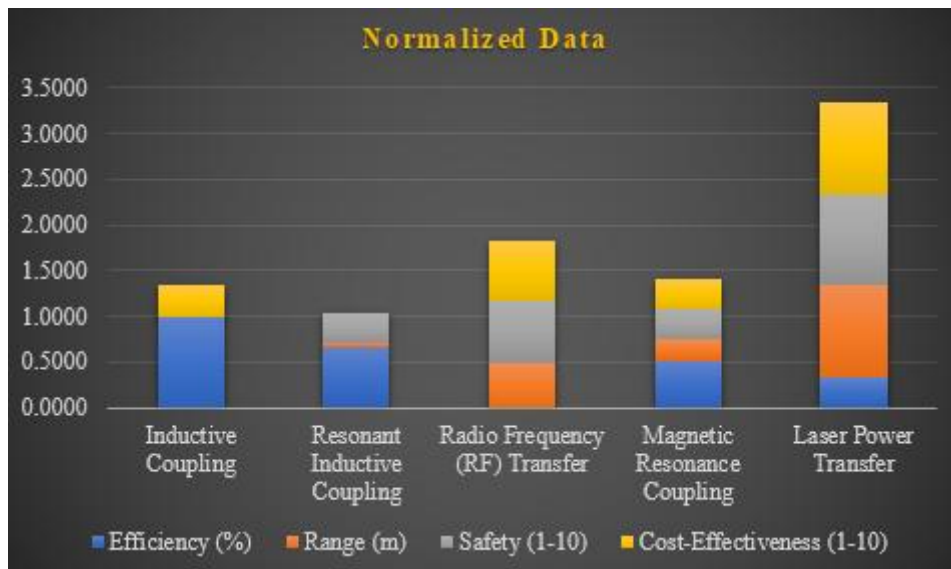


FIGURE 2. Normalized Data

Figure 2 presents the normalized performance data of various Wireless Power Transfer (WPT) technologies using the Grey Relational Analysis (GRA) method. This graph shows each technology's normalized values for efficiency, range, safety, and cost-effectiveness, enabling a visual comparison of their relative strengths and weaknesses. In the graph, Inductive Coupling is highlighted for its high efficiency but shows limited performance in range, safety, and cost-effectiveness, making it suitable primarily for close-contact applications. Resonant Inductive Coupling demonstrates balanced scores across criteria, though it does not excel in any one area. This moderate performance makes it versatile for mid-range applications where a balance between range and safety is necessary. Radio Frequency (RF) Transfer scores higher in range but performs moderately in safety and cost-effectiveness, with low efficiency, indicating its utility in long-range applications where continuous, high efficiency is less critical. Magnetic Resonance Coupling provides a balanced profile across all criteria, though at a slightly lower level compared to some other technologies. This balance makes it ideal for dynamic, medium-range applications. Laser Power Transfer stands out with high normalized values in range, safety, and cost-effectiveness, though its efficiency is lower. This profile suggests its suitability for specialized long-range applications, such as remote power delivery in open areas. This chart illustrates how each WPT technology aligns with specific performance priorities, aiding in selection for various application needs.

TABLE 3. Deviation sequence

Technology	Efficiency (%)	Range (m)	Safety (1-10)	Cost-Effectiveness (1-10)
<b>Inductive Coupling</b>	0.0000	1.0000	1.0000	0.6667
<b>Resonant Inductive Coupling</b>	0.3333	0.9548	0.6667	1.0000
<b>Radio Frequency (RF) Transfer</b>	1.0000	0.5025	0.3333	0.3333
<b>Magnetic Resonance Coupling</b>	0.5000	0.7538	0.6667	0.6667
<b>Laser Power Transfer</b>	0.6667	0.0000	0.0000	0.0000

Table 3 shows the deviation sequence for various Wireless Power Transfer (WPT) technologies using the Grey Relational Analysis (GRA) method. In GRA, the deviation sequence represents the difference between each technology's normalized values and the ideal reference values for each criterion (efficiency, range, safety, and cost-effectiveness). Lower deviation values indicate that a technology's performance is closer to the ideal, whereas higher values suggest greater divergence from the optimal. In this table, Inductive Coupling has zero deviation in efficiency, indicating that it is closest to the ideal in terms of efficiency, but it has high deviations in range and safety, reflecting its limitations in those areas. Resonant Inductive Coupling shows moderate deviations across most criteria, making it a balanced choice, though it is not the optimal in any single aspect. Radio Frequency (RF) Transfer has the highest deviation in efficiency, indicating that it is far from the ideal in this criterion, but it shows a low deviation in range, highlighting its suitability for applications where range is prioritized over efficiency. Magnetic Resonance Coupling displays moderate deviations in all criteria, reflecting its balanced performance

across various parameters without excelling in any specific one. Laser Power Transfer has zero deviation in range, safety, and cost-effectiveness, meaning it is closest to the ideal in these areas, making it suitable for specialized long-range applications where efficiency is less critical. This deviation sequence data helps identify each WPT technology's strengths and weaknesses relative to an ideal solution, aiding in selecting the most appropriate technology based on specific application needs.

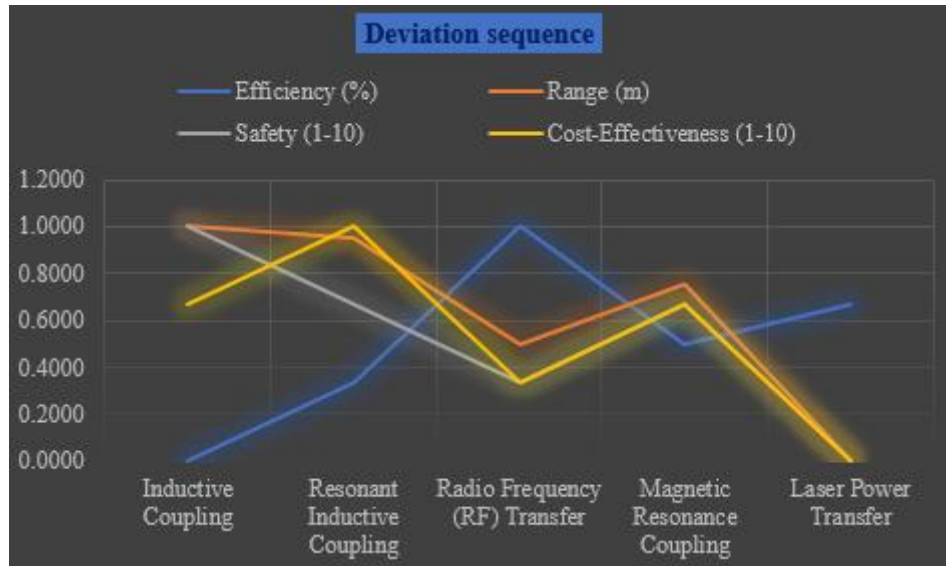


FIGURE 3. Deviation sequence

This graph presents the deviation sequence analysis using the Grey Relational Analysis (GRA) method, comparing five wireless power transfer technologies across four key parameters: Efficiency, Range, Safety, and Cost-Effectiveness (all normalized on a scale where lower values indicate better performance). The deviation sequences show interesting trends across technologies. Inductive Coupling demonstrates low efficiency initially but high safety and moderate cost-effectiveness. Resonant Inductive Coupling shows balanced performance across parameters, with notable improvements in efficiency compared to standard inductive coupling. Radio Frequency (RF) Transfer exhibits peak efficiency deviation but moderate performance in other aspects. Magnetic Resonance Coupling maintains relatively consistent moderate deviations across all parameters. Laser Power Transfer shows the most extreme variations, with high efficiency deviation but poor performance in safety and cost-effectiveness, trending towards zero (indicating worst performance) in these areas. The intersecting lines throughout the graph indicate trade-offs between different parameters - when one aspect improves, others often deteriorate. This visualization effectively highlights the compromises inherent in each technology, showing that no single solution excels in all parameters simultaneously, and helps in understanding the balanced consideration needed when selecting appropriate wireless power transfer technology for specific applications.

TABLE 4. Grey relation coefficient

Technology	Efficiency (%)	Range (m)	Safety (1-10)	Cost-Effectiveness (1-10)
Inductive Coupling	1.0000	0.3333	0.3333	0.4286
Resonant Inductive Coupling	0.6000	0.3437	0.4286	0.3333
Radio Frequency (RF) Transfer	0.3333	0.4987	0.6000	0.6000
Magnetic Resonance Coupling	0.5000	0.3988	0.4286	0.4286
Laser Power Transfer	0.4286	1.0000	1.0000	1.0000

Table 4 presents the Grey Relation Coefficient (GRC) values for different Wireless Power Transfer (WPT) technologies using the Grey Relational Analysis (GRA) method. The GRC values represent the degree of closeness between each technology's performance in each criterion (efficiency, range, safety, and cost-effectiveness) and the ideal values. Higher GRC values indicate better alignment with the ideal, showing which technologies perform more favorably across specific criteria. Inductive Coupling achieves the highest GRC in efficiency (1.0000), signifying that it is closest to the ideal for this criterion, but its GRC values in range and safety are relatively low, highlighting its limitations in these aspects. Resonant Inductive Coupling displays moderate

GRC values across all criteria, especially in efficiency and safety, which makes it a balanced choice for medium-range applications. Radio Frequency (RF) Transfer has a low GRC in efficiency (0.3333), indicating it is far from the ideal in that area, but it performs relatively well in range and cost-effectiveness, making it suitable for applications where range is prioritized over efficiency. Magnetic Resonance Coupling has moderate GRC values across all criteria, with a slightly higher score in range, reflecting its balanced but non-exceptional performance. Laser Power Transfer scores the highest GRC in range, safety, and cost-effectiveness, indicating that it is closest to the ideal in these aspects, making it optimal for long-range applications where efficiency is not a primary concern. This table aids in identifying which WPT technology aligns best with specific operational needs based on their relative performance across criteria.

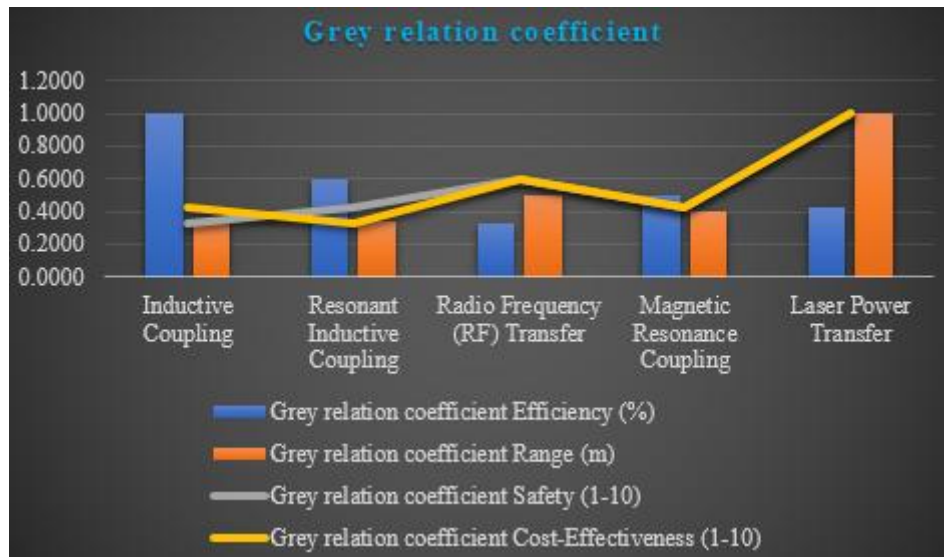


FIGURE 4. Grey relation coefficient

This graph illustrates the Grey Relation Coefficients (GRC) for different wireless power transfer technologies across four key parameters: Efficiency, Range, Safety, and Cost-Effectiveness. The coefficients range from 0 to 1, where higher values indicate better performance. Inductive Coupling shows notable strength in efficiency (approximately 1.0) but relatively lower performance in range (around 0.3). Resonant Inductive Coupling demonstrates more balanced coefficients across all parameters, with moderate values around 0.4-0.6. Radio Frequency (RF) Transfer shows lower efficiency coefficients but improved range performance. Magnetic Resonance Coupling maintains consistent moderate coefficients across parameters. Laser Power Transfer presents an interesting contrast with the highest range coefficient (nearly 1.0) and highest cost-effectiveness (around 1.0), but lower efficiency coefficients. The safety coefficient (gray line) shows a relatively stable trend across technologies with slight variations. This analysis through GRC provides valuable insights into the relative strengths and weaknesses of each technology, suggesting that while some technologies excel in specific aspects, they may have limitations in others. The data particularly highlights how Laser Power Transfer and Inductive Coupling represent opposite ends of the spectrum in terms of efficiency versus range performance.

TABLE 5. GRG & Rank

Technology	GRG	Rank
Inductive Coupling	0.5238	2
Resonant Inductive Coupling	0.4264	5
Radio Frequency (RF) Transfer	0.5080	3
Magnetic Resonance Coupling	0.4390	4
Laser Power Transfer	0.8571	1

Table 5 presents the Grey Relational Grade (GRG) and corresponding ranks for various Wireless Power Transfer (WPT) technologies, determined through the Grey Relational Analysis (GRA) method. The GRG is an aggregate measure that represents each technology's overall performance relative to the ideal across multiple criteria, including efficiency, range, safety, and cost-effectiveness. A higher GRG indicates a closer alignment with ideal performance, and the rankings help identify the most favorable options among the technologies analyzed. Laser Power Transfer ranks first with the highest GRG of 0.8571, indicating it is the closest to the ideal across the chosen criteria. This makes it a strong candidate for applications where long range, high safety, and cost-effectiveness are prioritized, despite its moderate efficiency. Inductive Coupling holds the second position with a GRG of

0.5238, excelling in efficiency but lacking in range, making it ideal for short-distance, high-efficiency applications. Radio Frequency (RF) Transfer ranks third with a GRG of 0.5080, balancing range and cost-effectiveness but falling behind in efficiency. Magnetic Resonance Coupling and Resonant Inductive Coupling take the fourth and fifth positions, respectively, with GRGs of 0.4390 and 0.4264, indicating moderate performance across criteria without exceptional scores. This GRG and ranking data provide a comprehensive comparison, allowing for the selection of the most suitable WPT technology based on specific operational needs.

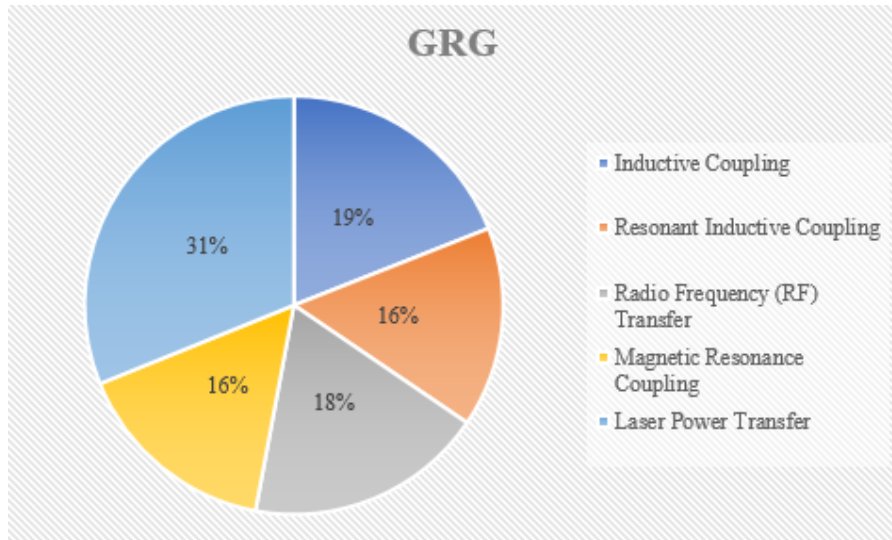


FIGURE 5. GRG

This pie chart illustrates the Grey Relational Grade (GRG) distribution among different wireless power transfer technologies based on Grey Relational Analysis (GRA). Laser Power Transfer dominates with the highest percentage at 31%, indicating its superior overall performance when multiple criteria are considered in the analysis. Inductive Coupling follows with 19% of the total GRG, suggesting it maintains a strong position as a reliable technology. Radio Frequency (RF) Transfer accounts for 18% of the grade, positioning it in the middle range of performance. Both Magnetic Resonance Coupling and Resonant Inductive Coupling share equal portions at 16% each, representing their comparable performance levels in the analysis. The GRG percentages reflect the comprehensive evaluation of these technologies, taking into account various performance parameters and their interrelationships. The significant lead of Laser Power Transfer (31%) over other technologies suggests it may offer distinct advantages in certain applications, while the relatively even distribution among the other technologies (ranging from 16-19%) indicates that each maintains competitive advantages in specific scenarios, making them viable options depending on the particular requirements of the wireless power transfer application.

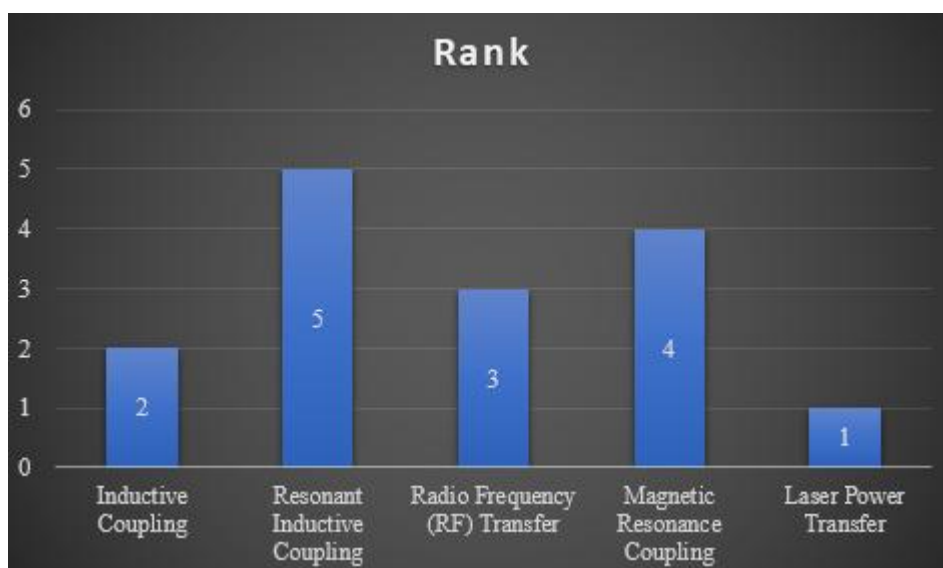


FIGURE 6. Rank

Looking at the ranking results from Grey Relational Analysis (GRA) method for wireless power transfer technologies, from best (Rank 1) to worst (Rank 5): Laser Power Transfer (Rank 1) - Achieves the highest ranking, indicating it's the most optimal solution when considering multiple performance criteria. This suggests superior performance characteristics and potential advantages in practical applications. Inductive Coupling (Rank 2) - Takes second place, demonstrating strong effectiveness and reliability among the compared technologies. Radio Frequency (RF) Transfer (Rank 3) - Places in the middle, showing moderate performance levels and balanced characteristics. Magnetic Resonance Coupling (Rank 4) - Ranks fourth, indicating some limitations in overall performance compared to the higher-ranked alternatives. Resonant Inductive Coupling (Rank 5) - Places at the bottom of the ranking, suggesting it may have more constraints or limitations when considering the evaluated criteria in the GRA analysis. Rank 1 being the best, shows that Laser Power Transfer technology demonstrates the most promising results, while Resonant Inductive Coupling may require further improvements to compete with other methods in terms of overall performance.

#### 4. CONCLUSION

The Grey Relational Analysis (GRA) applied to five different Wireless Power Transfer (WPT) technologies—Inductive Coupling, Resonant Inductive Coupling, Radio Frequency (RF) Transfer, Magnetic Resonance Coupling, and Laser Power Transfer—offers a clear comparison of each technology's performance across key criteria: efficiency, range, safety, and cost-effectiveness. The analysis highlights how each technology aligns with an ideal standard across these parameters, providing insights into their suitability for different application needs. The deviation sequence (Table 3) reveals that each technology has varying degrees of alignment with ideal values. Inductive Coupling demonstrates the highest alignment in efficiency but falls short in range and safety, making it a viable option for short-distance, high-efficiency applications. Resonant Inductive Coupling performs moderately across all criteria, reflecting its balanced yet non-optimal approach. Radio Frequency Transfer, while exhibiting low efficiency, shows better performance in range, making it suitable for applications prioritizing distance. Magnetic Resonance Coupling is also balanced across all criteria, with moderate performance without excelling in any one area, suggesting its utility for general applications without specific high-demand requirements. Laser Power Transfer stands out with the lowest deviation in range, safety, and cost-effectiveness, despite its lower efficiency, making it ideal for specialized long-range applications. The Grey Relation Coefficients (Table 4) further quantify these observations, illustrating the closeness of each technology to ideal values. Laser Power Transfer scores high in range, safety, and cost-effectiveness, while Inductive Coupling achieves a high score in efficiency. This reinforces Laser Power Transfer's potential in long-range applications where efficiency is less crucial and supports Inductive Coupling as an optimal choice for high-efficiency, short-distance needs. The Grey Relational Grade (GRG) and rank analysis (Table 5) provide an overall performance hierarchy. Laser Power Transfer ranks first with the highest GRG, indicating it is the most favorable for applications needing range, safety, and cost-effectiveness. Inductive Coupling ranks second, making it a reliable choice where efficiency is a priority. RF Transfer, Magnetic Resonance Coupling, and Resonant Inductive Coupling occupy the subsequent ranks, offering more balanced or moderate performance across the evaluated criteria. Overall, the GRA method proves effective in identifying the relative strengths and weaknesses of each WPT technology, facilitating an informed selection based on specific operational requirements. Laser Power Transfer leads in long-range, high-safety applications, while Inductive Coupling excels in short-range, efficient applications, showcasing the trade-offs inherent in each technology.

#### REFERENCES

- [1]. Song, M., & Hsu, C. Y. (2021). "A review of wireless power transfer for electric vehicles: Current status and future trends." *IEEE Transactions on Industry Applications*, 57(3), 2685–2696.
- [2]. Dai, J., & Ludois, D. C. (2015). "A survey of wireless power transfer and a critical comparison of inductive and capacitive coupling for small gap applications." *IEEE Transactions on Power Electronics*, 30(11), 6017–6029.
- [3]. Kurs, A., Karalis, A., Moffatt, R., Joannopoulos, J. D., Fisher, P., & Soljačić, M. (2007). "Wireless power transfer via strongly coupled magnetic resonances." *Science*, 317(5834), 83–86.
- [4]. Kim, J., Yoon, J. S., Park, D. H., & Jeong, S. J. (2020). "High efficiency wireless power transfer systems using magnetic resonance for implantable devices." *Journal of Mechanical Science and Technology*, 34(4), 1539–1546.
- [5]. Lu, F., Zhang, H., & Mi, C. C. (2015). "A review on the recent development of capacitive wireless power transfer technology." *Energies*, 8(11), 12166–12176.
- [6]. Fan, W., Han, Y., Zhou, C., & Guo, Y. (2018). "Wireless power transfer using resonant inductive coupling for electric vehicle charging." *Journal of Power Electronics*, 18(4), 1086–1093.
- [7]. Hui, S. Y. R., & Zhong, W. X. (2013). "Wireless power transfer by electric field resonance and magnetic field resonance: A comparison and review." *IEEE Transactions on Power Electronics*, 29(6), 2923–2933.

- [8]. Takeda, R., Kato, M., & Nagai, Y. (2017). "Safety standards and considerations for wireless power transfer." *IEEE Journal of Electromagnetics, RF and Microwaves in Medicine and Biology*, 1(1), 50–56.
- [9]. Varghese, S., & Singh, B. (2021). "Current developments in long-distance wireless power transfer." *Journal of Emerging Technologies and Innovative Research*, 8(4), 645–654.
- [10]. Peram, S. R. "Advanced Network Traffic Visualization and Anomaly Detection Using PCA-MDS Integration and Histogram Gradient Boosting Regression." *Journal of Artificial Intelligence and Machine Learning* 1, no. 3 (2023): 281.
- [11]. Barman, S., & Halder, S. (2019). "Multi-criteria decision-making using grey relational analysis (GRA) in WPT technologies." *International Journal of Research in Engineering and Science*, 7(7), 18–24.
- [12]. Liu, S., & Lin, Y. (2010). *Grey Systems: Theory and Applications*. Springer.
- [13]. Shinohara, N. (2014). *Wireless Power Transfer: Principles and Engineering Explorations*. Wiley-IEEE Press.
- [14]. Deng, J. (2011). *Introduction to Grey System Theory*. Science Press.
- [15]. Nayeemuddina Umme Salma, Green Fabrication of Nio Nano Particles Doped PS-PVDF Nanocomposite Films: Structural, Morphology and Electrical Studies, *Journal of Information Systems Engineering and Management*, 10(23), 2025, 794-800.
- [16]. Lu, X. (2018). *Wireless Power Transfer for Electric Vehicles and Mobile Devices*. Artech House.
- [17]. Zhang, X., & Zhang, Y. (2017). "Application of grey relational analysis in wireless power technologies." In *Advances in Grey System Theory and Applications* (pp. 245–260). Springer.
- [18]. Zhang, Y., & Ahn, C. H. (2016). "Comparative analysis of resonant wireless power transfer methods for efficient energy transmission." In *Proceedings of the International Conference on Power Electronics and Drive Systems*.
- [19]. Kanumarlapudi, Praveen Kumar, and S. Ballamudi. "Enhancing Generative AI Shopping Assistants through Advanced Multi-Attribute Decision Making Technique." *Journal of Artificial Intelligence and Machine Learning* 3, no. 2 (2025): 1-7.
- [20]. Kakulavaram, Sridhar. "Artificial Intelligence-Driven Frameworks for Enhanced Risk Management in Life Insurance." *Journal of Computational Analysis and Applications* 33, no. 8 (2024).
- [21]. Thota, Sandeep Kumar, Kumari Gubbala, Ashok Polavarapu, Vikram Narayandas, Hari Suresh Babu Gummati, Narendra Chennupati, Sreedhar Babu Seshagani, Shivakrishna Deepak Veeravalli, and Manisha Guduri. "Adversarial Training with Attention-Guided DCGAN for Robust Lung Segmentation in Medical Imaging." In *2025 IEEE Region 10 Symposium (TENSYMP)*, pp. 1-6. IEEE, 2025.
- [22]. Nayeemuddin, . and Salma, Umme, Analysis of a Drilling Hybrid Aluminum Metal Matrix Composites by Using SPSS (May 7, 2023). *Int. J. Adv. Res.* 11(01), 82-91, 2023, Available at SSRN: <https://ssrn.com/abstract=4440349>
- [23]. Kakulavaram, S. R. "Strategic Insights into Healthcare Waste Management through the DEMATEL Approach." *Journal of Business Intelligence and Data Analytics* 1, no. 3 (2024): 255.
- [24]. Park, J., & Kim, S. (2018). "Optimization of power efficiency in wireless power transfer systems for consumer electronics." In *IEEE MTT-S International Microwave Symposium Digest*.
- [25]. Peram, S. R. "Automated Label Detection and Recommendation System Using Deep Convolution Neural Networks and SPSS-Based Evaluation." *International Journal of Computer Science and Data Engineering* 1, no. 2 (2024): 258.
- [26]. Lee, H., & Kim, J. (2017). "Safety considerations in high-power wireless power transfer for industrial applications." In *Proceedings of the IEEE Power and Energy Conference*.
- [27]. Liu, J., & Zhang, H. (2019). "Multi-criteria optimization in WPT using grey relational analysis." In *International Conference on Advanced Power System Automation and Protection*.
- [28]. He, W., & Yuan, H. (2020). "Efficiency and cost-effectiveness evaluation of wireless power transfer technologies." In *Proceedings of the Annual IEEE Power Electronics Specialists Conference*.
- [29]. IEEE Standards Association. (2020). *IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz*. IEEE Std C95.1-2019.
- [30]. International Electrotechnical Commission (IEC). (2018). *Wireless Power Transfer (WPT) - Standards and Regulations Overview*. IEC White Paper.
- [31]. WiTricity Corporation. (2019). *Advancements in Magnetic Resonance WPT for EVs and Industry Applications* (White Paper).
- [32]. Chen, Z., & Liu, Y. (2019). "Inductive power transfer technology for wearable electronics." US Patent No. US10288464B2.
- [33]. Choi, S., & Kim, Y. (2021). "A high-efficiency resonant inductive wireless power transfer device." European Patent No. EP3623440A1.
- [34]. Abhinav, E. Meher, Sai Naveen Kavuri, Thota Sandeep Kumar, Maragani Thirupathi, M. Chandra Mohan, and A. Suresh Reddy. "Analysis of molecular single-electron transistors using silicene, graphene and germanene." In *Proceedings of the Second International Conference on Computer and Communication Technologies: IC3T 2015, Volume 1*, pp. 77-84. New Delhi: Springer India, 2015.
- [35]. Kanumarlapudi, P. K. "Improving Data Market Implementation Using Gray Relational Analysis in Decentralized Environments." *Journal of Artificial intelligence and Machine Learning* 2, no. 1 (2024): 1-7.