

Article

FEM-Based Performance Analysis of Circular and Rectangular Planar Spiral Coils for EV Wireless Power Transfer Under Turns Number, Air-Gap, and Misalignment Variation

Awatif Eshaimi ^{1,*} , Tamou Nasser ² and Ahmed Essadki ¹

¹ High National School of Arts and Crafts (ENSAM), Mohammed V University in Rabat, Rabat 10100, Morocco; ahmed.essadki.ensam@gmail.com

² High National School for Computer Science and Systems (ENSIAS), Mohammed V University in Rabat, Rabat 10000, Morocco; tamou.nasser@ensias.um5.ac.ma

* Correspondence: awatif.eshaimi@um5r.ac.ma

Abstract

This paper presents a 3D FEM-based comparative study of circular and rectangular planar spiral coils for electric vehicle (EV) wireless power transfer (WPT) at 85 kHz. A geometry-consistent simulation framework is adopted, where both coil types are evaluated under identical conductor material, conductor diameter, inner area, turn spacing, and excitation current, allowing the isolated effect of coil geometry to be analyzed. Three operating conditions are investigated: turn-number variation ($10 \leq N \leq 30$) under perfect alignment, air-gap variation (130–200 mm), and lateral misalignment variation ($\Delta x \in [-30, 30]$ mm). The transmitter self-inductance L_1 , receiver self-inductance L_2 , mutual inductance M , and coupling coefficient k are evaluated. The main contribution of this work is the identification of a geometry-dependent trade-off between coupling performance and robustness. The results show that increasing the number of turns enhances L_1 , L_2 , M , and k for both geometries, while self-inductances remain nearly insensitive to air gap and misalignment. The circular coil demonstrates higher robustness to coil separation and misalignment, whereas the rectangular coil can achieve higher coupling in configurations with a high number of turns under controlled misalignment conditions. These findings provide a solid basis for selecting the most suitable geometry for each wireless charging use case.

Keywords: wireless power transfer; electric vehicle; charging technologies



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1. Introduction

Electric vehicles (EVs) can currently be charged using three main methods. The first is battery replacement, which reduces downtime but poses challenges in terms of logistics and standardization [1]. The second is conductive charging, which is currently the most widespread solution as it delivers high power with high efficiency. Although it avoids the logistical constraints associated with battery replacement, the physical connection between the charger and the vehicle raises safety concerns and requires user intervention. The third approach is wireless power transfer (WPT), which enables contactless energy transfer via electromagnetic coupling between a transmitter coil (Tx) and a receiver coil (Rx) [2,3]. WPT improves user convenience and safety and can also support advanced use cases such as dynamic charging. To ensure interoperability and safe deployment, standards such as SAE J2954 recommend operation around 85 kHz and aim for an energy transfer efficiency (ETE) of at least 85% under specified conditions [4].

In wireless power transfer (WPT) systems, the geometry of the coils is one of the key factors determining magnetic coupling and overall transfer performance. In particular, self-inductance, mutual inductance and the coupling coefficient are strongly influenced by the shape of the coils, the air gap and the degree of misalignment. For this reason, numerous research groups have investigated various topologies and prototypes to validate the feasibility and performance of resonant inductive charging. Early work, such as the PATH program, demonstrated the feasibility of resonant inductive charging concepts, although limited efficiency was reported at low frequencies, partly due to resistive losses [5]. Subsequent developments, notably the KAIST OLEV series, explored different coil configurations and compensation strategies to improve performance [6,7]. High-power prototypes have further highlighted the importance of coil geometry and compensation design. For example, ORNL reported high efficiency at power levels of several tens of kilowatts using rectangular coils with LCC compensation [8,9]. Commercial and pilot deployments such as WAVE and Primove have also demonstrated the technical viability of wireless charging, although detailed coil design parameters are not always publicly available [10,11]. At the same time, electromagnetic compatibility (EMC) constraints and shielding requirements have been identified as important design considerations, particularly for dynamic WPT systems [12].

Recent studies confirm that the design of coils for wireless power transfer (WPT) remains an active and constantly evolving area of research. A 2024 study proposed a hybrid square–hexagonal coil structure to improve magnetic coupling, illustrating the ongoing interest in geometric innovation [13]. In 2024, Jaafari et al. investigated circular coils combined with ferrite structures and demonstrated that geometric parameters and ferrite configuration significantly affect coupling behavior and field concentration [14]. In a similar vein, Aganti et al. compared five coil geometries under identical design conditions and confirmed that geometry has a significant influence on coupling strength, air gap sensitivity, efficiency and misalignment tolerance [15]. Furthermore, in 2025, Yadav et al. examined the design and optimization of circular and rectangular couplers using ANSYS Maxwell, further emphasising the importance of geometric choice in wireless charging systems for electric vehicles [16]. More recently, studies and reviews published in 2026 have continued to highlight the importance of coupler design for robustness against misalignment and for deployment-focused wireless charging systems for electric vehicles [17,18].

With regard to comparisons with conventional planar geometries, previous studies have shown that rectangular or square coils can offer higher coupling under conditions of perfect alignment [19,20], whilst circular coils often exhibit better tolerance to lateral misalignment [20]. However, despite the growing body of work on WPT coupler design, the available comparisons between circular and rectangular planar coils remain insufficiently harmonized to serve as a direct guide to design. In particular, the number of turns, the air gap, and lateral misalignment are often examined under different modeling assumptions, geometric constraints, or excitation conditions, making it difficult to isolate the actual impact of the coil geometry.

To address this gap, this paper presents a controlled comparison, based on the 3D finite element method, between circular and rectangular planar spiral coils designed for wireless power transfer to electric vehicles. The aim is not only to evaluate the electromagnetic response of the two geometries but also to clarify the trade-off between coupling performance and robustness under representative design and operational variations. Using a consistent modeling framework, the study aims to isolate the influence of coil geometry on self-inductance, mutual inductance, and the coupling coefficient and to provide practical guidance for selecting planar coil geometries based on the expected operational constraints of wireless power transfer systems for electric vehicles.

The remainder of this paper is organized as follows:

- Section 2 states the theoretical background of WPT.
- Section 3 describes the FEM model, simulation setup, and performance metrics.
- Section 4 presents the FEM results for turn-number, air-gap, and misalignment variations.
- Section 5 discusses the main design insights.
- Section 6 concludes the paper.

2. Theoretical Background of Inductive WPT

Wireless power transfer (WPT) technology relies on magnetic coupling between two coils: the transmitter (Tx) and the receiver coil (Rx). When an alternating current is supplied to the transmitter coil, it produces a magnetic field. Part of this generated field interacts with the receiver coil, where it induces a voltage following Faraday's law of electromagnetic induction. The effectiveness of energy transfer depends on the coil geometry; the distance separating the coils, called the air gap; and how well they are aligned with each other.

For two magnetically coupled coils, the flux linkages can be expressed as

$$\lambda_1 = L_1 i_1 + M i_2, \quad (1)$$

$$\lambda_2 = L_2 i_2 + M i_1, \quad (2)$$

where L_1 and L_2 are the self-inductances of the transmitter and receiver coils, respectively, M is the mutual inductance, and i_1 and i_2 are the coil currents. The self-inductance describes the ability of each coil to store magnetic energy, whereas the mutual inductance quantifies the magnetic flux produced by one coil and linked to the other.

The mutual inductance can be written as

$$M = \frac{\lambda_{21}}{i_1}, \quad (3)$$

where λ_{21} is the flux linkage in the receiver coil caused by the current in the transmitter coil. A higher value of M indicates a stronger magnetic linkage between the two coils.

To normalize this interaction, the coupling coefficient k is used:

$$k = \frac{M}{\sqrt{L_1 L_2}}. \quad (4)$$

The coupling coefficient is a dimensionless quantity that describes the strength of magnetic coupling independently of the absolute inductance levels. In general, a higher value k indicates a stronger electromagnetic coupling and a better ability of the transmitter magnetic field to link to the receiver coil.

In EV wireless charging systems, M and k are key indicators for comparing coil geometries because they directly reflect the quality of magnetic coupling. However, these quantities are sensitive to the air gap and lateral misalignment, whereas the self-inductances are mainly governed by the coil geometry itself. For this reason, the present study evaluates L_1 , L_2 , M , and k in order to compare the electromagnetic behavior of circular and rectangular planar coils under different operating conditions.

3. FEM Model, Simulation Setup, and Performance Metrics

A 3D FEM model is developed to compare circular and rectangular planar spiral coils for EV wireless power transfer (WPT) at 85 kHz. To establish a common geometric baseline for comparison, the circular and rectangular coils were defined using approximately equal inner areas. The circular coil uses an inner radius of $r_0 = 5$ mm, corresponding to an inner area of approximately 78.54 mm², whereas the rectangular coil uses inner dimensions

of $w_0 = 10$ mm and $h_0 = 8$ mm, corresponding to an inner area of 80 mm^2 . These approximately equal inner areas were selected to enable a fair comparison between the two geometries while preserving their characteristic shapes. The coil parameters are listed in Table 1.

Table 1. Geometric and electrical parameters used in the FEM study.

Parameter	Circular Coil	Rectangular Coil
Conductor material	Copper	Copper
Conductor diameter d (mm)	0.5	0.5
Turn spacing s (mm)	1.5	1.5
Inner dimensions	$r_0 = 5$ mm	$w_0 = 10$ mm, $h_0 = 8$ mm
Excitation current I (A)	10	10
Number of turns N	$10 \leq N \leq 30$ (scenario-dependent)	

The comparison in this study was established using identical conductor material, conductor diameter, turn spacing, and excitation current, together with comparable geometric reference dimensions for the two coil shapes. The present FEM setup was intended to compare the electromagnetic behavior of circular and rectangular planar coils under common winding rules rather than under equal total copper volume or equal total wire length. Therefore, the results should be interpreted as a geometry-based comparison under shared design conditions, not as a material-normalized optimization study. For that, three simulation scenarios are considered:

1. Turn-number sweep under perfect alignment ($\Delta x = 0$ mm) and fixed air-gap,
2. Air-gap sweep over 130–200 mm under perfect alignment ($\Delta x = 0$ mm),
3. Lateral misalignment sweep ($\Delta x \in [-30, 30]$ mm) at an air gap of 130 mm.

Electromagnetic performance is evaluated using transmitter self-inductance (L_1), receiver self-inductance (L_2), mutual inductance (M), and coupling coefficient (k) using FEM.

To confirm the model stability, a mesh-convergence analysis was conducted. For this purpose, three mesh refinement levels were considered: large, medium, and fine. The three configurations are listed in Table 2.

Table 2. Mesh refinement configurations used for the mesh-convergence analysis.

Mesh Configuration	Coil Maximum Element Length	Region Maximum Element Length	Relative Refinement Level
Large	0.4 mm	0.8 mm	Baseline mesh
Medium	0.2 mm	0.4 mm	Refined mesh
Fine	0.1 mm	0.2 mm	Highly refined mesh

For each mesh configuration, the self-inductances, mutual inductance, and coupling coefficient were extracted and compared. The obtained results are summarized in Table 3.

Table 3. Verification results for circular and rectangular coil mesh configurations.

Mesh Configuration	L_1 (μH)	L'_1 (μH)	L_2 (μH)	L'_2 (μH)	M (nH)	M' (nH)	k	k'
Large	2.46	2.86	2.44	2.86	1.87	0.48	7.63×10^{-4}	1.66×10^{-4}
Medium	2.46	2.86	2.44	2.86	1.87	0.48	7.63×10^{-4}	1.66×10^{-4}
Fine	2.46	2.86	2.44	2.86	1.87	0.48	7.63×10^{-4}	1.66×10^{-4}

Since all parameters have approximately the same values across the three configurations, the FEM results can be considered mesh-independent within the investigated configuration. This supports the numerical stability of the model for the comparative analysis.

The obtained FEM results can be interpreted through simple benchmarking indicators. These indicators are derived from the coupling coefficient values and are defined to support geometry selection. The three indicators considered in the current study are

- High-turn coupling gain (Equation (5));
- Air-gap coupling retention (Equation (6));
- Misalignment coupling retention (Equation (7)).

$$G_N = \frac{k'_N - k_N}{k_N} \times 100, \quad (5)$$

where k_N and k'_N are the coupling coefficients of the circular and rectangular coils for a given number of turns.

$$R_{gap} = \frac{k(g_{max})}{k(g_{min})} \times 100, \quad (6)$$

where g_{min} and g_{max} are the minimum and maximum investigated air gaps, respectively.

$$R_{mis} = \frac{k(\Delta x)}{k(0)} \times 100, \quad (7)$$

where $k(0)$ is the coupling coefficient under perfect alignment and $k(\Delta x)$ is the coupling coefficient at a given lateral offset.

4. FEM Results

This section reports the FEM results for circular and rectangular coils under variations in the number of turns, air-gap, and lateral misalignment. The analysis focuses on self-inductances (L_1 , L_2), mutual inductance (M), and coupling coefficient (k) to quantify energy storage, magnetic linkage, and coupling strength. Plots and tables are used to summarize the results.

4.1. Effect of Number of Turns on Coil Performance

The objective of this step is to validate the behavior of the cited parameters when we vary the number of turns; for that, only the number of turns has been varied from 10 to 30. The rest of the parameters remained constant, including the copper conductor diameter, turn spacing, excitation current, and the inner dimensions of each geometry (inner radius r_0 for the circular spiral and inner width w_0 and height h_0 for the rectangular spiral). This scenario is described in Figure 1.

The simulation results are summarized in Table 4.

Table 4. Simulation results for circular and rectangular coil geometries with varying number of turns N .

N	L_1 (μH)	L'_1 (μH)	L_2 (μH)	L'_2 (μH)	M (nH)	M' (nH)	k	k'
10	2.46	2.86	2.44	2.8645	1.87	0.4750	7.63×10^{-4}	1.66×10^{-4}
15	6.36	7.88	6.33	7.8900	10.06	4.3556	15.85×10^{-4}	5.52×10^{-4}
20	12.93	16.56	12.91	16.6065	36.15	28.6058	28.01×10^{-4}	17.3×10^{-4}
25	23.19	29.61	23.18	29.7369	111.73	123.2508	47.73×10^{-4}	41.5×10^{-4}
28	31.20	39.82	31.21	40.0226	197.72	250.9706	63.36×10^{-4}	62.9×10^{-4}
30	37.52	47.63	37.54	47.8955	283.66	381.3465	75.58×10^{-4}	79.8×10^{-4}

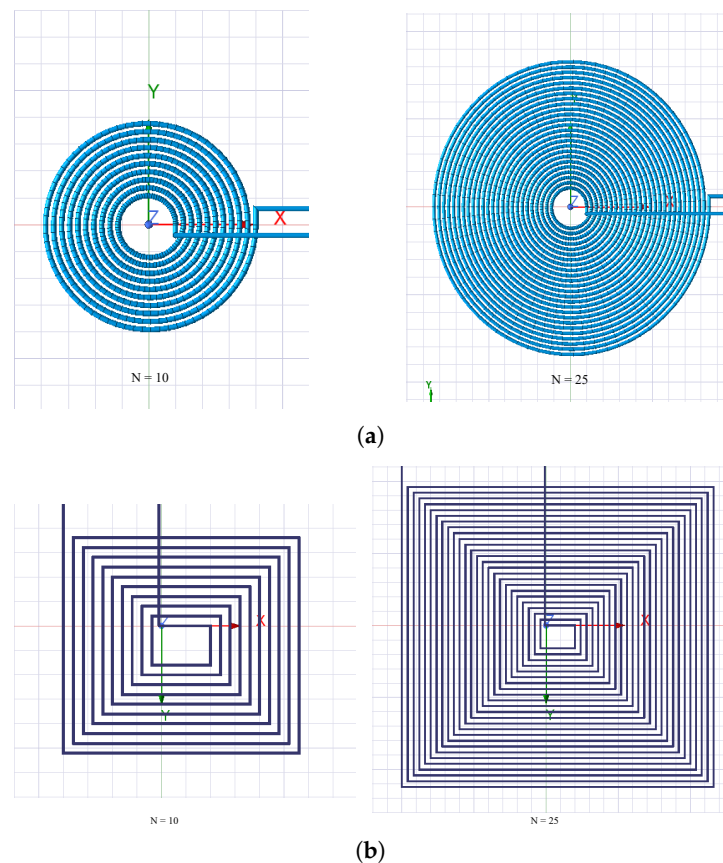


Figure 1. Top views of the studied planar coil geometries: (a) circular coil and (b) rectangular coil.

The variation in self-inductance with the number of turns is shown in Figure 2. Both geometries exhibit analogous behavior; as N increases, the self-inductances show a non-linear increase, rising from approximately $\sim 2.46 \mu\text{H}$ at $N = 10$ to around $\sim 37.5 \mu\text{H}$ at $N = 30$ for the circular geometry and from approximately $\sim 2.86 \mu\text{H}$ at $N = 10$ to between ~ 47.6 and $47.9 \mu\text{H}$ at $N = 30$ for the rectangular coil, surpassing the circular case at high turn counts.

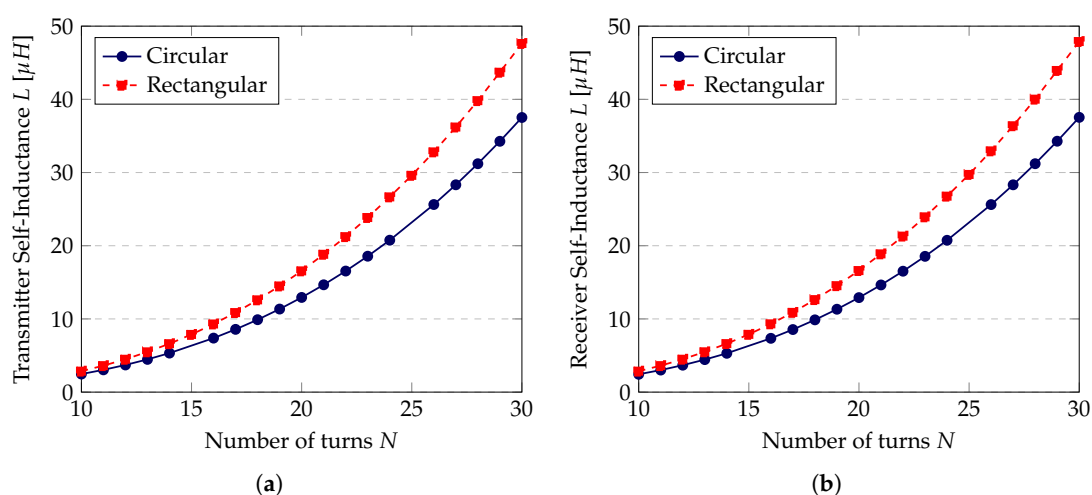


Figure 2. Variation in self-inductance with the number of turns for circular and rectangular planar coil geometries: (a) transmitter self-inductance and (b) receiver self-inductance.

Figure 3 shows the variation in mutual inductance and the coupling coefficient with the number of turns for both geometries. Since M and K exhibit similar increasing trends, although K also depends on the self-inductances, we can see that they have the same behavior for both geometries. They increase as N increases. The M of the circular coil rises from 1.87 nH at $N = 10$ to 283.66 nH at $N = 30$, resulting in the coupling coefficient varying from approximately 0.76×10^{-3} at $N = 10$ to 7.56×10^{-3} at $N = 30$. On the other hand, the M' of the rectangular coil varies from $M' = 0.475$ nH at $N = 10$ to 381.35 nH at $N = 30$ with a K increasing from 1.66×10^{-4} at $N = 10$ to 79.8×10^{-4} at $N = 30$ with a corresponding coupling gain of approximately 5.6% in favor of the rectangular coil. So, we can say that the flux linkage density becomes stronger when N increases. Furthermore, by comparing both geometries, we can see that the M' becomes higher than M by 10.31% when we reach $N = 24$, but the rectangular coil transfer becomes more efficient than the circular coil 5.58% only when we reach $N > 28$.

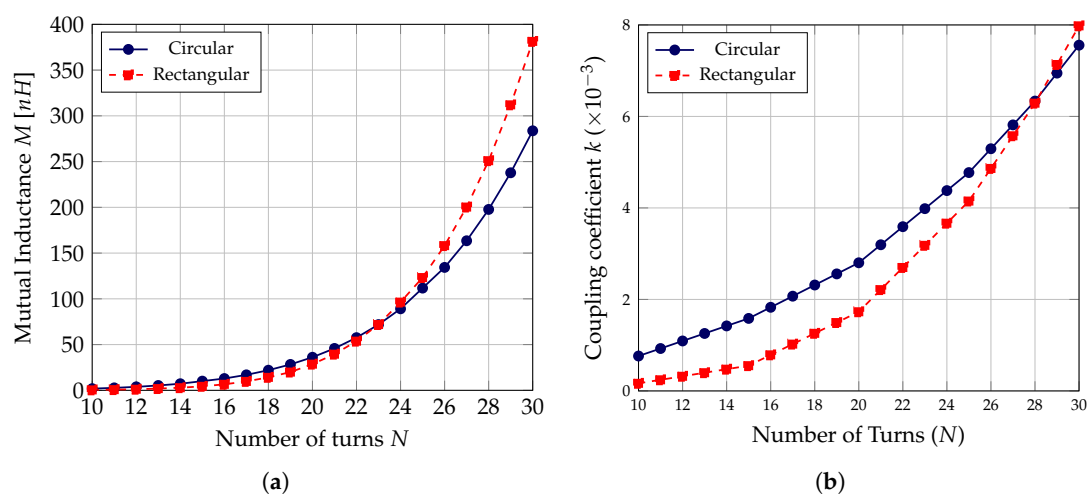


Figure 3. Variation in mutual inductance and coupling coefficient with number of turns for circular and rectangular planar coil geometries: (a) mutual inductance M and (b) coupling coefficient k .

4.2. Effect of Air Gap on Coil Performance

This section studies the influence of the air gap on magnetic coupling. All simulations are performed under perfect alignment ($\Delta x = 0$ mm) with an excitation current of $I = 10$ A, while keeping the coil geometric parameters identical to the previous given data as shown in Figure 4.

Although self-inductance is mainly governed by coil geometry and is expected to be weakly dependent on the separation distance, L_1 and L_2 are monitored across the air-gap sweep to confirm this behavior. The air-gap sensitivity is primarily quantified through the mutual inductance (M) and coupling coefficient (k), which directly capture the strength of Tx–Rx magnetic coupling.

Two winding configurations are considered: a baseline case with $N = 10$ (Table 5) and a high-turn case with $N = 25$ (Table 6). The second configuration has been selected to evaluate air-gap effects where the rectangular geometry exhibits stronger coupling performance at large N (Table 4).

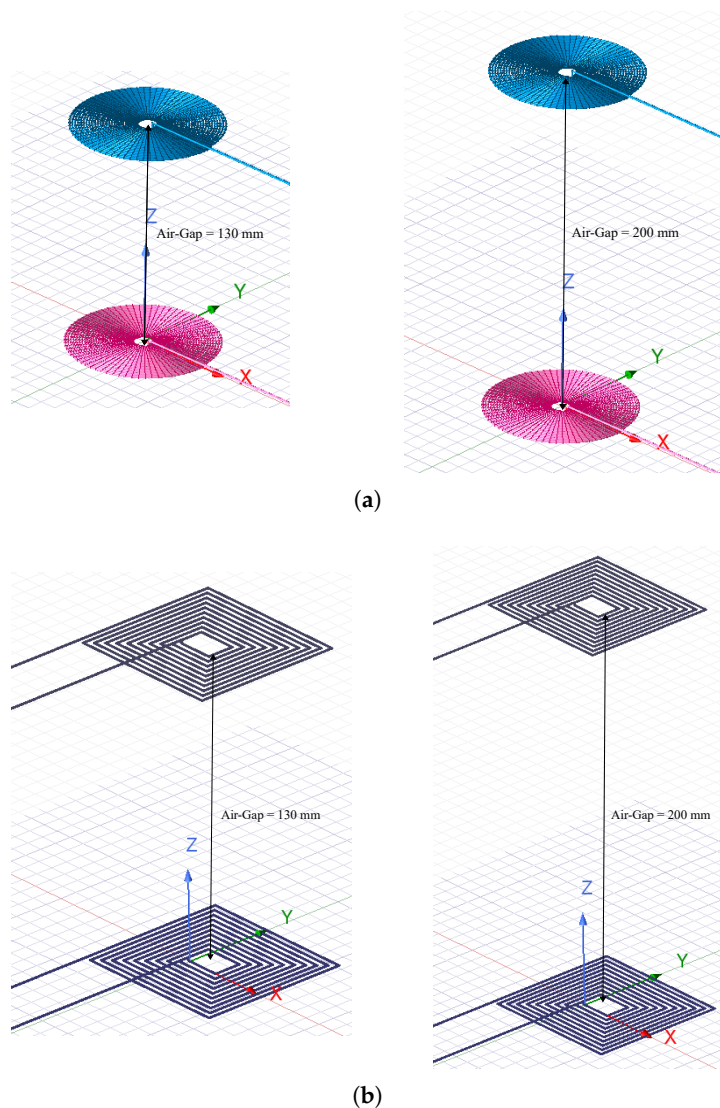
Figure 5 presents the variation in Tx and Rx self-inductances with the air gap for both geometries. Over an air gap ranging from 130–200 mm, the self-inductances remain constant. This confirms that the self-inductance is primarily impacted by coil geometry and is weakly affected by the air gap. Overall, the rectangular coil exhibits a higher self-inductance level (about 16% above the circular case).

Table 5. Simulation results for circular and rectangular coil geometries while varying the air-gap distance for $N = 10$.

<i>AirGap</i> (mm)	L_1 (μH)	L'_1 (μH)	L_2 (μH)	L'_2 (μH)	M (nH)	M' (nH)	k	k'
130	2.46	2.86	2.44	2.86	2.16	0.48	8.87×10^{-4}	1.69×10^{-4}
150	2.46	2.86	2.44	2.86	1.43	0.23	5.87×10^{-4}	0.80×10^{-4}
170	2.46	2.86	2.44	2.86	0.97	0.12	3.99×10^{-4}	0.41×10^{-4}
190	2.46	2.86	2.44	2.86	0.67	0.06	2.77×10^{-4}	0.22×10^{-4}
200	2.46	2.86	2.44	2.86	0.57	0.05	2.33×10^{-4}	0.16×10^{-4}

Table 6. Simulation results for circular and rectangular coil geometries while varying the air-gap distance for $N = 25$.

<i>AirGap</i> (mm)	M (nH)	M' (nH)	k	k'
130	127.51	592.02	5.47×10^{-3}	15.30×10^{-3}
150	80.79	372.15	3.46×10^{-3}	9.34×10^{-3}
170	53.27	230.51	2.28×10^{-3}	5.65×10^{-3}
190	36.01	141.27	1.54×10^{-3}	3.41×10^{-3}
200	29.77	111.6	1.27×10^{-3}	2.66×10^{-3}

**Figure 4.** The studied planar coil geometries (a) circular coil and (b) rectangular coil under air-gap variation.

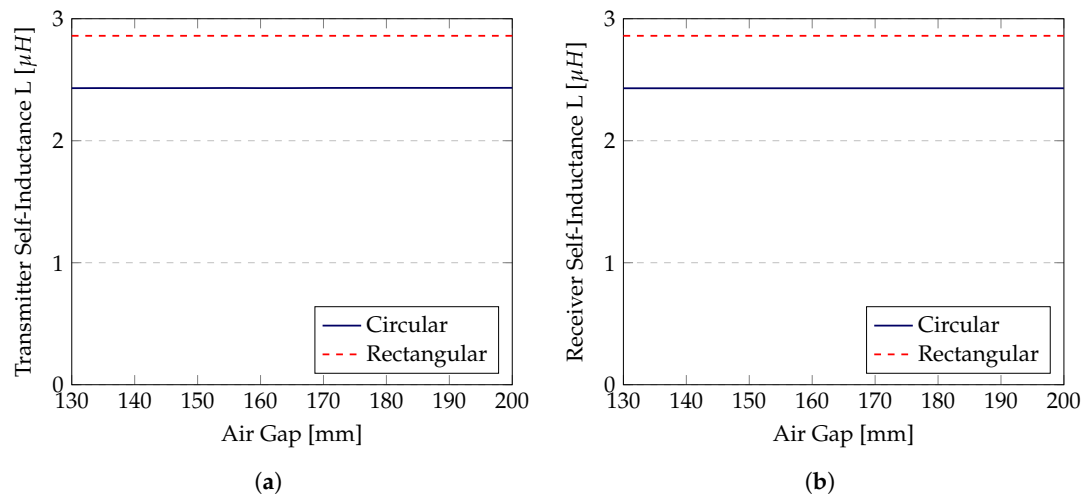


Figure 5. Variation in self-inductance with air gap for circular and rectangular planar coil geometries: (a) transmitter self-inductance, and (b) receiver self-inductance.

Figure 6 presents the variation in mutual inductance and the coupling coefficient with the air gap for both coil geometries. As observed, both parameters decrease with the air gap, which highlights the fact that increasing the distance between the transmitter and the receiver weakens the magnetic coupling. However, since the number of turns is small, it can be observed that the circular coil is stronger than the rectangular coil, as M decreases from ≈ 2.16 nH at 130 mm to ≈ 0.57 nH at 200 mm (about a 74% reduction), while M' drops from ≈ 0.48 nH to ≈ 0.05 nH over the same range (about a 90% reduction). This trend also affects the coupling coefficient, as K decreases from $\approx 8.87 \times 10^{-4}$ at 130 mm to $\approx 2.33 \times 10^{-4}$ at 200 mm (about a 74% reduction), whereas K' drops from $\approx 1.69 \times 10^{-4}$ to $\approx 0.16 \times 10^{-4}$ over the same range (about a 91% reduction). Across all distances, the circular geometry consistently maintains a higher coupling coefficient, with $k \approx 5.25, k'$ at 130 mm and $k \approx 14.6, k'$ at 200 mm.

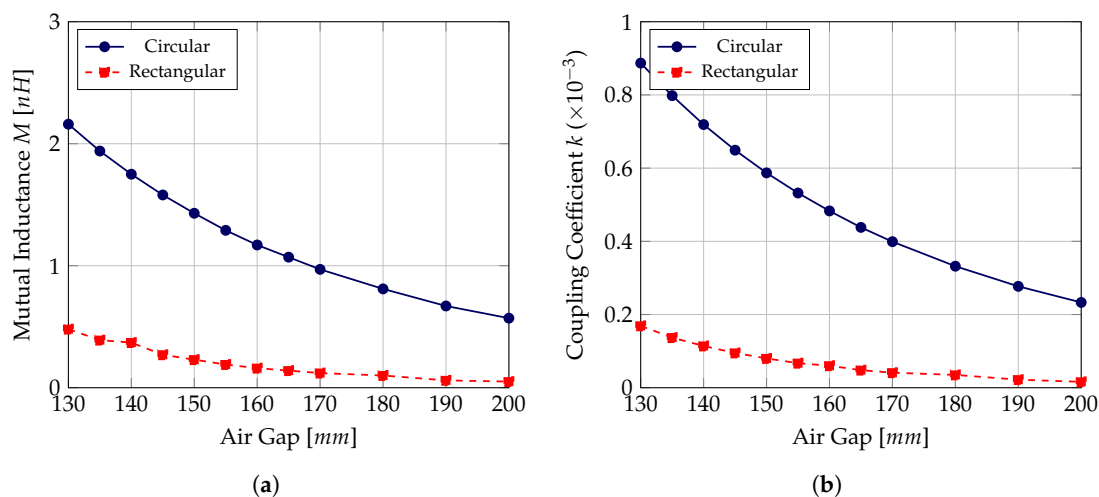


Figure 6. Variation in mutual inductance and coupling coefficient with air gap for circular and rectangular planar coil geometries at $N = 10$: (a) mutual inductance M and (b) coupling coefficient k .

Based on the previous observations, a second air-gap study is conducted using a different winding configuration with $N = 25$ and turn spacing $s = 1.5$ mm. Since the self-inductances were found to be essentially insensitive to the air-gap variation, the analysis in this case focuses only on the mutual inductance (M) and coupling coefficient (k).

Figure 7 shows the variation in the mutual inductance and the coupling coefficient as a function of the air gap for the configuration with $N = 25$ and $s = 2.5$ mm over the range 130–200 mm. For both geometries, the mutual inductance decreases nonlinearly as the air gap increases, reflecting the attenuation of the magnetic field with increased vertical separation. Both geometries exhibit the same general behavior observed for small values of N ; however, when N is increased, the rectangular coil maintains higher values across the entire range. In this case, M' decreases from 592.02 nH at 130 mm to 111.60 nH at 200 mm, while k' decreases from approximately 15.3×10^{-3} at 130 mm to approximately 2.7×10^{-3} at 200 mm. On the other hand, for the circular geometry, the mutual inductance M decreases from 127.51 nH at 130 mm to 29.77 nH at 200 mm, and the coupling coefficient k decreases from 5.47×10^{-3} at 130 mm to approximately 1.27×10^{-3} at 200 mm.

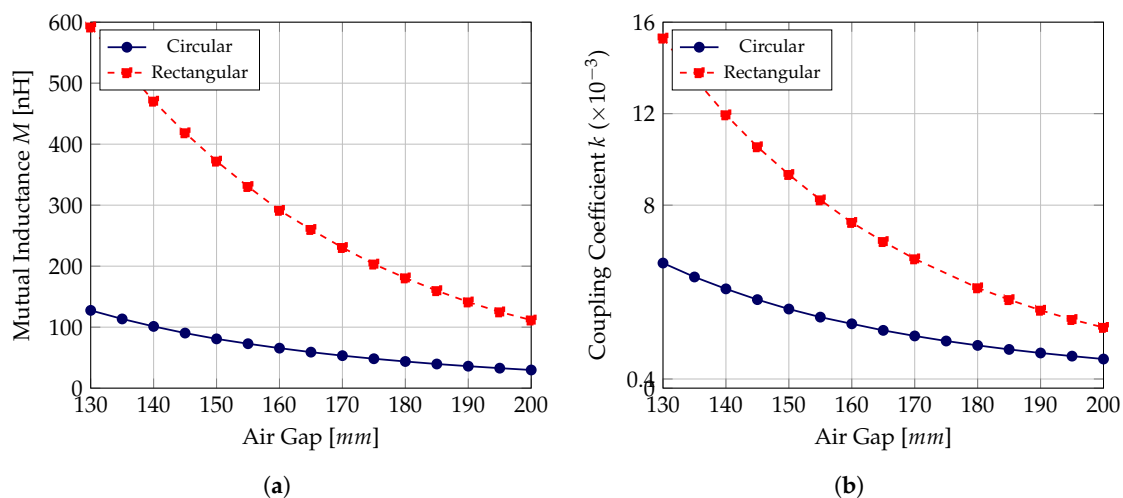


Figure 7. Variation in mutual inductance and coupling coefficient with air gap for circular and rectangular planar coil geometries at $N = 25$: (a) mutual inductance M and (b) coupling coefficient k .

For the low-turn configuration with $N = 10$, the circular coil maintains approximately 26.3% its initial coupling when the air gap increases from 130 mm to 200 mm, whereas the rectangular coil retains only approximately 9.5%. For the high-turn configuration with $N = 25$, the circular and rectangular coils retain approximately 23.2% and 17.4%, respectively. These values also confirm that the increase in the number of turns improves the absolute coupling level but does not eliminate the sensitivity to vertical separation.

4.3. Effect of Misalignment on Coil Performance

To evaluate the robustness of magnetic coupling under realistic use cases, a lateral misalignment sweep is performed for both coil geometries. The transmitter and receiver are shifted along the x -axis within $\Delta x \in [-30, 30]$ mm while keeping the air gap constant at 130 mm as shown in Figure 8. For the rectangular coil the x -axis side corresponds to the long edge direction. The results of this simulation are reported in Table 7.

All coil geometric and electrical parameters are kept constant so that the observed variations are only due to the change in lateral positioning. The impact of misalignment is assessed using the extracted self-inductances (L_1, L_2), mutual inductance (M), and coupling coefficient (k).

Figure 9 presents the behavior of the self-inductances as the lateral misalignment is varied for both coil geometries. As highlighted, the self-inductance does not change across the misalignment range $\Delta x \in [-30, 30]$ mm. This confirms that lateral misalignment does not significantly affect the self-inductance, which is primarily determined by the coil geometry.

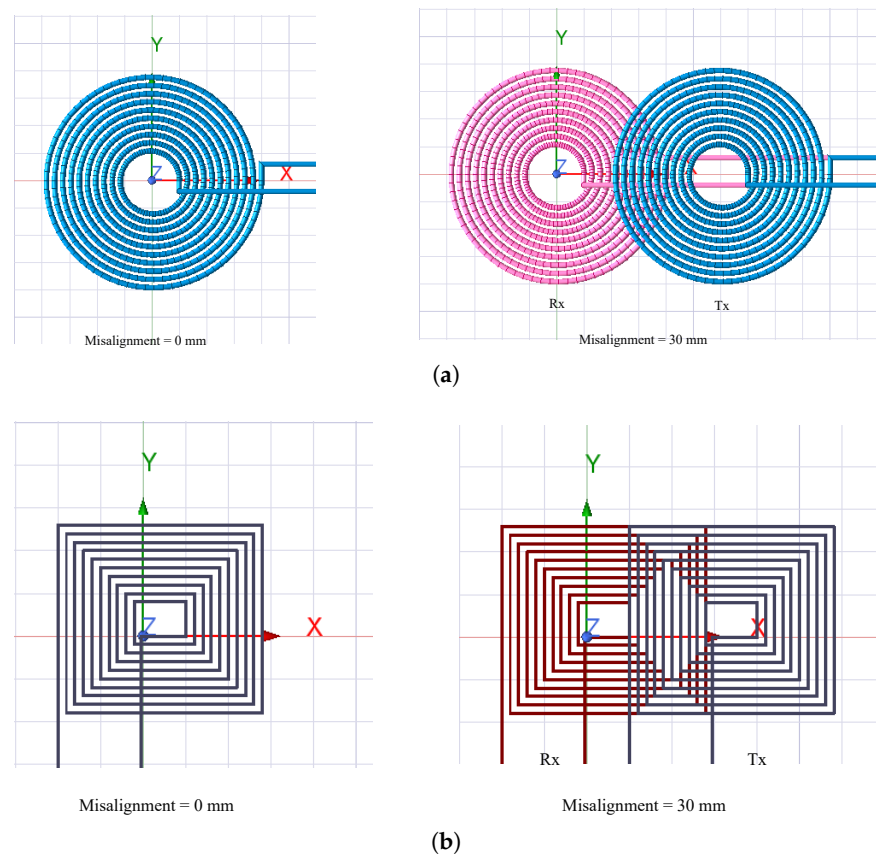


Figure 8. Top views of the studied planar coil geometries: (a) circular coil and (b) rectangular coil under misalignment variation.

Table 7. Simulation results for circular and rectangular coil geometries while varying the misalignment factor.

Misalignment (mm)	L_1 (μH)	L'_1 (μH)	L_2 (μH)	L'_2 (μH)	M (nH)	M' (nH)	k	k'
−30	2.46	2.86	2.44	2.86	1.61	−0.35	6.65×10^{-4}	-1.20×10^{-4}
−20	2.46	2.86	2.44	2.86	1.91	0.034	7.89×10^{-4}	0.12×10^{-4}
−10	2.46	2.86	2.44	2.86	2.1	0.33	8.65×10^{-4}	1.14×10^{-4}
0	2.46	2.86	2.44	2.86	2.19	0.48	8.99×10^{-4}	1.66×10^{-4}
10	2.46	2.86	2.44	2.86	2.16	0.31	8.79×10^{-4}	1.08×10^{-4}
20	2.46	2.86	2.44	2.86	2.1	−0.01	8.55×10^{-4}	-0.02×10^{-4}
30	2.46	2.86	2.44	2.86	1.87	−0.42	7.63×10^{-4}	-1.43×10^{-4}

Figure 10 shows the variation in the mutual inductance and the coupling coefficient with lateral misalignment for both coil geometries. As highlighted, for the circular coil, the mutual inductance M increases from 1.61 nH at −30 mm to a maximum of 2.19 nH around $x = 0$ mm, and then decreases to approximately 1.87 nH at 30 mm. The corresponding coupling coefficient k increases from $\approx 6.65 \times 10^{-4}$ at −30 mm to a maximum of $\approx 8.99 \times 10^{-4}$ around $x = 0$ mm, and then decreases to $\approx 7.63 \times 10^{-4}$ at 30 mm, maintaining approximately 84.9% of its aligned coupling value. This behavior indicates that the circular configuration achieves its strongest coupling near the aligned condition and degrades progressively as misalignment increases. In contrast, the mutual inductance of the rectangular coil, M' , exhibits a much sharper variation with misalignment, ranging from negative values at large offsets (e.g., ≈ -0.35 nH at −30 mm and ≈ -0.42 nH at 30 mm) to a peak of ≈ 0.48 nH at $\Delta x = 0$ mm. Similarly, the coupling coefficient k' exhibits a strong dependence on misalignment, ranging from negative values at large offsets (e.g., $\approx -1.20 \times 10^{-4}$ at

-30 mm and $\approx -1.43 \times 10^{-4}$ at 30 mm) to a peak of $\approx 1.66 \times 10^{-4}$ at $\Delta x = 0$ mm. By comparing the sensitivity of both geometries to misalignment, it is clear that the rectangular geometry is more sensitive to lateral displacement, exhibiting a rapid reduction in coupling as the coils move away from alignment.

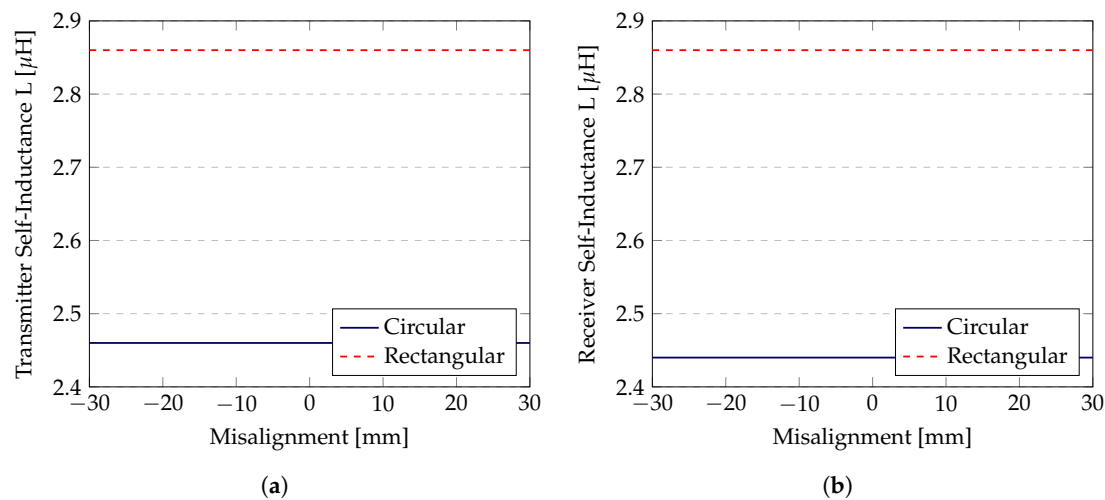


Figure 9. Variation in self-inductance with misalignment for circular and rectangular planar coil geometries: (a) transmitter self-inductance and (b) receiver self-inductance.

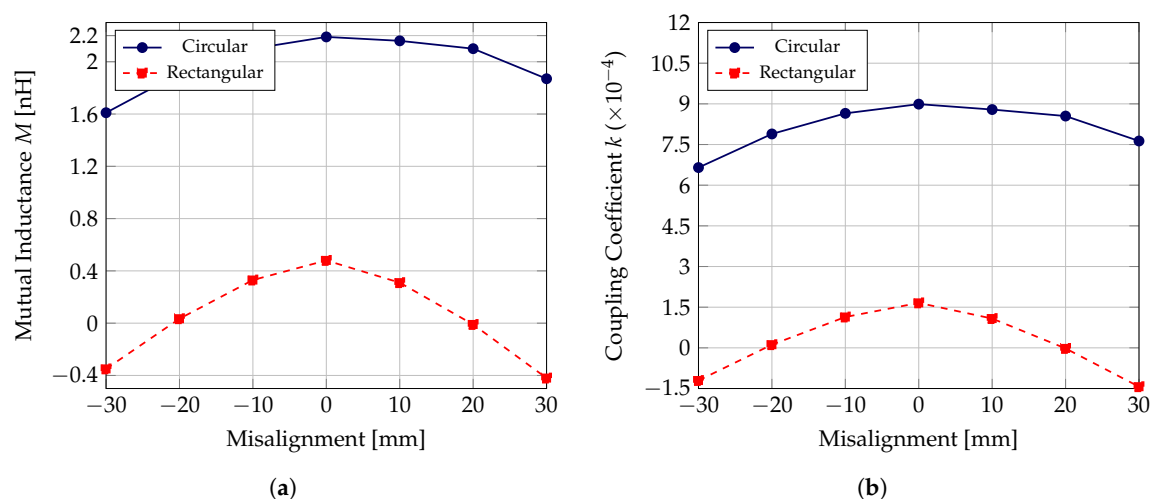


Figure 10. Variation in mutual inductance and coupling coefficient with misalignment for circular and rectangular planar coil geometries: (a) mutual inductance M and (b) coupling coefficient k .

5. Discussion

The current study confirmed that coil geometries and operating conditions directly impact WPT charger performances. The interaction between the transmitter side and receiver side is characterized by the mutual inductance (M) and coupling coefficient (k), while the self-inductances (L_1 , L_2) are primarily impacted by the coil's design. This distinction is important in order to choose the right design for our system. In this context, Table 8 provides a concise summary of the main findings and relates them to previous literature.

As the study highlights, the self-inductances of circular and rectangular planar geometries increase when N increases. This behavior is explained by the fact that with high N turns, the size of the windings is greater, and thus the magnetic energy that can be stored in the coil is higher. The increase in L results in a direct increase in mutual inductance M , demonstrating that a large part of the transmitter's magnetic field is well captured by the

receiver, which leads to an increase in the coupling coefficient k . So we can conclude that N is the primary design lever that enhances the magnetic interactions between the two parts as well as the coil inductive levels. However, this enhancement cannot answer to the WPT limitations, as it is necessary to interpret the effect of N using all extracted quantities (L_1 , L_2 , M , and k) rather than just one metric.

Table 8. Comparative summary of the main findings for circular and rectangular planar coils under the investigated scenarios, with qualitative consistency with previous literature.

Scenario	Circular Coil	Rectangular Coil	Main Insight	Consistency with Literature
Turn-number variation ($10 \leq N \leq 30$)	L_1 , L_2 , M , and k increase with N . Higher M and k are observed for the circular coil at low turn numbers.	L_1 , L_2 , M , and k also increase with N . The rectangular coil reaches higher self-inductance values and may exceed the circular coil in M and k at high N .	Increasing N strengthens magnetic coupling in both geometries. Circular coils are more favorable at low N , whereas rectangular coils become competitive at high N .	Consistent with recent studies showing that coil geometry and winding configuration strongly affect coupling behavior and performance [14–16].
Air-gap variation (130–200 mm)	L_1 and L_2 remain nearly constant, while M and k decrease with increasing air gap. The circular coil maintains higher coupling levels.	L_1 and L_2 remain nearly constant, while M and k decrease more sharply and show higher sensitivity to separation distance.	Air gap mainly affects magnetic coupling rather than self-inductance. The circular coil is more robust to air-gap increase.	Consistent with prior studies showing that air gap strongly reduces coupling, whereas self-inductance is mainly governed by geometry [15,19,20].
Lateral misalignment variation ($\Delta x \in [-30, 30]$ mm)	L_1 and L_2 remain nearly constant. M and k vary smoothly, indicating better tolerance to lateral offset.	L_1 and L_2 remain nearly constant. M and k vary more sharply and may become negative at large offsets.	Misalignment mainly affects coupling behavior. The circular coil is more robust, whereas the rectangular coil is more sensitive to offset.	In agreement with previous studies reporting better lateral misalignment tolerance for circular coils and stronger alignment dependence for rectangular or square geometries [19,20].
Overall design tendency	Better robustness to air-gap increase and lateral misalignment.	Higher inductance levels and stronger coupling potential in high-turn configurations.	Coil selection should depend on the intended operating conditions.	Consistent with recent literature emphasizing that coupler choice is application-dependent and must balance coupling level, robustness, and geometric constraints [15–18].

Unlike the variation in the number of turns, changes in the air gap and misalignment do not affect the self-inductances; they only impact the mutual inductance and, consequently, the coupling coefficient. As we confirmed in our study, the L_1 and L_2 are shaped by the coil design, and they are almost constant when we increase the air gap. Furthermore, both M and k decrease significantly as the air gap increases, indicating that the magnetic coupling weakens rapidly as the coils move further apart. Due to this behavior, the air gap is a major limiting factor in the system's performance. It is essential to note that the configuration of the windings can influence the comparison of geometries: the ranking of mutual inductances between circular and rectangular coils may vary when the number of turns and the arrangement of the windings change. Since k is a normalized measure that depends on both M and the self-inductances, this also explains why a higher mutual inductance does not always imply a higher coupling coefficient. Increasing the number of turns is the primary compensatory mechanism when a large air gap is unavoidable, but reducing the air gap remains the most effective means of maintaining coupling in practice.

For the last studied scenario, the results show that the mutual inductance and coupling coefficient are sensitive to the lateral misalignment, as we saw that when the two coils are approximately aligned, we have the maximum values of M and k , and they gradually decrease as misalignment varies from the center. This behavior could be explained as the misalignment modifying the overlap of the magnetic fields between the transmitter coil (T_x) and the receiver coil (R_x). In the case of a rectangular coil, the impact of misalignment not only decreases the coupling efficiency but also makes the magnetic flux produced by the Tx not effectively coupled to Rx in the same direction. Instead, part of the flux links to the receiver coil with the opposite orientation, leading to a phase inversion of the induced voltage and resulting in negative mutual inductance. Furthermore, like the air gap, the self-inductances remain constant when we vary the misalignment, as they are a design factor. As we observe the same behavior, it can be explained in the same way. Our study confirmed that the coil exhibits a smoother variation, unlike the rectangular coil, which showed a high sensitivity to variations in misalignment. This weakness is explained by the fact that when the misalignment becomes large, the magnetic flux produced by one coil is no longer linked to the other coil in a fully helpful way. A part of that flux may start acting in the opposite direction, so instead of reinforcing the coupling, it begins to partially cancel it. As a result, the effective or useful coupling becomes weaker. From a design perspective, the rectangular coil may be effective when used with a large coil (high N), but this is not true for dynamic applications where misalignment poses significant challenges; instead, this type of coil is better suited for applications with well-controlled misalignment.

Based on the following equation, we can conclude how the coupling coefficient affects the system performance:

$$\eta_{\max} = \frac{U^2}{(1 + \sqrt{1 + U^2})^2} \quad (8)$$

where:

$\eta_{\max}$ is the maximum theoretical system efficiency,

$U = k\sqrt{Q_1 Q_2}$ measures the quality of energy transfer,

and Q_1 and Q_2 are the quality factors of the Tx and Rx coils, respectively.

In fact, the coupling coefficient controls how much energy is transferred and directly influences the transfer efficiency.

In general, the findings point to a coupled design logic. Resonance tuning constraints are altered by the number of turns, which also sets the inductive level and can enhance coupling. The strongest factor lowering coupling is the air gap, which should be reduced whenever feasible. Even when a design performs well under perfect alignment, misalignment can still dominate geometry selection and primarily impact robustness. Consequently, rather than relying on a single parameter, the coil geometry should be chosen based on the combined evolution of (L_1, L_2, M, k) and the anticipated operating conditions (air gap and misalignment).

Although a general decrease in mutual inductance and coupling coefficient with air gap and misalignment is expected in WPT systems, the main design insight of this study lies in the different sensitivities of the two investigated geometries under the same modeling assumptions. The circular coil exhibits more stable coupling behavior in the event of separation and lateral displacement, making it more suitable for applications where alignment uncertainty is significant. Conversely, the rectangular coil can achieve higher mutual inductance and a higher coupling coefficient in configurations with a large number of turns, but its performance is more sensitive to misalignment. Consequently, this comparison highlights a practical design trade-off: rectangular planar coils may be advantageous for static or well-aligned load configurations, while circular coils offer greater robustness when variations in the air gap or lateral misalignment are to be expected. This

geometry-related trade-off provides a more straightforward design criterion than simply considering the maximum coupling value.

Based on this study, we can establish the framework presented in Table 9.

Table 9. Benchmarking-based geometry selection guideline derived from the FEM results.

Design Condition	Preferred Geometry	Reason
Low number of turns	Circular	Higher M and k at small N
High number of turns under good alignment	Rectangular	Higher coupling potential
Large air-gap variation	Circular	Lower sensitivity to vertical separation
Lateral misalignment expected	Circular	Smoother degradation and no coupling sign reversal
Static or well-controlled positioning	Rectangular	Higher coupling possible if alignment is controlled
Dynamic or uncertain positioning	Circular	Better robustness

Finally, it should be emphasized that the present study is limited to ideal planar copper coils and FEM-extracted electromagnetic quantities. Although the mesh-convergence analysis confirms the numerical stability of the model, experimental validation is still required to confirm the physical reliability of the predicted trends. Future work will therefore extend the model toward more realistic EV wireless charging conditions by incorporating ferrite and shielding structures, nearby conductive vehicle components, frequency-dependent losses, compensation networks, and system-level efficiency evaluation. In addition, a physical prototype will be developed to experimentally validate the FEM results and assess whether the identified circular–rectangular geometry trade-off remains valid under practical EV charging constraints.

6. Conclusions

In this article, we explored the variation in the number of turns, air gap, and lateral misalignment to evaluate the electromagnetic coupling performance of the two geometries: circular and rectangular planar coils. As observed, the self-inductances are parameters that could be influenced by the geometry parameters; hence, the mutual inductance and coupling coefficient are two parameters that could be influenced by air gap and misalignment. Comparing the circular coil and rectangular coil on a small scale ($N < 25$), the circular coil is more robust, but the rectangular coil begins to have higher coupling potential with high turns ($N > 25$) and well-aligned positioning, which opens a door to discover opportunities to implement rectangular coils in automotive applications. Thus, upcoming work will be focused on optimizing this geometry to address current EV charging challenges.

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Abbreviations

The following abbreviations are used in this manuscript:

EV	Electric Vehicle
k	Circular coil coupling coefficient
k'	Rectangular coil coupling coefficient
L_1	Transmitter circular coil
$L'1$	Transmitter rectangular coil
L_2	Receiver circular coil
$L'2$	Receiver rectangular coil
M	Circular coil mutual inductance
M'	Rectangular coil mutual inductance
N	Number of turns
T_x	Transmitter
R_x	Receiver
WPT	Wireless Power Transfer

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