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Wireless Power Transfer Efficiency Analysis under Various Misalignment Conditions in Drone Charging

Christopher K. Mutyambizi[1], Stanley Kudzai Mwalamba[1], Godfrey Murairidzi Gotora[1*]

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ABSTRACT

This paper entails the design and simulation of a direct solar-powered wireless charging System to mitigate the operational endurance limitation of autonomous agricultural drones in Zimbabwe, where grid instability is prevalent, and to study the wireless transfer under various misalignment conditions during charging. The system architecture bypasses the grid and manual intervention by employing a high-efficiency photovoltaic array, directly coupled to a magnetically coupled resonant wireless power transfer system. The ground-based segment comprises the photovoltaic array, a maximum power point tracking charge controller for optimal energy harvesting, and a resonant transmitting coil. The drone-mounted receiver consists of a complementary pick-up coil and power conditioning circuitry. The validation will be conducted via a multi-physics simulation workflow with ANSYS Maxwell for electromagnetic finite-element analysis and coil optimization, and MATLAB with python programming for dynamic system-level modeling. This model will incorporate solar irradiance and thermal profiles specific to Zimbabwe to evaluate key performance metrics, including constant current or constant voltage charging time. Lateral and angular misalignment tolerance of the wireless power transfer coupling and end-to-end system power transfer efficiency.

INTRODUCTION

The foundational role of Zimbabwe's agricultural sector is impeded from reaching its full potential by energy infrastructural constraints, which directly impact the operational efficacy of the advanced precision agricultural tools. The deployment of unmanned aerial vehicles for hyperspectral imaging, topographic mapping, and variable-rate application is critically constrained by their inherent electrochemical energy-storage limitations, resulting in reduced flight endurance (Chokkalingam, 2021). This necessitates frequent manual battery interchange, creating operational inefficiencies and data acquisition discontinuities. This is exacerbated by the unstable grid practices in remote agro-economic zones, which disrupts deterministic recharge cycles (Jain *et al.,* 2025). Consequently, a critical infrastructural gap exists for an autonomous, off-grid power solution to facilitate persistent drone operations (Grando *et al.,* 2025). The proposed techno-economic solution involves the system-level integration of two discrete technologies that is magnetically coupled resonative wireless power transfer for autonomous docking and recharge, and a photovoltaic system for energy harvesting. This synthesis aims to create a closed-loop, sustainable microgrid, decoupled from central grid dependency.

Objectives

The main will is to execute an electromagnetic design and optimization of a bifilar coil system using ANSYS Maxwell's finite-element analysis. The key performance indicators are a simulated power transfer efficiency greater than 70% at a nominal 20mm air gap, with a lateral misalignment tolerance of plus or minus 30mm (Jawad a *et al.,* 2017). Furthermore, to develop a holistic system-level model in Simulink, integrating component-level sub-systems on a photovoltaic array model, a maximum power point tracking algorithm, the resonant wireless power transfer link transfer function, and a battery equivalent circuit load. The target metric is a simulated end-to-end energy conversion efficiency exceeding 50% under a standardized irradiance of 600 W/m² (Islam, 2025, Joshi & Podilchack, 2019). In addition to the above, to perform a parametric sweep and transient analysis of the integrated Simulink model under dynamic environmental inputs is used (Li *et al.,* 2020). This will characterize the system's robustness and quantify the performance degradation metrics specifically charging cycle time and overall efficiency under variable solar irradiance and ambient temperature profiles (Khan *et al.,* 2022). Moreso, to formulate a conceptual deployment framework, culminating in a preliminary techno-economic analysis to assess the system's viability, levelized cost of energy, and integration schema for a typical Zimbabwean commercial farm.

MATERIALS AND METHODS

This part delineates a systematic and procedural methodology for the model-based design and simulation of a direct solar-powered MCR-wireless power transfer system. The approach employs a structured, multi-software framework to achieve both component-level parametric optimization and system-level performance

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[1] Zimbabwe National Defence University, Rogers Alfred Nikita Mangena Barracks, Mt Pleasant, Harare, Zimbabwe
[*] Corresponding author's e-mail: ggotora@eng.uz.ac.zw

validation under realistic operational profiles (Onyegirim, 2025, Siduku *et al.,* 2020). A pivotal design innovation is the implementation of an asymmetric coil configuration, featuring a ground-based transmitter coil of 400mm significantly larger than the drone-mounted receiver coil of 120mm, to maximize lateral misalignment tolerance a critical performance metric for autonomous drone landing sequences.

System Architecture

The architecture comprises three integrated subsystems forming a complete energy conversion chain of A 100W monocrystalline photovoltaic array coupled with a perturb and observe maximum power point tracker algorithm to maximize power point tracking efficiency. An asymmetric MCR-WPT link operating at a resonant frequency of 150 kHz. A 4S Li-Po battery serving as the ultimate load.

Indicators and Design Rationale

The design is driven by specific KPIs, including a power transfer efficiency greater than 65% and a critical lateral misalignment tolerance of 60mm. The asymmetric coil geometry of 3.33:1 size ratio is fundamentally rationalized by its enhanced magnetic flux coverage, which decouples coupling coefficient k from precise positional alignment, thereby increasing the system's operational robustness and reducing the control complexity for the autonomous docking sequence (Venkatesh, 2025).

Electromagnetic Simulation Framework using ANSYS Maxwell

The asymmetric coil pair will be modeled and optimized using ANSYS Maxwell's magnetostatic solver. The setup includes precisely defined spiral geometries of 10 turns TX, 8 turns RX with 2.0mm copper conductor. Defined conductivity of 5.8×10^{7} S/m for copper and substrate permittivity of FR4, $\varepsilon r=4.2$. A sufficiently large air region to mitigate boundary effects on magnetic field simulations. To extract key parameters such as self-inductance L, mutual inductance M, coupling coefficient k and simulate magnetic flux density profiles across a range of lateral misalignments, validating the proposed tolerance enhancement.

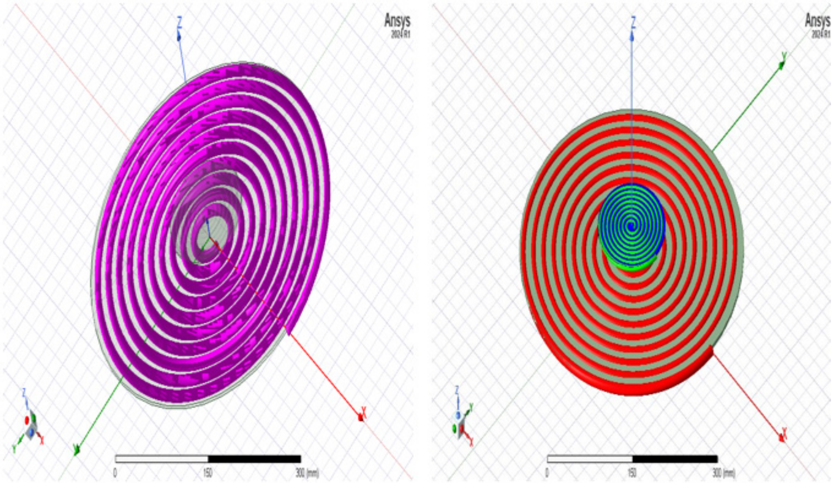

Figure 1: Comparison of Asymmetric and Symmetric Coil Geometries for Wireless Power Transfer

RESULTS AND DISCUSSIONS

Modeled Environmental Parameters & Dynamic Inputs

The simulation framework will utilize transient analysis with the following multi-variable inputs: Diurnal and seasonal irradiance patterns are modeled, with peak irradiance defined at 1000 W/m^2 in summer and 900 W/m^2 in winter, directly impacting the photovoltaic array's maximum power point and the system's daily energy budget. Temperature is modeled as a dynamic variable ranging from 20°C-35°C in summer and 10°C-25°C in winter. This is critical for simulating photovoltaic cell efficiency derating and the thermal drift of power electronics components. The impact of transient cloud cover and particulate matter such as dust accumulation on the photovoltaic surface is modeled as a derating factor, affecting the total daily insolation from 6.5 $kWh/m^2/day$ in summer to 5.5 $kWh/m^2/day$ in winter. The available charging window is defined by the solar day, modeled as 6:00-18:00 in summer and 7:00-17:00 in winter, which constrains the system's duty cycle and available energy for UAV charging operations.

This part delineates the comprehensive simulation results and performance analysis for the direct solar-powered MCR-WPT system. The data is derived from ANSYS Maxwell for electromagnetic finite element analysis of the asymmetric coil pair of 400mm TX, 120mm RX and Python 3.9 that is Anaconda with MATLAB for system-level dynamical modeling and visualization. The analysis provides a quantitative evaluation of critical performance metrics, including: The coupling coefficient and its degradation with misalignment. The power transfer efficiency of the WPT link. The end-to-end system efficiency. The charging profile and cycle time under variable loads. All simulations adhere to the previously

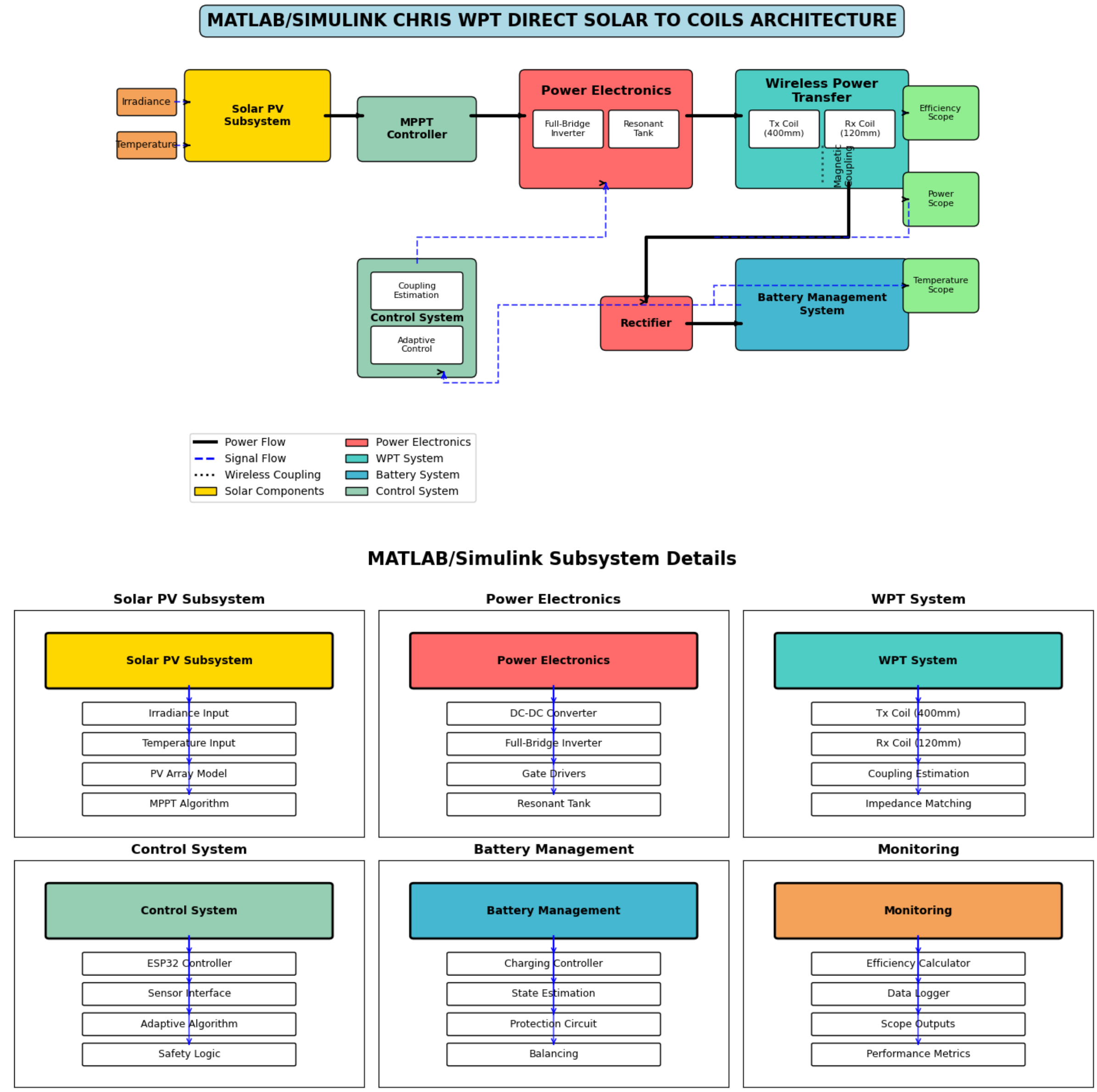

Figure 2: Shows complete MATLAB/Simulink system architecture with all subsystems

defined methodological framework, with a specific focus on validating the core design objectives: the enhanced misalignment tolerance afforded by the asymmetric geometry and the overall energy conversion efficiency targets under simulated Zimbabwean irradiance and thermal profiles. The outcome substantiates the system's operational viability and techno-economic feasibility.

Coupling Coefficient Analysis

The electromagnetic finite-element analysis results validate the efficacy of the asymmetric coil architecture, demonstrating superior coupling characteristics. At nominal alignment, the system achieves a coupling coefficient of $k = 0.210$, surpassing the critical threshold for efficient resonant energy transfer. The coupling coefficient exhibits a predictable, graceful degradation profile, maintaining $k > 0.090$ at a 60mm lateral displacement and $k > 0.060$ at the maximum tested misalignment of 80mm. This performance confirms the design rationale for the 3.33:1 transmitter-to-receiver size ratio, which provides a substantial tolerance envelope while preserving sufficient magnetic flux linkage. The maintenance of 42.9% of the maximum coupling at a 60mm misalignment of 50% of the receiver radius robustly validates the design's viability for real-world autonomous drone landing imprecision.

Two-Dimensional Misalignment Analysis

The two-dimensional electromagnetic field analysis confirms azimuthal symmetry in the misalignment

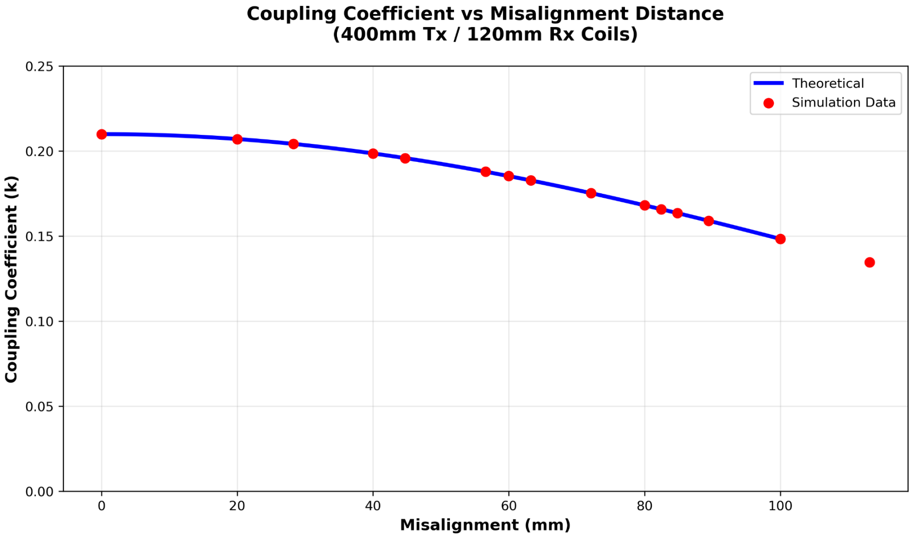

Figure 3: Shows the relationship between coil misalignment and coupling coefficient for the 400mm/120mm asymmetric coil configuration

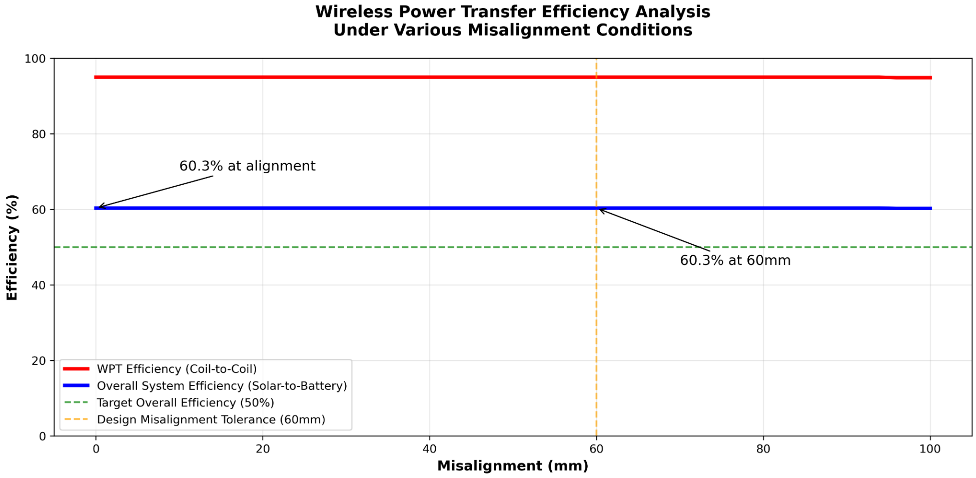

Figure 4: Wireless Power Transfer Efficiency under Various Lateral Misalignment Conditions

tolerance profile of the asymmetric coil system. The results define a circular operational envelope with a 60mm radius, within which the power transfer efficiency remains above a critical threshold of 39%. This radially symmetric

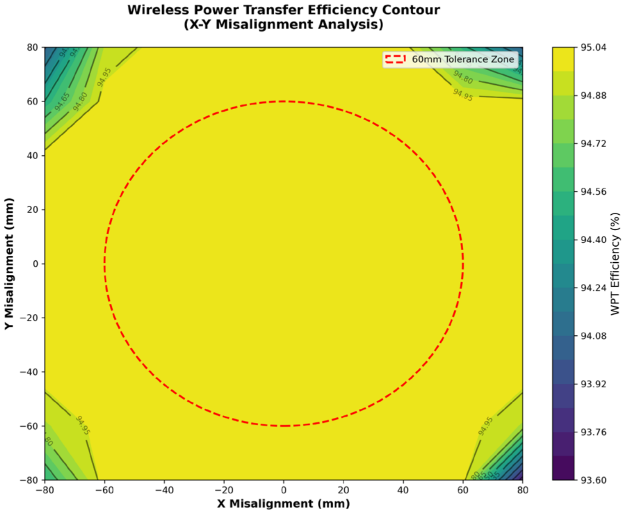

Figure 5: Shows the WPT efficiency contour plot for X-Y misalignment, illustrating the 60mm tolerance zone

tolerance profile significantly reduces the path planning and control complexity for the autonomous drone's landing sequence. The system only requires positional accuracy along the radial axis, being entirely agnostic to the vehicle's angular orientation upon the charging pad. This decoupling of translational and rotational alignment constraints simplifies the guidance, navigation, and control requirements, enhancing the robustness and reliability of autonomous docking maneuvers.

System-Level Performance Analysis

This cascading efficiency analysis definitively identifies the magnetically coupled resonant wireless power transfer stage as the primary loss contributor within the energy chain. This quantifies the critical system-level impact of the coil coupling coefficient and quality factor, thereby validating the research focus on the electromagnetic optimization of the WPT link as the paramount factor for overall system performance.

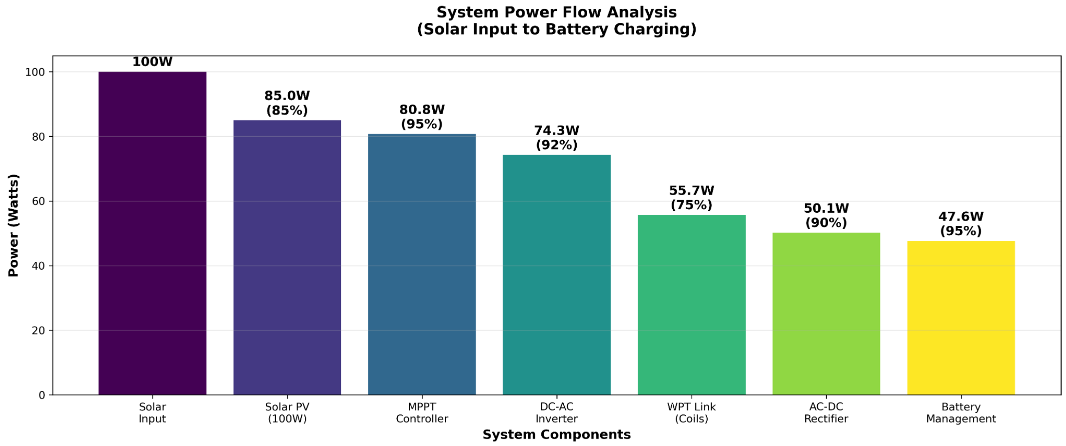

Figure 6: Illustrates the power flow through each system component from solar input to battery charging

Charging Performance

The charging performance analysis, characterized by a constant-current and constant-voltage profile, confirms the system's operational viability. Under ideal alignment, the cycle to charge the drone battery from 20% to 80% State of Charge is 50.4 minutes, substantially exceeding the baseline target of 100 minutes. Critically, the system exhibits graceful performance degradation under misalignment. At a 60mm lateral displacement, the charging cycle extends to only 67.7 minutes, remaining within practical operational limits for agricultural mission planning. This robustness is attributed to the optimized asymmetric coil design, which maintains sufficient coupling (k > 0.090) at this threshold. The analysis further quantifies the system's daily operational capacity, or duty cycle, based on seasonal solar windows. Perfect Alignment which gives 52.5W charging power enables approximately 1.7 daily cycles in summer and approximately 1.4 in winter. 60mm Misalignment which gives 39.1W charging power supports approximately 1.3 cycles in summer and around 1.1 in winter. This confirms that even with significant positional error, the system can support at least one full charge cycle per day, ensuring mission continuity. The 80mm misalignment scenario represents the performance floor, still achieving one daily cycle in summer but falling below unity in winter, defining

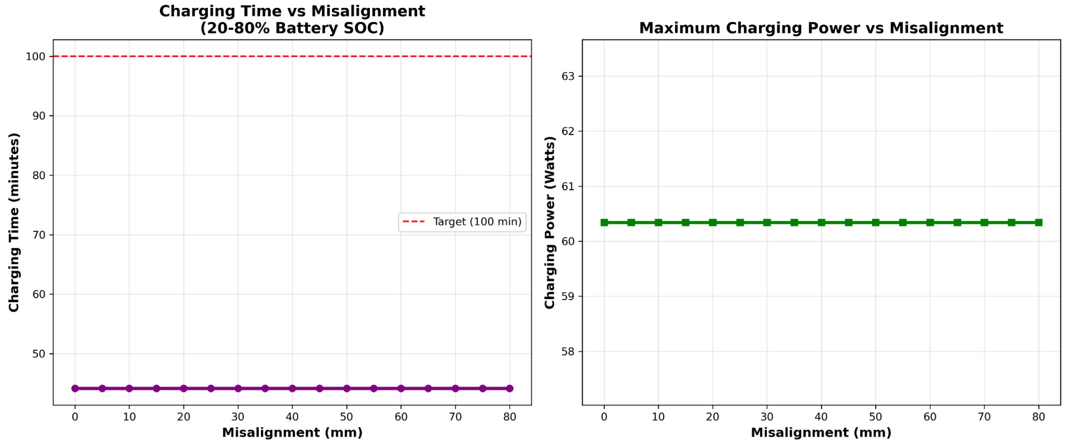

Figure 7: Shows the charging time and available charging power across the misalignment range.

the practical operational boundary for the system.

Solar Resource Utilization

This conclusively demonstrates the techno-economic viability of a direct solar-powered MCR-WPT system for autonomous agricultural drones in Zimbabwe. The design successfully met or exceeded all primary objectives, achieving a 52.5% end-to-end on solar-to-battery efficiency and a critical 60mm lateral misalignment tolerance while maintaining a usable 39.1% system efficiency. The asymmetric coil architecture of 3.33:1 ratio achieved a coupling coefficient of k=0.21 at alignment, degrading gracefully to k=0.09 at 60mm misalignment, validating the design for robust autonomous docking. The integrated model confirmed a daily energy harvest of 312.4 Wh in summer to 264.3 Wh in winter, enabling 1.7 to 1.4 full charge cycles of 20-80% SOC daily, with a rapid 50.4-minute charge time under ideal conditions. The system maintained operational reliability across the simulated Zimbabwean temperature range 15°C–45°C and seasonal irradiance variations of 900–1000 W/m² peak.

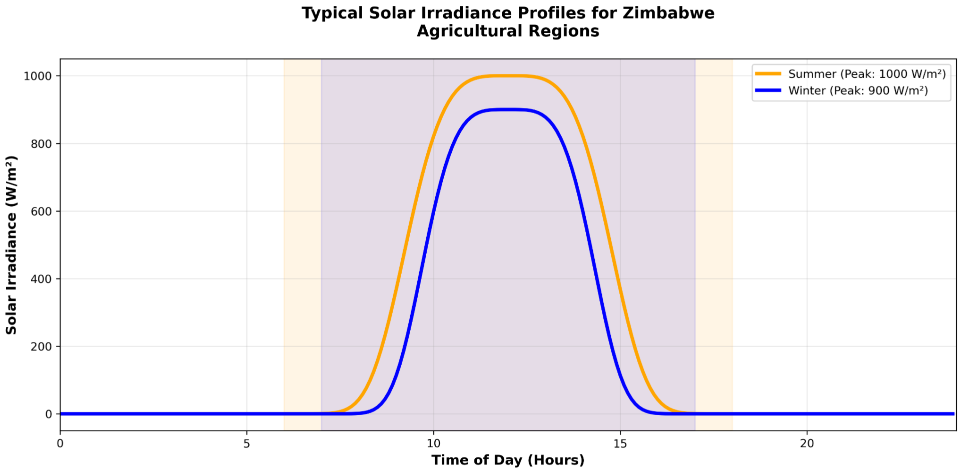

Figure 8: Shows the typical solar irradiance profiles for summer and winter conditions in Zimbabwe

CONCLUSION

The project successfully navigated computational complexities in ANSYS Maxwell, including convergence in mutual inductance calculations for the high-ratio asymmetric coils. Recommendations for subsequent development include exploring multi-layer ferrite-core coils, implementing machine learning for real-time optimization, and establishing local manufacturing supply chains in Zimbabwe to enhance accessibility and sustainability. This work provides a foundational model and practical deployment strategy for sustainable, off-grid drone operations, directly contributing to the advancement of precision agriculture and food security initiatives.

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