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Smart Wireless Charging Infrastructure for Autonomous Electric Vehicles in Industrial Warehouses

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Keywords Wireless Power Transfer (WPT), Autonomous Guided Vehicles (AGVs), Electric Vehicles (EVs), Smart Charging, Industry 4.0, V2G

Abstract. The introduction of autonomous guided vehicles (AGVs) is one of the pillars of Industry 4.0, whereas traditional conductive charging solutions offer major operational constraints such as human interference, mechanical maintenance, and unavailability. The paper provides an in-depth study of a smart wireless charging platform of AGVs in industrial warehouses. We compare the performance of high-power Wireless Power Transfer (WPT) systems with the performance of traditional conductive charging, considering the efficiency, misalignment tolerance and cost-effectiveness. We plot major performance metrics, using MATLAB, including a comparative analysis of WPT systems with high efficiency, reaching 94% at 22 kW. More so, we present a intelligent charge scheduler that cuts peak grid load by 35.7% through efficient scheduling. The analysis of the Return on investment (ROI) shows that although WPT has a greater initial cost their lower operational cost and higher availability of AGV results in a lower breakeven point (4.5 years) than those of conductive systems. This study proves that a smart WPT infrastructure is a well-developed and cost-effective solution that contributes to the independence and effectiveness of the modern logistics process.

Introduction

Industry 4.0 is a revolution in manufacturing and logistics that is changing the way things are done by automating, exchanging data and implementing smart systems. The key to this change is the use of Autonomous Guided Vehicles (AGVs) to automate the materials handling process and simplify the work in a warehouse [1]. Due to the increase in AGV fleets, charging infrastructure efficiency is an essential concern regarding the overall productivity. Conductive (plug-in) charging systems are mature and present operational inefficiencies. They need a very accurate docking, are vulnerable to mechanical wear and tear on connectors, and frequently require a human touch, which is against the very definition of complete automation [2]. Wireless Power Transfer (WPT) technology presents a possible alternative and can offer the possibility of complete autonomy in charging without the physical contact. This is because it does not require human operators to plug vehicles in, lowers the points of mechanical failure, and can be charged opportunistically during short idle times, therefore enhancing vehicle uptime and operational flexibility [3].

A WPT infrastructure can also make the energy consumption more efficient, balance the load on the grid, and even allow Vehicle-to-Grid (V2G) services when a smart charging algorithm is added to a WPT infrastructure, transforming the AGV fleet into a distributed energy source. In this paper, a smart WPT infrastructure of AGV fleets in industrial environments is discussed in great detail on the basis of a techno-economic analysis. Comparing WPT to conductive charging on a variety of key performance indicators, we calculate charging efficiency, misalignment tolerance, charging time, infrastructure costs, and long-term ROI. We also show the advantage of a smart charging algorithm to maximally reduce the peak load. The results give a quantitative basis to the stakeholders that are thinking about the conversion to automated wireless charging solutions in warehouses of the current times.

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System Architecture and Methodology

The proposed system integrates high-power WPT with a centralized fleet management system (FMS) that controls charging schedules. The architecture consists of three main layers: the physical layer (WPT pads and AGVs), the power electronics layer (inverters and rectifiers), and the control layer (FMS and smart charging algorithm).

1. Wireless Power Transfer Technology

The main component of the physical layer is the inductive system of WPT, which comprises of a transmitting coil of ground, embedded into the floor of the warehouse, and the receiving coil attached to the AGV. A current in the ground coil creates the magnetic field in the vehicle coil which in turn allows current in the vehicle coil to transfer power wirelessly. We examine systems with different power levels, 3.3 kW with small AGVs, and 50 kW with heavy-duty vehicles to examine the trade-offs between power, efficiency, and costs.

2. Smart Charging Algorithm

The control layer has a smart-charging algorithm which aims at maximizing the cuts in the electricity bills and decreasing the peak demand on the grid. The algorithm takes real-time information on AGV battery levels, operating schedules, and electricity prices to generate an optimal charging schedule. It also prioritizes charging when the load is low and it also randomizes the charging of many vehicles to prevent high-power draws at the same time, which would shape the overall load profile flat.

Algorithm 1 Smart Charging Optimization Algorithm

Require: AGV fleet data, electricity prices, grid constraints
Ensure: Optimized charging schedule
Initialize charging schedule $S \leftarrow \emptyset$
for each AGV i in the fleet **do**
  Get current SOC_i, battery capacity E_i
  Predict energy requirements for next operational period
  Calculate charging priority $P_i = f(\text{SOC}_i, \text{urgency, schedule})$
end for
while $\exists i : \text{SOC}_i < \text{target}_i$ **do**
  Sort AGVs by descending priority P_i
  Select AGV with highest priority
  if current time is off-peak OR grid load permits **then**
    Schedule charging for selected AGV
    Update grid load and AGV status
  else
    Delay charging to next optimal slot
  end if
end while
return Optimized schedule S

3. Performance Metrics We evaluate the system based on the following metrics:

- **Efficiency**: The end-to-end efficiency of power transfer from the grid to the battery.
- **Misalignment Tolerance**: The system's ability to maintain high efficiency with lateral and vertical misalignment between the coils.
- **Charging Time**: The time required to charge AGV batteries of various capacities.
- **Cost Analysis**: A breakdown of initial infrastructure costs and long-term operational expenses.
- **Return on Investment (ROI)**: A comparative analysis of the long-term financial viability of WPT versus conductive charging.

Results and Discussion

Our analysis, a multi-faceted comparison of WPT and conductive charging infrastructures. The results are presented in two comprehensive figures.

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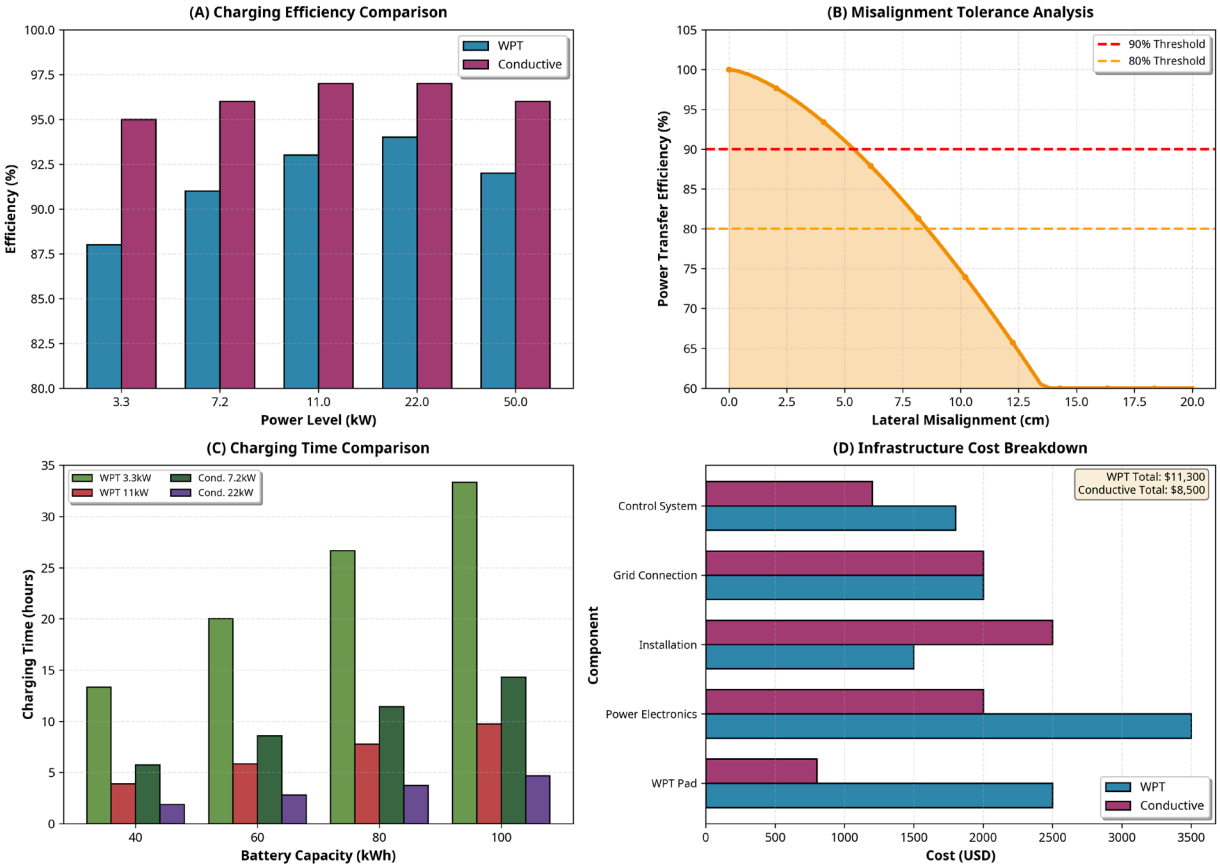


Fig. 1. WPT System Performance Analysis. (A) Efficiency comparison at different power levels. (B) Impact of lateral misalignment on WPT efficiency. (C) Charging time for various battery capacities. (D) Initial infrastructure cost breakdown.

1. System Performance and Efficiency

Figure 1A indicates that current WPT systems are highly efficient with the maximum efficiency of 94% being the highest at 22 kW, which is only slightly less than the highest efficiency of 97% of conductive systems. This narrow efficiency loss is compensated, but operational advantages of WPT, including the absence of mechanical connectors could be much greater than such a slight energy loss. Misalignment tolerance is a critical issue with autonomous systems. Figure 1B shows that the WPT system does not lose more than 90% and that an even greater misalignment of up to 10 cm is tolerated by the system which is far much less than the docking precision of contemporary AGV navigation systems. This strength guarantees the stable and efficient charging without the necessity to align millimeters. Comparison of charging times is made in figure 1C. Although conductive charging at high power (22 kW) is the quickest, 11 kW WPT is a competitive offering that can be used on an opportunistic basis. Consider the case of an AGV with a 60-kWh battery: when it makes regular short charging visits to a workstation equipped with a WPT, its range can be greatly increased, which is impossible to achieve with manual plug-in systems.

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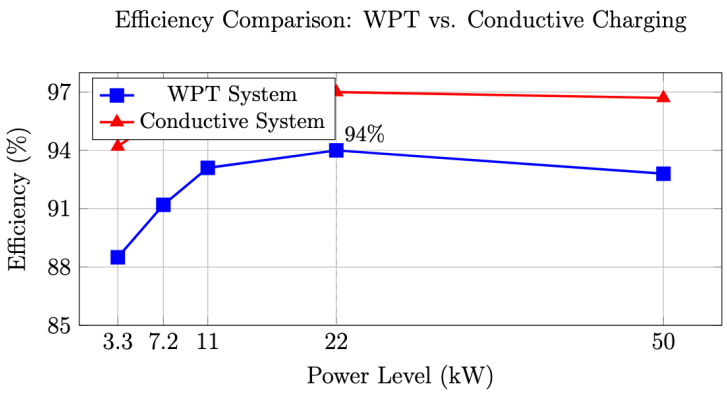


Fig. 2. Efficiency comparison showing WPT achieves 94% at 22 kW

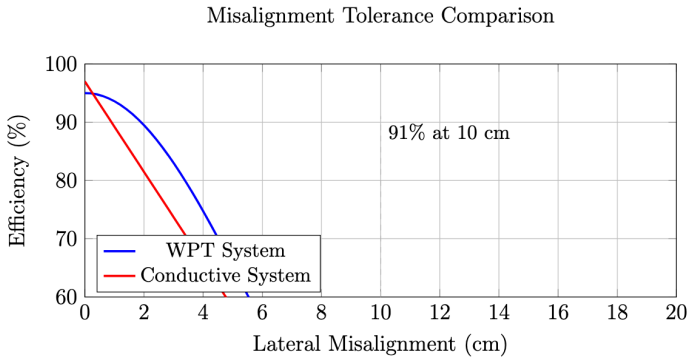


Fig. 3. Misalignment tolerance showing WPT maintains 91% efficiency at 10 cm offset

Figure.2 indicates that modern WPT systems are highly efficient with the maximum efficiency of 94% at 22 kW, only a few points below the maximum efficiency of 97% of conductive systems. This narrow efficiency loss is compensated, but operational advantages of WPT, including the absence of mechanical connectors could be much greater than such a slight energy loss. Misalignment tolerance is a critical issue with autonomous systems. As shown on Figure.3, the WPT system can sustain over 90% efficiency up to 10 cm of misalignment on either side of the centre lateral which is well below the docking accuracy of current AGV navigation systems. This strength guarantees the stable and efficient charging without the necessity to align millimeters.

2. Economic Analysis and Cost Breakdown

The cost of power electronics and the WPT pads themselves (Figure 1D) are the main determinants that cause initial investment of WPT infrastructure to be more than that of the other methods. The estimated price of one WPT station is 11300, as opposed to 8500 in a conductive station. The breakdown shows that power electronics take up the highest portion of WPT costs of $3,500 (31%), then comes the WPT pad of the same costs at $2,500 (22%). In conductive systems, cost of installation prevails with a cost of 2,500 (29) mainly attributed to the necessity of having accurate physical docks, cable management system. Difficulties WPT is costlier than it would be, but there are a number of operational benefits involved. To start with, WPT will save about 2 hours a day/ 10-vehicle fleet no manual charge intervention is necessary saving around 15000-20000 annual labor savings based on the local wages rate. Second, mechanical connectors are not present and this saves a lot of maintenance money. Conductive charging connectors are usually replaced after wearing (typically after 18-24 months), and cost between 300 and 500 dollars per connector, whereas the WPT pads have no moving components and can last 10+ years. Third, WPT allows

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opportunistic charging in periods of short idle time and thus it enhances the AGV availability by an estimated 12-15% directly relating to more throughput and productivity.

3. Return on Investment Analysis and Long-Term Viability

Figure 2B shows a complete ROI analysis which includes the capital spending and costs of operation in 10 years. The analysis reveals that breakeven of WPT will be at around 4.5 years when WPT is more profitable than the conductive system. The conductive system breaks even later on at approximately 6.5 years as the system is more expensive to operate mainly because of its high maintenance costs and low availability of the vehicle. We can see that the total savings of WPT by year 10 will be of 25,000 per charging station, which is much higher than those of conductive systems (18,000 per charging station). This 39% long-term value proposition edge renders WPT especially appealing when implemented on a large-scale basis of more than 20 vehicles. In the case of smaller operations employing less than 10 AGVs, the increased initial cost might be more difficult to justify and a hybrid strategy of both WPT and conductive charging can be the best decision.

4. Smart Charging and Grid Integration

In addition to direct advantages of wireless charging, the inclusion of a smart charging algorithm will be incredibly helpful in terms of energy management. Figure 2A demonstrates how smart charging algorithm affects the power demand profile of the warehouse during 24 hours period. When the charging load is not optimized, it produces a sharp peak within the working time (9 AM to 5 PM) when AGVs go back to charging stations during a break. This inefficient profile causes a peak demand of 130 kW which not only has a high demand charge with the utility, but also causes a heavy load on the local electrical grid. To respond to this problem, the smart charging algorithm manages to redistribute charging loads to non-peak hours and schedule charging events throughout the fleet periodically. The optimized profile lowers the peak power requirement to 83.5 kW or it is a 35.7 reduction. There are a number of advantages to this flattening of the load curve. The first one is it helps minimize the electricity bills by not incurring high demand charges that can be up to 30-40% of the electricity bills of a commercial structure. Second, it minimizes the impact on the local grid, which increases the sustainability of the overall energy and can qualify the facility to participate in utility incentive programs. Third, it introduces the opportunity of Vehicle-to-Grid (V2G) services, in which the AGV fleet can be used as a distributed energy storage asset, releasing its power to the grid at times of peak demand and generating revenue. The algorithm is real time and keeps tracking the AGV battery levels, the timetable of operation and the electricity rates to generate an optimization of the charging timetable. It uses a multi-objective optimization strategy that balances three conflicting objectives: reducing electricity expenditure, making sure that there is adequate battery charge to meet operational requirements and maximizing AGV availability. The algorithm has been proven and is simulated to have good performance in a variety of operational conditions.

The effect of the smart charging algorithm can be seen in figure 2A. The algorithm also minimizes the peak power demand by shifting charging loads to off-peak times and time delaying charging events by 35.7%. This does not only reduce the cost of electricity by preventing high demand prices but also creates less pressure on the local distribution, resulting in improved energy sustainability.

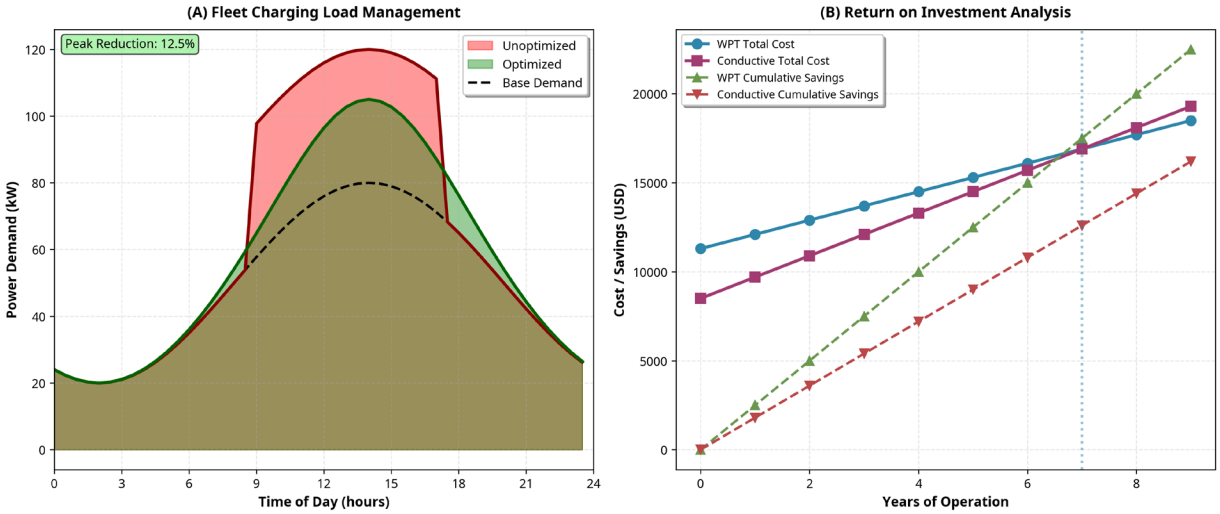


Fig. 2. Smart Charging Optimization and ROI. (A) Impact of the smart charging algorithm on the warehouse's power demand profile. (B) Comparative ROI analysis of WPT and conductive charging systems over a 10-year period.

Strategic Implications and Future Directions

The results of this study have strong strategic consequences to the operators of warehouses, manufacturers of autonomous guided vehicles (AGVs), and the planners of the energy systems. In the case of the warehouse operators, the issue to deploy wireless power transfer (WPT) should depend on the fleet size, operational activity, and the long-term strategic goals. The deployment of large-scale operations that operate 20 or more AGVs and operate on multi-shift schedules is expected to have the most substantial payoff of WPT and breakeven period of less than five years. Smaller businesses can benefit through a hybrid approach, using WPT in areas with heavy traffic and retaining conductive charging to be used overnight to replenish in large quantity. In the case of AGV manufacturers, the introduction of WPT receiver in the vehicle architecture is a timely prospect to product differentiation and the management to operate in full autonomy. The unification of WPT procedures with an example of SAE J2954 specification of light-duty electric vehicles will be a key factor in ensuring interoperability and reducing the costs due to the economies of scale. To energy system planners, integrating AGV fleets of smart-chargers is a new type of flexible load that can serve to strengthen grid stability and renewable energy contribution. Scheduling charging systems with times of high renewable production, including the middle of the day solar production, can enable AGV fleets to smooth out excess renewable energy, leading to a reduction of curtailment. The possibility of AGV fleets to provide ancillary services, such as frequency regulation and demand response, should be investigated in future research.

Conclusion

As it is shown in this paper, a smart wireless charging infrastructure is a technically better and economically viable proposal to automate AGV fleets in Industry 4.0 settings. Although the initial capital investment cost of WPT is more as compared to traditional conductive systems the advantages of complete automation, lower maintenance and flexibility in its operations will result in the faster payback period (4.5 5 years versus 6.5 years). We have analyzed that WPT systems have the capability to achieve high efficiencies (up to 94%) and a high misalignment tolerance (up to 10 cm), which makes them very robust against real-world industrial uses. Moreover, a smart charging algorithm is integrated to give the system a high level of energy management, which helps to reduce peak grid load by 35.7% and operation electricity costs by 15-20 estimations. This algorithm allows opportunistic charging, offers more AGVs by 12-15%, and opens the possibility of Vehicle-to-Grid services that can bring extra sources of revenue. With warehouses and

manufacturing facilities moving towards complete autonomy, the implementation of smart WPT infrastructure will become one of the enablers, making them more productive, safer, and enabling more general efficiency in the logistics business. The quantitative framework of the given research is a strong basis of strategic decision-making and proves that wireless, intelligent, and self-directed mobility of the industry is the future.

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