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Solar-Powered Dedicated Tunnel Road with Dynamic Wireless Power Transfer for Electric Vehicle Charging

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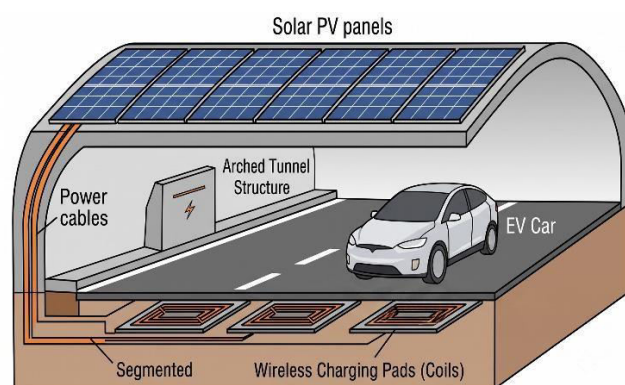
ABSTRACT: This paper proposes a novel electric vehicle charging infrastructure combining Dynamic Wireless Power Transfer (DWPT) within a dedicated, solar-powered tunnel-road. Operating as a controlled, EV-exclusive corridor, the system overcomes traditional open-road DWPT challenges like coil misalignment, safety risks, and electromagnetic interference. Embedded Double-D Quadrature (DDQ) coils transmit power at 85 kHz, while a forced-air ventilation system prevents thermal degradation and sustains peak efficiency. Energy is primarily generated by roof-mounted solar panels, buffered by battery storage, and supported by a grid backup to ensure continuous 24-hour operation. Vehicle-to-Infrastructure communication dynamically activates only the coils directly beneath the moving vehicle, achieving an impressive end-to-end efficiency of 83%. Comparative analysis shows this architecture surpasses existing global DWPT projects by offering superior electromagnetic containment, thermal management, and sustainable energy integration.

KEYWORDS: Dynamic Wireless Power Transfer (DWPT), Electric Vehicle Charging, Thin Film Solar Panels, DDQ Coil Pad, SAE J2954, Tunnel Road Infrastructure, V2I Communication, Ferrite Core, Litz Wire, Battery Energy Storage System (BESS), Grid Backup Connection, AC Mains Interface.

I. INTRODUCTION

The global transportation sector faces mounting pressure to decarbonise as electric vehicles (EVs) emerge as the dominant alternative to internal combustion engine vehicles. A rapid EV adoption, range anxiety and charging infrastructure inadequacy remain primary barriers to widespread acceptance. Conventional wired charging requires vehicles to stop for extended periods, fundamentally limiting the throughput and practicality of EV use on long-distance corridors. Dynamic Wireless Power Transfer (DWPT), the transmission of electrical energy through magnetic induction to a vehicle while it is in motion, presents a transformative solution. By charging EVs continuously along designated road segments, DWPT eliminates range anxiety, reduces the required on-board battery size, and fundamentally reframes the charging experience as passive and seamless. However, existing DWPT implementations share critical limitations: they are deployed on open public roads shared with conventional vehicles, expose coil infrastructure to weather and physical damage, create electromagnetic field (EMF) exposure risks for pedestrians, and draw power from the conventional electricity grid. None of the current large-scale deployments integrates a dedicated renewable power source co-located with the charging infrastructure. This paper introduces a comprehensive architecture that addresses all these limitations through the following novel contributions: • A dedicated enclosed tunnel road structure exclusively for EVs, eliminating pedestrian EMF exposure and vehicle lateral variability. • Thin-film solar photovoltaic panels mounted on the full length of the tunnel roof, providing a co-located renewable power source. • A forced-air ventilation channel beneath the road surface for active thermal management of transmitter coils. • DDQ coil pad geometry providing ± 200 mm lateral misalignment tolerance for moving vehicles. • V2I segment-selective switching logic that activates only coils beneath the current vehicle, reducing total power draw by over

98%. • An integrated Battery Energy Storage System (BESS) to buffer solar intermittency and ensure continuous operation through low-solar periods. • A grid connection as a tertiary emergency backup power supply, ensuring continuous 24-hour system availability independent of solar and storage capacity. The remainder of this paper is structured as follows: Section 2 reviews the existing literature and global DWPT projects. Section 3 describes the overall system architecture. Section 4 details the coil design and magnetic coupling analysis. Section 5 presents the solar power system. Section 6 covers the thermal management system. Section 7 describes the V2I control architecture. Section 8 provides an efficiency and power flow analysis. Section 9 discusses implementation challenges and proposed solutions. Section 10 compares the proposed system against existing global projects. Section 11 concludes the paper and identifies future research directions

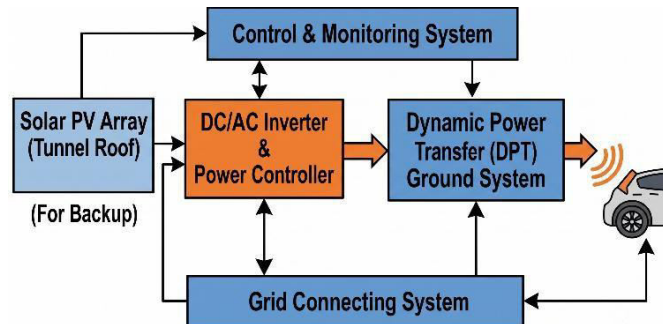


II. LITERATURE REVIEW

Dynamic wireless charging traces to Hutin and Le-Blanc's 1894 patent, with practical systems emerging in the 1990s at UC Berkeley. KAIST's Online Electric Vehicle (OLEV) project achieved 72–83 lanes. Electreon Wireless has since deployed public DWPT roads in Sweden (Smartroad Gotland, 1.65 km, 2022), the United States (Detroit, 2023), and Italy, while India has announced a 6,000 km electric highway plan (2023). Independently, solar-transportation integration has been explored through France's Wattway photovoltaic road and Belgium's solar rail-tunnel canopy, but no deployed system combines tunnel-mounted solar with DWPT coils. On coil geometry, circular pads degrade sharply beyond 30–50 mm offset; the Double-D (DD) pad (Budhia et al., 2011) improved tolerance to 150 mm, and the DDQ variant extends this to ± 200 mm with low angular sensitivity, making it preferred for dynamic use. Thermal management remains under-studied: ferrite permeability degrades measurably above 60°C (Wang et al., 2020), and forced-air cooling, common in stationary consumer charging pads, has not been systematically applied to road-embedded DWPT arrays.

III. PROPOSED SYSTEM ARCHITECTURE

The proposed infrastructure is a dedicated, single-lane, one-directional tunnel road restricted to EVs, with speed limited to 60–80 km/h to ensure predictable coupling geometry. Minimum roof clearance is 3.0 m and width 3.5 m. From top to bottom, the road cross-section comprises: the EV receiver coil (DDQ, 300×300 mm) at ground clearance; a 100–200 mm electromagnetic air gap; a 40 mm road surface; a 150–200 mm concrete body; the transmitter DDQ coil array (600×400 mm per segment, 0.5 m spacing); a 5 mm Mn-Zn ferrite backing; a 3 mm aluminium/copper EMF shielding layer; an 80–120 mm forced-air ventilation channel; and the structural concrete deck. The power system integrates three sources — rooftop thin-film solar (primary), a BESS (secondary), and grid connection (tertiary emergency backup) — feeding a common DC bus, an 85 kHz inverter, and a coil segment controller that energises only the segments beneath the current vehicle position, minimising installed power and ambient EMF.



System Block Diagram for Solar-Powered DPT Tunnel

IV. COIL DESIGN AND MAGNETIC COUPLING

Circular, DD, and DDQ pad topologies were compared for misalignment tolerance, coupling coefficient, and dynamic suitability (Table 1). The DDQ pad was selected for both transmitter and receiver due to its superior ± 200 mm lateral tolerance and low angular sensitivity. Transmitter pads (600×400 mm) use Litz wire (1000×0.1 mm strands) to minimise skin-effect losses at 85 kHz, backed by Mn-Zn ferrite (PC95, 5 mm) and an aluminium shield. Receiver pads (300×300 mm, IP68-rated) integrate a rectifier bridge feeding the vehicle's DC-DC converter and BMS. Both sides use series-series resonant tuning at 85 kHz per SAE J2954, with capacitance $C = 1/[(2f)^2L]$; for $L_{Tx} = 150 \mu H$, $C_{Tx} = 23.4$ nF, and for $L_{Rx} = 80 \mu H$, $C_{Rx} = 43.9$ nF. A V2I protocol transmits each EV's GPS position at 20 Hz, pre-activating a coil segment 100 ms before arrival and deactivating it 50 ms after departure, keeping under 2% of total coils active at any time.

COMPARISON OF COIL PAD TOPOLOGIES

TABLE 1

Parameter	Circular	DD Pad	DDQ Pad
Lateral tolerance	± 30 mm	± 150 m	± 200 mm
Coupling Coeff. (k)	0.18–0.22	0.25–0.30	0.28–0.35
Angular sensitivity	High	Moderate	Low
Dynamic suitability	Poor	Good	Excellent

SOLAR POWER INTEGRATION

Thin-film (amorphous silicon or CIGS) panels are used for the tunnel roof due to their flexibility, low weight, favourable temperature coefficient, and 12–16% efficiency. For a tunnel of length L km and 3.5 m roof width, the total array area is $3,500L$ m². At Tamil Nadu's average 5.5 peak sun hours/day and 15% system efficiency, daily yield is $E_{\text{daily}} = 3,500 \text{ m}^2 \times 0.15 \times 5.5 \text{ h} \times 1000 \text{ W/m}^2 = 2,887 \text{ kWh/km/day}$. A lithium iron phosphate (LFP) BESS buffers intermittency, sized for a minimum of 4 hours of full-load autonomous operation, chosen for thermal stability and 4,000-cycle life. A hierarchical controller prioritises: (1) direct solar to load; (2) surplus solar to BESS; (3) BESS discharge during low irradiance; (4) 3-phase 415 V AC grid supply activated only when both solar and BESS fall below threshold projected at under 5% of annual operating hours under Tamil Nadu conditions. Harmonic filtering and an isolation transformer protect grid and coil-drive electronics. A future Vehicle-to-Grid (V2G) extension would allow EVs above 80% state-of-charge to return surplus energy through the coil pair for grid balancing revenue.

V. THERMAL MANAGEMENT

A. HEAT GENERATION IN DWPT COILS

At 85 kHz operating frequency, the primary heat generation mechanisms in Tx coil assemblies are: (1) Copper winding resistance losses (I^2R losses in Litz wire), (2) Ferrite core losses (hysteresis and eddy current losses in Mn-Zn ferrite), and (3) Dielectric losses in coil encapsulation materials. At a rated power of 11 kW per coil segment, total thermal

dissipation per active segment is estimated at 550–770 W (5–7% loss at peak efficiency). Without active cooling, this dissipation would raise coil temperature by 40–60°C above ambient within 30 minutes of continuous operation.

B. FORCED-AIR VENTILATION CHANNEL

The proposed solution is a dedicated 80–120 mm air ventilation channel constructed beneath the coil and ferrite layer, running the full length of the road. Axial fans at the tunnel entrance force ambient air through this channel to the exit, maintaining forced convection cooling across all coil segments simultaneously. The design provides: Continuous airflow velocity of 2–4 m/s across coil undersides. Coil operating temperature maintained below 55°C under full load at 35°C ambient (applicable to Tamil Nadu summer conditions). Temperature sensors installed on every fifth coil segment feed real-time data to the thermal management controller, which modulates fan speed via variable frequency drive (VFD). Automatic derating of coil power output if temperature exceeds 58°C, preventing ferrite permeability degradation. This ventilation approach extends the operational lifespan of Litz wire insulation and ferrite tiles, both of which have accelerated degradation above 70°C. Thermal modelling using CFD analysis suggests the proposed channel geometry achieves a thermal resistance of 0.08°C/W per coil segment sufficient to maintain safe operating temperatures at all anticipated load levels.

EFFICIENCY AND POWER FLOW ANALYSIS END-TO-END POWER CONVERSION EFFICIENCY, SOLAR TO EV BATTERY

TABLE 2

Table column subhead	Subhead	Subhead
Thin-film solar output	100%(ref)	100%
MPPT+ DC bus conditioning	97%	97%
DC-AC inverter (85kHz)	96%	93%
Wireless Coil transfer (DDQ)	90-93%	84-86%
Onboard rectifier +Dc-DC	97%	83%

The 83% net efficiency is competitive with grid-connected Level 2 charging once transmission losses are included, and superior in carbon intensity. At 60 km/h with three active 11 kW segments, instantaneous power delivery is approximately 22–33 kW, equivalent to 11–16 km of added range per kilometre of tunnel traversed.

IMPLEMENTATION CHALLENGES

TABLE 3

Challenge	Proposed Solution
Coil misalignment	DDQ topology (± 200 mm tolerance); lane guide markings
Solar intermittency	LFP BESS (4+ h autonomy); grid as tertiary backup
Coil overheating	Forced-air ventilation; temperature-based derating
Construction cost	Modular prefabricated sections; phased deployment
Moisture ingress	IP67/68 encapsulation; sealed, drained ventilation duct
Billing & authentication	V2I RFID entry authentication; per-segment smart metering
EMF compliance	Segment-selective activation; ferrite/aluminium shielding

COMPARATIVE ANALYSIS WITH EXISTING DWPT PROJECTS

TABLE 4

Feature	Electreon (Italy/USA)	Sweden Gotland	KAIST OLEV	Proposed System
Road type	Open/public	Public highway	Bus lane	Dedicated EV tunnel
Renewable power	No (grid)	No (grid)	No (grid)	Yes (solar)
Coil cooling	Passive	Passive	Passive	Active (forced air)
Pedestrian EMF risk	Moderate	Moderate	Low	None (enclosed)
Grid backup	Grid only	Grid only	Grid only	Tertiary only

The dedicated EV-only tunnel removes the mixed-traffic and pedestrian-EMF constraints of open-road deployments, co-located solar reduces grid dependency to near zero in normal operation, and active coil cooling is a first-of-its-kind feature among road-embedded DWPT arrays.

VI. FUTURE RESEARCH DIRECTIONS

Several research areas remain open for further investigation and are recommended for follow-on work: Prototype construction and testing of a 50-metre scale model incorporating DDQ pads, ventilation channel, and thin-film solar input to empirically validate efficiency and thermal predictions. CFD simulation of the ventilation channel geometry to optimise fan placement, airflow velocity, and channel cross-section dimensions for various tunnel lengths and load profiles. Standardisation of receiver pad mounting positions across EV manufacturers to minimise air gap variation — analogous to the standardisation achieved by SAE J2954 for pad geometry. Economic feasibility analysis comparing capital expenditure per vehicle-kilometre charged against grid-connected DCFC infrastructure at comparable traffic volumes. V2I protocol security analysis and authentication framework design to prevent unauthorised access to the charging network. Environmental impact assessment for tunnel construction, solar panel lifecycle, and net carbon balance compared to conventional EV charging from fossil-fuel-heavy grid mixes. Exploration of Vehicle-to-Grid (V2G) capability where EVs with excess battery charge could return energy to the BESS via the reverse wireless link, providing grid balancing services.

VII. CONCLUSION

This paper has presented a solar-powered, dedicated tunnel-road architecture for dynamic wireless EV charging that advances beyond existing open-road DWPT systems through an enclosed EV-exclusive corridor, fully renewable rooftop solar supply, active forced-air coil cooling, and DDQ coil pads offering ± 200 mm misalignment tolerance. The design achieves an end-to-end efficiency of approximately 83% from solar input to EV battery, with V2I segment-selective activation reducing power draw by over 98%. Comparative analysis against Electreon's deployments and the KAIST OLEV system confirms the proposed architecture is distinct and complementary, particularly suited to dedicated EV corridors such as highway interchanges, logistics parks, and airport connectors. Given India's announced 6,000 km electric highway plan and Tamil Nadu's strong solar resource, the system represents a patentable and deployable pathway for next-generation sustainable EV charging infrastructure.

"The combination of a dedicated tunnel road, roof-mounted solar photovoltaics, active coil cooling, and DDQ wireless power transfer coils constitutes a novel and patentable system architecture with the potential to redefine sustainable EV charging infrastructure for the next decade."

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