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Exploring the Synergies of Dedicated Metering, Energy Management Systems, and Time-of-Use Rates for Electric Vehicles: A Sustainable Governance Framework Towards Urban Microgrids and Circular Economy

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Abstract: Amid the global transition toward net-zero emissions, installing electric vehicle (EV) charging infrastructure in existing residential complexes faces capacity limits, perceived risks, and severe collective action problems. This study develops a governance-oriented framework integrating the "Dedicated Meter Power Supply" policy, Energy Management Systems (EMS), and Time-of-Use (TOU) tariffs to address these structural barriers. Taking Community S in Taichung City (264 units, 306 parking spaces) as an empirical case, the research analyzes how management committees can utilize financial engineering to overcome special resolution thresholds. Results demonstrate that an innovative "early-bird dynamic refund" fundraising model triggered significant economies of scale, slashing per-unit infrastructure costs by 59.1% and achieving a 4.9-fold oversubscription rate. Furthermore, EMS dynamic load control perfectly aligned with Taipower's 18-hour off-peak window achieves optimal peak shaving, reducing user energy charges by over 60%. By integrating the Technology Acceptance Model (TAM), Innovation Diffusion Theory, and Markov Chain market forecasting, this study theoretically confirms that extreme peak-to-off-peak price spreads effectively internalize the external costs of grid congestion. This framework not only advances SDG 12 (Responsible Consumption) but also accelerates the market transition from internal combustion engine (ICE) vehicles to battery electric vehicles (BEVs), maximizing carbon reduction in the Tank-to-Wheel (TTW) phase and laying a scalable foundation for future Vehicle-to-Grid (V2G) microgrids.

Keywords: Circular economy, Collective action problem, Dedicated metering, Energy management system (EMS), Technology acceptance model (TAM), Time-of-use (TOU) rates

1. Introduction

1.1 Background and Conceptual Redefinition

The global community is actively accelerating the transition toward the 2050 net-zero emission goals, with transport electrification serving as a critical pathway. The rapid proliferation of electric vehicles (EVs) has brought unprecedented challenges to overall power systems and urban distribution networks. A significant bottleneck in this transition is that up to 80% of EV charging behavior occurs in residential and community parking lots, yet the vast majority of existing residential complexes in high-density urban areas were not pre-equipped with adequate charging trunk lines and power capacity.

A review of existing empirical practices indicates that traditional "behind-the-meter private wiring" violates inspection regulations, causes disorganized cable trays, and significantly increases the risk of power outages and fires. This unregulated charging approach intensifies the "perceived safety risk" among non-EV owners. Consequently, the Taiwan Power Company (Taipower) mandated that EV charging equipment in residential complexes must adopt a "Dedicated Meter Power Supply" combined with an Energy Management System (EMS) for centralized and secure load control. Despite this being the only legal and scalable technical pathway, practical implementation remains severely hindered by the high voting thresholds mandated by the Condominium Administration Building Act. Requiring all residents to share millions of dollars in initial infrastructure costs often leads to the "collective action problem" defined by Olson, resulting in governance deadlocks.

To break this deadlock, this research adopts an empirical case study of Community S in Taichung City to investigate how financial engineering innovations—specifically an "early-bird dynamic refund model"—can precisely translate heterogeneous incentives and overcome governance barriers. Furthermore, the core objective of this paper is to deeply analyze the operational synergies between Taipower's latest EV-specific TOU tariffs and EMS dynamic scheduling. By integrating the Technology Acceptance Model (TAM), innovation characteristics, and Markov Chain market evolution predictions, this study demonstrates how the integration of TOU and EMS serves as a dynamic feedback mechanism that internalizes grid congestion externalities. Ultimately, this research provides a quantifiable governance framework for circular urban energy economies.

2. Literature Review and Theoretical Foundations

2.1 Global TOU Tariffs and Demand-Side Management

To mitigate the grid congestion caused by the overlap of EV charging loads and peak residential power demand, international energy markets widely adopt Time-of-Use (TOU) tariffs as the core instrument for Demand-Side Management (DSM). The design logic across global markets universally centers on two pillars: minimizing basic capacity charges and maximizing the peak-to-off-peak price spread. For example, Southern California Edison (SCE) in the US and KEPCO in South Korea offer substantial discounts on basic fees, coupled with TOU price spreads of 3.4 and 3.3 times, respectively. China temporarily exempts capacity fees for charging facilities until 2030 while imposing an extreme 4.8-fold price spread. These global precedents confirm that strong price signals can effectively shift highly elastic EV charging behaviors away from peak hours.

2.2 Distinctive Design of Taiwan's EV TOU Tariffs

Taipower's "EV Charging and Swapping Facility Tariff," implemented on May 30, 2022, aligns with global trends but introduces structural optimizations tailored for high-density urban condominiums. First, it slashes basic capacity charges by 80% compared to standard low-voltage TOU rates and reduces line installation fees to 20% of the current unit price, significantly alleviating the initial fixed-cost burden during the early stages of infrastructure deployment. Second, it creates an extreme pricing incentive: the summer peak rate (16:00-22:00) is 12.47 NTD/kWh, while the off-peak rate plummets to 3.05 NTD/kWh—a dramatic 4.1-fold spread. Most notably, it pioneers an ultra-long 18-hour off-peak window, providing community EMS with exceptional scheduling flexibility.

2.3 Application of TAM and Perceived Risk Theory

Consumer psychology plays a pivotal role in the adoption of EV infrastructure. Integrating the Technology Acceptance Model (TAM) and perceived risk theory, Peng (2025) highlights that the adoption intention for high-involvement, high-tech products heavily relies on "Perceived Usefulness (PU)," "Perceived Ease of Use (PEOU)," and the mitigation of "Perceived Risk (PR)". In residential scenarios, "financial risk" (initial capital expenditure) and "functional risk" (insufficient charging access and power tripping) are the primary barriers. A community-wide deployment of "Dedicated Metering + EMS" leverages economies of scale to drastically reduce financial risk. Simultaneously, the fully automated load control of EMS maximizes PEOU, thereby elevating residents' positive attitudes and adoption intentions toward the infrastructure.

2.4 Innovation Diffusion and eWOM Acceleration

The market penetration of leading EV brands (e.g., Tesla) depends not only on infrastructure but also on the inherent innovative characteristics of the vehicles. Applying Rogers' Innovation Diffusion Theory, Cheng (2026) demonstrates that "Relative Advantage" and "Compatibility" are the strongest drivers of EV purchase intention. Moreover, highly credible electronic Word-of-Mouth (eWOM) circulated through social networks effectively diminishes psychological uncertainties among potential buyers, reinforcing brand image and purchase motivation. Consequently, establishing a robust EMS-managed home charging environment creates a powerful synergy with the vehicle's innovative appeal.

2.5 Market Evolution and Carbon Emission Assessment

Regarding how charging infrastructure influences macro-market structures, Huang (2026) utilized a Markov Chain model to conduct in-depth dynamic forecasting. The research confirms an irreversible market transition in Taiwan from internal combustion engine (ICE) vehicles to battery electric vehicles (BEVs) and hybrid electric vehicles (HEVs). Without reliable charging infrastructure, consumers often settle for HEVs as a transitional choice, causing a "crowding-out effect." However, when technological conditions and home charging networks (such as EMS integrations) improve, the transition probability matrix shifts dramatically, accelerating the direct migration from ICE to BEV. Accelerating this transition maximizes direct carbon reduction during the Tank-to-Wheel (TTW) phase, directly contributing to national climate targets.

3. Methodology and Empirical Case

3.1 Case Background and Infrastructure Challenges

This research adopts an empirical case study approach, focusing on Community S in Taichung City. The residential complex comprises 264 units and 306 underground parking spaces. Because the building license predates current EV-ready regulations, the electrical room lacked a dedicated main meter and sufficient power capacity. Tolerating disorganized "behind-the-meter wiring" would inevitably breach the building's contract capacity and trigger severe public safety crises, significantly elevating the perceived safety risk among residents.

3.2 Taipower Compliance and Three-Phase Construction

Strictly adhering to Taipower's User Self-Checklist for EV Charging Equipment, the management committee prohibited private wiring and executed a three-phase "Dedicated Metering + EMS" plan. Phase 1 (Public Infrastructure): Installed two new low-voltage dedicated meters at the Taipower distribution facility, deployed 400A/250A busways across all basement levels, and established a cloud-based EMS host. Taipower regulations strongly recommend EMS load management for contract capacities exceeding 100 kW. Phase 2 (Branch Extension): Owners routed individual circuit breaker boxes from the busway to their private parking stalls. Phase 3 (Terminal Equipment): Residents purchased OCPP-compliant chargers connected to the EMS network. The OCPP protocol enables seamless communication between diverse charger brands and the CSMS, facilitating smart load balancing.

3.3 Innovative Early-Bird Dynamic Refund Model

The Phase 1 infrastructure quote was a staggering 5.8 million NTD. To prevent the wait-and-see attitude typical of collective action problems, the committee engineered a "Dynamic Average Price Formula" (5.8 million NTD divided by the number of participating spaces). Setting a minimum threshold of 60 households, the committee introduced a low-barrier 20,000 NTD deposit to lock in early-bird status, creating strong selective incentives that fundamentally dismantled the financial risk perception.

4. Proposed Solutions and Results

4.1 Financial Governance: Economies of Scale from FOMO

Empirical results indicate that the dynamic pricing and small deposit mechanism successfully triggered the Fear of Missing out (FOMO) effect. Even non-EV owners and investors rushed to participate to secure "asset preservation" and avoid future construction inflation, completely dissolving collective resistance.

Table 1: Performance of Phase 1 EMS Infrastructure Fundraising

Comparison Dimension	**BaselineThreshold (Conservative)**	**Actual Fundraising Results (Final Settlement)**
Total Construction Cost	5,800,000 NTD	5,800,000 NTD
Participating Spaces	60 units	147 units (2.45-fold growth)
Oversubscription Rate	2.0 times	4.9 times
Average Cost per Unit	96,667 NTD	39,455 NTD (59.1% reduction)

As shown in Table 1, 147 parking spaces participated, achieving a remarkable 4.9-fold oversubscription rate. This immense economy of scale plummeted the final cost to 39,455 NTD per unit—a 59.1% reduction. This strategy proves that unified early-stage deployment ensures system stability and unparalleled future scalability.

4.2 Energy Synergy: Smart Peak Shaving via EMS and TOU

The core value of EMS lies in dynamic load balancing and scheduled charging. Without EMS, uncoordinated high-speed charging during evening return hours (18:00-21:00) breaches contract capacities and incurs massive penalties.

Table 2: Taipower Low-Voltage EV Time-of-Use (TOU) Rates

Classification	**Summer (June 1 - Sept 30)**	**Non-Summer (Oct 1 - May 31)**
Peak Time (Mon-Fri)	16:00-22:00 (12.47 NTD/kWh)	15:00-21:00 (12.14 NTD/kWh)
Off-Peak (Mon-Fri)	Remaining 18 hours (3.05 NTD/kWh)	Remaining 18 hours (2.90 NTD/kWh)
Off-Peak (Weekends/Holidays)	Full 24 hours (3.05 NTD/kWh)	Full 24 hours (2.90 NTD/kWh)

Community S mandated "Load Control" via EMS, precisely distributing the charging power across Taipower's 18-hour off-peak window (22:00-08:00). For a 49kW contract capacity with 3,000 kWh of monthly off-peak charging, the total bill is approximately 11,725 NTD—translating to an average cost of only 3.9 NTD/kWh. Compared to public fast chargers (9-12 NTD/kWh), residents save over 60%-70%. Taipower data suggests that optimal off-peak charging can reduce monthly EV energy costs to 1,550 NTD, saving nearly 11,700 NTD annually compared to ICE vehicles.

4.3 Accelerating Market Transition and Carbon Reduction

The micro-level governance success of this case holds profound macro-level academic significance. According to Huang's (2026) Markov Chain predictions, the biggest bottleneck restricting BEV penetration is the functional risk of inadequate charging environments. By eradicating this barrier through EMS and dedicated metering, Community S dramatically increased the transition probability matrix coefficient from ICE directly to BEV. This avoids the "crowding-out effect" where range-anxious consumers settle for HEVs, thereby maximizing direct carbon reductions in the Tank-to-Wheel (TTW) phase. Furthermore, aligning with Cheng's (2026) findings, an optimized home-charging infrastructure amplifies the innovative advantages and positive eWOM of leading EV brands, generating a robust impetus for ICE owners to switch.

5. Conclusion and Managerial Implications

Under the severe challenges of global climate change and the overarching goal of achieving net-zero emissions by 2050, the electrification of transportation has become an irreversible international trajectory. However, existing residential condominiums—the most critical hubs for urban charging—have long been constrained by insufficient electrical capacity, fire safety concerns, and complex property rights that trigger severe collective action problems. Utilizing Community S in Taichung City as an empirical case study, this research systematically validates a tripartite governance framework integrating "Dedicated Metering, Energy Management Systems (EMS), and Time-of-Use (TOU) tariffs." This framework not only successfully resolves complex community governance deadlocks but also provides a highly replicable, sustainable governance blueprint for urban energy transitions. The empirical findings and theoretical contributions of this study can be comprehensively articulated through financial governance innovation, energy demand regulation, and deep alignment with the United Nations Sustainable Development Goals (SDGs).

5.1 Financial Governance Innovation: Breaking the Collective Action Problem and Perceived Risks

During the initial phases of promoting infrastructure, exorbitant construction costs frequently constitute the primary source of "financial risk" that deters resident participation. The management committee of Community S successfully dismantled the collective action problem, as defined by Olson, through financial engineering innovations—specifically, the "early-bird dynamic refund model" and a low-barrier 20,000 NTD deposit system. This mechanism precisely translated the sunk costs of infrastructure into a "selective incentive" with asset-preservation benefits, triggering a powerful Fear of Missing out (FOMO) effect within the community. Empirical data demonstrate that this strategy generated a 4.9-fold oversubscription rate. Through massive economies of scale, the per-unit infrastructure cost was drastically compressed from an estimated 96,667 NTD to an actual 39,455 NTD, representing a remarkable 59.1% reduction. This not only significantly diminished consumers' perceived financial risk but also thoroughly eliminated the exclusionary resistance of non-EV owners, providing a highly practical financialsolution for large-scale charging infrastructure deployment in high-density urban condominiums.

5.2 Smart Demand-Side Synergy and Internalization of Externalities via EMS and TOU Tariffs

Having resolved the financial barriers to hardware deployment, the core challenge during the operational phase lies in preventing the massive impact of uncoordinated charging on the power grid. This study confirms that Taipower's EV-specific Time-of-Use (TOU) tariffs, when coupled with the building's EMS, generate exceptional smart demand-side synergies. Taipower's new tariff drastically reduces the basic capacity charge by 80% and creates an extreme 4.1-fold peak-to-off-peak price spread (12.47 NTD during summer peaks versus 3.05 NTD during off-peak hours), while pioneering an unprecedented 18-hour off-peak window. Analyzed through the lens of microeconomics, this extreme 4.1-fold price spread is not a mere commercial concession or subsidy; rather, it operates as a sophisticated mechanism for the "internalization of externalities". Traditional, uncoordinated charging behaviors induce night-time peak surges, forcing grid operators to activate high-cost, carbon-intensive gas or coal peaker plants. These environmental and infrastructure upgrade costs, historically borne by the public as negative externalities, are successfully internalized into financial incentives for end-users through strong TOU pricing signals. Within this architecture, the EMS acts as the "automated technical executor," enforcing mandatory load control to shift massive charging loads precisely into the 18-hour off-peak window. Empirical calculations reveal that residents' average charging costs drop to approximately 3.9 NTD per kWh, saving 60% to 70% in energy expenses compared to external public fast chargers. This achieves a perfect win-win scenario: stabilizing the macro-grid while maximizing micro-level user savings.

5.3 Deep Alignment with SDG 7: Ensuring Affordable and Clean Energy and Urban Microgrid Resilience

The management mechanisms delineated in this study resonate profoundly with SDG 7 (Ensure access to affordable, reliable, sustainable and modern energy for all). First, regarding "Affordability," the integration of EMS and TOU tariffs drastically compresses the Total Cost of Ownership (TCO) for Battery Electric Vehicles (BEVs). Empirical evidence indicates that the annual operating cost of a mass-market BEV saves up to 66% compared to its hybrid counterpart, ensuring that urban residents can acquire the energy necessary for daily mobility at exceptionally low economic costs. Second, concerning "Clean and Sustainable" energy, shifting large-scale charging loads to late-night and early-morning off-peak hours yields macro-environmental benefits. This action maximizes the absorption rate of idle night-time baseload power and off-peak wind energy generation, avoiding the activation of carbon-intensive fossil fuel plants during peak hours. Consequently, this fundamentally elevates the green energy ratio and cleanliness of the electricity utilized for charging. Most forward-looking is the fact that the dedicated metering infrastructure, combined with the Open Charge Point Protocol (OCPP), lays a critical hardware foundation for future urban microgrids. As bidirectional Vehicle-to-Grid (V2G/V2H) technologies rapidly mature, these massive EV fleets parked in residential basements will no longer be unidirectional energy-consuming vehicles; instead, they will seamlessly transform into decentralized Battery Energy Storage Systems (BESS). During extreme climate disasters or grid overload events, the EMS can orchestrate reverse dispatch, feeding vehicle power back to the community or the macro-grid. This capability will fundamentally fortify the energy resilience of urban infrastructure, thoroughly actualizing the ultimate vision of SDG 7 for modernized, reliable energy systems.

5.4 Deep Alignment with SDG 12: Responsible Consumption and Production and Circular Economy

Another core academic contribution of this study lies in elevating condominium charging governance to directly align with SDG 12 (Ensure sustainable consumption and production patterns). In the dimension of "Responsible Consumption," traditional electricity consumption is a unidirectional, blind behavior lacking temporal elasticity. Through the intervention of TOU price signals and EMS Demand-Side Management (DSM), the system endows power consumption with immense temporal and spatial flexibility. This compels EV owners to be accountable for the overall load status of the grid during their daily charging routines, successfully guiding consumers to evolve from passive electricity "Consumers" into grid-responsive "Prosumers." In the dimension of "Responsible Production and Infrastructure Deployment," the community-wide "Busway" deployment advocated by this research epitomizes the philosophy of the Circular Economy. In contrast to the traditional "behind-the-meter private wiring" model—where every EV owner must individually route hundreds of meters of redundant copper wire from their apartment floor to the basement—private wiring not only wastes massive amounts of valuable metals but also faces total scrappage during future equipment upgrades. The dedicated metering busway system utilizes a modular design featuring plug-and-play scalability. Future charging points require only the addition of a tap-off box, drastically reducing unnecessary raw material extraction and wiring waste. From the very source of hardware production and facility deployment, this thoroughly implements the Circular Economy principles of maximizing resource utilization and minimizing waste emphasized by SDG 12.

5.5 Cross-Disciplinary Theoretical Contributions and Market Dynamic Evolution

The analytical framework of this study successfully integrates multiple frontier academic theories. Viewed through the lenses of the Technology Acceptance Model (TAM) and Innovation Diffusion Theory, this empirical case thoroughly removes consumers' "functional risk" and "financial risk" toward EVs by establishing an optimized EMS charging environment. When charging infrastructure is no longer a pain point, it maximizes the innovative appeal of leading EV brands (e.g., Tesla) regarding their "relative advantage" and "compatibility". Simultaneously, highly credible electronic Word-of-Mouth (eWOM) fermenting within social networks further fortifies potential buyers' brand trust and purchase motivation. Injecting these micro-level behavioral shifts into macroeconomic market forecasting perfectly corroborates the projections of Markov Chain dynamic evolution models. This research confirms that when the community charging environment undergoes fundamental improvement, it drastically increases the transition probability matrix coefficient of internal combustion engine (ICE) owners migrating directly to pure battery electric vehicles (BEVs). This not only effectively circumvents the "crowding-out effect"—where consumers suffering from range anxiety settle for transitional hybrid electric vehicles (HEVs)—but also enables the passenger vehicle replacement curve to converge toward zero-emission BEVs at maximum velocity. Accelerating this market transition process maximizes direct carbon emission reductions during the "Tank-to-Wheel (TTW)" phase, making the most direct and quantifiable contribution to the national net-zero carbon policy.

5.6 Policy Recommendations and Future Research Directions

Synthesizing the aforementioned empirical and theoretical findings, this study offers concrete recommendations for policymakers: government subsidy resources should not be confined solely to basic "vehicle purchase subsidies." Instead, resources should be strategically redirected toward "subsidizing the deployment of EMS charging infrastructure in high-density condominiums." Only by resolving the hardware bottlenecks of urban home charging at the source, coupled with highly incentivizing dynamic TOU tariffs, can policymakers leverage minimal administrative costs to ignite maximum momentum for private market transformation. Although this research provides detailed case evidence and theoretical dialogue, single-case studies inherently possess inferential limitations. Future research could further expand the sample scope and incorporate Time-inhomogeneous Markov Chain models to integrate dynamic macro-variables into the forecasting matrix, such as future carbon pricing mechanisms, international energy price fluctuations, and full Life Cycle Assessment (LCA) data. This expansion will facilitate a more comprehensive evaluation of the climate resilience and economic viability of urban green mobility and microgrid systems under multiple external shocks over their long-term evolutionary trajectories, continually deepening the academic theoretical framework of sustainable governance.

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