

The Spatial Dynamics of Decoupling: Urban Traffic Externalities, Telework, and the Role of Metaverse Systems in Shaping Future Mobility

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Received: 08/04/2026

Accepted: 26/05/2026

Published: 10/06/2026

Abstract: This study examines the complex relationship between telework adoption, urban traffic congestion, and the emergence of Metaverse technologies, situating its contribution explicitly within the economics of urban energy demand and sustainable mobility. Utilizing an integrated framework combining Innovation-Diffusion Theory (IDT) and the Alonso Bid-Rent spatial model, the analysis explores how hybrid work arrangements alter Vehicle Miles Traveled (VMT), foster the 'Donut Effect' of suburban dispersal, and weaken established commuting gradients. These behavioral shifts constitute direct demand-side interventions in urban energy systems, with measurable implications for transport-sector fossil fuel consumption and CO₂ emission trajectories. The methodology advocates for Agent-Based Modeling (ABM) and Latent Class Choice Models (LCCM) to capture behavioral heterogeneity. Findings confirm peak-hour trip reduction but reveal ambiguous net VMT outcomes owing to travel rebound effects. The Metaverse, conceptualized as a 'Cityverse' infrastructure, extends sustainability gains beyond VMT reduction to encompass industrial dematerialization and energy efficiency. Market-based policy mechanisms, notably road impact fees calibrated to the social discount rate, are proposed to internalize externalities. This integrated analysis offers a forward-looking policy foundation for sustainable, equitable metropolitan energy transitions.

Keywords: Telework; Urban Traffic Congestion; Vehicle Miles Traveled; Metaverse; Energy Transition

JEL Codes: R41; Q43; O33.

Citation : Bouguelaa Mohammed, Bouguenna Salim, (2026). The Spatial Dynamics of Decoupling: Telework, Urban Traffic Externalities, and the Role of Metaverse Systems in Shaping Future Mobility, *Journal of economics studies and researches in renewable energies*, 13(01), 288-304.

I. Introduction

1.1. Study Variable Definitions

For the purposes of this analysis, **telework** (remote work, work-from-home, or WFH) denotes any arrangement in which an employee performs professional duties from a location other than the principal employer premises, mediated by information and communication technologies (ICT). **Urban traffic congestion** is defined as the condition in which road network demand exceeds designed throughput capacity, producing delays, excess fuel combustion, and elevated greenhouse-gas emissions per vehicle-kilometer. **The Metaverse** is understood as the convergent platform of Spatial Computing technologies—Virtual Reality (VR), Augmented Reality (AR), Mixed Reality (MR)—integrated with Digital Twins (DTs) and persistent virtual

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environments, enabling presence-rich remote interaction that replaces or supplements physical co-location (Li & Chen, 2025). Each of these variables intersects directly with urban energy demand: commuting determines transport-sector fossil fuel consumption; congestion multiplies energy waste per unit of mobility; and the Metaverse represents an infrastructure of industrial dematerialization with demand-side energy implications.

1.2. Research Problem

This paper addresses the problem of the **paradoxical energy and spatial outcomes of widespread telework adoption**. Post-pandemic hybrid work has reduced peak-hour commuting, a result initially celebrated as a structural gain for urban sustainability. However, a growing body of evidence reveals countervailing mechanisms: travel rebound effects redistribute rather than eliminate VMT; residential dispersal (the 'Donut Effect') transfers energy and infrastructure costs to suburban peripheries; and policy oscillations—such as the reversal of the U.S. federal telework mandate in early 2025—demonstrate that congestion alleviation dependent on organizational mandates is inherently fragile (Work From Anywhere Team, 2025). Simultaneously, the scaling of Metaverse infrastructure requires massive investments in energy-intensive networks (5G, edge computing), introducing a new dimension to the energy economics of remote work that the current literature has yet to fully integrate.

1.3. Literature Gap and Research Questions

Prior literature has addressed telework's transportation substitution effect (de Abreu e Silva et al., 2025) and, separately, the social implications of the Metaverse (Work From Anywhere Team, 2025). However, no study has integrated: (a) the VMT rebound effect as a demand-side energy economics problem; (b) the Metaverse as a compound dematerialization strategy with energy efficiency benefits beyond transport; and (c) the social discount rate (SDR) mechanism as an instrument analogous to Pigouvian carbon pricing for internalizing sprawl externalities. This gap is particularly consequential for emerging economies and isolated regions—the core mandate of JoERRe—where distributed energy infrastructure and local development strategies must anticipate the spatial restructuring driven by hybrid work.

This study poses two linked research questions: (RQ1) To what extent does widespread telework adoption yield a measurable net reduction in urban transport energy consumption when travel rebound effects and residential relocation are fully accounted for? (RQ2) Can Metaverse-enabled remote operations generate compounded sustainability gains—encompassing both transport VMT reduction and industrial dematerialization—sufficient to constitute a coherent demand-side component of urban energy transition strategy?

1.4. Hypotheses

H1: Widespread telework adoption yields a measurable net reduction in urban transport energy consumption in the short term (commuting substitution), but this gain is partially or fully offset over the medium-to-long term by the combined effect of the travel rebound and telework-induced residential sprawl, such that only near-full-day telework schedules produce durable net VMT decreases (de Abreu e Silva et al., 2025; Kiko et al., 2025).

H2: Metaverse-enabled remote operations generate compounded sustainability gains beyond commuting VMT reduction—specifically through virtual prototyping, tele-operations, and elimination of expert-specialist travel—thereby positioning the Metaverse as a functional complement to renewable energy supply-side investment on the demand management side of urban energy transition (Bulla et al., 2025).

1.5. Value and Importance

This research contributes to the economics of renewable energy and sustainable urban development by establishing the conceptual and analytical bridge between telework behavioral economics, spatial restructuring theory, and urban energy demand forecasting. The reduction of VMT through hybrid work represents a direct demand-side intervention in the urban energy system: transport accounts for a substantial share of global final energy consumption, predominantly from fossil fuels (IEA, 2023). Any measurable, sustained reduction in commuting trips therefore aligns with national energy transition goals and complements renewable capacity expansion. Furthermore, the Cityverse concept offers a lens highly relevant to JoERRE's mandate on isolated areas: by enabling access to urban services and economic opportunities through virtual platforms, Metaverse technologies may reduce infrastructure investment requirements for geographically dispersed communities, with direct implications for distributed renewable energy network economics. Road impact fees and SDR analysis constitute energy externalities pricing—core energy economics methodology.

The remainder of this manuscript is structured as follows: Section II reviews the literature on telework and urban mobility. Section III develops the integrated conceptual framework. Section IV presents the methodology. Section V analyzes the Metaverse technology trajectory. Section VI synthesizes the discussion. Section VII addresses policy implications. Section VIII concludes.

II. Literature Review: Teleworking and the Urban Mobility Paradigm

2.1. Structural Foundations of Urban Agglomeration and Energy Density

Pre-pandemic urban economics were structured by classical models, notably Alonso's (1960) Bid-Rent theory, which posited that households and firms trade off accessibility to the Central Business District (CBD) against land costs. This framework explained the historical concentration of economic activity and population in major global metropolises (Ramani & Bloom, 2024). High land prices near the CBD internalized the value of density and minimized commuting costs. Critically, high-density urban cores also exhibit superior energy efficiency per capita: shared transit, building adjacency, and proximity to services reduce the per-capita energy footprint relative to dispersed suburban landscapes. The spatial concentration of economic activity was, in energy terms, a form of unintentional efficiency.

The emergence of widespread telework fundamentally threatens this structure. Telework disconnects work and home locations, inducing residential sprawl (Sweet & Scott, 2024). Empirical evidence corroborates this disruption: the ability to work remotely weakens the

traditional Bid-Rent gradient, transforming the definition of workplace from a fixed point to a 'probability space' (Sweet & Scott, 2024).

2.2. Telework's Direct Mitigation: Peak-Hour Demand Reduction

A strong empirical consensus confirms that telework substantially reduces the frequency of mandatory commuting trips, particularly for full-time remote arrangements (de Abreu e Silva et al., 2025). U.S. federal agencies employed metrics including commute miles avoided, commuting time saved, and transit subsidy reductions to quantify these benefits, citing explicit goals of reduced traffic congestion and improved environmental outcomes (U.S. Office of Personnel Management, 2022). The Commonwealth of Massachusetts formally adopted a hybrid work model citing reduced environmental pollution related to transportation as a key objective (Massachusetts Executive Department, 2023).

Studies conducted during pandemic containment measures showed clear reductions in travel. However, reliance on pandemic-period data fails to capture the long-term, systemic impacts of normalized hybrid work (de Abreu e Silva & et al., 2025). The energy economics relevance is direct: Li et al. (2023) demonstrated measurable carbon reduction benefits from teleworking in a Beijing case study, confirming the VMT-to-CO₂ pathway.

2.3. The Travel Rebound Effect and VMT Accumulation

The most critical challenge to telework as a definitive congestion mitigation strategy is the travel rebound effect (Motte-Baumvol et al., 2023). Time flexibility enabled by telework allows individuals to reorganize schedules, making it easier to engage in non-work travel such as shopping and leisure (Motte-Baumvol et al., 2023). Teleworkers often shift remaining non-work trips to off-peak hours—optimizing temporal distribution but not reducing spatial extent (de Abreu e Silva et al., 2025).

Empirical evidence on net VMT impact is mixed. Some pre-pandemic studies suggested that teleworkers accumulated longer total distances than non-teleworkers (de Abreu e Silva et al., 2025). More recent evidence shows that while full-day teleworkers are more likely to reduce total trip frequency, part-day teleworkers may accept longer commuting distances on office days (de Abreu e Silva et al., 2025). This VMT conflict has direct energy implications: fewer but longer trips may generate equivalent or greater fuel consumption and CO₂ emissions than the baseline commuting pattern they replace (Li et al., 2023b). This tension necessitates deeper empirical study, particularly in emerging economy contexts.

2.4. Telework and Metropolitan Spatial Restructuring: The Donut Effect

The sustained trend of remote work is restructuring the urban landscape through the 'Donut Effect': economic activity and population disperse from dense city centers to suburban regions (Ramani & Bloom, 2024). U.S. microdata indicate that roughly three-fifths of households leaving city centers moved to suburbs of the same metropolitan area—a pattern driven by hybrid work requirements for periodic office attendance (Ramani & Bloom, 2024). This dispersal has profound energy economics implications: it extends the length of remaining commuting trips, increases automobile dependence in areas with limited public transit, and elevates per-capita energy consumption for mobility and building heating/cooling.

The macro consequences are compounded by a documented decline in commercial real estate prices and rents in central density locations (Van Nieuwerburgh, 2022). The spatial transfer of financial and physical costs to suburban jurisdictions—which experience rising demand for road maintenance and local services without commensurate tax revenue—necessitates new regulatory tools that internalize the externalities of suburban travel behavior (Kiko et al., 2025). This is precisely the challenge addressed by road impact fees modeled on Pigouvian environmental pricing logic.

III. Conceptual Framework: Modeling Diffusion and Spatial Choice

3.1. An Integrated Framework

This study proposes an integrated theoretical framework that moves beyond simple econometric analysis by combining sociological theories of innovation adoption with established economic choice models. This enables prediction of the spatial diffusion of both remote work practices and the enabling technologies. The framework is situated within the energy economics perspective that treats VMT reduction as a demand-side sustainability mechanism, complementary to renewable energy supply-side investments.

3.2. Innovation-Diffusion Theory Applied to Telework and the Cityverse

Innovation-Diffusion Theory (IDT) provides structure for analyzing how innovations achieve geographic coverage by spreading across settlements and distances (Akhavan et al., 2022). The adoption of both telework and the Metaverse follows hierarchical diffusion (from larger to smaller cities) overlapping with neighborhood diffusion (spreading across proximate areas) (Akhavan et al., 2022). Key adoption factors include flexibility, low-cost intervention, and the role of opinion leaders (Akhavan & Colclough, 2024). Seoul, South Korea—which has invested in an entire virtual ecosystem including virtual replicas of public infrastructure (IEEE Metaverse Reality, 2023)—exemplifies how governmental entities act as early adopters that accelerate hierarchical diffusion. This has direct implications for isolated communities: IDT predicts that adoption of Cityverse services in peripheral areas will lag metropolitan centers, potentially widening rather than narrowing urban-rural energy service disparities unless deliberate policy intervention accelerates diffusion.

3.3. Technology Acceptance Models: TOE and UTAUT

For Metaverse enterprise implementation, established technology acceptance models are indispensable. The Unified Theory of Acceptance and Use of Technology (UTAUT) identifies performance expectancy and facilitating conditions as critical determinants of Metaverse-based optimization uptake in SMEs (Al-Husseini, 2024). Employee comfort with immersive technologies and high hardware costs remain limiting factors for individual adoption (Focus People, 2025). The Technology-Organization-Environment (TOE) framework emphasizes the role of technological context (platform fragmentation, technical complexity) and organizational context: the lack of inter-organizational collaboration hinders design processes and negatively impacts end-consumer experience (Al-Husseini, 2024). Organizational readiness—including specialized expertise in AR/VR, IoT, AI, and cloud computing—remains a major barrier to scaling (Meegle, 2024).

3.4. Reframing the Spatial Definition of Work and the Cityverse

Telework requires formalizing the concept of work location as a 'probability space,' as anticipated by urban geography scholars (Sweet & Scott, 2024). The rise of the Metaverse introduces the concept of the 'Metaverse City' (Cityverse)—a digital complement to the physical city that integrates physical infrastructure with interactive virtual replicas, providing next-generation services (Mozumder et al., 2023). The Cityverse is not merely a simulation; it is a critical infrastructure layer designed to enhance governance, service provision, and community interaction, decoupling physical location from access to high-quality urban amenities (Mozumder et al., 2023). For energy economics, this decoupling is significant: it could reduce the infrastructure investment required for physical service delivery in geographically isolated communities, aligning with JoeRRe's mandate on financing strategies for isolated areas.

IV. Methodology: Analytical Approaches for Dynamic Systems

4.1. The Imperative for Dynamic and Individual-Level Modeling

Traditional aggregate traffic models are insufficient for analyzing the complex impacts of telework because they fail to capture behavioral nuances inherent in flexible work: they overlook self-selection bias—where observed behavioral changes reflect pre-existing differences among teleworkers rather than the causal effect of telework itself—and structural changes in activity scheduling (de Abreu e Silva & et al., 2025). Furthermore, early telework research focused on static peak-hour analysis. The impact of telecommuting must be evaluated on the full 24-hour travel profile, necessitating dynamic modeling that simulates daily individual activities across the entire metropolitan area (McNally, 2000). Effective integration of energy implications requires models that extend beyond VMT to incorporate estimates of fuel consumption, emission factors, and land-use energy intensity at the suburban periphery.

4.2. Agent-Based Modeling (ABM) and System Dynamics

Agent-Based Modeling (ABM) is well-suited to model complex transportation systems by focusing on autonomous decision-making entities (agents) (Macal & North, 2005). In transportation contexts, ABM simulates personal activities and behavior, capturing emergent dynamics from repetitive interactions between commuters and teleworkers (Macal & North, 2005). For telework analysis, ABM models the nested choices—departure time, mode, and destination—that teleworkers make following remote work adoption (McNally, 2000), generating realistic adoption curves and enabling analysis of teleworking promotion strategies (Zhao & et al., 2023). System Dynamics (SD), as applied in Transportation 5.0 frameworks, complements ABM by modeling feedback loops within the urban ecosystem (Alghamdi & et al., 2024). SD integrates emerging technologies, policy interventions (including road impact fees), infrastructure investment, and their systemic interplay with long-term sustainability outcomes (Alghamdi & et al., 2024).

4.3. Latent Class Choice Models (LCCM) for Behavioral Heterogeneity

Latent Class Choice Models (LCCM) address population heterogeneity by simultaneously estimating class membership and class-specific choice behavior (Ben-Akiva & Boccara, 2017).

LCCM segments the population into distinct classes—innovators, imitators, non-adopters—formulating adoption probability conditional on class (Ben-Akiva & Boccara, 2017). This is critical for mitigating self-selection bias prevalent in earlier studies, which produced ambiguous or neutral findings regarding behavioral changes (de Abreu e Silva & et al., 2025). By capturing variation in tastes and sensitivities, LCCM provides a more rigorous basis for predicting the long-term diffusion of both telework practices and Metaverse technologies, including the distributional implications for energy consumption across socioeconomic segments.

4.4. Data Requirements and Model Calibration

Effective ABM and LCCM calibration requires comprehensive, high-frequency datasets capturing not only commuting metrics but also changes in spending, migration, and housing choices to validate spatial restructuring effects (Ramani & Bloom, 2024). Integration of Metaverse technology impacts requires data on 5G network penetration, hardware costs, latency sensitivity, and the professional category and education level of workers—factors that determine who can sustain teleworking post-pandemic (de Abreu e Silva & et al., 2025). Energy modeling additionally requires fuel consumption factors by vehicle type and trip purpose, residential energy intensity by density zone, and renewable energy grid penetration by metropolitan area—data streams that future longitudinal studies must explicitly incorporate.

V. Analysis: The Trajectory of Metaverse Technologies in Remote Work

5.1. Spatial Computing, Digital Twins, and Immersive Presence

Spatial computing encompasses AR, VR, and MR technologies that fundamentally transform remote work by enabling collaboration beyond two-dimensional screens (Li & Chen, 2025). This paradigm allows employees to interact in shared digital spaces that effectively mimic physical environments, fostering real-time collaboration and strengthening communication through elevated presence (TechAhead Corp., 2024). The functional capacity of spatial computing is significantly amplified through integration with Digital Twins (DTs): dynamic virtual models that replicate complex physical systems in real-time (Li & Chen, 2025; Meegle, 2024). DT systems leveraging AR and MR deliver immersive visualization experiences, allowing engineers to virtually walk through production lines, identify bottlenecks, and test solutions before physical implementation (Meegle, 2024). This convergence enables cross-domain data integration and real-time optimization (Li & Chen, 2025).

From an energy economics perspective, the Metaverse represents a technology of industrial dematerialization—replacing energy-intensive physical processes (prototyping, long-distance expert travel, on-site inspection) with low-energy virtual equivalents. This positions the Metaverse as a functional complement to renewable energy investment: while renewable capacity addresses the supply side of the energy transition, Metaverse-enabled operational efficiency attacks the demand side, reducing total primary energy consumption across manufacturing and logistics value chains (Bulla & et al., 2025).

5.2. Infrastructure Imperatives: Latency, 5G, and Edge Computing

Large-scale Metaverse and DT adoption is fundamentally dependent on robust digital infrastructure. Immersive environments require high bandwidth, high scalability, and critically, ultra-low latency for accurate real-time response (NADDOD Blog, 2023). Users interacting in VR or tele-operating machinery are highly latency-sensitive, requiring response times far superior to conventional network topologies (NADDOD Blog, 2023). The widespread rollout of 5G networks and Edge Computing infrastructure are the foundational requirements for meeting these demands (FusionLayer, 2023). Edge Computing brings processing power closer to the data source, reducing travel distances for data and thereby drastically lowering latency (NADDOD Blog, 2023). This combination bolsters DT real-time capabilities across diverse industries (Li & Chen, 2025).

The energy economics of this infrastructure layer are complex: 5G networks and edge data centers are themselves energy-intensive. However, research suggests that the energy consumed by digital infrastructure is substantially offset by the energy savings from dematerialized industrial processes and eliminated business travel (Bulla et al., 2025). This net calculation is essential for evaluating the Metaverse's true contribution to urban energy transition.

5.3. Industry 5.0 and Measurable Sustainability Gains

The most compelling Metaverse applications extend into high-impact industrial sectors, aligning with the human-centric focus of Industry 5.0 (Bulla et al., 2025). 'MfgVerse' systems offer an unprecedented opportunity to disrupt manufacturing practices through virtual design and prototyping—testing product and process changes before physical construction—thereby drastically reducing material waste and rework (Bulla et al., 2025). Remote collaboration and tele-operations reduce the need for high-VMT business travel by specialized experts (Bulla et al., 2025). AR-enhanced maintenance minimizes human errors and reduces scrap materials (Bulla et al., 2025). These benefits necessitate an expanded sustainability metric that captures resource consumption, waste reduction, and energy efficiency alongside traditional transportation metrics—a methodological extension with direct relevance to energy economics modeling.

5.4. Organizational and Technical Barriers to Scaling Adoption

Despite this potential, Metaverse workplace adoption remains in exploratory phases for most organizations (Focus People, 2025). Barriers fall into two categories: (1) Technological and financial: developing and deploying spatial computing and DT systems requires substantial investment in specialized hardware, software, and technical expertise; high initial costs impede many enterprises (Meegle, 2024); and platform fragmentation risks incompatibility with future infrastructure (Focus People, 2025). (2) Organizational and human: difficulty identifying clear use cases justifying high implementation costs (Focus People, 2025); the requirement for collaboration across the entire value chain between suppliers, buyers, retailers, wholesalers, and distributors (Al-Husseini, 2024); and employee comfort levels and specialized training needs that represent friction points for widespread adoption (Focus People, 2025). Table 1 provides a structured comparison of the primary technology adoption frameworks applicable to Metaverse integration in urban remote work systems.

Table 1. Technology Adoption Frameworks Applied to Metaverse Integration in Urban Remote Work Systems

<i>Framework</i>	<i>Core Construct</i>	<i>Application to Metaverse</i>	<i>Key Barriers Identified</i>	<i>Source</i>
<i>UTAUT (Unified Theory of Acceptance and Use of Technology)</i>	Performance expectancy, effort expectancy, social influence, facilitating conditions	Explains individual employee intention to adopt VR/AR collaboration tools; performance expectancy (work efficiency gain) identified as dominant predictor for SMEs	High hardware cost; low facilitating conditions in SMEs; employee discomfort with immersive HMDs	Al-Husseini, 2024
<i>TOE (Technology-Organization-Environment Framework)</i>	Technological context, organizational context, environmental context	Enterprise-level adoption and scaling of DT systems; emphasizes platform fragmentation (tech), lack of inter-organizational collaboration (org), and regulatory uncertainty (env)	Platform fragmentation; insufficient inter-organizational collaboration across supply chains; absence of industry standards	Al-Husseini, 2024
<i>IDT (Innovation-Diffusion Theory)</i>	Relative advantage, compatibility, complexity, trialability, observability	Explains hierarchical diffusion of Metaverse platforms from early-adopter cities (Seoul) to smaller municipalities; governmental opinion leadership accelerates diffusion	Complexity of implementation; low observability of ROI in early stages; absence of reference cases in developing economies	Akhavan et al., 2022; Akhavan & Colclough, 2024
<i>LCCM (Latent Class Choice Model)</i>	Heterogeneous preferences across latent population segments; class-specific adoption probability	Models differential adoption rates by worker category (innovators, imitators, laggards) and professional type; corrects self-selection bias in empirical telework-Metaverse adoption studies	Data availability for class segmentation; calibration requires longitudinal panel data not yet widely available	Ben-Akiva & Boccara, 2017

Source: Authors' own elaboration based on Al-Husseini (2024), Akhavan et al. (2022), Akhavan & Colclough (2024), and Ben-Akiva & Boccara (2017).

VI. Discussion: Net VMT Effect, Digital Infrastructure, and Policy

6.1. The Net Long-Term VMT Effect and Energy Implications

The synthesis of empirical evidence reveals a complex trade-off in the long-term impact of telework on VMT. While telework's efficacy in reducing peak-hour traffic is undeniable, total accumulated VMT across the metropolitan region is subject to two opposing forces: the direct substitution of commuting trips and the travel rebound effect caused by dispersed non-work travel (de Abreu e Silva et al., 2025). Unless hybrid work models shift decisively toward near-full-day telework, a massive net reduction in overall VMT is unlikely (de Abreu e Silva et al., 2025).

Consequently, the most durable transportation benefit of telework is the temporal smoothing of demand—relieving concentrated stress on peak-hour infrastructure (OPM, 2022). This shifts the transportation planning challenge from large-scale capacity expansion to dynamic management and optimization (Transportation 5.0) (Alghamdi et al., 2024). In energy economics terms, this is a structural shift from supply-side solutions (road capacity expansion, equivalent to energy grid expansion) to demand-side management (equivalent to energy efficiency and load-shifting programs). The energy economics parallel is direct: both road congestion pricing and carbon pricing are Pigouvian instruments designed to internalize external costs into private decision-making (Kiko et al., 2025). Table 2 summarizes the complex, often paradoxical, effects of widespread telework on urban dynamics and energy outcomes.

Table 2. The Telework Paradox — Net Impact on Travel Metrics, Urban Externalities, and Energy Outcomes

<i>Metric</i>	<i>Impact of Widespread Telework</i>	<i>Underlying Mechanism</i>	<i>Energy Economics Dimension</i>	<i>Evidence</i>
<i>Commuting Trip Frequency (Peak-Hour)</i>	Substantial Decrease	Direct substitution of office trips; temporal flexibility shifts remaining trips off-peak	Reduced fossil fuel combustion per commuting cycle; lower peak-load demand on energy-intensive transit infrastructure	de Abreu e Silva et al., 2025
<i>Total VMT (All Trip Purposes)</i>	Mixed/Ambiguous	Rebound effect: saved commute time reinvested in non-work travel; longer office-day commutes by part-day teleworkers	Net energy consumption impact ambiguous; depends critically on vehicle type, trip length, and energy grid carbon intensity	de Abreu e Silva et al., 2025; Li et al., 2023
<i>Congestion Externalities (Peak)</i>	Significant Alleviation	Reduction in peak load factor; immediate relief to major commuter corridors	Reduces idling-related fuel waste; improves urban air quality; lowers public health costs of transport pollution	OPM, 2022; Massachusetts Exec. Dept., 2023
<i>Urban Spatial Density</i>	Decreased Centralization	'Donut Effect': economic activity and population disperse to suburbs, weakening Bid-Rent theory	Suburban dispersal increases per-capita transport energy consumption; extends renewable energy grid requirements to peripheral areas	Ramani & Bloom, 2024
<i>Commercial Real Estate Value (CBD)</i>	Substantial Reduction	Reduced organizational need for centralized physical office footprint; fiscal erosion of CBD tax base	Potential adaptive reuse of commercial buildings reduces embodied energy waste; fiscal stress limits municipal green infrastructure investment capacity	Van Nieuwerburgh, 2022

Source: Authors' own elaboration based on cited sources.

6.2. The Digital Infrastructure Mandate for Sustainable Remote Work

The future viability of high-fidelity remote work is fundamentally contingent on significant investment in advanced digital infrastructure (NADDOD Blog, 2023). Without the low-latency infrastructure provided by 5G and Edge Computing, the quality of Spatial Computing interactions deteriorates, potentially driving employees back to centralized physical offices, as observed in governmental policy reversals (WFA Team, 2025). The network systems must be

engineered for high reliability, availability, and security to protect large volumes of real-time IoT data (NADDOD Blog, 2023). Public-private partnerships are essential for developing these solutions at scale (Alghamdi et al., 2024).

The energy economics of digital infrastructure investment must be explicitly modeled: the energy footprint of 5G base stations, edge computing clusters, and immersive hardware must be weighed against energy savings from dematerialized operations. This net calculation determines whether the Metaverse constitutes a genuine demand-side energy transition tool or simply relocates energy consumption from the transport sector to the ICT sector.

6.3. Policy Intervention: Internalizing Externalities and Counteracting Sprawl

The inherent limitations of telework policies alone—specifically, the persistence of the rebound effect and the induction of urban sprawl—make them insufficient for achieving socially optimal congestion and energy management (Kiko et al., 2025). Telework effectively transfers congestion costs and infrastructure demands from central cities to suburban peripheries (Kiko et al., 2025). This mandates regulatory measures designed to internalize these external social costs. The analysis provides strong theoretical support for: (a) implementing a road impact fee for home-based motorists upon private vehicle purchase; and (b) removing income tax exemptions for high-level employees who receive expensed company vehicles for telework (Kiko et al., 2025). These instruments adjust financial incentives to achieve a socially optimal traffic congestion level and promote sustainable suburban growth, counteracting the rising social discount rate (SDR) associated with telework-induced sprawl (Kiko et al., 2025). The SDR analysis is directly analogous to standard energy economics methodology for evaluating infrastructure externalities: both road impact fees and carbon pricing are instruments designed to align individual behavior with socially optimal resource allocation.

6.4. The Metaverse, Governance, and the New Urban Spatial Contract

The development of the Cityverse presents a dual governance challenge and opportunity (IEEE, 2023). Digital Twins facilitate dynamic governance, enabling city authorities to use virtual simulations and real-time data analysis to evaluate policy impacts and enhance urban efficiencies (Teng et al., 2022). On the other hand, spatial restructuring driven by remote work threatens the traditional municipal financial structure. The erosion of the CBD tax base due to declining commercial real estate values (Van Nieuwerburgh, 2022) necessitates reconsideration of the fiscal geography of the city. As economic processes increasingly rely on digital platforms (Teng et al., 2022), cities must pivot from taxing physical presence to generating revenue from the virtual economy created within the Cityverse (Mozumder et al., 2023). Legal and economic frameworks must evolve to capture value from digital interactions and virtual assets to sustain funding for physical infrastructure—increasingly strained by dispersed suburban populations (Sweet & Scott, 2024). For isolated areas and peripheral communities, the Cityverse creates a potential new development pathway: if equitably implemented, virtual access to urban-quality services could reduce the per-capita infrastructure investment required for physical service delivery, lowering the cost of extending renewable energy networks to dispersed populations.

VII. Policy Implications: Planning, Governance, and Equity

7.1. Strategic Transportation Planning in the Era of Hybrid Mobility

The shift to hybrid mobility necessitates a reorientation of strategic transportation planning away from capital-intensive centralized transit expansions and toward optimizing distributed suburban road networks and local infrastructure (Alghamdi et al., 2024). Transportation 5.0 principles—leveraging AI and IoT for predictive maintenance, adaptive traffic control, and eco-friendly route planning—are essential to manage the dynamic 24-hour travel patterns of teleworkers (Alghamdi et al., 2024). Planning must emphasize multi-modal flexibility, recognizing that teleworkers organize remaining trips around new activity nodes utilizing varied transport modes from dispersed locations (Motte-Baumvol et al., 2023). Crucially, energy efficiency metrics must be integrated into transportation planning assessment: investment priorities should explicitly account for per-vehicle-kilometer CO₂ emissions, not merely throughput capacity.

7.2. Addressing the Digital Divide and Spatial Equity

The implementation of Metaverse technologies—characterized by high initial costs, complex technical requirements, and reliance on cutting-edge infrastructure—poses a significant threat of exacerbating existing social inequalities (Focus People, 2025). If access to high-fidelity remote collaboration is restricted by economic or geographical barriers, the adoption of these tools risks widening the digital divide (WEF, 2023). In this scenario, access to resilient remote work capabilities could become a critical predictor of future economic mobility, disproportionately benefiting employees with higher education and professional status (de Abreu e Silva et al., 2025).

To mitigate this risk, governments must implement infrastructure tiering: establishing municipal VR centers in underserved communities would ensure equitable access to high-cost hardware and high-speed networks required for Cityverse participation (Shirazi et al., 2025). For isolated communities—central to JoeRRe's mandate—this infrastructure tiering strategy intersects directly with renewable energy extension economics: co-locating municipal digital infrastructure with renewable energy micro-grids could reduce the marginal cost of both digital inclusion and clean energy access in peripheral areas.

7.3. Legal and Ethical Governance of Platformized Cities

The platformization of urban life facilitated by the Metaverse requires rigorous, adaptive regulatory frameworks (Teng et al., 2022). Policy efforts must address data privacy, cybersecurity, and ethical use of large IoT and Digital Twin datasets (Shirazi et al., 2025). Establishing city-wide 'Metaverse Trusts' with clear citizen data governance models is critical for accountability (Shirazi et al., 2025). Collaboration between governments, NGOs, and private sector is crucial to foster controlled growth while safeguarding inclusivity and responsible design (WEF, 2023). Table 3 summarizes the key policy interventions.

Table 3. Policy Interventions for Sustainable and Equitable Telework Adoption

<i>Urban Challenge</i>	<i>Policy Intervention Strategy</i>	<i>Expected Outcome</i>	<i>Energy Economics Dimension</i>	<i>Source</i>
<i>Telework-Induced Sprawl / Rising SDR</i>	Implement road impact fees for home-based motorists; remove tax exemptions for expensed company vehicles	Internalize social cost of increased suburban VMT; promote socially optimal traffic levels and rural growth	Pigouvian pricing aligns private mobility costs with social energy and carbon costs; equivalent mechanism to carbon pricing in transport sector	Kiko et al., 2025
<i>Widening Digital Divide</i>	Infrastructure Tiering: establish Municipal VR Centers; co-locate with renewable micro-grids in isolated areas; fund digital literacy programs	Equitable access to high-fidelity remote work and Cityverse services; minimize access barriers by income and location	Co-investment in digital infrastructure and distributed renewable energy reduces marginal cost of extending both to peripheral communities	Shirazi et al., 2025; WEF, 2023
<i>CBD Fiscal Decline</i>	Develop regulatory frameworks for taxing virtual economic activity (Cityverse value); virtual zoning codes and digital asset taxation	Shift municipal governance models to capture value from platformization of urban life; sustain physical infrastructure funding	Preserves municipal capacity to invest in green urban infrastructure; stabilizes fiscal base for energy transition investment	Mozumder et al., 2023; Teng et al., 2022
<i>Systemic Complexity / Adaptation</i>	Adopt AI/IoT for real-time adaptive traffic control (Transportation 5.0); integrate DT-based urban energy monitoring	Enhance system responsiveness to changing travel conditions; optimize resource allocation across metropolitan network	Real-time energy-use feedback enables dynamic demand management; integrates transport and energy grid optimization into unified urban platform	Alghamdi et al., 2024

Source: Authors' own elaboration based on cited sources.

VIII. Conclusion

The confluence of widespread telework adoption and the emergence of immersive technologies represents the most significant structural shift in urban organization since the advent of the automobile, with direct and consequential implications for the economics of urban energy demand and the trajectory of energy transition. The initial benefits of telework—demonstrated reduction and temporal smoothing of peak-hour congestion—constitute genuine demand-side interventions in urban transport energy systems, reducing fossil fuel combustion and improving urban air quality. However, these gains are fragile, vulnerable to political mandates and behavioral rebound effects that disperse travel, promoting sprawl and challenging both the fiscal sustainability of central cities and the energy efficiency gains of spatial concentration.

To navigate this transformation in alignment with energy transition objectives, transportation policy must evolve from mere encouragement of telework to the implementation of market-based mechanisms—specifically road impact fees calibrated to the social discount rate of telework-induced sprawl—designed to internalize the external social and energy costs generated by dispersed VMT across the metropolitan periphery. This is not simply a transportation policy recommendation; it is an application of the Pigouvian pricing logic central to energy economics, extended to the mobility sector. Simultaneously, municipal planning must strategically invest in advanced digital infrastructure (5G, Edge Computing) to support the next generation of remote collaboration and Industry 5.0 applications, which offer more comprehensive sustainability benefits beyond transportation through industrial dematerialization.

The promise of the Metaverse—manifested as the 'Cityverse' supported by Digital Twins—is the permanent decoupling of high-value work and urban services from mandatory physical proximity. From the perspective of energy economics, this promise is doubly significant: it reduces demand for energy-intensive physical commuting while simultaneously enabling the dematerialization of industrial processes that currently rely on physical expert presence and material prototyping. Realizing this promise requires overcoming substantial barriers of cost and technical complexity. Policymakers must adopt a comprehensive, equity-focused strategy—characterized by infrastructure tiering, co-investment in renewable micro-grids for isolated communities, and adaptive regulatory governance—to ensure that the benefits of this digital transformation are broadly accessible.

This research contributes to the economics of renewable energy by establishing telework VMT reduction and Metaverse-enabled dematerialization as legitimate and analytically tractable demand-side components of urban energy transition. Future longitudinal studies must integrate transport VMT data with energy consumption metrics across residential zones to test H1 and H2 empirically, particularly in MENA and Algerian contexts where the intersection of urban growth, hybrid work adoption, and distributed renewable energy deployment is rapidly evolving. The future of sustainable urban development lies in the harmonious, equitable integration of physical and virtual urban systems—a synthesis that is simultaneously an urban planning imperative and an energy economics research frontier.

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