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THE TWIN TRANSITION: SYNERGIZING AI AND GREEN INNOVATION-ORIENTED INVESTMENT FLOWS FOR AGGREGATE PRODUCTIVITY

Abstract

This study examines the macroeconomic premise that the "Twin Transition"—the concurrent advancement of digitalization and decarbonization—inherently produces complementary productivity gains. Utilizing a three-way matched firm-level microdata infrastructure integrating FactSet RSCR, PATSTAT, and Orbis, this research evaluates whether data-intensive investments promote clean-tech efficiency or generate competing resource demands across the global supply chain. The empirical findings challenge the synergy hypothesis. At the firm level, scaling artificial intelligence infrastructure displaces the capital expenditure, Research and Development (R&D) resources, and organizational capacity required for concurrent green innovation. Furthermore, dynamic network modeling indicates that upstream digital modernization heavily utilizes regional energy grids and critical hardware outputs, creating bottlenecks that delay downstream sustainability targets. To prevent AI expansion from impeding global sustainability goals, policymakers should consider financial screening mechanisms for state-directed innovation finance and require that data-centric expansions be paired with new renewable energy generation.

Keywords: twin transition, artificial intelligence, green innovation, supply chain bottlenecks, aggregate productivity.

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Introduction

The global economy is currently undergoing a structural shift defined by the simultaneous acceleration of digitalization and decarbonization, conceptualized as the "Twin Transition." Recent frameworks define this transition as the reinforcing relationship between digital and green organizational practices [1]. As macroeconomic policy mandates climate-aligned sustainability alongside digital modernization, firms are required to allocate capital expenditures across two domains: data-intensive infrastructure (such as artificial intelligence and cloud computing) and green innovation technologies. While prevailing macro-economic narratives often assume these two investment flows are complementary, this paper questions that theoretical baseline. By integrating digital and environmental capital theories, this study analyzes whether data-intensive investments improve clean-tech efficiency or generate competing resource demands across the entire supply chain.

The primary theoretical friction lies in the distinct resource requirements of these capital investments. Artificial intelligence and data-intensive technological growth—often categorized as intangible capital—require substantial physical resource capacity. Deploying advanced computational models involves high energy consumption, intensive semiconductor production, and large-scale data center expansions. Simultaneously, the green transition requires internal financing and supply chain capacity to overhaul manufacturing processes, adopt clean technologies, and mitigate environmental risks. Consequently, at the firm level, expanding AI infrastructure risks crowding out the financial capital and physical resources necessary for green innovation, potentially constraining aggregate productivity.

Traditional macroeconomic accounts and generalized industry-level data often fail to capture these frictions. By grouping digital and environmental capital into broad aggregated categories, standard national statistics obscure the supply-demand dynamics that propagate upstream and downstream throughout the global production network. To address this gap in the literature, this paper shifts the analytical focus from macro-aggregates to firm-level microdata. This research employs a three-way matched data infrastructure integrating FactSet Revere Supply Chain Relationships, the EPO Worldwide Patent Statistical Database (PATSTAT), and Bureau van Dijk's Orbis. This structural mapping permits the isolation of climate-aligned innovation flows and data-intensive technological capital across interconnected buyer-supplier networks. Ultimately, this paper seeks to clarify a dilemma in modern economic growth theory: whether integrating digital and green capital creates synergies that elevate aggregate total factor productivity, or whether the resource intensity of AI limits the global transition to a sustainable economy.

Theoretical framework and literature review

The theoretical foundation of this study rests at the intersection of two strands of macroeconomic literature: the productivity dynamics of intangible digital capital and the spillover effects of climate-aligned investments. The concurrent advancement of digitalization and decarbonization presents a unique theoretical challenge. While prior scholarship has documented the isolated impacts of artificial intelligence (AI) and green technologies on aggregate productivity, the mechanisms governing their interaction remain underexplored. This paper addresses this gap by analyzing whether data-intensive investments promote clean-tech efficiency or create competing resource demands across the supply chain.

The first strand of literature focuses on the measurement and productivity implications of data-intensive investment flows. Historically, AI and data-centric investments have been categorized as intangible capital, complicating their integration into standard national accounts. Advancements in growth theory emphasize that data-intensive capital operates as a general-purpose technology, capable of generating knowledge spillovers and reducing transaction costs. However, this intangible growth is linked to physical constraints. The literature on digital capital often overlooks the energy intensity and hardware prerequisites required to sustain advanced computational models, necessitating a reassessment of long-run productivity.

Synthesizing these domains reveals a theoretical friction: the competing resource demands of the twin transition across the global production network. At the firm level, financial constraints and organizational capacity are finite. When a firm or its upstream suppliers allocate capital expenditures toward scaling data-intensive infrastructure, the accompanying energy consumption and capital lock-in may crowd out the resources necessary for adopting clean-tech innovations. Conversely, the synergy hypothesis suggests that AI applications can enhance clean-tech efficiency, accelerating the environmental transition. Studies supporting this view find that AI adoption can drive enterprise energy transformation by reducing internal financing constraints and improving human capital efficiencies [2]. Furthermore, integrating data-intensive resources alters the economic mechanisms of green risk management, highlighting the need for a comprehensive approach [3].

To address the dichotomy between AI as an energy transformation enabler and AI as a resource sink, this framework incorporates supply chain network theory. Modern production is interconnected; shocks to capital allocation propagate asymmetrically through buyer-supplier networks. By evaluating how upstream digital investments impact downstream environmental efficiencies, this study establishes a micro-founded theoretical model. The ultimate effect of synergizing AI and green innovation-oriented investment flows on aggregate productivity depends on whether these capital forms act as structural complements or competing resource sinks.

Data model and methodology

The three-way matched microdata ınfrastructure. To evaluate whether data-intensive investments create synergy or crowding-out effects across the global production network, macro-level aggregates are often insufficient. Therefore, this study constructs a three-way matched firm-level microdata infrastructure. Advancements in enterprise-level global supply chain databases highlight the necessity of disaggregating firm-level transaction links to resolve macro-level uncertainties [4]. The foundation of this architecture relies on three global databases:

The Production Network: The structural map of the global supply chain is established using FactSet Revere Supply Chain Relationships (RSCR) [5]. This database tracks buyer-supplier linkages across more than 150,000 global firms, which is essential for estimating input-output linkages in production networks and evaluating the potential for systemic risk [6]. By mapping these inter-firm linkages, we can isolate how an upstream digital investment shock impacts the resource allocation and green efficiency of downstream suppliers.

Technological Capital Measurement: To track intangible capital without relying on self-reported corporate metrics, this study utilizes the EPO Worldwide Patent Statistical Database (PATSTAT) [7]. We apply Cooperative Patent Classification (CPC) codes to filter each firm's innovation portfolio, mapping green patenting strategies against competitors within the digital techno-economic ecosystem [8]. Specifically, climate-aligned innovation is isolated using the Y02 code (Climate Change Mitigation Technologies), while AI and data-intensive flows are measured using the G06N code (Computer systems based on specific computational models). Tracking the convergence of these historical innovation outputs mathematically captures the crowding out of innovation capacity at the firm level, rather than immediate capital expenditure or real-time liquidity shocks.

Financial and Productivity Metrics: Bureau van Dijk’s Orbis serves as the financial anchor, providing standardized microdata for both public and private entities [9]. Orbis provides the firm-level financial metrics, specifically Capital Expenditure (CapEx), R&D spending, and value-added productivity. By unifying Orbis financial data with FactSet network matrices and PATSTAT innovation flows using Global Ultimate Owner (GUO) identifiers, we can execute panel regressions. This allows us to observe total factor productivity (TFP) impacts at the firm level before aggregating them to the sector level.

Empirical strategy and model specification. The empirical strategy is designed to test two competing economic hypotheses: the Synergy Hypothesis, which posits that AI acts as a general-purpose technology accelerating downstream green innovation, and the Crowding-Out Hypothesis, which argues that the immense financial and physical demands of data-intensive investments cannibalize green initiatives. To quantify the direct, internal firm-level friction between these two capital flows—measuring the crowding out of innovation capacity rather than literal liquid cash flows—we first estimate a baseline fixed-effects panel regression model. The baseline equation is specified as follows:

$$ln\left(TFP_{i,t}\right) = \alpha_i + \gamma_t + \beta_1 Y02_{i,t-3} + \beta_2 G06N_{i,t-3} + \beta_3\left(Y02_{i,t-3} \times G06N_{i,t-3}\right) + \delta X_{i,t-1} + \epsilon_{i,t}$$

Where:

- $TFP_{i,t}$ represents the Total Factor Productivity of firm i in year t.
- $Y02_{i,t-3}$ and $G06N_{i,t-3}$ denote the cumulative patent stocks in climate-aligned and AI technologies, respectively, lagged by three years to capture the macroeconomic total factor productivity (TFP) impacts of complex technological patents.
- The interaction term $\left(Y02_{i,t-3} \times G06N_{i,t-3}\right)$ is the critical variable of

interest. A positive coefficient ($beta_3 > 0$) supports internal firm-level synergy, whereas a negative coefficient ($beta_3 < 0$) signals internal resource crowding-out.

- $X_{i,t-1}$ is a vector of firm-level control variables (e.g., total CapEx, R&D expenditure, firm size, and leverage ratio) extracted from Orbis.
- α_i and γ_t represent firm and time fixed effects, respectively, to control for unobserved heterogeneity, while $\epsilon_{i,t}$ is the idiosyncratic error term.

Supply chain network spillovers. Because the "Twin Transition" dynamically alters input-output relations, internal firm models are inadequate for capturing structural network effects. To measure whether data-intensive investments in upstream "superstar" firms bottleneck or accelerate downstream clean-tech efficiency, we introduce a dynamic space-time autoregressive lag model. Using the FactSet RSCR database, we construct a row-normalized adjacency matrix, W, utilizing fractional weights where the elements of each row sum to 1, based on direct upstream supplier linkages to firm i in year t. The network spillover equation is defined as:

$$Y02_{i,t} = \alpha_i + \gamma_t + \rho \sum_{j \neq i} W_{i,j,t} Y02_{j,t-3} + \theta \backslash sum_{j \neq i} W_{i,j,t} G06N_{j,t-3} + \phi X_{i,t-1} + \mu_{i,t}$$

In this equation:

The parameter θ measures the upstream-to-downstream spillover effect. It calculates how the AI and data-intensive capital scaling of a firm's suppliers ($G06N_{j,t-3}$) influences the focal firm's ability to generate green innovations ($Y02_{i,t}$).

A significantly negative θ provides empirical confirmation of the Crowding-Out Hypothesis across the supply chain, indicating that supplier-level digital modernization monopolizes bandwidth and physical resources, thereby stifling downstream sustainability transitions. By aggregating these micro-founded network metrics, this study bridges the gap between isolated corporate investment behaviors and broader macroeconomic productivity trends.

Empirical results and supply chain dynamics. The empirical analysis indicates structural friction between digitalization and decarbonization. The baseline panel regressions and dynamic space-time autoregressive lag models applied to the three-way matched microdata infrastructure challenge the macroeconomic assumption that data-intensive capital and climate-aligned investments are inherently complementary. Instead, the results point to significant resource constraints, revealing a displacement effect that propagates asymmetrically across the global production network.

Internal firm-level frictions: the baseline model. The baseline fixed-effects panel regression assesses the internal capacity of firms to manage the "Twin Transition" simultaneously. Evaluated in isolation, the independent coefficients for both climate-aligned patent stocks ($Y02$) and data-intensive technological capital ($G06N$) show positive and statistically significant direct effects on firm-level total factor productivity (TFP). This aligns with standard growth theory, indicating that investments in either artificial intelligence or green innovation independently reduce long-run marginal costs and improve organizational productivity.

The central finding, however, lies in the interaction term (β_3). Across the primary model specifications, the coefficient for the interaction between AI expansion and green innovation is negative and statistically significant at the 1% level, supporting the Crowding-Out Hypothesis. The data suggests that as a firm rapidly expands its data-intensive infrastructure, the marginal productivity of its concurrent climate-aligned investments declines.

This internal friction is driven largely by capital expenditure (CapEx) displacement and finite organizational capacity. Deploying advanced computational models requires substantial immediate liquidity alongside sustained operational expenditure (OpEx) for energy consumption and hardware maintenance. Because internal financing is subject to liquidity constraints, capital allocated to digital infrastructure diverts resources from the physical modifications required for green manufacturing. This is consistent with recent findings showing that high network centrality and resource monopolization negatively impact a firm's total innovation output by reducing R&D input [10]. Rather than creating a synergistic general-purpose technology effect, concurrent investment strains the firm's balance sheet, potentially limiting overall economic growth.

Network spillovers and upstream bottlenecks. While the baseline model captures internal corporate dynamics, the dynamic space-time autoregressive lag model evaluates the macro-structural consequences of the twin transition across buyer-supplier linkages. The network spillover parameter (θ), which measures how upstream data-intensive investments affect downstream green innovation, remains negative throughout the observation period.

This negative upstream-to-downstream spillover effect suggests that digitalization can create supply chain bottlenecks. As upstream suppliers—particularly those providing intermediate goods, semiconductors, or cloud infrastructure—direct capital toward AI expansion, they increasingly draw on regional energy grids and hardware outputs. This dynamic supports foundational models indicating that supply shocks propagate asymmetrically, leading to vertical creative destruction across production networks [13]. Additionally, portfolio-level analyses suggest that supply chain network centrality limits adaptive capacity [11, 12]; downstream firms reliant on central AI-scaling hubs experience disproportionate reductions in their sustainability R&D inputs [10].

Consequently, downstream manufacturers often absorb higher transaction costs, reducing the capital available for their own environmental transitions. The empirical network matrix indicates that data-intensive capital functions less as a decentralized enabler of clean-tech and more as a competing resource demand. Upstream digital modernization utilizes significant physical infrastructure capacity, potentially delaying the achievement of global sustainability targets across the broader production network.

Sectoral heterogeneity and "Superstar" dynamics. Stratifying the sample by firm size and market capitalization reveals variation in how the twin transition is experienced. The negative coefficients in both the baseline and network models are driven primarily by small and medium-sized enterprises (SMEs) and mid-cap manufacturing firms. For these entities, the financial friction between digital and green capital is particularly pronounced.

In contrast, a concentrated subset of ultra-large-cap technology and industrial conglomerates—the "superstar" firms—exhibits a neutral or marginally positive interaction term. These entities typically possess the retained earnings and access to external innovation credit necessary to fund both transitions without violating liquidity constraints. The network model, however, indicates that these firms operate largely as "walled gardens." The internal efficiencies achieved through AI-optimized clean-tech do not readily spill over into the broader economy. Instead, their concurrent accumulation of digital and environmental capital widens the productivity gap, generating localized high-efficiency growth that does not necessarily translate into broad macroeconomic convergence.

Robustness checks and endogeneity controls. Several robustness checks were conducted to verify the stability of the Crowding-Out Hypothesis. To account for potential endogeneity and reverse causality—where less productive firms might be forced to choose between AI and green tech—the models were re-estimated using a Generalized Method of Moments (GMM) framework with internally generated instrumental variables. The negative interaction term remained robust.

Second, applying temporal lags to the independent variables in alternative specifications confirmed that the $t-3$

realization window appropriately captured the delayed effects of complex technological capital. Across these extended windows, upstream AI expansion continued to negatively impact downstream green patent generation. Finally, standard errors were clustered at both the industry and regional levels to account for localized energy grid capacities and state-directed innovation finance policies, yielding consistent results. The evidence suggests that without structural intervention, the resource intensity of AI development may constrain the supply chain's transition to a sustainable economy.

Policy implications for aggregate productivity. The observation of crowding-out effects across the production network implies a need to reassess macroeconomic investment strategies. Because the financial and physical frictions between data-intensive capital and climate-aligned investments are most pronounced at the firm level, relying primarily on unguided market forces for the twin transition may contribute to aggregate productivity stagnation. To address these firm-level frictions in the context of macroeconomic growth, policymakers should consider shifting from generalized subsidy models to targeted structural interventions.

First, state-directed innovation finance requires optimization to minimize resource misallocation. As governments expand credit to stimulate digital modernization and decarbonization, there is a risk of subsidizing "zombie innovation," where unstructured credit inadvertently stifles creative destruction. To limit capital allocation to unproductive incumbent firms, institutional credit policies should incorporate distinct financial screening parameters. For example, structural financing mechanisms could classify firms with an Altman Z-score in the Grey Zone as uncertain investments [14]. Furthermore, valuing firms for green and digital subsidies requires subtracting both Capital Expenditure (CapEx) and Working Capital investment from Net Income to isolate the free cash flow available to effective innovators. Implementing such screening mechanisms allows state-directed finance to alleviate liquidity constraints for downstream manufacturers while limiting support for inefficient market actors.

Second, macroeconomic infrastructure policy should address the upstream bottlenecks associated with AI scaling. The dynamic space-time autoregressive lag models indicate that the resource requirements of AI expansion draw heavily on regional energy grids and hardware outputs, which can delay downstream sustainability targets. Consequently, investment policies could require that large-scale upstream data infrastructure expansions be coupled with localized, new renewable energy generation. Managing the energy consumption of large technology conglomerates is important for ensuring that downstream manufacturing sectors retain the physical capacity and affordable input costs needed for their environmental transitions.

Finally, structural policy interventions may be necessary to address the "walled gardens" of ultra-large-cap entities. While superstar firms often achieve internal synergies between AI and clean-tech, these localized efficiencies do not consistently diffuse into the broader economy. Competition policy, intellectual property frameworks, and supply chain regulations should be examined to incentivize technology spillovers. Encouraging the transfer of AI-optimized clean-tech capabilities from leading upstream firms to their downstream supplier networks can help translate isolated green innovations into broader macroeconomic convergence.

Conclusion

The concurrent pursuit of digitalization and decarbonization presents a complex structural challenge for the global economy. This study examined the theoretical premise that the "Twin Transition" inherently generates complementary productivity gains. Using a three-way matched firm-level microdata infrastructure across global supply chains, the empirical findings challenge the synergy hypothesis. The data indicates that data-intensive capital investments and climate-aligned innovation flows often function as competing resource demands rather than natural complements.

At the firm level, the financial and physical demands of expanding artificial intelligence infrastructure displace the capital expenditure and organizational capacity required for concurrent green innovation. Furthermore, dynamic space-time autoregressive network modeling demonstrates that this crowding-out effect propagates asymmetrically across the production network. Upstream digital modernization draws heavily on regional energy grids and hardware outputs, increasing transaction costs and creating bottlenecks that delay downstream sustainability targets. Although ultra-large-cap "superstar" firms achieve localized synergies, these benefits remain largely confined to walled gardens, widening the productivity gap rather than fostering macroeconomic convergence.

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ƏKİZ KEÇİD: MƏCMU MƏHSULDARLIQ ÜÇÜN SÜNİ İNTELLEKT VƏ YAŞIL İNNOVASİYAYÖNÜMLÜ İNVESTİSİYA AXINLARININ SİNERGİYASI

Xülasə

Bu tədqiqat "Əkiz Keçid"in—rəqəmsallaşma və dekarbonizasiyanın eyni vaxtda inkişafının—özlüyündə tamamlayıcı məhsuldarlıq artımı yaratdığına dair makroiqtisadi fərziyyəni tədqiq edir. FactSet RSCR, PATSTAT və Orbis-i birləşdirən üçqat uyğunlaşdırılmış firma səviyyəli mikrodata infrastrukturundan istifadə edərək, bu tədqiqat məlumat tutumlu investisiyaların təmiz texnologiya səmərəliliyini təşviq etdiyini, yoxsa qlobal tədarük zənciri boyu rəqabətli resurs tələbləri yaratdığını qiymətləndirir. Empirik nəticələr sinergiya fərziyyəsini sual altına alır. Firma səviyyəsində, süni intellekt infrastrukturunun genişləndirilməsi paralel yaşıl innovasiyalar üçün tələb olunan əsaslı xərcləri, Tədqiqat və İnkişaf (Tİ) resurslarını və təşkilati potensialı sıxışdırıb çıxarır. Bundan əlavə, dinamik şəbəkə modelləşdirməsi göstərir ki, yuxarı axın rəqəmsal modernləşdirmə regional enerji şəbəkələrindən və kritik təchizat çıxışlarından yüksək dərəcədə istifadə edərək, aşağı axın davamlılıq hədəflərini gecikdirən maneələr yaradır. Süni intellektin qlobal davamlılıq məqsədlərini ləngitməsinin qarşısını almaq üçün siyasətçilər dövlət tərəfindən yönləndirilən innovasiya maliyyəsi üzrə maliyyə yoxlamaları mexanizmlərini nəzərdən keçirməli və məlumat mərkəzli genişlənmələrin yeni bərpa olunan enerji istehsalı ilə əlaqələndirilməsini tələb etməlidirlər.

Açar sözlər: əkiz keçid, süni intellekt, yaşil innovasiya, tədarük zənciri maneələri, məcmu məhsuldarlıq.

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ДВОЙНОЙ ПЕРЕХОД: СИНЕРГИЯ ИСКУССТВЕННОГО ИНТЕЛЛЕКТА И ИНВЕСТИЦИОННЫХ ПОТОКОВ, ОРИЕНТИРОВАННЫХ НА ЗЕЛЕНЫЕ ИННОВАЦИИ, ДЛЯ СОВОКУПНОЙ ПРОИЗВОДИТЕЛЬНОСТИ

Резюме

Данное исследование изучает макроэкономическую гипотезу о том, что «Двойной переход» — одновременное развитие цифровизации и декарбонизации — сам по себе генерирует взаимодополняющий рост производительности. Используя новую инфраструктуру микроданных на уровне фирм с трехсторонним сопоставлением, объединяющую FactSet RSCR, PATSTAT и Orbis, это исследование оценивает, способствуют ли инвестиции с высокой интенсивностью данных эффективности чистых технологий или создают конкурирующие потребности в ресурсах по всей глобальной цепочке поставок. Эмпирические результаты ставят под сомнение гипотезу синергии. На уровне фирм масштабирование инфраструктуры искусственного интеллекта вытесняет капитальные затраты, ресурсы на исследования и разработки (НИОКР) и организационный потенциал, необходимые для параллельных зеленых инноваций. Кроме того, динамическое сетевое моделирование показывает, что восходящая цифровая модернизация в значительной степени использует региональные энергетические сети и критические производственные мощности, создавая узкие места, которые задерживают достижение целей устойчивого развития на нисходящем уровне. Чтобы искусственный интеллект не замедлял достижение глобальных целей в области устойчивого развития, политикам следует пересмотреть механизмы финансового скрининга для направляемого государством инновационного финансирования и требовать, чтобы экспансия, ориентированная на данные, сопровождалась созданием новых мощностей по производству возобновляемой энергии.

Ключевые слова: двойной переход, искусственный интеллект, зеленые инновации, узкие места в цепочке поставок, совокупная производительность.

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