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Institutional Architectures of AI-Enabled Green Industrial Transformation: Comparative Business Systems Evidence from Germany and the Republic of Korea

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ABSTRACT

This article examines how institutional structures shape business transformation, policy implementation, economic performance, and sustainable socio-economic development in AI-enabled green industrial transition. Using a comparative case study of Germany and the Republic of Korea, the study investigates two advanced manufacturing economies that combine high export dependence, strong industrial capabilities, sophisticated innovation systems, and rising exposure to digital, geopolitical, and sustainability pressures. The article argues that technological modernization does not automatically generate competitiveness or sustainability; rather, outcomes depend on the institutional capacity to coordinate firms, finance, skills, regulation, infrastructure, and environmental objectives. Germany represents a coordinated market economy whose Industrie 4.0 and green transition agenda relies on decentralized industrial networks, regulatory standard-setting, Mittelstand capabilities, and social partnership, but faces weaknesses in digital diffusion, investment speed, and administrative complexity. The Republic of Korea represents a strategic developmental innovation system characterized by rapid state-led coordination, semiconductor-centered industrial policy, high corporate R&D intensity, and accelerated AI adoption, but faces structural risks related to conglomerate dominance, SME productivity gaps, energy dependence, and carbon-intensive industrialization. The findings show that sustainable competitiveness emerges when institutional coherence, digital interoperability, innovation finance, and climate-oriented industrial policy are jointly embedded in

business systems. The article contributes to comparative business systems, innovation governance, and sustainable industrial policy scholarship by developing propositions on institutional coordination, digital transformation, and resilience-oriented development.

Keywords
Artificial intelligence; green industrial transformation; comparative business systems; institutional governance; Germany; Republic of Korea; innovation policy; sustainable competitiveness; digital economy; industrial resilience

INTRODUCTION

The global economy is undergoing a structural transformation in which digitalization, artificial intelligence, supply-chain reconfiguration, climate transition, and industrial policy are no longer separate policy domains but mutually reinforcing forces that reshape business systems and national development trajectories. Digital technologies are increasingly central to productivity, competitiveness, trade organization, financial governance, market transparency, and industrial upgrading. The OECD reports that the information and communication technology sector expanded around three times faster than the wider economy across OECD countries between 2013 and 2023, with average ICT-sector growth of 7.6% in 2023, indicating that digital capabilities have become a core source of economic dynamism rather than a peripheral service-sector phenomenon (OECD, 2024a). At the same time, the economic effects of artificial intelligence remain institutionally mediated: AI has the potential to operate as a general-purpose technology, but its productivity contribution depends on complementary investment in data systems, human capital, organizational redesign, regulatory trust, and market diffusion (Bresnahan & Trajtenberg, 1995; Filippucci et al., 2024).

This transformation is also occurring under conditions of trade fragmentation and climate constraint. The WTO's 2026 Global Trade Outlook reported that world merchandise trade volume grew by 4.6% in 2025, partly because surging demand for AI-related goods offset tariff pressures and geopolitical uncertainty (WTO, 2026). Yet this does not imply a stable globalization cycle; rather, it suggests that AI hardware, semiconductors, data infrastructure, and advanced manufacturing have become strategic trade assets whose allocation is increasingly shaped by industrial policy, export controls, energy security, and regional investment competition. UNCTAD similarly emphasizes that the digital economy must be governed as an environmentally consequential system because digital infrastructure depends on energy, water, critical minerals, electronic devices, and disposal systems (UNCTAD, 2024). Consequently, the frontier of business transformation is no longer simply digital adoption but the institutional organization of digital sustainability: how firms and states build competitive production systems while reducing carbon intensity, widening inclusion, and strengthening resilience.

Germany and the Republic of Korea provide theoretically useful cases for examining this problem. Both are high-income, manufacturing-intensive, export-oriented economies with globally significant industrial firms, advanced innovation capabilities, and strong public policy traditions. Yet they differ

markedly in institutional structure, business coordination, financial governance, market organization, and policy implementation. Germany remains associated with a coordinated market economy built around patient capital, vocational skills, codetermination, industrial associations, regulatory standardization, and strong medium-sized manufacturing firms (Hall & Soskice, 2001; Streeck, 1997). Its Industrie 4.0 strategy aims to strengthen the manufacturing base through smart and digitally networked production, while its green industrial agenda seeks to align competitiveness with decarbonization (BMWE, 2024; OECD, 2025a). However, Germany's recent economic performance illustrates the limits of institutional strength when coordination becomes administratively slow, investment is constrained, and digital diffusion remains uneven. The OECD's 2025 Economic Survey of Germany identifies weak business dynamism, regulatory burdens, skilled labour shortages, and insufficient infrastructure investment as constraints on growth and innovation (OECD, 2025a).

The Republic of Korea, by contrast, represents a developmental innovation system that combines state-led strategic coordination, high business R&D expenditure, large corporate groups, export discipline, semiconductor specialization, and rapid adoption of frontier technologies. WIPO's Global Innovation Index 2025 ranked Korea fourth globally and reported that it ranked first in business-performed R&D and researchers in business, second in overall R&D expenditure, and third in PCT patents by inventor origin (WIPO, 2025). Korea's Ministry of Science and ICT also reported, based on the OECD Digital Economy Outlook 2024, that Korea ranked first among OECD members in enterprise adoption of AI, big data analytics, and the Internet of Things (MSIT, 2024). These indicators suggest an innovation system capable of mobilizing technological capacity at speed. Yet Korea's model is not free from structural constraints: the OECD's 2024 Economic Survey of Korea highlights declining productivity growth, large productivity gaps between large firms and SMEs, and the need for pro-competition reforms to improve domestic market dynamism (OECD, 2024b).

The academic problem addressed in this article is that existing business and economic scholarship often explains digital transformation, industrial policy, corporate governance, and sustainability transition through partially separated analytical lenses. Strategic management studies emphasize dynamic capabilities, business model adaptation, and firm-level resource recombination (Teece, 2007; Warner & Wäger, 2019). Innovation studies analyze technological systems, policy missions, and knowledge diffusion (Edler & Fagerberg, 2017; Mazzucato, 2021). Comparative political economy explains how institutional complementarities shape corporate strategy, labour relations, finance, and skill formation (Hall & Soskice, 2001; Whitley, 1999). Development economics and industrial policy research examine state capacity, structural transformation, and productive capabilities (Aiginger & Rodrik, 2020; Juhász et al., 2023; Rodrik, 2004). Sustainability transition literature explains socio-technical change, regime transformation, and multi-level transition pressures (Geels, 2019; Schot & Steinmueller, 2018). While each tradition provides important insights, current scholarship remains limited in explaining how institutional structures translate digital and green policy ambitions into business-system implementation and measurable economic outcomes.

This limitation matters because the transition from industrial competitiveness to sustainable

competitiveness requires causal analysis across levels. Institutional structures influence how governments coordinate policy, how firms invest, how financial systems allocate capital, how labour markets generate skills, how markets reward innovation, and how sustainability constraints are internalized into production systems. Business systems do not respond uniformly to AI, climate policy, or geopolitical risk. In coordinated economies, strong associations and standards may facilitate trust and interoperability but may also slow experimentation. In developmental innovation systems, strategic state coordination may accelerate investment but may deepen concentration and dependency risks. Theoretical models that treat digital transformation as a general process of technology adoption therefore understate the institutional variation through which firms convert technologies into productivity, resilience, and sustainability outcomes.

A critical reading of the literature reveals several unresolved debates. Porter (1990) argues that national competitiveness depends on factor conditions, demand sophistication, related industries, and firm rivalry, but the model insufficiently explains how digital infrastructure and sustainability regulation reshape competitive advantage in an AI economy. North (1990) demonstrates that institutions structure incentives and transaction costs, yet his framework requires extension to data governance, algorithmic accountability, and climate-related policy coordination. Hall and Soskice (2001) show that institutional complementarities explain differences between coordinated and liberal market economies, but their framework was developed before AI-enabled platforms, global semiconductor politics, and carbon-constrained industrial policy became central to competitiveness. Teece (2007) explains firm-level sensing, seizing, and reconfiguring capabilities, yet dynamic capabilities are themselves conditioned by national systems of finance, skills, procurement, and regulation. Mazzucato (2021) and Juhász et al. (2023) revive mission-oriented and modern industrial policy, but more comparative evidence is needed on how missions operate differently across business systems. Geels (2019) and Schot and Steinmueller (2018) show that sustainability transitions require regime change, but transition theory often pays insufficient attention to corporate governance, export structures, and financial-market incentives. Existing literature therefore remains limited in connecting institutional structures, business implementation, policy coordination, economic performance, and sustainable socio-economic development within a single comparative framework.

The empirical gap is equally significant. Much research on AI and digital transformation relies either on firm-level surveys or macroeconomic projections, leaving limited comparative evidence on how national business systems mediate technology adoption. Similarly, studies of industrial decarbonization frequently focus on energy systems or emissions pathways without adequately analyzing corporate governance, innovation finance, market structure, and labour institutions. Germany and Korea are particularly instructive because both have advanced manufacturing systems, yet their recent trajectories diverge. Germany has maintained a large manufacturing base—Destatis reported that manufacturing accounted for 19.9% of German gross value added in 2024—but the IMF and OECD identify stagnation, weak productivity, and investment bottlenecks as persistent challenges (Destatis, 2026; IMF, 2026; OECD, 2025a). Korea has sustained stronger high-technology export specialization and semiconductor-centered growth, with semiconductors accounting for 21% of exports in 2024, but the economy faces concentration risk, SME productivity weakness, and energy-transition constraints (IMF, 2025; OECD, 2024b; Reuters, 2025).

This article addresses six interrelated gaps. The theoretical gap concerns the insufficient integration of comparative capitalism, innovation governance, strategic management, and sustainability transition theory. The empirical gap concerns the limited cross-case evidence on how advanced manufacturing economies operationalize AI-enabled green transformation. The comparative institutional gap concerns insufficient analysis of why similar technological pressures generate different policy and business outcomes. The business implementation gap concerns the under-explained mechanisms through which firms convert policy signals into investment, productivity, and resilience. The policy coordination gap concerns the difficulty of aligning digital policy, industrial policy, competition policy, skills policy, and climate policy. The economic sustainability gap concerns the unresolved question of how high-tech industrial competitiveness can generate inclusive and low-carbon development rather than merely reinforcing technological concentration.

The novelty of this article lies in its integrated comparative argument: AI-enabled green industrial transformation is not primarily a technological transition but an institutional coordination problem. The article contributes to business and economic scholarship by linking institutional capacity → innovation coordination → business-system transformation → economic resilience → sustainable socio-economic development. It shows that Germany and Korea represent two distinct but incomplete pathways. Germany possesses strong institutional trust, industrial standards, labour coordination, and sustainability governance, but its transformation is constrained by slow digital diffusion and administrative complexity. Korea possesses rapid policy mobilization, high R&D intensity, semiconductor leadership, and accelerated AI adoption, but its transformation is constrained by corporate concentration, SME dualism, and carbon-intensive energy structures. The comparison therefore shows that sustainable competitiveness requires not only technological assets but also institutional adaptability.

The analytical framework developed here is causal and multi-level. First, institutional capacity shapes the credibility, coherence, and speed of policy implementation. Second, policy implementation influences innovation coordination through funding, standards, skills, infrastructure, and regulation. Third, innovation coordination affects business competitiveness by enabling firms to adopt AI, reorganize production, integrate supply chains, and upgrade capabilities. Fourth, business competitiveness influences economic resilience through productivity, export performance, diversification, and crisis absorption. Fifth, resilience contributes to sustainable socio-economic development only when digital and industrial upgrading are aligned with decarbonization, inclusion, regional diffusion, and responsible governance. The research objective is therefore to explain how institutional differences between Germany and the Republic of Korea shape AI-enabled green industrial transformation, and what this comparison reveals about the governance conditions under which business systems generate sustainable economic performance.

METHODOLOGY

This study employs a comparative institutional political economy and business systems methodology to examine how Germany and the Republic of Korea translate AI-enabled digital transformation and green industrial

policy into business-system outcomes. The comparative design follows a most-similar systems logic: both countries are high-income, export-oriented, technologically advanced manufacturing economies with sophisticated innovation systems, yet they differ in institutional coordination, corporate governance, financial structures, labour-market organization, policy implementation mechanisms, and industrial concentration. This design is theoretically aligned with comparative capitalism, national innovation systems, dynamic capabilities, and sustainability transition theory because it treats firms not as isolated strategic actors but as institutionally embedded organizations whose investment, innovation, and resilience depend on regulatory incentives, public finance, skill systems, market governance, and global value-chain positioning. Germany is selected as a coordinated market economy with strong industrial associations, codetermination, Mittelstand networks, technical standards, and a regulatory approach to digital sovereignty and sustainability. Korea is selected as a developmental innovation economy with strong state coordination, conglomerate-led export systems, semiconductor-centered technology policy, high business R&D intensity, and rapid digital adoption. The core variables examined are institutional coherence, policy coordination capacity, digital infrastructure, business-system structure, innovation finance, corporate governance, labour and skills formation, market competition, supply-chain resilience, and sustainability performance. The causal logic is interpretive rather than experimental: institutional structures are analyzed as enabling and constraining conditions that shape policy implementation, firm behavior, economic performance, and sustainable development outcomes.

The empirical basis of the study consists of triangulated secondary evidence from international datasets, policy documents, and peer-reviewed literature. The analysis draws on World Bank World Development Indicators for manufacturing value added, high-technology exports, and macroeconomic structure; OECD Economic Surveys and Digital Economy Outlook reports for productivity, business dynamism, SME performance, AI adoption, and digital policy; IMF Article IV consultations for macroeconomic performance and fiscal-policy constraints; WIPO Global Innovation Index data for R&D, patents, innovation inputs, and business sophistication; WTO and UNCTAD reports for digital trade, AI-related goods, supply-chain restructuring, inclusiveness, and sustainability implications; IEA country and energy transition reports for energy dependency and decarbonization constraints; European Commission digital policy materials for Germany's EU-level digital context; Korean government communications and industrial policy documents for AI and semiconductor strategy; and academic literature from business systems, industrial policy, strategic management, innovation studies, corporate governance, and socio-technical transition research. Evidence is interpreted through structured focused comparison, process tracing of institutional mechanisms, and cross-case analytical mapping. Reliability is strengthened by source triangulation, theoretical replication across cases, and explicit separation between documented empirical indicators and analytical inference. Ethical considerations arise because the study uses public institutional and economic data rather than human subjects; nevertheless, the analysis avoids fabricated interviews, unsupported causal claims, and normative policy prescriptions detached from institutional feasibility. The principal limitation is that the study does not estimate econometric effects; its contribution is instead explanatory and theory-building, appropriate for identifying causal mechanisms and comparative institutional propositions.

Findings and Discussion

1. Institutional Architectures: Coordinated Decentralization versus Strategic State-Led Concentration

The comparison reveals that Germany and Korea do not differ primarily in whether the state matters to

industrial transformation; both countries use public policy to structure markets, guide innovation, and support strategic industries. The deeper difference lies in how institutional coordination is organized. Germany's institutional architecture is decentralized and negotiated. Its industrial transformation strategy relies on federal ministries, Länder governments, business associations, standard-setting organizations, research institutes, works councils, vocational training institutions, and dense networks of specialized firms. Industrie 4.0 reflects this logic: it is not a single subsidy program but a coordination framework that links smart factories, cyber-physical systems, technical standards, industrial data, SMEs, and manufacturing modernization (BMWE, 2024). This structure produces high institutional trust and technical sophistication, but it also generates implementation complexity because authority is distributed across multiple actors.

Korea's institutional architecture is more centralized and strategically concentrated. Industrial transformation is often coordinated through national strategies, targeted fiscal instruments, public-private councils, large-scale technology missions, and leading conglomerates. The Korean state has used AI and semiconductor policy to mobilize firms, infrastructure, finance, and skills at high speed. In 2024, the government announced an AI investment agenda to support Korea's ambition to become a top-three AI power, while in 2025 it expanded semiconductor support to 33 trillion won, including financial assistance for chipmakers facing global competition and tariff uncertainty (Korea.net, 2024; Reuters, 2025). This institutional model enables rapid mobilization but creates risks of concentration, uneven diffusion, and policy dependence on a small number of dominant corporate actors.

This divergence supports and extends the comparative capitalism literature. Hall and Soskice (2001) argue that coordinated market economies rely on non-market coordination, while developmental-state traditions emphasize state-led capability formation and export discipline. The Germany–Korea comparison shows that digital and green industrial transformation modifies both models. Germany's coordinated system supports standards, trust, and incremental upgrading, but the pace of AI adoption and infrastructure deployment can be slowed by administrative burden, regulatory fragmentation, and cautious investment. Korea's developmental innovation system accelerates strategic technology adoption, but it may reproduce dualism between globally competitive conglomerates and less productive SMEs. The OECD's diagnosis of Germany emphasizes weak business dynamism and regulatory barriers, while its Korea survey highlights the need to raise SME productivity toward that of large companies (OECD, 2024b, 2025a).

The theoretical implication is that institutional coherence is not equivalent to institutional centralization. Germany demonstrates coherence through negotiated standards, stakeholder legitimacy, and institutionalized trust; Korea demonstrates coherence through strategic state direction and business-government alignment. Each model produces different economic mechanisms. In Germany, competitiveness emerges through distributed specialization, quality production, embedded skills, and engineering-based incremental innovation. In Korea, competitiveness emerges through rapid scale-up, export discipline, concentrated R&D, and technology-intensive corporate investment. Both models can support AI-enabled transformation, but each faces a different coordination failure. Germany's risk is slow transition despite strong capabilities; Korea's risk is fast transition with uneven diffusion.

For business strategy, this means that firms must understand institutional constraints as strategic variables. German firms benefit from stable institutional relationships and technical standards but must overcome digital inertia, data-sharing hesitation, and investment bottlenecks. Korean firms benefit from state-backed technology missions and integrated supply chains but must manage geopolitical exposure, corporate governance pressures, and SME ecosystem fragility. For public policy, the implication is that governments should not simply copy foreign industrial policies. Germany cannot become Korea by centralizing its system without undermining its institutional strengths, and Korea cannot become Germany by decentralizing coordination without weakening strategic mobilization. Sustainable

transformation requires institutional upgrading within existing business-system logics.

2. Business Systems, Innovation Capabilities, and Productivity Outcomes

The empirical evidence indicates that both Germany and Korea possess strong industrial capabilities, but their productivity challenges differ. Germany remains one of the world's most manufacturing-intensive advanced economies. In 2024, manufacturing accounted for 19.9% of German gross value added, a much higher share than in many other large European economies (Destatis, 2026). Germany's competitive advantage continues to rest on machinery, automobiles, chemicals, industrial equipment, precision engineering, and supplier networks. However, the OECD argues that weak business dynamism, skilled labour shortages, infrastructure constraints, and declining productivity growth have limited Germany's recent economic performance (OECD, 2025a). IMF data also show that Germany moved through a period of weak growth, with policy debates focusing on public investment, innovation, digitalization, and structural reform (IMF, 2026).

Korea's business system is more strongly organized around high-technology exports, electronics, semiconductors, batteries, automobiles, shipbuilding, and digital infrastructure. World Bank high-technology export indicators show Korea as a highly technology-intensive exporter, while WIPO ranks it among the world's leading innovation economies. Korea's semiconductor sector is especially central: in 2024, semiconductors represented about 21% of Korean exports and were valued at approximately US$141.9 billion (Reuters, 2025). This export structure gives Korea a powerful position in the AI supply chain, particularly in memory chips and advanced manufacturing inputs. Yet the same structure creates vulnerability to semiconductor cycles, export controls, tariff uncertainty, and energy demand from chip fabrication.

The comparison reveals that innovation intensity and productivity diffusion are not identical. Korea performs exceptionally well in R&D and high-tech exports, but the OECD notes that SME productivity is only about one-third that of large companies, despite extensive SME support (OECD, 2024b). This indicates a dualistic business structure in which globally competitive conglomerates coexist with weaker domestic SMEs. Germany has a more balanced supplier ecosystem and stronger medium-sized industrial firms, but it faces weaker digital dynamism and slower scale-up in frontier digital business models. The German Mittelstand provides resilience through specialization and long-term relationships, yet many firms struggle with AI adoption, cybersecurity investment, data infrastructure, and platform-based business transformation. Korea's chaebol-centered model provides scale and speed, but its smaller firms often lack the bargaining power, digital resources, and international channels needed to benefit equally from AI-led upgrading.

This finding extends Teece's (2007) dynamic capabilities framework by showing that firm-level sensing, seizing, and reconfiguring are institutionally distributed. German firms often possess deep engineering capabilities and incremental innovation routines, but digital transformation requires new capabilities in software, data governance, cloud integration, AI-enabled process optimization, and platform participation. Korean conglomerates possess the financial and organizational capacity to seize AI-related opportunities rapidly, but ecosystem-wide reconfiguration depends on whether SMEs, suppliers, workers, and regional firms can access complementary assets. Dynamic capabilities are therefore not merely firm properties; they are system properties shaped by finance, labour, regulation, competition, and public infrastructure.

The implication for economic performance is that advanced manufacturing economies face a transition from production efficiency to adaptive intelligence. In the previous industrial paradigm, competitiveness could be sustained

through quality, scale, process control, and export networks. In the AI-enabled paradigm, competitiveness increasingly depends on data integration, real-time supply-chain visibility, digital twins, predictive maintenance, autonomous production, cybersecurity, and interoperability across firms. Germany's strengths in industrial standards and supplier networks could support trusted industrial data spaces, but only if administrative and investment barriers are reduced. Korea's strengths in AI adoption and semiconductor capacity could support rapid smart manufacturing diffusion, but only if the productivity gap between large firms and SMEs is narrowed.

The sustainability implication is equally important. Productivity gains from AI can either reinforce carbon-intensive industrial growth or support resource efficiency, energy optimization, circular production, and lower-emission supply chains. Germany's green industrial policy is more explicitly embedded in climate governance, while Korea's AI-industrial strategy is more directly tied to semiconductor and export competitiveness. Yet Korea's energy transition constraint is substantial: the IEA notes that Korea's energy system remains characterized by fossil-fuel dominance, strong import dependence, and one of the highest shares of industrial energy use among IEA countries, even as the country targets carbon neutrality by 2050 (IEA, 2025). Germany's challenge is different: it has made stronger progress in renewable power expansion but faces industrial cost pressures, grid constraints, and contested climate-policy implementation.

3. Digital Economy Governance, AI Adoption, and Market Trust

Digital transformation is not only a technological process but a governance problem involving data access, privacy, interoperability, cybersecurity, competition, standards, and institutional trust. Germany's digital economy governance reflects a European regulatory orientation in which data protection, digital sovereignty, competition policy, and social legitimacy are central. This approach has advantages in building trust, protecting rights, and ensuring responsible innovation. However, it can also slow experimentation if firms perceive regulatory compliance as uncertain or costly. The European Commission's Digital Decade reporting framework assesses progress in digital infrastructure, business digitalization, digital skills, and public-service digitalization, underscoring that digital transformation is a multi-dimensional institutional process rather than a narrow technology-adoption objective (European Commission, 2025).

Korea's digital governance is more adoption-oriented and industrially strategic. The Ministry of Science and ICT reported that Korea led OECD countries in adoption of AI, big data analytics, and IoT, and separate government communications indicate that enterprise AI adoption remained a policy concern, with 28% enterprise adoption identified in 2024 as part of a broader initiative to diffuse AI among people, industry, and the public sector (MSIT, 2024). This combination of high comparative ranking and continued policy concern is analytically important: Korea's relative digital strength does not eliminate internal diffusion gaps. It indicates that frontier adoption can coexist with uneven organizational absorption.

The cross-case comparison suggests that market trust is produced through different mechanisms. Germany seeks trust through regulation, certification, codetermination, technical standards, and institutionalized negotiation. Korea seeks trust through state-led technology validation, public-private coordination, infrastructure investment, and rapid commercialization. Germany's trust model is strong for industrial safety, data protection, and stakeholder legitimacy, but may be less effective for rapid scaling of AI platforms. Korea's trust model is strong for coordinated technology deployment, but may face concerns about market concentration, data governance, labour displacement, and unequal access. This distinction matters because AI-enabled business transformation depends on willingness to share

data across firms, deploy algorithms in production, use predictive analytics in supply chains, and integrate digital services into manufacturing systems.

The literature on platforms and digital markets emphasizes network effects, data accumulation, and scale economies (Cusumano et al., 2019; Kenney & Zysman, 2020). Yet the Germany–Korea comparison shows that platformization in industrial economies differs from consumer-platform capitalism. Industrial AI requires interoperability between machines, suppliers, customers, regulators, and infrastructure providers. German industrial firms are well positioned to develop trusted industrial data spaces, but fragmented digital investment can inhibit scale. Korean firms are well positioned to integrate AI into semiconductor, electronics, and advanced manufacturing ecosystems, but the dominance of large groups may limit open ecosystem participation. The policy challenge is therefore not simply to increase AI adoption but to govern the market architecture through which AI becomes a shared productive resource.

The business implications are significant. German firms need institutional support for cloud adoption, data interoperability, cybersecurity, and AI skills, particularly among SMEs. Korean firms need mechanisms that diffuse AI capabilities beyond conglomerates into smaller suppliers, regional manufacturers, and service-sector firms. In both cases, AI adoption must be evaluated not only by the number of firms using AI but by the depth of organizational transformation. Superficial adoption, such as limited analytics pilots, does not generate systemic productivity. Deep adoption requires process redesign, worker training, data governance, managerial learning, and integration with investment strategy.

This finding contributes to institutional theory by showing that digital markets require governance capacity before they generate productivity. North's (1990) insight that institutions reduce uncertainty remains relevant, but uncertainty in AI systems includes algorithmic opacity, data-quality risk, cybersecurity vulnerability, interoperability failures, and regulatory ambiguity. Economic governance therefore influences business transformation by shaping the trust conditions under which firms invest in digital systems. In Germany, excessive uncertainty may arise from complex regulatory implementation; in Korea, uncertainty may arise from concentration, geopolitical exposure, and uneven diffusion. Sustainable digital development requires reducing both forms of uncertainty.

4. Financial Governance, Industrial Policy, and Supply-Chain Resilience

The findings indicate that financial governance is a crucial mechanism linking institutional structures to business transformation. Germany's financial system has traditionally supported long-term industrial investment through bank relationships, regional finance, public development banks, and patient capital. This system complements Mittelstand specialization and incremental innovation. However, AI-enabled green industrial transformation requires large-scale investment in digital infrastructure, semiconductor supply chains, renewable energy, grid modernization, hydrogen, batteries, advanced materials, cybersecurity, and industrial software. The IMF and OECD both emphasize that Germany needs stronger public and private investment to revive growth, modernize infrastructure, and support digital and green transition (IMF, 2026; OECD, 2025a). Germany's fiscal rules and administrative procedures have historically constrained the speed of such investment, although recent policy debates have increasingly recognized the need for greater strategic public investment.

Korea's financial governance is more directly linked to industrial strategy. Public finance, policy loans, tax incentives, and state-backed initiatives are used to support strategic sectors. The expansion of semiconductor support to 33 trillion won demonstrates how Korea uses targeted finance to protect and upgrade critical industries under

geopolitical uncertainty (Reuters, 2025). The advantage of this system is rapid mobilization in sectors with clear strategic priority. The disadvantage is potential capital concentration, path dependency, and underinvestment in less politically visible areas such as SME upgrading, service productivity, regional innovation, and social infrastructure.

Supply-chain resilience further differentiates the two cases. Germany's export-oriented industries depend on global markets for automobiles, machinery, chemicals, and industrial goods. Its vulnerability arises from energy shocks, Chinese competition, tariff risks, and slow adjustment in automotive electrification and digital services. Korea's vulnerability is concentrated in semiconductors, batteries, and technology supply chains exposed to US-China strategic rivalry, export controls, and demand cycles. WTO and global value-chain research suggest that supply chains are becoming more digital, shorter, and regionally diversified as firms and governments prioritize reliability, resilience, and lower-carbon competitiveness (WTO, 2025). This shift creates opportunities for both Germany and Korea, but also requires different policy responses. Germany must modernize industrial infrastructure and reduce energy-cost disadvantages. Korea must diversify technology dependencies and strengthen domestic ecosystem resilience beyond a few flagship firms.

The comparison supports modern industrial policy scholarship. Rodrik (2004) argued that industrial policy should be understood as a process of strategic collaboration between public and private actors, not simply as sectoral protection. Juhász et al. (2023) argue that contemporary industrial policy is returning because states must manage externalities, supply-chain risks, technological capabilities, and climate transition. Germany and Korea demonstrate this return, but with different institutional forms. Germany's industrial policy is increasingly shaped by European sovereignty, green transition, and infrastructure modernization. Korea's industrial policy is shaped by semiconductor leadership, AI infrastructure, export competitiveness, and geopolitical positioning. Both cases show that market forces alone are insufficient to coordinate investment in strategic technologies because firms face uncertainty, public-good problems, and systemic risks.

Business resilience depends on how firms convert public policy into adaptive capacity. German firms require investment certainty, faster permitting, digital public infrastructure, and skills availability to maintain competitiveness. Korean firms require geopolitical risk management, supplier diversification, energy security, and governance reforms that strengthen ecosystem-wide competitiveness. The evidence suggests that resilience is not simply redundancy or inventory accumulation. It is the ability of business systems to reorganize production, finance, technology, and supply relationships under uncertainty. AI can support resilience through predictive analytics, supply-chain visibility, demand forecasting, and production flexibility, but these tools require high-quality data and institutional trust.

Development implications follow directly. If industrial policy primarily supports incumbent firms without broad diffusion, it may strengthen export performance while widening domestic inequality. If sustainability policy increases costs without innovation support, it may weaken industrial competitiveness. If digital transformation improves productivity only in frontier firms, it may deepen dualism. Therefore, the governance challenge is to design industrial finance that links competitiveness with diffusion and sustainability. Public support should be conditional on capability upgrading, supplier inclusion, decarbonization, workforce development, and measurable innovation outcomes. Germany's challenge is accelerating investment without weakening institutional legitimacy. Korea's challenge is broadening transformation without losing strategic speed.

5. Sustainability Transition, ESG Governance, and Socio-Economic Development

The sustainability comparison shows that Germany and Korea face different but convergent pressures to align industrial competitiveness with climate responsibility. Germany has legally embedded climate neutrality by 2045 and seeks major emissions reductions by 2030, but recent assessments warn that the country may miss 2030 targets without stronger implementation, especially in transport, buildings, land use, and industrial modernization (Reuters, 2026). Germany's industrial base is exposed to electricity prices, hydrogen infrastructure delays, carbon pricing, and global competition in green technologies. Its sustainability challenge is not a lack of climate ambition but the difficulty of coordinating rapid decarbonization with industrial competitiveness, social legitimacy, and regional employment.

Korea has committed to carbon neutrality by 2050, but its industrial structure makes decarbonization especially difficult. The IEA emphasizes that Korea remains heavily dependent on fossil fuels and energy imports, with a high share of industrial energy use among IEA economies (IEA, 2025). Semiconductor fabrication, steel, petrochemicals, batteries, and shipbuilding are energy-intensive sectors. Korea's strength in AI and semiconductors therefore creates a paradox: the industries most central to future competitiveness also increase pressure on electricity supply, energy security, and emissions governance. Korea's target to raise zero-carbon electricity sources by 2038, including nuclear, renewables, and hydrogen, reflects recognition that industrial competitiveness increasingly depends on low-carbon energy availability.

The ESG governance implications are significant. Germany's corporate governance system includes stakeholder representation, codetermination, sustainability reporting under European rules, and institutional investor pressure. These mechanisms can embed social and environmental objectives into corporate strategy, but they may also create compliance complexity. Korea has strengthened ESG disclosure and stewardship expectations, but corporate governance remains influenced by conglomerate control, family ownership, and uneven minority shareholder protections. For sustainability-oriented investment, Germany offers stronger institutionalized stakeholder governance, while Korea offers faster strategic deployment in green technologies where government and large firms align. Neither model is sufficient alone. Sustainable business systems require both accountability and adaptability.

This finding extends sustainability transition theory. Geels (2019) argues that transitions involve interactions between regimes, niches, and landscape pressures. Germany's industrial regime is mature, institutionally dense, and socially negotiated, making transition politically complex but potentially legitimate. Korea's industrial regime is concentrated, export-oriented, and technologically ambitious, making transition faster in selected sectors but potentially uneven across society. Schot and Steinmueller's (2018) transformative innovation policy framework stresses directionality, inclusion, and socio-technical change. The Germany–Korea comparison confirms that directionality is not merely choosing green technologies; it is aligning business incentives, finance, labour, infrastructure, and regulation toward sustainable outcomes.

The socio-economic development implications reach beyond these two countries. Emerging economies often seek to learn from Germany's industrial quality model or Korea's rapid technology upgrading model. The comparison suggests that neither should be copied mechanically. Germany teaches the importance of standards, vocational skills, stakeholder trust, and specialized SMEs. Korea teaches the importance of strategic state capacity, R&D concentration, export discipline, and rapid digital adoption. However, sustainable development requires combining these lessons with institutional fit. Countries with weaker governance capacity may not be able to implement Korea-style strategic concentration without rent-seeking. Countries without strong firm associations and vocational institutions may not be able to replicate German coordination. The transferable lesson is not institutional form but institutional function: coherent coordination, capability diffusion, accountable finance, and sustainability alignment.

The findings also indicate that AI-enabled green transformation can produce inclusive development only when productivity gains are socially distributed. AI can improve energy efficiency, reduce waste, optimize logistics, and enhance predictive maintenance, but it can also concentrate value among capital-intensive firms and high-skilled workers. Korea's SME productivity gap and Germany's skilled labour shortage show that human capital remains central to digital transformation. Policy must therefore link AI adoption with workforce reskilling, SME support, regional innovation, and social protection. Otherwise, the digital-green transition may generate high aggregate competitiveness while weakening social cohesion.

Table 1. Analytical Matrix of Comparative Business and Economic Development

Variable	Case 1: Germany	Case 2: Republic of Korea	Empirical Evidence	Analytical Interpretation
Institutional coordination model	Decentralized, negotiated, federal, association-based, and standard-driven coordination	Centralized, strategic, mission-oriented, and state-business coordinated governance	Germany's Industrie 4.0 agenda relies on smart production and industrial networks; Korea uses national AI and semiconductor missions	Germany generates trust and standards but risks slow execution; Korea generates speed and scale but risks concentration
Business system architecture	Mittelstand networks, sectoral associations, codetermination, engineering capabilities, and incremental innovation	Chaebol-centered export system, semiconductor leadership, large corporate R&D, and fast commercialization	Germany maintains a high manufacturing share of gross value added; Korea ranks highly in R&D and high-tech innovation	Germany's distributed specialization supports resilience; Korea's concentrated technological scale supports frontier competitiveness
Digital transformation pathway	Industrial data spaces, regulatory trust, cybersecurity, digital sovereignty, and gradual SME diffusion	Rapid AI, big data, IoT, semiconductor, and platform infrastructure adoption	OECD and Korean government sources identify Korea as a leading OECD adopter of AI-related technologies; Germany faces digital diffusion constraints	Germany must accelerate implementation; Korea must broaden diffusion beyond large firms
Innovation and R&D system	Strong applied research institutes, engineering knowledge, standards,	High business-performed R&D, strong patenting, semiconductor clusters, and	WIPO ranks Korea fourth globally in 2025 and first in business-performed R&D;	Korea's R&D intensity is stronger in frontier scale; Germany's

	and public-private research networks	export-linked innovation	Germany remains an industrial innovation power but faces slower digital momentum	strength lies in industrial depth and technical reliability
Financial governance	Patient capital, public development banks, bank-firm relations, but fiscal and administrative constraints	Targeted public finance, policy loans, tax incentives, and strategic industrial subsidies	Germany faces investment needs in infrastructure and digitalization; Korea expanded semiconductor support to 33 trillion won	Financial systems shape transformation speed; Germany needs faster capital deployment, Korea needs broader capability diffusion
Market competition and SME productivity	Strong specialized SMEs but weaker startup scaling and regulatory barriers to entry	Strong global conglomerates but pronounced SME–large firm productivity gap	OECD identifies weak German business dynamism and Korea's SME productivity challenge	Competitive upgrading requires both frontier firms and diffusion mechanisms
Supply-chain resilience	Vulnerable to energy costs, automotive transition, Chinese competition, and tariff exposure	Vulnerable to semiconductor cycles, US-China rivalry, chip export controls, and energy-intensive production	WTO highlights AI-related goods and supply-chain restructuring; Korea's semiconductor exports are macroeconomically central	Resilience depends on diversification, interoperability, energy security, and strategic investment
Sustainability transition	Climate neutrality by 2045, strong ESG regulation, renewable expansion, but implementation gaps	Carbon neutrality by 2050, industrial energy dependence, low renewable share, and strategic zero-carbon power goals	IEA identifies Korea's fossil-fuel dependence; Germany faces risk of missing 2030 targets	Germany has stronger climate governance but implementation friction; Korea has industrial speed but deeper energy-transition constraints
Socio-economic development outcome	High social protection and stakeholder governance, but regional and skill-transition pressures	Rapid technology upgrading and export growth, but dualism between conglomerates and SMEs	OECD identifies labour and productivity constraints in both countries	Sustainable competitiveness requires linking AI productivity with inclusion, skills, and

	regional diffusion

The table demonstrates that institutional variation produces different causal pathways from policy to business performance. Germany's model operates through negotiated coordination, which supports legitimacy, institutional trust, technical quality, and sustainability accountability. Its weakness is that transformation depends on the alignment of many actors, making implementation vulnerable to administrative delay and investment fragmentation. Korea's model operates through strategic concentration, which supports rapid mobilization of capital, technology, and corporate commitment. Its weakness is that transformation may be uneven because technological upgrading is concentrated in large firms and strategic sectors. The key analytical insight is that neither institutional model is inherently superior. Germany's system is stronger in distributed trust and stakeholder governance; Korea's system is stronger in speed, R&D intensity, and export-linked technology mobilization. Sustainable economic development requires combining institutional trust with strategic agility.

This interpretation also clarifies the causal chain linking institutions to outcomes. Institutional structures influence policy implementation by defining who coordinates, who finances, who bears risk, and who captures value. Policy implementation shapes business systems by directing investment, standards, incentives, and infrastructure. Business systems influence economic performance by determining productivity diffusion, export capacity, innovation speed, and resilience. Economic performance contributes to sustainable socio-economic development only when competitiveness is aligned with decarbonization, inclusion, and institutional accountability. The Germany–Korea comparison therefore supports the argument that AI-enabled green industrial transformation is a systemic governance challenge rather than a technology-adoption problem.

Conceptual Model and Theoretical Propositions

This article develops the following conceptual model:

Institutional Coordination Capacity → Innovation and Digital Implementation → Business-System Transformation → Economic Resilience → Sustainable Socio-Economic Development

The model argues that institutional coordination capacity is the foundational condition for AI-enabled green industrial transformation. Coordination capacity refers to the ability of public and private institutions to align policy goals, investment incentives, regulatory standards, financial resources, skills systems, infrastructure, and sustainability obligations. Without such capacity, digital technologies remain isolated tools and green industrial policy becomes fragmented intervention. Germany and Korea demonstrate different forms of coordination capacity: Germany relies on negotiated institutional coherence, while Korea relies on strategic state-led mobilization.

Proposition 1: Institutional coherence strengthens adaptive business resilience when it aligns finance, skills, standards, and sustainability regulation with firm-level investment incentives.

Germany shows that institutional trust and standards can support high-quality industrial adaptation, but coherence must be accompanied by execution speed. Korea shows that rapid state-business alignment can accelerate transformation, but coherence must include SMEs, labour, energy systems, and governance accountability.

Proposition 2: Digital interoperability mediates the relationship between AI adoption and productivity growth.

AI adoption alone does not guarantee productivity. Productivity gains occur when firms integrate data systems, supply-chain visibility, cybersecurity, worker capabilities, and organizational redesign. Germany's challenge is to scale interoperability across decentralized SMEs; Korea's challenge is to diffuse interoperability beyond conglomerate-controlled ecosystems.

Proposition 3: Strategic industrial finance improves competitiveness when it is conditional on capability diffusion and sustainability performance.

Public support for semiconductors, green technologies, digital infrastructure, and advanced manufacturing can strengthen resilience, but unconditional support risks rent concentration. Industrial finance should require measurable progress in supplier upgrading, emissions reduction, workforce development, and innovation spillovers.

Proposition 4: Sustainable competitiveness emerges when business systems convert technological upgrading into low-carbon, inclusive, and institutionally trusted economic performance.

A country can be technologically advanced without being sustainably competitive. Sustainable competitiveness requires that AI, R&D, industrial upgrading, and export performance contribute to decarbonization, social inclusion, regional development, and institutional legitimacy.

These propositions contribute to comparative business systems theory by integrating technological transformation with institutional governance and sustainability. They also contribute to industrial policy scholarship by showing that state intervention is not sufficient unless policy implementation is embedded in business-system capabilities. Finally, they contribute to sustainability transition research by emphasizing that green transformation depends on corporate governance, financial architecture, market structures, and innovation ecosystems as much as on climate targets.

CONCLUSION

This article set out to explain how institutional differences between Germany and the Republic of Korea shape AI-enabled green industrial transformation and what this comparison reveals about the governance conditions under which business systems generate sustainable economic performance. The direct answer is that digital and green transformation depends less on the availability of AI, advanced manufacturing technologies, or policy ambition alone than on the institutional capacity to coordinate firms, finance, infrastructure, regulation, skills, innovation, competition, and sustainability objectives. Germany and Korea both possess advanced industrial capabilities, yet their institutional architectures generate different transformation pathways, bottlenecks, and development implications.

The main analytical finding is that Germany's coordinated and decentralized business system provides strong foundations for trust, standards, stakeholder governance, and sustainability accountability, but faces constraints in digital diffusion, business dynamism, infrastructure investment, and administrative speed. Korea's strategic developmental innovation system provides rapid mobilization, high business R&D intensity, semiconductor leadership, and accelerated AI adoption, but faces risks associated with conglomerate concentration, SME productivity gaps, energy dependence, and uneven sustainability diffusion. These findings demonstrate that institutional strengths can become transition constraints when the

economic environment changes. Germany's negotiated coordination can slow transformation; Korea's strategic concentration can limit broad-based inclusion.

The theoretical contribution of the article is to integrate comparative capitalism, national innovation systems, dynamic capabilities, industrial policy, and sustainability transition theory into a single institutional-business framework. The article contributes to business scholarship by showing that firm-level transformation is institutionally embedded. Dynamic capabilities depend on finance, labour markets, regulatory trust, digital infrastructure, and public policy. It contributes to economic governance scholarship by demonstrating that industrial policy must be assessed not only by investment volume but by coordination quality, diffusion capacity, and sustainability alignment. It contributes to sustainability research by showing that green transition is inseparable from business systems and market structures.

The empirical contribution lies in the structured comparison of two advanced manufacturing economies facing similar global pressures but operating through different institutional mechanisms. Germany illustrates the challenge of transforming a mature, stakeholder-oriented, engineering-intensive industrial system under conditions of digital disruption and climate pressure. Korea illustrates the challenge of transforming a high-speed, export-oriented, technology-intensive economy whose global competitiveness depends heavily on semiconductors and energy-intensive production. Together, the cases show that sustainable competitiveness is achieved when institutional coordination converts technological upgrading into productivity, resilience, decarbonization, and inclusion.

The business implications are clear. Firms should treat institutional governance as part of strategy rather than as an external environment. AI adoption requires organizational redesign, data governance, skills development, and supply-chain interoperability. Industrial firms must move beyond efficiency-oriented automation toward resilience-oriented and sustainability-oriented transformation. The policy implications are equally significant. Governments should design industrial policy that combines strategic investment with competition, supplier upgrading, workforce development, and emissions reduction. Germany needs faster implementation capacity without sacrificing institutional legitimacy. Korea needs broader diffusion and sustainability accountability without weakening strategic speed.

The sustainability and development implications extend beyond Germany and Korea. Emerging and middle-income economies seeking industrial upgrading should avoid copying institutional models without considering governance capacity. The transferable lesson is that industrial transformation requires coherent institutions, capable firms, accountable finance, skilled labour, digital interoperability, and sustainability-oriented policy discipline. AI-enabled green transformation can support inclusive development only when productivity gains are distributed across firms, regions, workers, and supply chains.

This study has limitations. It relies on secondary datasets and institutional documents rather than firm-level interviews or econometric estimation. It therefore identifies comparative mechanisms rather than measuring causal effect sizes. Future research should test the propositions through firm-level panel data, sector-specific studies of semiconductors, automotive systems, batteries, and industrial AI, and comparative

analysis involving emerging economies. Further research should also examine how ESG disclosure, digital trade rules, AI regulation, and carbon-border policies reshape corporate strategy across different business systems. Despite these limitations, the article provides a theoretically grounded and empirically informed framework for understanding how institutional structures mediate the relationship between business transformation, economic governance, and sustainable socio-economic development.

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