

American Journal of Economics and Business Management

Vol. 9 Issue 6 | **pp.** 49-57 | **ISSN:** 2576-5973

Available online @ https://www.globalresearchnetwork.us/index.php/ajebm

Article

Benchmarking Electrotechnical Industry Competitiveness Across Development Stages: A DEA and Global Value Chain Analysis of Germany, China, South Korea, Turkey, and Uzbekistan

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Abstract: This study benchmarks the competitiveness of the electrotechnical industry across five countries representing distinct stages of industrial development: Germany (advanced), South Korea (innovation-driven late industrializer), China (scale-intensive emerging power), Turkey (middle-income industrializer), and Uzbekistan (early-stage transition economy). Employing Data Envelopment Analysis (DEA) to measure relative technical efficiency and Global Value Chain (GVC) framework analysis to map upgrading trajectories, the study identifies the efficiency gaps that separate Uzbekistan from its benchmark peers and delineates a phased upgrading pathway. DEA results indicate that Uzbekistan's electrotechnical sector operates at 41.8% technical efficiency relative to the frontier defined by Germany, with the efficiency gap attributable primarily to pure technical inefficiency (PTE = 0.492) rather than scale inefficiency (SE = 0.850). GVC analysis reveals that Uzbekistan occupies a backward-integrated assembly position, comparable to China in the 1985–1995 period and Turkey in the 1990s. A PESTEL analysis contextualizes these findings within Uzbekistan's macroeconomic and institutional environment. The study proposes a four-phase upgrading roadmap—from backward assembly through process upgrading, product upgrading, and functional upgrading—calibrated to the empirical benchmarks derived from the reference countries' historical trajectories.

Keywords: data envelopment analysis, global value chains, electrotechnical industry, competitiveness benchmarking, industrial upgrading, Uzbekistan

Citation: Jakhongir, B. Benchmarking Electrotechnical Industry Competitiveness Across Development Stages: A DEA and Global Value Chain Analysis of Germany, China, South Korea, Turkey, and Uzbekistan. American Journal of Economics and Business Management 2026, 9(6), 49-57

Received: 10th Mar 2026
Revised: 21th Apr 2026
Accepted: 08th May 2026
Published: 02th June 2026

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1. Introduction

The electrotechnical industry—encompassing the manufacture of transformers, cables, switchgear, electric motors, and associated components—constitutes a critical enabler of economic infrastructure. The quality and cost efficiency of a nation's electrotechnical output directly condition the reliability of its power grid, the competitiveness of its construction sector, and its capacity to attract industrial investment [1]. For Uzbekistan, whose ambitious economic diversification agenda requires massive infrastructure expansion, building a competitive domestic electrotechnical sector is not merely desirable but strategically imperative [2].

Yet competitiveness is not an absolute attribute; it exists in relational terms, measurable only against the performance of relevant peers. Understanding where Uzbekistan's electrotechnical industry stands relative to countries that have already

traversed the development trajectory it now faces is essential for calibrating expectations, identifying binding constraints, and designing effective industrial policies [3]. This study therefore undertakes a systematic benchmarking exercise, comparing Uzbekistan's electrotechnical sector against four reference countries: Germany, as the global technology frontier; South Korea, as a late-industrializer that achieved world-class electrotechnical capabilities through deliberate catch-up; China, as a scale-driven competitor that has rapidly ascended global value chains; and Turkey, as a middle-income economy with an electrotechnical sector at an intermediate stage of development [4].

The analytical framework combines two complementary approaches. Data Envelopment Analysis (DEA), a nonparametric frontier technique originating in the operations research tradition, is used to compute relative efficiency scores that decompose the overall performance gap into pure technical inefficiency and scale inefficiency components. Global Value Chain (GVC) analysis, following Gereffi et al [5]. and Humphrey and Schmitz, maps each country's position within the international production architecture of electrotechnical goods and identifies the upgrading pathways that have historically enabled movement from lower-value to higher-value activities. A PESTEL analysis complements these quantitative and structural assessments by situating Uzbekistan's prospects within its macroeconomic, institutional, and regulatory context [6].

The contribution of this study is threefold. First, it provides the first systematic DEA benchmarking of electrotechnical industry efficiency across countries at different development stages, a comparison that is common in manufacturing studies of textiles or automobiles but notably absent for the electrotechnical sector. Second, it applies GVC upgrading pathway analysis to derive concrete, time-bound recommendations for Uzbekistan's industrial policy. Third, by combining efficiency measurement with value-chain positioning, it offers a richer diagnostic than either approach could yield alone [7].

Theoretical Framework

Competitiveness Benchmarking and DEA

The concept of productive efficiency, formalized by Farrell, distinguishes between technical efficiency (producing maximum output from given inputs) and allocative efficiency (selecting the cost-minimizing input mix). DEA, introduced by Charnes et al. operationalizes this concept through linear programming, constructing an empirical best-practice frontier from observed data without requiring specification of a production function. The BCC extension further decomposes technical efficiency under constant returns to scale (CRS) into pure technical efficiency (PTE, under variable returns to scale) and scale efficiency (SE = TE/PTE), revealing whether inefficiency stems from managerial underperformance or from suboptimal scale of operations. DEA has been extensively applied to manufacturing sector benchmarking, but its application to cross-country electrotechnical industry comparison is, to our knowledge, novel [8].

Global Value Chain Analysis and Industrial Upgrading

The GVC framework conceptualizes production as a geographically dispersed chain of activities—design, component manufacture, assembly, marketing, and after-sales service—governed by lead firms that coordinate cross-border transactions [9]. For developing-country firms, GVC participation typically begins at the lowest value-adding node (assembly of imported components) and progresses through four upgrading modes: process upgrading (increasing efficiency within existing tasks), product upgrading (moving into higher-value products), functional upgrading (acquiring new functions such as design or branding), and intersectoral upgrading (leveraging capabilities into new industries) [10].

The electrotechnical GVC exhibits a modular governance structure in which standardized interfaces between components allow relatively easy entry at the assembly node but create significant barriers to functional upgrading, as design capabilities and brand recognition are concentrated among a small number of lead firms in Germany, Japan, and increasingly, China. Understanding this governance structure is critical for assessing Uzbekistan's upgrading prospects [11].

PESTEL as a Contextual Diagnostic

While DEA and GVC analysis provide, respectively, efficiency measurement and structural positioning, they do not directly account for the macroeconomic, regulatory, and social context that shapes the feasibility of upgrading strategies. PESTEL analysis—examining Political, Economic, Social, Technological, Environmental, and Legal factors—serves as a complementary diagnostic that identifies context-specific opportunities and constraints [12]. For transition economies such as Uzbekistan, where institutional conditions are both rapidly evolving and critically important, PESTEL provides an essential framing for policy recommendations.

2. Materials and Methods

Data and Methodology

Data Sources

Country-level data for the DEA analysis are drawn from multiple sources: UNIDO Industrial Statistics Database for production output, value added, and employment; World Bank World Development Indicators for R&D expenditure and gross fixed capital formation; national statistical offices (Statistisches Bundesamt for Germany, KOSIS for South Korea, NBS for China, TURKSTAT for Turkey, and stat.uz for Uzbekistan); IEC sectoral reports for automation rates and technology indicators; and UN Comtrade for trade data. The analysis period is 2018–2022, chosen to provide the most recent complete data while avoiding the acute distortions of the COVID-19 pandemic's early phase. For the GVC analysis, data are supplemented with information from enterprise surveys, industry association reports, and firm-level case studies [13].

DEA Specification

An output-oriented DEA model is specified, consistent with the objective of maximizing output from given resources. The decision-making units (DMUs) are the five national electrotechnical sectors, each characterized by three inputs (labor force in the sector, gross fixed capital stock, and intermediate input consumption) and two outputs (gross production value and export value). Both CRS (CCR) and VRS (BCC) models are estimated to decompose total technical efficiency into its pure technical and scale components. The DEA models are solved using DEAP software [14].

GVC Mapping Methodology

GVC positions are assessed using a combination of quantitative trade indicators (domestic value added in exports, foreign value added share, revealed comparative advantage) and qualitative governance analysis based on Gereffi et al.'s typology. Historical trajectories of the reference countries are reconstructed from secondary literature and industry case studies to establish temporal benchmarks for upgrading phases. This historical-comparative approach allows Uzbekistan's current position to be located on a developmental timeline and upgrading targets to be calibrated against empirical precedent [15].

3. Result and Discussion

Results

Country Profiles

Table 1 presents selected indicators for the five countries' electrotechnical sectors.

Table 1.
Electrotechnical Industry Indicators by Country (2022)

Country	Output ($ bn)	Exports ($ bn)	R&D (% GDP)	Auto. (%)	GVC Position
Germany	87.4	62.3	3.14	92	Forward (OEM/design)

China	412.6	148.7	2.43	78	Mixed (assembly + brand)
South Korea	53.2	38.1	4.81	89	Forward (tech-intensive)
Turkey	18.7	9.4	1.10	61	Mixed (OEM + domestic)
Uzbekistan	1.8	0.3	0.17	23	Backward (assembly)

The data reveal the vast scale of the disparities confronting Uzbekistan. Germany's sector is nearly 50 times larger by output, while China's exceeds Uzbekistan's by a factor of 230. The automation rate gap is equally stark: at 23%, Uzbekistan trails Germany (92%) and South Korea (89%) by roughly 70 percentage points. The R&D intensity differential —0.17% versus South Korea's 4.81%—underscores the limited innovation infrastructure currently available to Uzbek enterprises [16].

DEA Efficiency Results

Table 2 reports the DEA efficiency scores for the five national sectors.

Table 2.
DEA Efficiency Scores for Electrotechnical Sectors

Country	TE (CRS)	PTE (VRS)	SE	Returns to Scale
Germany	1.000	1.000	1.000	CRS
South Korea	0.964	1.000	0.964	IRS
China	0.912	0.953	0.957	DRS
Turkey	0.734	0.811	0.905	IRS
Uzbekistan	0.418	0.492	0.850	IRS

Germany defines the efficient frontier (TE = 1.000) and serves as the benchmark. South Korea's near-frontier performance (TE = 0.964) reflects its advanced technological capabilities, with a slight scale inefficiency suggesting room for further output expansion. China operates at 91.2% efficiency, with moderate shortfalls in both pure technical efficiency and scale efficiency; its DRS (decreasing returns to scale) classification suggests that the sector may have expanded beyond its optimal scale in some subsegments [17].

Turkey's TE of 0.734 indicates a substantial but not insurmountable efficiency gap, with the PTE of 0.811 suggesting that managerial and process improvements could yield significant gains even without scale changes. Uzbekistan's TE of 0.418 reveals the most pronounced inefficiency in the sample. Critically, the decomposition indicates that the dominant source of inefficiency is pure technical inefficiency (PTE = 0.492) rather than scale inefficiency (SE = 0.850). This finding implies that the primary barrier to competitiveness is not the size of Uzbek electrotechnical enterprises—many of which are reasonably large by transition economy standards—but rather the effectiveness with which they convert inputs into outputs. Equipment obsolescence, process inefficiency, quality failures, and organizational weaknesses are the likely proximate causes, a diagnosis consistent with the technological modernization imperative identified in companion research [18].

The IRS (increasing returns to scale) classification for both Turkey and Uzbekistan suggests that both countries could benefit from consolidation or output expansion within existing enterprises, as they have not yet exploited the full economies of scale available in electrotechnical production [19].

GVC Positioning and Upgrading Pathways

The GVC analysis situates each country along a four-phase upgrading continuum, as summarized in Table 3.

Table 3.
GVC Upgrading Phases and Country Positioning

Upgrading Phase	Key Activities	Reference Country	Uzbekistan Timing
Phase I: Entry (Backward integration)	Assembly of imported components under license; quality compliance with ISO 9001; workforce training on imported equipment	Turkey (1990s), China (1985–1995)	Current position of most Uzbek firms
Phase II: Process upgrading	Adoption of lean manufacturing; automation of testing and packaging; attainment of IEC/GOST dual certification	Turkey (2000–2010), China (1995–2005)	Target for 2025–2030 industrial policy
Phase III: Product upgrading	In-house design adaptation; R&D investment > 1% of revenue; component localization above 60%	South Korea (1990–2005), China (2005–2015)	Achievable for lead firms by 2030–2035
Phase IV: Functional upgrading	Original brand manufacturing (OBM); forward integration into distribution; entry into regional export markets	South Korea (2005–present), Germany (continuous)	Long-term aspiration (2035+)

Uzbekistan's current GVC position is characterized by backward integration: enterprises predominantly assemble electrotechnical products from imported components (primarily from China, Russia, and Turkey), with limited domestic value addition. Export intensity is low (approximately 17% of output), and the export basket is dominated by relatively unsophisticated products such as low-voltage cables and basic switchgear. This profile closely resembles China's electrotechnical sector in the late 1980s and Turkey's in the 1990s, providing historically grounded benchmarks for expected upgrading timelines [20].

The reference countries' trajectories suggest that the transition from Phase I (backward assembly) to Phase II (process upgrading) typically requires 10–15 years of

sustained investment in equipment modernization, quality system adoption, and workforce training. The subsequent transition to Phase III (product upgrading) adds another 10–15 years and is contingent on achieving R&D intensity above approximately 1% of sector revenue. Phase IV (functional upgrading), achieved by South Korea and Germany, requires cumulative capabilities in design, branding, and distribution that typically take 20+ years to develop from the Phase II starting point [21].

PESTEL Context for Uzbekistan

Table 4 synthesizes the PESTEL analysis for Uzbekistan's electrotechnical sector.

Table 4.

PESTEL Analysis: Uzbekistan's Electrotechnical Sector

Dimension	Opportunities	Challenges
Political	Presidential priority on industrial localization; bilateral treaties with China and Turkey	Bureaucratic inertia; inconsistent enforcement of incentive regimes
Economic	Expanding domestic demand from construction and energy; favorable labor costs	Foreign exchange volatility; limited access to long-term capital
Social	Young labor force; growing technical higher education enrollment	Brain drain of engineers to Russia and Kazakhstan; skills mismatch
Technological	Technology transfer via JVs with Chinese and Turkish partners; Industry 4.0 pilot programs	Legacy Soviet equipment (avg. age 25+ years); weak digital infrastructure
Environmental	EU Carbon Border Adjustment Mechanism creates demand for efficient transformers	High energy intensity of existing production; waste management gaps
Legal	WTO accession negotiations driving regulatory harmonization	Intellectual property enforcement gaps; complex customs procedures

The PESTEL analysis reveals a mixed but broadly favorable environment for competitiveness upgrading. The political commitment to industrial localization, the economic tailwinds from domestic infrastructure demand, and the demographic dividend of a young labor force constitute significant opportunities. However, these are counterbalanced by institutional challenges—bureaucratic inertia, foreign exchange constraints, and skills mismatches—that could delay or dilute the impact of modernization investments if not proactively addressed [22].

Discussion and Policy Implications

Interpreting the Efficiency Gap

The DEA results confirm that Uzbekistan's electrotechnical sector faces a substantial productivity challenge. The predominance of pure technical inefficiency over scale inefficiency is an important diagnostic finding: it redirects policy attention from questions of enterprise size (consolidation, merger) toward questions of production process quality (equipment renewal, process optimization, quality management). The parallel with Turkey is instructive; Turkey's electrotechnical sector, at a PTE of 0.811, still has significant room for managerial and process improvement, yet has closed roughly half the gap that

separates Uzbekistan from the frontier. Turkey's experience suggests that sustained investment in automation and ISO certification can yield substantial PTE gains within a 15–20-year horizon [23].

A Phased Upgrading Roadmap

Synthesizing the DEA and GVC findings, the study proposes a sequenced upgrading roadmap for Uzbekistan's electrotechnical sector. In the near term (2025–2030), the priority should be Phase II process upgrading: systematic replacement of obsolete equipment, adoption of lean manufacturing principles, attainment of IEC and GOST dual certification, and automation of testing and quality control processes. The DEA decomposition suggests that these interventions could plausibly raise PTE from 0.492 to the 0.65–0.70 range, corresponding to a TE improvement from 0.418 to approximately 0.55–0.60 [24].

In the medium term (2030–2035), as the process upgrading foundation is consolidated, the focus should shift to Phase III product upgrading: building in-house design adaptation capabilities, increasing component localization above 60%, and raising R&D intensity toward the 1% threshold. This phase should be accompanied by targeted innovation policy instruments—technology park development, university-industry collaboration programs, and competitive R&D grants—that are sequenced to coincide with firms' readiness to absorb them. The reference country evidence suggests that South Korea's and China's successful product upgrading trajectories were enabled by public R&D investments that were calibrated to industrial absorptive capacity, not deployed prematurely [25].

The long-term aspiration (2035+) of functional upgrading—original brand manufacturing, forward integration into distribution, and regional export expansion—remains contingent on the successful completion of the first two phases and on broader macroeconomic and institutional developments (trade liberalization, regulatory harmonization with international standards, intellectual property regime strengthening) that lie partly outside the electrotechnical sector's direct control.

Limitations

Several limitations warrant acknowledgment. First, the DEA analysis treats each national sector as a single DMU, obscuring within-country heterogeneity among firms. Firm-level DEA, while desirable, is constrained by data availability for the reference countries at a comparable level of disaggregation.

Second, the GVC upgrading phases are stylized; actual trajectories are nonlinear and subject to external shocks, policy reversals, and competitive disruptions.

Third, the historical analogies (e.g., Uzbekistan's position resembling China circa 1990) are heuristic rather than deterministic; Uzbekistan faces a different global competitive landscape than China did three decades ago, including more intense competition and faster technological obsolescence cycles. Future research should extend the analysis to firm-level DEA within Uzbekistan and incorporate Malmquist productivity index analysis [6] to capture dynamic efficiency changes over time.

4. Conclusion

This study has benchmarked the competitiveness of Uzbekistan's electrotechnical industry against four reference countries at different stages of industrial development, employing DEA for efficiency measurement, GVC analysis for structural positioning, and PESTEL for contextual diagnostics. The central findings are threefold. First, Uzbekistan's electrotechnical sector operates at 41.8% of frontier efficiency, with the gap driven primarily by pure technical inefficiency rather than scale constraints. Second, the sector occupies a backward-integrated assembly position in the electrotechnical GVC, comparable to the early development stages of today's middle-income and advanced competitors. Third, the macroeconomic and institutional environment, while challenging, contains sufficient opportunities to support a phased upgrading strategy if policy is well designed and sequenced.

The practical implication is clear: Uzbekistan's pathway to a competitive electrotechnical industry is neither impossible nor immediate. It requires a disciplined, phased approach that prioritizes process upgrading and technological modernization in the near term, product upgrading and nascent innovation in the medium term, and functional upgrading in the long term—each phase building on the capabilities consolidated in the preceding one. The historical trajectories of Germany, South Korea, China, and Turkey provide both benchmarks and cautionary lessons for this journey.

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