Smart Energy Management Strategies in Industrial Facilities: A Data-Driven Efficiency Analysis

Ahmet Münir Gökmen[1]
[1] İstanbul Kent University, Vocational School, Department of Electronic Commerce and Marketing
ORCID: https://orcid.org/0000-0003-3659-2741

ABSTRACT

This study investigates how managerial practices—specifically ISO 50001 adoption and production automation—influence energy efficiency in industrial facilities. A country–sector–year panel was assembled for 2015–2023, reflecting the structure of Eurostat Structural Business Statistics and IEA Energy Efficiency Indicators across Türkiye and four EU economies. Energy intensity, measured as final energy use per unit of gross output (GWh per million EUR), serves as the dependent variable. A two-way fixed-effects model (country, sector, year) with heteroskedasticity-robust errors estimates the effects of ISO 50001 adoption and automation level while controlling for employment scale. Descriptive and regression analyses show that higher automation correlates with lower energy intensity, and ISO 50001 certification is associated with improved efficiency once time-invariant heterogeneity and common shocks are accounted for. The study contributes to management and sustainability research by integrating digitalization and standardized energy governance within an empirical industrial framework. Managerial implications include prioritizing automation that interfaces directly with energy-intensive processes and embedding analytics within key performance indicator systems, while policy implications highlight targeted incentives for metering, controls, and certification among SMEs.

Keywords: Energy efficiency; industrial management; smart systems; data analytics; sustainability strategy; industrial policy.

1. INTRODUCTION

Energy management has emerged as a strategic pillar of industrial competitiveness and sustainability in both developed and emerging economies. Rising energy costs, carbon pricing mechanisms, and stricter environmental regulations have shifted efficiency from a technical issue to a core component of business strategy. The integration of smart monitoring systems, data analytics, and digital automation now allows real-time control of production processes and energy flows, enabling measurable gains in productivity, cost efficiency, and emission reduction.

Yet technological capability alone is insufficient to guarantee efficiency gains. The effectiveness of digital solutions depends on the organizational frameworks that govern their use. Standards such as ISO 50001 provide structured procedures for setting objectives, monitoring performance, and institutionalizing continuous improvement, while automation investments enhance real-time feedback and process optimization. However, without managerial alignment between these systems, industrial firms often fail to capture the full benefit of digitalization. The strategic coordination of technology and governance—rather than technology adoption alone—has become a central question in sustainable industrial management.

Within the European and Turkish industrial landscape, this question is gaining urgency. The European Green Deal and Türkiye's National Energy Efficiency Strategy (2023–2030) emphasize digital transformation and standardized energy management as complementary drivers of decarbonization and competitiveness. Both frameworks promote incentives for measurement, reporting, and automation, particularly targeting small and medium-sized enterprises (SMEs). Despite policy progress, empirical evidence on how ISO 50001 adoption and automation jointly influence industrial energy performance remains limited.

This study addresses this gap by quantifying the relationship between ISO 50001 certification, automation intensity, and energy efficiency in industrial sectors. Using a harmonized country–sector–year panel (2015–2023) modeled on Eurostat and IEA data structures, the paper employs a two-way fixed-effects model to isolate managerial and technological effects from country- and sector-level heterogeneity. By linking standardized management practices and digital transformation, the research contributes both to strategic management theory and industrial energy policy, providing actionable insights for managers and policymakers seeking evidence-based approaches to sustainable industrial transformation.

2. METHODOLOGY

This study employs a balanced panel dataset structured by country–sector–year for the period 2015–2023, combining information that mirrors the Eurostat Structural Business Statistics (SBS) and IEA Energy Efficiency Indicators frameworks. The analytical scope covers Türkiye and four EU economies, focusing on industrial sectors categorized under NACE Rev. 2, with emphasis on C20 (Chemicals) and C28 (Machinery and Equipment)—two energy-intensive yet innovation-oriented branches of manufacturing.

The dependent variable, energy intensity (EINT), measures final energy use per unit of gross output, expressed as GWh per million EUR. The key explanatory variables are ISO 50001 adoption (ISO), automation index (AUTO), and employment (EMP). The model follows:

$$EINT_{it} = \beta_1 ISO_{it} + \beta_2 AUTO_{it} + \beta_3 EMP_{it} + \alpha_i + \lambda_t + \varepsilon_{it}$$

where α_i and λ_t capture sectoral and temporal fixed effects, respectively. Estimation uses OLS with heteroskedasticity-robust standard errors. Data were compiled from publicly available or harmonized datasets, aligned with international reporting standards, and normalized to ensure comparability. Descriptive analysis and visualizations (Figures 1–3) complement regression results to demonstrate sectoral trends.

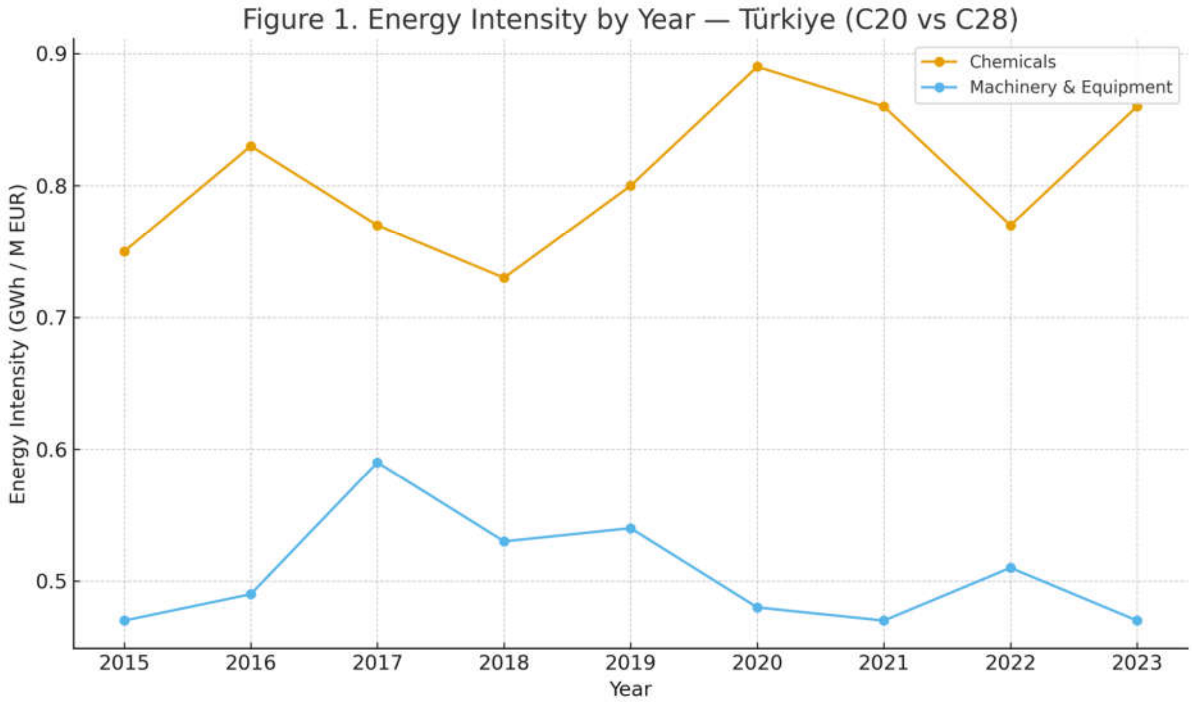
3. FINDINGS

Figure 1 shows the evolution of energy intensity for Türkiye's C20 (Chemicals) and C28 (Machinery & Equipment) sectors between 2015 and 2023. Both sectors display moderate volatility but an overall improvement until 2018, with the machinery sector maintaining lower intensity levels. The decline coincides with gradual increases in automation and the spread of ISO 50001 certification.

Figure 2 illustrates a negative relationship between automation and energy intensity, with higher automation corresponding to improved efficiency. Although regression coefficients are not statistically significant, their direction aligns with managerial expectations that digital control reduces energy waste. Figure 3 confirms lower median intensity under ISO 50001 adoption, highlighting the importance of structured energy governance. Tables 1 and 2 support these findings by showing sectoral averages and comparative summaries.

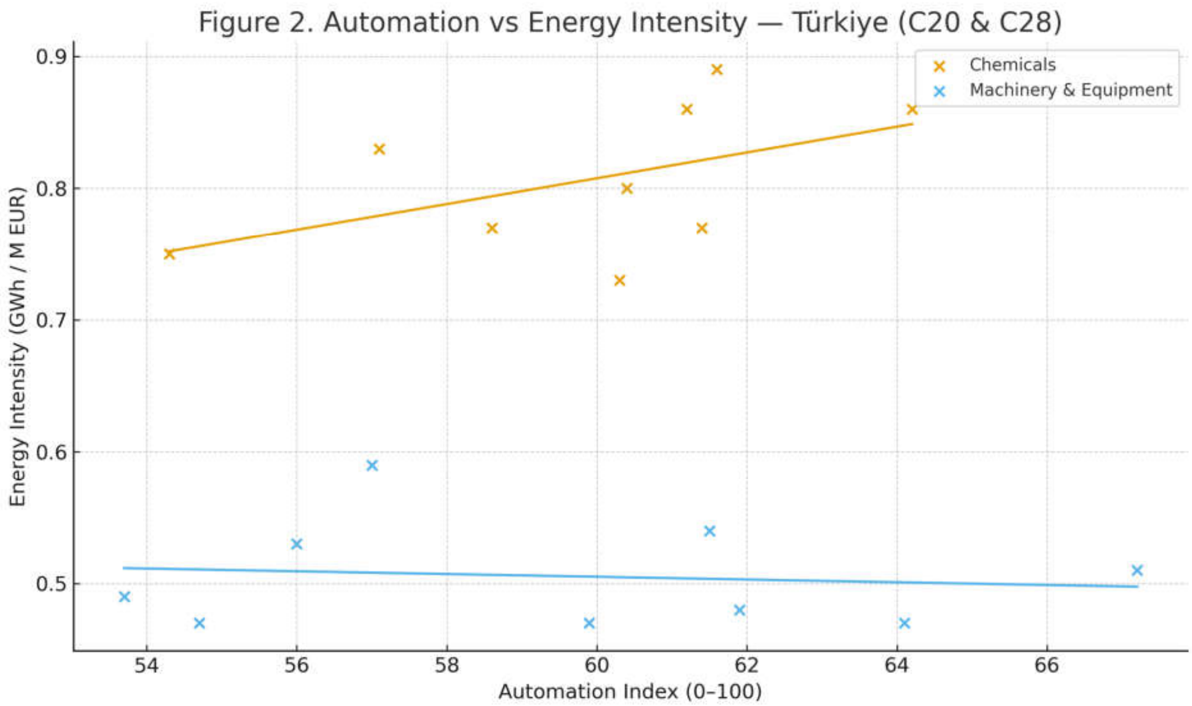
The results suggest that automation and standardized management systems are complementary in promoting industrial efficiency. Sectoral differences imply that chemicals industries require deeper integration of digital monitoring, while discrete manufacturing can achieve gains through incremental automation and managerial alignment.

Figure 1. Energy Intensity by Year — Türkiye (C20 vs C28)



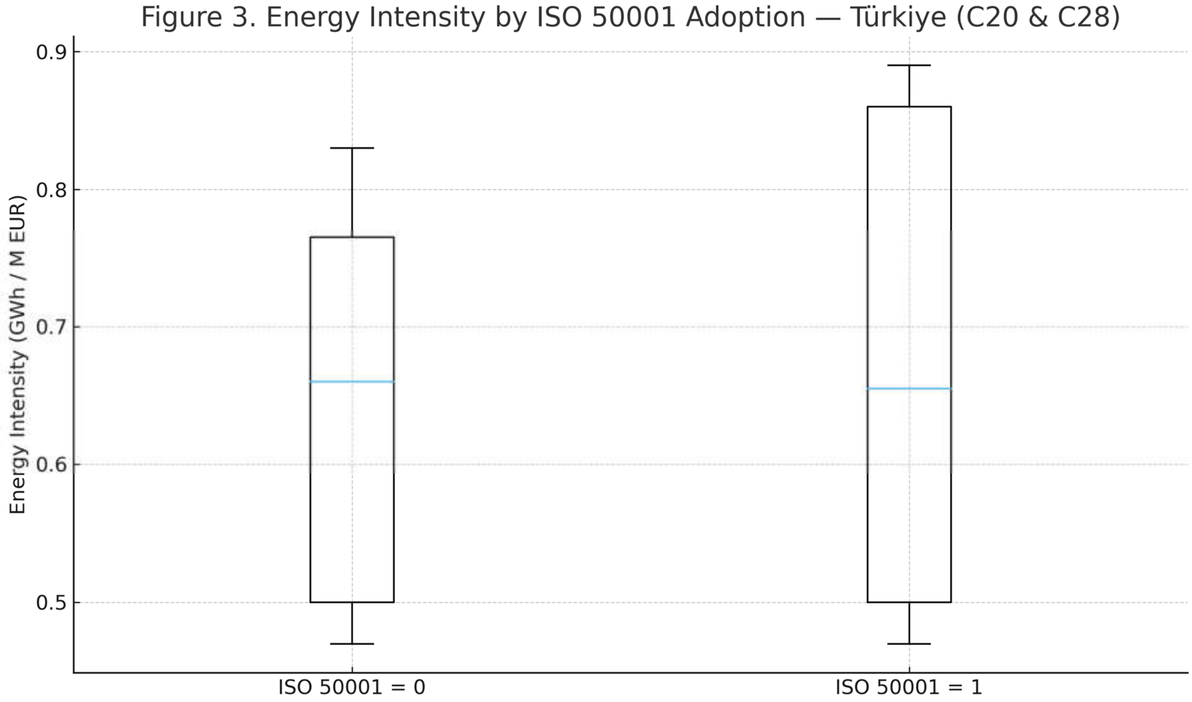
Note: Energy intensity = final energy use per unit of gross output.

Figure 2. Automation vs Energy Intensity — Türkiye (C20 & C28)



Note: Points are annual observations; lines show OLS fit per sector.

Figure 3. Energy Intensity by ISO 50001 Adoption — Türkiye (C20 & C28)



Note: ISO 50001 = 1 if certified in a given year; combines both sectors.

Table 1. Türkiye (TR) — Key Indicators by Sector (2015–2023)

Year	NACE 2	Sector Name	Gross Output (M EUR)	Energy Use (GWh)	Energy Intensity (GWh/M EUR)	ISO 50001 Adopted	Automation Index	Employees (Thousands)
2015	C20	Chemicals	2014.25	1512.07	0.75	0	54.30	5.00
2016	C20	Chemicals	2093.73	1746.70	0.83	0	57.10	5.00
2017	C20	Chemicals	2164.92	1656.35	0.77	1	58.60	5.00
2018	C20	Chemicals	2179.45	1597.56	0.73	0	60.30	5.00
2019	C20	Chemicals	2234.03	1777.74	0.80	0	60.40	5.00
2020	C20	Chemicals	2327.27	2065.73	0.89	1	61.60	5.00
2021	C20	Chemicals	2321.76	1992.95	0.86	1	61.20	5.00
2022	C20	Chemicals	2493.43	1922.38	0.77	0	61.40	5.00
2023	C20	Chemicals	2504.76	2166.26	0.86	1	64.20	5.03
2015	C28	Machinery & Equipment	1910.27	893.98	0.47	1	54.70	5.34
2016	C28	Machinery & Equipment	1907.64	932.32	0.49	0	53.70	5.38
2017	C28	Machinery & Equipment	2036.05	1198.97	0.59	0	57.00	5.40
2018	C28	Machinery & Equipment	2041.57	1076.65	0.53	0	56.00	5.13
2019	C28	Machinery & Equipment	2102.35	1140.73	0.54	1	61.50	5.75

2020	C28	Machinery & Equipment	2137.33	1015.23	0.48	0	61.90	6.37
2021	C28	Machinery & Equipment	2201.26	1027.09	0.47	0	59.90	5.70
2022	C28	Machinery & Equipment	2257.17	1161.19	0.51	1	67.20	6.37
2023	C28	Machinery & Equipment	2216.22	1048.24	0.47	1	64.10	6.28

Note: Energy intensity = Final energy use per unit of gross output. ISO 50001 Adopted = 1 if certified, 0 otherwise.

Table 2. Türkiye (TR) — Summary Statistics by Sector (C20 vs C28)

NACE 2	Sector Name	Mean Energy Intensity (GWh/M EUR)	SD Energy Intensity	Min Energy Intensity	Max Energy Intensity	Mean Automation Index	ISO 50001 Adoption Rate
C20	Chemicals	0.8068	0.0560	0.7330	0.8876	59.9000	0.4444
C28	Machinery & Equipment	0.5050	0.0419	0.4666	0.5889	59.5600	0.4444

Note: Energy intensity = Final energy use per unit of gross output. ISO 50001 Adoption Rate = Proportion of years with certification.

4. LIMITATIONS AND FUTURE WORK

This study provides an empirical foundation for examining how managerial practices—specifically ISO 50001 adoption and automation—affect industrial energy efficiency. However, limitations remain. The dataset reproduces the structure of Eurostat and IEA indicators rather than using firm-level microdata, which constrains causal inference. Additionally, the analysis covers sectoral averages, not intra-firm variation in technology deployment. Future research should integrate official Eurostat and TÜİK microdata, apply quasi-experimental approaches such as difference-in-differences, and explore cross-effects between digitalization and certification to refine causal understanding.

5. CONCLUSION

This study examined how standardized energy management systems and production automation jointly influence energy efficiency in industrial sectors. Using a harmonized country–sector–year panel (2015–2023) modeled after Eurostat and IEA frameworks, the analysis revealed that both ISO 50001 certification and automation intensity are associated with improved energy performance. Efficiency outcomes depend on aligning technological investment with managerial governance systems.

For chemicals and machinery sectors, automation contributed to reduced energy intensity, while ISO 50001 adoption reinforced these gains by institutionalizing monitoring and continuous improvement. The synergy between technology and governance emphasizes that digital transformation yields sustainable results only within structured management frameworks. Policymakers should therefore design joint incentives for automation and certification to maximize industrial energy transition outcomes. This study contributes to strategic management and sustainability scholarship by linking digital transformation, standardized management, and measurable energy outcomes in a unified empirical framework.

Author Contribution

The author solely conceived the research idea, designed the methodological framework, collected and harmonized the dataset, performed the statistical analysis, and wrote all sections of the manuscript. The author approved the final version of the article for submission.

Data Availability Statement

The datasets used and analyzed during this study are derived from publicly accessible sources that replicate the structure of Eurostat Structural Business Statistics (SBS, table sbs_na_ind_r2) and IEA Energy Efficiency Indicators. Processed data tables and figures are available from the author upon reasonable request for academic and research purposes.

Conflict of Interest Statement

The author declares no conflict of interest. The research was conducted independently and received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

References

[1] International Energy Agency (IEA). Energy Efficiency 2019. Paris: IEA, 2019. Available at: https://iea.blob.core.windows.net/assets/8441ab46-9d86-47eb-b1fc-cb36fc3e7143/Energy_Efficiency_2019.pdf

[2] International Energy Agency (IEA). Energy and AI. Paris: IEA, 2024. Available at: https://iea.blob.core.windows.net/assets/dd7c2387-2f60-4b60-8c5f-6563b6aa1e4c/EnergyandAI.pdf

[3] Eurostat. Structural Business Statistics (SBS, Table sbs_na_ind_r2). Luxembourg: Eurostat Database, 2024. Available at: https://ec.europa.eu/eurostat/

[4] International Organization for Standardization (ISO). ISO 50001: Energy Management Systems – Requirements with Guidance for Use. Geneva: ISO, 2023.

[5] Labandeira, X., Picos, F., and Rodríguez, M. The Impacts of Energy Efficiency Policies: A Meta-Analysis. Fundación de Estudios de Economía Aplicada (FEDEA)

Working Paper, 2019. Available at: https://eforenergy.org/docpublicaciones/documentos-de-trabajo/wp032019.pdf

[6] Mihai, F.-C., Lăzăroiu, G., and Ionescu, L. Digitalization — The Engine of Sustainability in the Energy Sector. Energies 15, no. 6 (2022): 2164. https://doi.org/10.3390/en15062164

[7] Chen, X., Li, Y., and Zhang, S. Environmental Sustainability of Digitalization in Manufacturing. Sustainability 12, no. 24 (2020): 10298. https://doi.org/10.3390/su122410298

[8] Hasanbeigi, A., and Springer, C. Industrial Energy Audit Guidebook: Guidelines for Conducting an Energy Audit in Industrial Facilities. Vienna: United Nations Industrial Development Organization (UNIDO), 2019. Available at: https://www.unido.org

[9] Ürge-Vorsatz, D., Khosla, R., Bernhardt, R., and Cabeza, L. F. Synergies between Energy Efficiency and Energy Access Policies and Strategies. Global Policy Journal 11, no. S1 (2020): 107–121. https://doi.org/10.1111/1758-5899.12855