Environmental Management System (ISO 14001) and Total-Factor Carbon Emission Performance: A Two Stage Malmquist Data Envelopment Analysis

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Abstract

As global decarbonization goals become more urgent, it is vital to understand that decoupling carbon from growth is not a purely mechanical process of adopting green machines; it is a socio-technical transition. Understanding carbon productivity requires analyzing the synergy between voluntary standards and strict regulation, demonstrating that technology only drives societal change when embedded in a robust institutional framework that prevents mere compliance. Therefore, this cross-country panel study examines whether the diffusion of Environmental Management System (EMS) ISO 14001 is associated with improvements in total-factor carbon emission performance in 15 countries with the highest ISO 14001 adoption intensity over 2010-2024, yielding a balanced panel of 210 country-year observations. Using a two-stage Malmquist Data Envelopment Analysis (DEA) model, we decompose change in carbon performance into two critical vectors: change in efficiency (catch-up effect) and technological change (frontier shift). The decomposition results indicate that, for most countries, 24% in carbon performance observed gains were more closely associated with efficiency catch-up than with frontier-shifting technological change. Whereas Germany shows consistently shifted the carbon-efficiency frontier during the study period. Moreover, panel regression analysis indicates that ISO 14001 adoption intensity remains conditionally associated with these improvements, after controlling for energy intensity and industrial structure. This study contributes to the literature by demonstrating that management systems act as technology absorption mechanisms, enabling lagging nations to reach the frontier of existing best practices. Finally, the findings provide a forward-looking basis suggesting that, without an acceleration in radical technological innovation (frontier-shift), current efficiency efforts based on voluntary standards will be insufficient to achieve net-zero emissions goals.

Keywords: Environmental management system; ISO 14001; climate change; carbon efficiency; environmental performance; Malmquist index

1. Introduction

Climate change mitigation has become a significant challenge for governments and industries globally, leading to the development of effective strategies to decrease carbon dioxide (CO_2) emissions while maintaining economic growth. Conventional regulatory methods, characterized by command-and-control mechanisms, are frequently enhanced by environmental initiatives that promote organizations to exceed compliance in their environmental performance (Jiang et al., 2021). The ISO 14001

Environmental Management System (EMS) certification is a significant initiative, serving as a global standard that offers a framework for organizations to manage and mitigate their environmental impacts (Ikram et al., 2019). Since its introduction in 1996, ISO 14001 has experienced significant expansion. As of 2024, more than 670,000 ISO 14001 certificates were issued globally, indicating widespread adoption in both developed and developing economies (ISO, 2024). The widespread diffusion of ISO 14001 raises a critical question: Does its implementation as an organizational innovation enhance environmental performance by promoting knowledge transfer, supporting the uptake of green technologies, and improving carbon emission efficiency? Clarifying this relationship is crucial for understanding how voluntary standards interact with formal regulation to advance climate goals.

The effective implementation of ISO 14001 represents a distinct form of organizational innovation from the perspective of technology management. Substantial modifications in corporate processes, culture, and knowledge systems are necessary to comply with the standard's requirements. Organizations are required to establish new procedures for environmental auditing, performance measurement, and management review, which frequently results in the development of internal capabilities and expertise that were previously lacking (W. He & Shen, 2019). The mere adoption of ISO 14001 is inadequate without significant transformations in corporate culture, skills, and systems. Companies must invest in enhancing core capabilities such as skills, knowledge, technical systems, and management practices to fully realize the advantages of an EMS (Duque-Grisales et al., 2020). The development of new capabilities constitutes a technology management process wherein firms systematically learn to manage environmental technologies and practices, analogous to their management of production technologies or information systems (Cheng et al., 2026). In doing so, ISO 14001 implementation serves as a foundation for organizational learning and knowledge generation, potentially leading to innovation. The EMS framework establishes a continuous improvement cycle (Plan-Do-Check-Act) that promotes employee experimentation with process modifications and technical solutions to environmental issues, thereby cultivating a culture of innovation beyond simple compliance (Camilleri, 2022).

A key way ISO 14001 drives innovation is by facilitating knowledge transfer and cross-functional learning within and between organizations. To achieve and uphold certification, organizations implement training programs, establish environmental committees, and document best practices, thereby ensuring systematic dissemination of knowledge regarding environmental processes throughout the organization (Elvis Kwame Ofori et al., 2023). Furthermore, the implementation of ISO 14001 substantially enhances organizational innovation, with this effect being mediated by improved knowledge transfer within the organization. Adopting the EMS standard facilitates the dissemination of environmental knowledge, including information on new cleaner production methods and regulatory requirements, among employees and departments, thereby fostering innovation within the company (Cestau-Oyhantçabal and Arocena, 2025; Khan and Johl, 2019). Furthermore, ISO 14001's focus on documentation and internal audits enables firms to consistently analyze their performance data, recognize inefficiencies, and share solutions, thereby reinforcing a continuous cycle of experiential learning essential for technological progress. ISO 14001 functions as a conduit for the dissemination of green technology; a certified organization enhances its own practices and may also convey environmental innovations to its business partners, such as through collaborative solutions or requirements for elevated environmental performance (Ong et al., 2023). The ripple effect influences entire sectors and regions; as an increasing number of firms within a value chain achieve certification, the diffusion of environmental technologies such as energy-efficient equipment, recycling systems, and pollution control devices occurs at an accelerated pace. The network-driven diffusion associated with ISO 14001 highlights its function as a global technology management system, uniting various organizations in pursuit of shared environmental performance objectives (Elvis Kwame Ofori et al., 2023).

Crucially, ISO 14001 promotes both the adoption of current technologies and the advancement of novel innovative solutions. The standard encourages organizations to adopt a mindset of continuous improvement, prompting them to exceed mere compliance and explore innovative methods to achieve environmental goals (Ahmed & Mathrani, 2021). Distinguishing between two types of improvements stimulated by ISO 14001 is beneficial: efficiency enhancements and technological innovations. Efficiency enhancements entail the utilization of existing technologies and processes in more intelligent and responsible manners, fundamentally improving the execution of similar tasks. Numerous initial advantages of ISO 14001 pertain to this category: organizations optimize processes, reduce waste, and enhance resource efficiency. A recent study of international manufacturers indicates that increased adoption of ISO 14001 correlates with significantly lower energy intensity and reduced greenhouse gas emission rates (Dinh et al., 2025). Efficiency gains result from various incremental innovations on the factory floor, including the optimization of energy use in production, enhancements in maintenance to prevent leaks, and material recycling, all of which are facilitated by ISO 14001. Moreover, the ISO 14001 standard results in operational efficiencies by enhancing resource utilization and waste management systems, thereby leading to cost savings and improved environmental performance (João et al., 2025). ISO 14001-driven efficiencies demonstrate innovations in work processes, utilizing existing methods and technologies more effectively to attain environmentally sustainable outcomes.

Conversely, technological innovation within the framework of ISO 14001 pertains to the introduction of novel technologies or fundamentally new processes that enhance capabilities, rather than merely improving existing practices. The standard serves as an enabler for innovation by establishing the organizational infrastructure, including clear goals, monitoring, and management commitment, which promotes the exploration of novel solutions (Arana-Landín et al., 2025). The latest revision, ISO 14001:2015, enhanced the innovation-oriented approach by integrating a life-cycle perspective and a more explicit analysis of strategic context. This evolution prompts firms to evaluate the environmental implications of their products and processes throughout their lifecycle, thereby fostering product-oriented environmental innovations. Moreover, the emphasis on life cycle thinking in ISO 14001:2015 resulted in increased adoption of specific product-oriented environmental practices among certified companies (Hernandez-Vivanco & Bernardo, 2023). The adoption of EMS encourages companies to reevaluate product design, material sourcing, and product reuse or recycling, thereby fostering innovation beyond traditional manufacturing boundaries. It helps to develop a product design that facilitates disassembly and recycling, in accordance with ISO 14001's life-cycle criteria (Franceschelli et al., 2019). Such changes frequently require the development or adoption of novel technologies such as new recyclable materials or cleaner production techniques, demonstrating how ISO 14001 can stimulate technological innovation in products and services, beyond mere processes.

The relationship between EMS and innovation has been a topic of considerable debate. Conventional perspectives warned that ISO 14001 or Total Quality Management (TQM) might impose rigidity and hinder radical innovation by favoring standardized procedures over creative experimentation. Furthermore, ISO 14001 certification did not enhance firms' likelihood of participating in R&D and, in some instances, was negatively correlated with radical, new-to-market innovations (Ferrón Vílchez, 2017). The findings indicate that organizations viewing ISO 14001 merely as a compliance measure may prioritize incremental improvements over more innovative explorations. Recent research offers a complex perspective, suggesting that under appropriate conditions, ISO 14001 can serve as a catalyst for significant innovation. The concept of change catalysis within the context of EMS represents a profound form of organizational learning, wherein the firm utilizes the implemented practice as a catalyst to reevaluate business processes and explore new innovations (Lim & Prakash, 2014). Companies can attain second-order learning; elements such as robust internal commitment to environmental concerns and proactive customer and stakeholder feedback have enabled certain firms to leverage ISO 14001 as a foundation for substantial innovations. The findings indicate that, when supported by organizational and external factors, the implementation of ISO 14001 can serve as a foundation for innovation that extends beyond the standard's explicit requirements. This suggests that a flexible and proactive approach to implementing ISO 14001, which motivates employees to exceed the literal requirements of the practice, can mitigate rigidity and foster creativity (Ikram et al., 2020). Firms that incorporate ISO 14001 into their strategic planning and promote experimentation, such as investing in environmental research and development or pilot projects aligned with environmental management system objectives, are more likely to achieve radical innovations. In contrast, firms that regard the environmental management system as a static procedure may only realize efficiency improvements (João et al., 2025). The distinction is found in management's methodology: ISO 14001 establishes a framework for environmental innovation, yet it proves most effective when employed dynamically as a platform for learning and innovation, rather than merely as a compliance checklist.

At the national level, the impact of ISO 14001 is neither automatic nor solely additive. The mechanism is accumulated and functions through multiple interrelated channels. ISO 14001 modifies firm-level routines by formalizing environmental monitoring, internal auditing, target setting, and corrective actions (Hayat & Lohano, 2024; Song et al., 2026). Moreover, these routines enhance managerial capacity, promote knowledge transfer, and augment firms' capacity to integrate cleaner processes and energy-efficient technologies. Further, ISO 14001 certification grows among numerous firms within the same economy, these benefits start to accumulate through reduced energy intensity, broader dissemination of best practices across supply chains, and accelerated imitation of effective operational solutions (Goldar & Goldar, 2024). In dynamic terms, this process can be characterized as efficiency change, wherein countries approach the existing best-practice frontier by implementing available techniques, or as technological change, which occurs when the frontier shifts due to the emergence of more advanced production possibilities. This study addresses the diffusion of ISO 14001 as a potential transmission mechanism linking organizational innovation to national carbon performance, rather than presuming that firm-level certification directly results in macro-level environmental benefits.

Figure 1 depicts the global distribution of ISO 14001 certificates and highlights the top 15 contributing countries, showing a highly concentrated pattern of adoption. China dominates by a wide margin (381,019 certificates), while second-tier Italy, the Republic of Korea, Spain, Japan, and the United Kingdom record substantial but far smaller totals, indicating that ISO 14001 diffusion is strongest in a limited set of industrial and export-oriented economies. The remaining countries such as Germany, India, France, Sweden, Poland, Romania, Türkiye, Australia, and the United States contribute more moderate counts, reinforcing the visual message that worldwide certifications (676,232 in total) are unevenly distributed across regions rather than broadly dispersed.

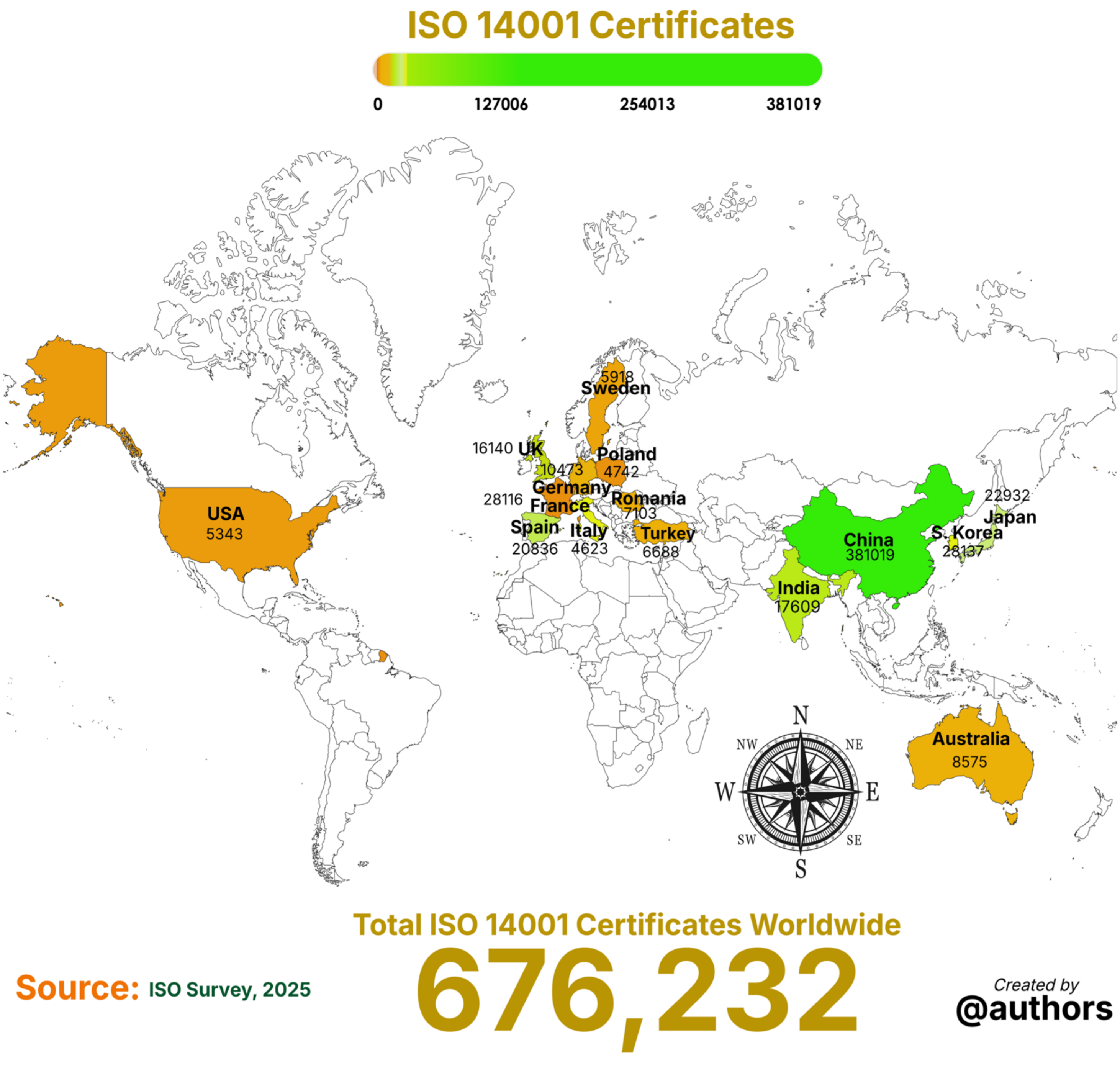


Figure 1: ISO 14001 distribution of top 15 countries in 2024 (Source ISO, 2025)

This study addresses the gap by employing a total-factor approach to assess carbon emission performance at the national level. Utilizing the productivity and efficiency literature, we apply a Malmquist index framework to assess dynamic variations in carbon emission performance, referred to as the Malmquist CO_2 Performance Index (MCPI). This method, proposed by Zhou *et al.* (2010), enables the assessment of an economy's efficiency in generating output (GDP) in relation to its inputs (capital, labor, energy) and negative outputs (CO_2 emissions), as well as the temporal variations in this efficiency. The Malmquist index is a recognized tool in productivity analysis, utilized for assessing changes in total factor productivity (Caves *et al.*, 1982; Ray and Desli, 1997). The extension to environmental performance, frequently referred to as the Malmquist Luenberger index when accounting for negative outputs, facilitates a comprehensive evaluation of the progress of economies towards cleaner production practices.

The MCPI offers a dynamic assessment of carbon efficiency over time, contrasting with static cross-sectional efficiency scores or basic intensity ratios. It indicates whether a country is improving (MCPI>1), regressing (MCPI<1), or remaining static in its carbon efficiency. This index disaggregates performance change into two components: efficiency change, which measures the extent to which a country approaches the best-practice frontier, and technological change, which assesses the movement of the best-practice frontier itself as a result of innovation. Applying this method to a panel of countries allows for the discernment of both the magnitude of carbon performance improvements and the underlying drivers, whether they stem from broad technological advancements, such as breakthroughs in clean energy, or from individual countries adopting existing best practices.

To address these gaps, this study analyzes a balanced panel of 15 countries including Australia, China, Germany, Spain, France, the United Kingdom, India, Italy, Japan, South Korea, Poland, Romania, Sweden, Turkey, and the United States, which exhibited the highest ISO 14001 diffusion during 2010-2024. Country selection is based on the concentration of ISO 14001 certificates and certified sites reported in the ISO Survey, making the sample appropriate for assessing whether substantial diffusion of the standard is associated with measurable carbon performance effects. The 2010-2024 window captures a period of mature ISO 14001 adoption, intensified climate policy activity after the Paris Agreement, and major economic disruptions that test the resilience of carbon performance trajectories.

The study makes three contributions. First, it connects ISO 14001 diffusion to a dynamic total-factor measure of carbon performance rather than to a static intensity indicator. Second, it decomposes performance change into efficiency change and technological change, which sharpens interpretation of the mechanisms underlying decarbonization. Third, it provides policy-relevant evidence on whether a voluntary environmental standard can complement formal regulation by diffusing environmental management capability at the national level. This study extends the literature by integrating dynamic frontier analysis with panel evidence on ISO 14001 adoption intensity.

This paper is organized as follows: Section 2 presents the literature review, synthesizing prior evidence on ISO 14001, environmental management systems, and total-factor carbon emission performance and identifying the unresolved gaps that motivate the study. Section 3 details the research design and the two-stage CO_2 Malmquist index framework, including data, variable construction, and the econometric strategy used to examine the role of ISO 14001 diffusion. Section 4 reports the empirical results from both the MCPI estimation and the second-stage panel analysis, while Section 5 discusses the findings in relation to theory and policy-relevant mechanisms. Section 6 concludes by summarizing the main contributions, acknowledging limitations, and outlining directions for future research.

2. Literature Review

Environmental management standards serve as a bridge between rigorous command-and-control regulation and market-driven approaches. In contrast to mandatory regulations, ISO14001 depends on the proactive engagement of firms and offer flexibility in the attainment of environmental objectives (Oyelakin et al., 2025). The emergence of programs such as industry codes of conduct and third-party certifications indicates a pursuit of collaborative and cost-efficient methods for environmental protection (Abisourour *et al.*, 2021; He *et al.*, 2018). ISO 14001 is recognized as one of the most extensively implemented environmental standards. ISO 14001 can be viewed as a mechanism for capability building that facilitates the absorption of environmental knowledge, the standardization of best practices, and the gradual operational diffusion of cleaner technologies. This standard is categorized as a process standard, emphasizing management procedures over specific performance outcomes, and has attained global recognition, with numerous certified sites spanning various industries and countries. Moreover, beyond its formal procedural focus, ISO 14001 can act as a strategic catalyst for innovation, encouraging firms to integrate new environmental technologies and share best practices as part of their environmental management efforts (Chiarini, 2017).

ISO 14001 establishes a framework for the ongoing enhancement of environmental performance through the principle of continuous improvement (Kaizen). Organizations frequently establish objectives related to energy or waste reduction and assess their progress, thereby fostering a series of incremental innovations (Erauskin-Tolosa et al., 2020). These typically manifest as process optimizations and cleaner production techniques that reduce resource consumption and emissions. The findings indicate significant efficiency improvements, as reflected in reduced energy intensity and increased resource productivity among ISO 14001 adopters, suggesting that these companies are optimizing the use of existing technologies (Jeong & Lee, 2022). These improvements, although not revolutionary, are essential for minimizing environmental impact and frequently establish the foundation and justification for subsequent technological advancements.

The empirical literature lacks the conclusive evidence that certification inherently enhances environmental performance. Prior research indicates that certified firms exhibit lower emissions, enhanced compliance, and improved resource efficiency, implying that the adoption of EMS can facilitate operational advancement (W. A. A. Bukhari et al., 2025). A second stream identifies null or weak effects, particularly in contexts where certification is sought for reputational signaling or is implemented under inadequate regulatory oversight. Potoski and Prakash (2005) demonstrated that facilities in the United States implementing ISO 14001 experienced greater reductions in toxic releases compared to non-adopters, indicating a positive impact of the EMS. Goldar and Majumder, (2022) conducted an analysis of manufacturing plants in India and identified notable decreases in energy intensity and waste generation among ISO-certified firms, suggesting enhanced eco-efficiency. Arocena *et al.* (2023) conducted a study on 44 emerging and non-emerging countries and found that ISO 14001 certification exhibited superior compliance records and reduced pollutant emissions in comparison to their uncertified counterparts. Ofori *et al.* (2024) conducted an international study across BRICS, revealing a positive correlation between ISO 14001 certification and several performance metrics, including a reduced likelihood of environmental incidents and enhanced pollution prevention practices. The rationale is that the structured framework of ISO 14001 compels organizations to identify pollution sources, establish reduction targets, train personnel, and consistently monitor progress, resulting in incremental and occasionally significant performance improvements.

The EMS implementation enhances the firm's environmental knowledge. Training programs, cross-functional teams for environmental projects, and internal audits collectively enhance a repository of expertise. This organizational learning improves the firm's ability to assimilate and apply new technologies, a notion similar to absorptive capacity in innovation theory. Research indicates that knowledge transfer serves as a crucial mediator connecting ISO 14001 to innovation outcomes (Long et al., 2017). Organizations acquire knowledge not only to adhere to regulations but also to enhance their practices beyond mere compliance, discovering innovative solutions through employee input, benchmark data, or industry best practices. Over time, the EMS evolves into a knowledge-driven mechanism that enables firms to experiment with and implement emerging green technologies, such as a new water recycling system or an alternative energy source (Li et al., 2019).

Prior studies have investigated contingencies and moderating factors to reconcile these varying results. The stringency of the external regulatory environment is a critical factor. In jurisdictions or industries with stringent pollution regulations, organizations implement ISO 14001 to systematically manage compliance and exceed regulatory requirements, resulting in quantifiable enhancements. In contrast, in environments characterized by weak enforcement, organizations may adopt ISO 14001 in a symbolic manner, resulting in minimal substantive change (Ferrón Vílchez, 2017; Hayat & Lohano, 2024). The influence of ISO 14001 is enhanced in regions characterized by strict environmental regulations and adaptable, performance-oriented regulatory frameworks. Strong regulations generate pressure and incentives for firms to effectively utilize the EMS to achieve cost-effective pollution reductions; in the absence of such pressure, the EMS may be underutilized (Kwon et al., 2002). Moreover ISO 14001 tends to yield greater benefits in high-polluting industries, such as chemicals and heavy manufacturing, where inefficiencies and waste are more apparent, compared to low-polluting sectors where firms are already relatively clean. A recent study by Song *et al.* (2026) indicates that ISO 14001 markedly enhanced technical efficiency in high-polluting industries, resulting in an approximate 2% increase in economic output without a corresponding rise in emissions (A. A. A. Bukhari et al., 2025). In contrast, the impact on low-polluting industries was minimal, supporting the notion that potential improvements from enhanced management are more substantial in contexts of poor baseline performance.

The literature extensively discusses the issues of endogeneity and self-selection. Prior studies strive to account for the non-random nature of the decision to pursue ISO 14001 certification. Camacho and Thornhill, (2024) employed a systematic review approach, specifically the availability of government support for EMS adoption, to isolate the causal impact of ISO 14001. Their findings indicated a positive effect on energy efficiency and emissions, thereby enhancing confidence that the observed relationship is not solely attributable to proactive firms self-selecting into certification. He and Shen, (2019) utilized propensity score matching to analyze comparable facilities with and without ISO 14001, finding that ISO-certified facilities, on average, reduced their toxic emissions more significantly.

ISO 14001 promotes the systematic management of environmental aspects, compelling organizations to enhance their technical capabilities in pollution control, energy management, and eco-design (Ozusaglam et al., 2018). Companies frequently allocate resources to monitoring technologies, such as emissions sensors and energy management software, while collaborating with environmental technology providers to enhance their EMS. The investments and partnerships enhance the firm's technological capabilities. Companies often identify new improvement opportunities during the EMS process, such as an audit may uncover that an outdated boiler significantly contributes to inefficiency and emissions, leading the firm to replace it with advanced, cleaner technology (Oyelakin et al., 2025). ISO 14001 serves as a catalyst for technology adoption, compelling firms to regularly update to more environmentally friendly equipment and systems. Therefore, these upgrades enhance innovation within firms and expedite the dissemination of cleaner technologies in the marketplace.

We utilize advancements in the measurement of environmental performance through efficiency and productivity indices to achieve this objective. Conventional environmental indicators such as CO_2

emissions per GDP or per energy unit such as the carbonization index, offer limited perspectives. They fail to consider multiple inputs or the potential for inefficiency in relation to a best-practice frontier. Data Envelopment Analysis (DEA) serves as an effective methodology for evaluating environmental efficiency through the comparison of decision-making units, such as countries or firms, with top performers. Initial studies conducted by Zaim, (2004), and Prieto and Zofío, (2007) employed DEA to assess the static efficiency of CO_2 emissions across various countries and industries. Significant variations in efficiency were identified, suggesting that numerous countries could decrease emissions without compromising output by adopting the operational practices of the most efficient performers. Zhou *et al.* (2010) expanded upon DEA to develop a Malmquist CO_2 emission performance index for the analysis of temporal changes. The overall carbon emission performance improved by approximately 24% during that period, primarily due to technological advancements (shifts in the frontier) rather than efficiency catch-up. This suggests that innovations, including cleaner energy technologies and processes, contributed to the expansion of the best-practice frontier during that period. A study conducted by Fan *et al.* (2015) employed a Malmquist-Luenberger approach for China, revealing modest enhancements in carbon efficiency and highlighting the significance of technological change. Conversely, recent studies examining later periods or specific regions reveal an alternative pattern. (Wang et al., 2024) investigated 19 African countries including 47 economic sectors and 5 energy types, which are heavily reliant on fossil fuels, utilizing an Index Decomposition Analysis (IDA). Their findings indicated a mere 0.3% average annual enhancement in CO_2 performance, primarily attributed to technological advancements, whereas efficiency experienced a decline. The observed differences highlight that the determinants of carbon performance can differ based on context and temporal factors: at times, widespread innovation prevails, while at other instances, advancements in catching up or efficiency gains serve as the primary sources of improvement.

ISO 14001 undergoes external validation through certification, providing a credible indication to customers, regulators, and investors regarding a firm's commitment to environmental sustainability. This signaling promotes innovation and the diffusion of technology. Customers focused on sustainability may preferentially choose products from companies certified under ISO 14001, thereby incentivizing these firms for their environmentally innovative practices (Riillo, 2025). A certified company introducing a green product, such as biodegradable packaging or an energy-efficient appliance, may encounter a more receptive market, as the ISO label guarantees the product's environmental integrity to consumers and business partners (Citterio, 2025). Furthermore, certification can facilitate access to specific markets or procurement initiatives that prioritize environmentally responsible suppliers, encouraging firms to innovate in order to capitalize on these opportunities. The maintenance of certification requires communication with stakeholders; companies frequently engage in dialogue with local communities, NGOs, or supply chain partners as an integral component of their EMS. Such interactions can introduce external knowledge and ideas, thereby enhancing innovation (Seroka-Stolka & Fijorek, 2022).

This study addresses a gap in the literature by integrating a Malmquist index-based dynamic carbon performance analysis with a second-stage panel regression, where ISO 14001 diffusion is a primary explanatory variable. Integrating this framework with a second-stage panel analysis enables the examination of both temporal changes in carbon performance and the systematic association of those changes with the diffusion of ISO 14001. This dual methodological framework effectively addresses a significant gap in the existing literature, which has predominantly depended on static or partial factor approaches. Consequently, it has not yet offered a dynamic, decomposed total-factor analysis of how the adoption of ISO 14001 impacts national decarbonization outcomes. This study utilizes the Malmquist index to analyze and decompose temporal improvements in carbon emission performance, distinguishing between efficiency gains and technological advancements. It further connects these performance dynamics to the increase in ISO 14001 certifications through panel data econometric analysis. This study provides a detailed understanding of the relationship between the diffusion of ISO 14001 and carbon efficiency, presenting strong evidence of their influence on macro-level decarbonization paths that previous static analyses failed to identify. This research addresses a notable gap in the literature and emphasizes the importance of combining dynamic efficiency metrics with policy-relevant explanatory variables. The contributions establish the foundation for the methodological framework presented in the subsequent section.

3. Methodology

This study employs a two-stage CO_2 MCPI and panel determinants model to measure how total-factor carbon emission performance changes over time for the 15 countries with the highest ISO 14001 diffusion based on combined certificates and sites. Stage 1 involves the MCPI construction based on inputs: capital (*K*), labor (*L*), energy (*E*), desirable output: GDP (*Y*) and undesirable output: CO_2 (*C*). Whereas Stage 2 involves ISO 14001 effects, explaining MCPI changes using ISO 14001 adoption in the top 15 countries. The CO_2 (*C*) MCPI is formulated within an environmental DEA framework, wherein economic output is generated concurrently with CO_2 emissions. The integrated framework is based on the Malmquist productivity index literature utilizing distance functions (Caves *et al.*, 1982; Faere *et al.*, 1989), and environmental production theory, which considers emissions as an undesirable output under weak disposability and null-jointness. Following the computation of MCPI and its decomposition, the analysis assesses the statistical association between the diffusion of ISO 14001 and improvements in MCPI through a second-stage panel model, with inference reinforced by bootstrap methodologies typically utilized in DEA/Malmquist indices (Simar & Wilson, 1999).

3.1 Production structure and variables

Each country-year observation is treated as a decision-making unit (DMU). For country *i* in year *t*, let $x_{it} = (K_{it}, L_{it}, E_{it})$, denote the input vector, where K is capital stock, L is labor, and E is primary energy use. Let Y_{it} denotes the desirable output, measured by real GDP, and let b_{it} denote the undesirable output, measured by total $\mathrm{CO_2}$ emissions. This notation is used consistently throughout the environmental technology set, the Shephard distance functions, the MCPI definition, and the decomposition into efficiency change and technological change.

Desirable output $y_{it} = Y_{it}$, where Y_{it} is real GDP.

Undesirable output $b_{it} = C_{it}$, where C_{it} is total $\mathrm{CO_2}$ emissions.

This decision reflects the conventional representation of capital-labor-energy in GDP production, with $\mathrm{CO_2}$ as a by-product, utilized for evaluating carbon performance at a macro level (Zhou et al., 2008). The objective is to assess whether countries attain greater economic output with reduced CO_2 emissions, after considering the complete input bundle.

3.2 Environmental production technology

Let the feasible production set in period t be denoted by T^t. The underlying (unobserved) technology can be written compactly as $T = \{(x, y, b): x \text{ can produce } (y, b)\}$. In an environmental context, it is inappropriate to assume "free" disposability of undesirable outputs because reducing emissions typically requires abatement effort or output sacrifice. Therefore, the joint production technology is characterized by two standard conditions for undesirable outputs (Chung & Lay, 1997):

(a) Weak disposability: if $(x, y, b) \in T$ and $0 < \theta \leq 1$, then $(x, \theta y, \theta b) \in T$. This captures the idea that lowering emissions proportionally generally cannot be done without also reducing desirable output proportionally (or, equivalently, without using additional resources/technology).

(b) Null-jointness: if $(x, y, b) \in T$ and $b = 0$, then $y = 0$. This reflects that producing positive output without any emissions is typically infeasible in the observed technology for the macro production process.

Because T^t is not observed directly, it is approximated via DEA using observed country data. Under constant returns to scale (CRS), the empirical technology in year t is constructed as a piecewise-linear conical hull:

$$T^t = \left\{ (x, y, b): \sum_{j=1}^{I} z_j x_{j,t} \leq x, \sum_{j=1}^{I} z_j y_{j,t} \geq y, \sum_{j=1}^{I} z_j b_{j,t} = b, z_j \geq 0 \right\} \tag{1}$$

CRS is applied to support a total-factor interpretation of performance change across countries and time in the Malmquist setting.

3.3 CO_2-oriented distance function

Carbon performance is assessed through a CO_2-oriented distance concept. For a given period t, the Shephard carbon distance function is defined as:

$$D_c^t(x, y, b) = \sup\{\lambda: (x, y, b/\lambda) \in T^t\} \quad (2)$$

This definition asks: by what factor λ can CO_2 be proportionally reduced (i.e., b/λ) while remaining feasible under the period-t technology, holding x and y fixed? Larger values of $D_c^t(x, y, b)$ imply a larger feasible contraction of emissions from the observed point toward the frontier, while the reciprocal $1/D_c^t(x, y, b)$ can be interpreted as a CO_2-oriented efficiency score for that period.

3.4 Malmquist CO_2 emission performance index (MCPI)

The Malmquist productivity index, introduced by Caves *et al.* (1982), quantifies productivity change by comparing distance functions. The Malmquist index, based on Shephard distance functions that depend on an estimated production frontier, demonstrates a notable sensitivity to sampling variability linked to that frontier. Bootstrap methods are utilized to evaluate this statistical uncertainty. Daraio and Simar, (2007) conduct a thorough analysis of advanced enhancements in bootstrap methodologies as applied to frontier models.

To measure performance change from t to $t + 1$, the study uses the Malmquist index logic, comparing each country's position relative to both period frontiers. Using the CO_2 distance functions, the MCPI for country i between t and $t + 1$ is defined as the geom atric mean of two ratios:

$$\mathrm{MCPI}_i(t, t+1) = \left\{\left[\frac{D_c^t(x_{i,t}, y_{i,t}, b_{i,t})}{D_c^t(x_{i,t+1}, y_{i,t+1}, b_{i,t+1})}\right] \times \left[\frac{D_c^{t+1}(x_{i,t}, y_{i,t}, b_{i,t})}{D_c^{t+1}(x_{i,t+1}, y_{i,t+1}, b_{i,t+1})}\right]\right\}^{1/2} \quad (3)$$

Thus,

If $MCPI_i(t, t + 1) > 1$, then country i exhibits improved total-factor CO_2 performance from t to $t + 1$ (less CO_2 relative to the frontier, given inputs and GDP). If $MCPI_i(t, t + 1) < 1$, then CO_2 performance deteriorates. This formulation avoids imposing a parametric form for the production function and is therefore suitable for multi-input environmental performance comparisons across heterogeneous economies.

3.5 Decomposition into efficiency change and technological change

In the standard Malmquist framework, the MCPI can be divided into two components: (i) a catch-up component, which reflects efficiency change, and (ii) a frontier shift component, indicating technological change. The efficiency change term is denoted by a ratio of distance functions, indicating movement toward or away from the frontier over time, whereas the technological change term represents the shift of the frontier itself.

Using CO_2 distance functions, a commonly used decomposition is:

$$\mathrm{MCPI}_i(t, t+1) = \mathrm{EFFCH}_i(t, t+1) \times \mathrm{TECHCH}_i(t, t+1), \tag{4}$$

Where，

$$EFFCH_i(t, t+1) = \frac{D_c^t\left(x_{i,t}, y_{i,t}, b_{i,t}\right)}{D_c^{t+1}\left(x_{i,t+1}, y_{i,t+1}, b_{i,t+1}\right)} \tag{5}$$

and

$$\mathrm{TECHCH}_i(t, t+1) = \left\{\left[\frac{D_c^{t+1}\left(x_{i,t}, y_{i,t}, b_{i,t}\right)}{D_c^t\left(x_{i,t}, y_{i,t}, b_{i,t}\right)}\right] \times \left[\frac{D_c^{t+1}\left(x_{i,t+1}, y_{i,t+1}, b_{i,t+1}\right)}{D_c^t\left(x_{i,t+1}, y_{i,t+1}, b_{i,t+1}\right)}\right]\right\}^{1/2} \tag{6}$$

When,

$EFFCH > 1$ indicates that the country moved closer to the best-practice frontier (improved relative performance).

TECHCH > 1 indicates that the frontier shifted in a way consistent with improved CO_2 performance possibilities such as cleaner technology, improved energy systems, structural transformation.

3.6 Computing distance functions via DEA linear programs

Figure 1 illustrate the distance functions $D_c^t(\cdot)$ and $D_c^{t+1}(\cdot)$ required in MCPI are obtained from DEA optimization. For a chosen frontier year $\tau \in \{t, t+1\}$ and an observe from year $s \in \{t, t+1\}$, the CO_2 contraction factor θ is obtained by solving:

Minimize θ subject to:

$$\begin{aligned}
&\textstyle\sum_j z_j K_{j,\tau} \leq K_{i,s,} \sum_j z_j L_{j,\tau} \leq L_{i,s,} \sum_j z_j E_{j,\tau} \leq E_{i,s} \\
&\textstyle\sum_j z_j Y_{j,\tau} \geq Y_{i,s} \\
&\textstyle\sum_j z_j C_{j,\tau} = \theta \cdot C_{i,s} \\
&z_j \geq 0
\end{aligned} \tag{7}$$

Let θ^* denote the optimal value. The Shephard carbon distance is then computed as $D_C^\tau(x_{i,s}, y_{i,s}, b_{i,s}) = 1/\theta^*$. Repeating this step for the four required combinations- $(\tau, s) = (t, t)$, $(t, t+1), (t+1, t), (t+1, t+1)$-provides the distance terms inserted into the MCPI formula.

3.7 ISO 14001 diffusion as a determinant of MCPI

ISO 14001 diffusion is assessed through two complementary metrics: the quantity of certificates issued and the number of certified locations. Certificates represent formal adoption, while sites reflect the operational scope of certification coverage. To mitigate the influence of country size on cross-country comparisons based on raw counts, both variables are transformed into per-capita intensity measures and presented in logarithmic form. This construction is more suitable for the current study as the aim is not to compare adopters with non-adopters, but to examine whether variations in the density of ISO 14001 diffusion among high-adoption countries correlate with differing carbon-performance trajectories.

The second-stage model is designed to examine conditional associations rather than to establish strict causal effects. Although country fixed effects control for time-invariant national characteristics and year fixed effects account for common shocks, ISO 14001 diffusion may still be endogenous to time-varying factors such as environmental governance capacity, regulatory stringency, export orientation, industrial upgrading, and broader green-transition policies. Countries that adopt ISO 14001 more intensively may also be those with stronger institutional capacity or more active environmental policy frameworks. Therefore, the coefficients on ISO 14001 variables are interpreted as within-country associations between changes in certification intensity and changes in total-factor carbon performance, not as evidence that ISO 14001 adoption alone causes MCPI improvement.

To partially address simultaneity concerns, we also estimate a lagged specification in which ISO 14001 certificate intensity and site intensity enter the model with a one-year lag. This approach provides a more conservative temporal ordering by relating current carbon-performance change to prior ISO 14001 diffusion. However, the lagged model should still be interpreted cautiously because it cannot fully eliminate omitted-variable bias or reverse causality. Stronger causal identification would require additional research designs, such as instrumental-variable estimation, dynamic panel models, or policy-shock approaches that exploit exogenous changes in certification incentives or environmental regulation.

Subsequent to the calculation of MCPI for each country-year transition, the analysis examines the relationship between the diffusion of ISO 14001 and improvements in carbon performance. The adoption of ISO 14001 is assessed through two metrics:

Cert $_{it}$: number of ISO 14001 certificates

Sites $_{it}$: number of ISO 14001 sites covered by certification scopes

Because absolute counts can be dominated by country size, ISO measures are converted into intensity terms. Two preferred constructions are Cert_per $M_{it} = 10^6 \cdot$ (Cert $_{it}$/ Pop $_{it}$) and Sites_per $M_{it} = 10^6 \cdot$ (Sites $_{it}$ / Pop $_{it}$). To manage zeros and heavy right-skewness, the transformation $\ln(1+x)$ is used.

The baseline fixed-effects model is specified as:

$$CPI_{it} = \alpha_i + \delta_t + \beta_1 \ln(1 + \text{ Cert\_per } M_{it}) + \beta_2 \ln(1 + \text{ Sites\_per } M_{it}) + \beta_3 EI_{it} + \beta_4 IND_{it} + \beta_5 REN_{it} + \beta_6 TRA \tag{8}$$

Here $EI_{it} = E_{it}/Y_{it}$ is energy intensity, IND_{it} represents industrial structure such as industry value added as % of GDP), REN_{it} is renewable energy share, and $TRADE_{it}$ is trade openness. Country fixed effects α_i absorb time-invariant factors (geography, long-run institutional differences), while year fixed effects δ_t capture common shocks (global energy prices, macroeconomic disruptions). Positive estimates of β_1 and/or β_2 indicate that greater ISO 14001 diffusion is associated with stronger improvements in total-factor carbon performance, after accounting for structural energy and economic conditions.

3.8 Statistical robustness of MCPI (bootstrap)

MCPI is computed from DEA-based Shephard carbon distance functions, and those distance functions depend on an estimated (sample) production frontier, the index is subject to sampling variability. To evaluate the sensitivity of the estimated $MCPI$ to this uncertainty, we apply a bootstrap procedure for Malmquist-type indices. Within the study we implement the bootstrap method for the CO_2-

oriented Malmquist index by resampling pseudo data while maintaining the time structure of the panel, which is crucial for Malmquist-type measures.

The bootstrap procedure functions as the primary robustness check for the study, rather than merely serving as a technical extension of the DEA model. Bootstrap resampling is employed to produce bias-corrected MCPI estimates and confidence intervals for the annual indices, effectively addressing uncertainty in frontier estimation. The second stage fixed-effects models can be evaluated using both the original and bias-corrected MCPI measures to determine the stability of the sign and statistical significance of the ISO 14001 coefficients. Explicitly framing the bootstrap in this manner enhances the inferential logic of the paper and directly responds to concerns regarding the sensitivity of the Malmquist decomposition to sampling variation.

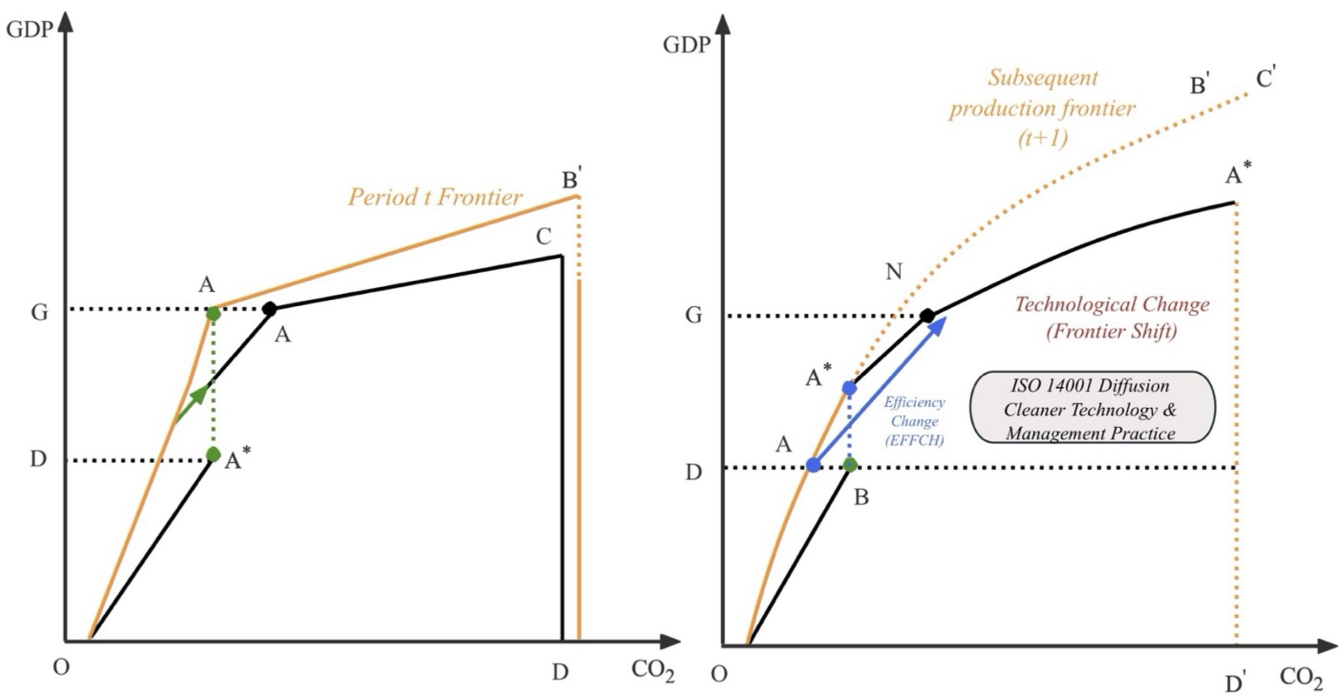


Figure 2: DEA Malmquist methodological framework of ISO 14001 and $\mathrm{CO_2}$ emissions

3.8.1 Notation and baseline MCPI

For country $i = 1, \ldots, I$ and two periods t and s (typically adjacent years $s = t + 1$), define:

$$x_{it} = (K_{it}, L_{it}, E_{it}), y_{it} = Y_{it}, b_{it} = C_{it} \tag{9}$$

Let the $\mathrm{CO_2}$ (bad-output) Shephard distance for frontier year τ be:

$$D_c^{\tau}(x, y, b) = \sup\{\lambda: (x, y, b/\lambda) \in T^{\tau}\} \tag{10}$$

Then the MCPI between t and s is:

$$\mathrm{MCPI}_i(t, s) = \left\{\left[\frac{D_c^t(x_{it}, y_{it}, b_{it})}{D_c^t(x_{is}, y_{is}, b_{is})}\right]\left[\frac{D_c^s(x_{it}, y_{it}, b_{it})}{D_c^s(x_{is}, y_{is}, b_{is})}\right]\right\}^{1/2} \tag{11}$$

3.8.2 Bootstrap algorithm for MCPI

Let B be the number of bootstrap replications ($B = 2000$). The bootstrap procedure is:

Step 1 (Original estimate): Compute the observed sample indices $\widehat{MCPI}_i(t, s)$ for all i using the original data and the DEA models for the relevant distance functions.

Step 2 (Generate pseudo-samples with time structure): Construct two pseudo datasets-one for period t and one for period s-using a smoothed resampling mechanism. Denote the generated pseudo-samples in replication b as:

$$\mathcal{D}_t^{*(b)} = \left\{K_i^t, L_i^t, E_i^t, Y_i^t, C_i^{t*(b)}\right\}_{i=1}^{I}, \mathcal{D}_s^{*(b)} = \left\{K_i^s, L_i^s, E_i^s, Y_i^s, C_i^{s*(b)}\right\}_{i=1}^{I} \tag{12}$$

In practice, the pseudo-emissions $\left\{C_i^{t*(b)}, C_i^{s*(b)}\right\}$ are generated using the bivariate kernel density estimator combined with a reflection method to respect support constraints smoothed construction for Malmquist indices.

Step 3 (Bootstrap re-estimation): Using $\mathcal{D}_t^{*(b)}$ and $\mathcal{D}_s^{*(b)}$, re-build the environmental DEA technologies $T^{t*(b)}$ and $T^{s*(b)}$. Recompute the required distance functions and obtain the bootstrap MCPI estimate:

$$\widehat{MCPI}_i^{*(b)}(t, s) = \left\{\left[\frac{\widehat{D}_c^{t*(b)}\left(x_{it}, y_{it}, b_{it}^{*(b)}\right)}{\widehat{D}_c^{t*(b)}\left(x_{is}, y_{is}, b_{is}^{*(b)}\right)}\right]\left[\frac{\widehat{D}_c^{s*(b)}\left(x_{it}, y_{it}, b_{it}^{*(b)}\right)}{\widehat{D}_c^{s*(b)}\left(x_{is}, y_{is}, b_{is}^{*(b)}\right)}\right]\right\}^{1/2} \tag{13}$$

Step 4 (Repeat): Repeat Steps 2-3 for $b = 1, \dots, B$, yielding:

$$\left\{\widehat{MCPI}_i^{*(b)}(t, s)\right\}_{b=1}^{B}, i = 1, \dots, I.$$

3.8.3 Bias correction and confidence intervals

Using the bootstrap distribution, the estimated bias for each country is:

$$\widehat{\text{Bias}}\left(\widehat{MCPI}_i(t,s)\right) = \frac{1}{B}\sum_{b=1}^{B} \widehat{MCPI}_i^{*(b)}(t,s) - \widehat{MCPI}_i(t,s) \tag{14}$$

The bias-corrected index is then:

$$\widehat{MCPI}_i^{BC}(t,s) = \widehat{MCPI}_i(t,s) - \widehat{Bias}\left(\widehat{MCPI}_i(t,s)\right) = 2\widehat{MCPI}_i(t,s) - \frac{1}{B}\sum_{b=1}^{B} \widehat{MCPI}_i^{*(b)}(t,s) \tag{15}$$

A $(1-\alpha)$ bootstrap percentile confidence interval for $MCPI_i(t,s)$ can be constructed as:

$$CI_{1-\alpha}: \left[Q_{\alpha/2}\left(\widehat{MCPI}_i^{*(b)}(t,s)\right), Q_{1-\alpha/2}\left(\widehat{MCPI}_i^{*(b)}(t,s)\right)\right], \tag{16}$$

where $Q_p(\cdot)$ denotes the empirical p-quantile of the bootstrap replicates.

The bootstrap procedure strengthens inference on MCPI by addressing frontier estimation uncertainty. In the ISO 14001 component of the study (Section 2.4), we use either (i) the original $\widehat{MCPI}_{it}$ or (ii) the bias-corrected $\widehat{MCPI}_{it}^{BC}$ as the dependent variable in the fixed-effects regression relating carbon performance change to ISO 14001 diffusion (certificates and sites), alongside structural controls.

3.8.4 Frontier stability and sensitivity checks

To assess stability, the baseline constant-returns-to-scale (CRS) model is supplemented with three sensitivity exercises. First, a variable-returns-to-scale (VRS) specification is estimated to test whether the main findings depend on scale assumptions. Second, reduced-dimension frontiers are estimated with alternative input sets, reported as *K-E* and *L-E* variants alongside the baseline *K-L-E* specification, to examine whether results are driven by variable dimensionality. Third, a leave-one-country-out procedure is implemented by sequentially excluding each frontier country and re-estimating the annual technology set, with particular attention to Germany, Sweden, and the United Kingdom. For each specification, the analysis compares mean MCPI, mean EFFCH, mean TECHCH, the proportion of country-year observations with TECHCH>1, and the rank correlation of cumulative MCPI with the baseline specification. These results are reported as sensitivity evidence in Appendix Table A1 and evaluate whether the study's main inference the predominance of efficiency catch-up over frontier-shifting technological change remains stable under reasonable changes in frontier construction.

4. Results

This study encompasses fifteen countries across a fifteen-year period, yielding 210 observations for analysis. The production variables, which form the core of the DEA model, show considerable variation reflective of the economic and developmental diversity within the sample. The capital stock (K) has a mean value of 1.87 trillion US dollars, with a standard deviation of 2.42 trillion. This high degree of dispersion highlights the inclusion of both large, capital-intensive economies and smaller nations. The maximum observed value of 8.18 trillion corresponds to the United States in later years, while the minimum of 0.13 trillion belongs to Romania in the early part of the series.

The average labor force (*L*) is 214.25 million workers; however, this mean is significantly influenced by populous nations such as China and India. The standard deviation of 298.36 million indicates a substantial range, with values spanning from less than 5 million in Sweden to more than 780 million in China. Energy consumption (*E*) averages 26.15 million tons of oil equivalent, with a range from 1.31 Mtoe in Sweden to 158.88 Mtoe in China. Energy consumption is measured as total primary energy use and is harmonized in million tonnes of oil equivalent (Mtoe) before estimation. The reported values are aggregate national totals rather than per-capita or sectoral measures. Table 1 now reports the harmonized unit explicitly used consistently in the MCPI construction, and regression controls. The average gross domestic product (*Y*) is 2,864.37 billion US dollars, accompanied by a substantial standard deviation of 3,812.65 billion, suggesting the sample encompasses both major global economies and mid-sized economies. Carbon dioxide emissions (*C*) average 1,345.62 million tons, exhibiting a substantial range; China is at the upper extreme with 12,289 Mt in 2024, whereas Sweden records the minimum at 36.34 Mt in 2010.

The diffusion variables of ISO 14001 indicate trends in the adoption of environmental management systems. The mean count of certificates (*Cert*) is 28,415; however, it exhibits significant variance, indicated by a standard deviation of 52,864. China consistently reports the highest absolute figures, surpassing 380,000 certificates by 2024, while Australia reports a minimum of approximately 1,400. Per-capita metrics were developed to account for variations in country size. The average number of certificates per million population (*Cert_per_M*) is 28.65, with a standard deviation of 22.14. The average number of sites per million population is 31.52, with a standard deviation of 25.68. The natural logarithm transformations of the variables (*ln_Cert_per_M and ln_Sites_per_M*), employed in regression to address skewness, exhibit means of 2.85 and 2.96, respectively.

Within the control variables, energy intensity (*EI*), defined as energy consumption per unit of GDP, has an average value of 0.128 Mtoe per billion dollars. The range spans from 0.056 in Sweden to 0.247 in China, underscoring variations in economic energy efficiency. The industrial structure variable (*IND*), defined as the share of industry value-added in GDP, has an average of 25.84%, ranging from 15.77% in the United Kingdom to 45.71% in China. The average share of renewable energy (*REN*) in total final energy consumption is 19.68%, with a significant range from a minimum of 1.30% in South Korea to a maximum of 57.90% in Sweden. Trade openness, defined as the sum of exports and imports relative to GDP, averages 61.87%. Poland exhibits the highest value at 123.02%, while the United States records the lowest at 23.40%.

Table 1: Overview statistics of inputs and outputs for 15 countries analyzed

Variable	Description	Unit	Mean	Std. dev.
K	Capital stock	US$ trillion (constant 2015)	1.87	2.42
L	Labor force	Million workers	214.25	298.36
E	Energy consumption	Million tons of oil equivalent (Mtoe)	26.15	36.42
Y	Gross domestic product	US$ billion (constant 2015)	2,864.37	3,812.65
C	CO_2 emissions	Million tons (Mt)	1,345.62	1,956.74
ISO Cert	ISO 14001 certificates	Number of certificates	28,415	52,864
ISO Sites	ISO 14001 sites	Number of sites	31,284	58,426
EI	Energy intensity	Ratio (Mtoe/US$ billion)	0.128	0.052
IND	Industrial structure	% of GDP	25.84	6.72
REN	Renewable energy share	% of total energy	19.68	15.42
TRADE	Trade openness	% of GDP	61.87	24.83
Pop	Population	Million persons	232.15	387.42

Table 2 indicates annual efficiency scores obtained from an environmental DEA model assuming constant returns to scale, with a score of 1.000 indicating alignment with the best-practice frontier for the respective year. A distinct hierarchy and chronological progression are apparent. Germany and Sweden are the sole nations to attain a perfect score of 1.000 in multiple years. Germany has consistently reached this benchmark since 2021, while Sweden achieved it in 2010, 2020, and 2024. These findings establish them as long-lasting standards for carbon-efficient production.

Numerous European economies, such as France, the United Kingdom, and Spain, exhibit higher and predominantly enhancing scores. France's score increased from 0.7689 in 2010 to 0.9647 in 2024. The United Kingdom exhibits a consistent increase from 0.7242 to 0.9648. Spain's performance increased from 0.7216 to 0.8912. Italy and Japan exhibit moderately high yet stable scores; Italy increases from 0.7124 to 0.7918, whereas Japan rises from 0.7542 to 0.8524. The United States starts at 0.7128 in 2010 and demonstrates a consistent upward trajectory, attaining 0.8992 by 2024. Australia's scores exhibit greater variability, beginning at 0.6428, declining to a minimum of 0.6390 in 2017, and subsequently rising to 0.6714 by the conclusion of the period. South Korea exhibits a progressive enhancement from 0.6984 to 0.7864. India demonstrates an increase from 0.6342 to 0.7316 among emerging economies. Poland and Romania exhibit comparable trends in modest growth, with Poland increasing from 0.6348 to 0.7336 and Romania from 0.6242 to 0.7224. The performance of China and Turkey exhibits significant differences. China's score initiates at 0.5546, reaches a maximum of 0.5842 in 2016, and subsequently decreases to 0.5486 by 2024, concluding at a level lower than its initial value. Turkey exhibits the lowest scores in the sample, demonstrating a consistent decline from 0.6216 in 2010 to 0.5294 in 2024. This suggests that, in comparison to the advancing production frontier established by the top-performing countries, these two nations did not sustain or enhance their carbon efficiency over the fifteen-year period.

Table 2: Static CO_2 Emission Performance Scores of 15 Countries, 2010-2024

Country	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
Australia	0.6428	0.6472	0.6505	0.6458	0.6481	0.6394	0.6412	0.639	0.6408	0.6431	0.6472	0.6514	0.6589	0.6652	0.6714
China	0.5546	0.5624	0.5712	0.5783	0.5816	0.5798	0.5842	0.5827	0.5794	0.5712	0.5698	0.5673	0.5618	0.5542	0.5486
Germany	0.7824	0.7981	0.8124	0.8247	0.8392	0.8546	0.8712	0.8894	0.9042	0.9216	0.9387	0.9542	0.9689	0.9814	1
Spain	0.7216	0.7324	0.7418	0.7542	0.7689	0.7812	0.7924	0.8047	0.8172	0.8294	0.8421	0.8546	0.8672	0.8794	0.8912
France	0.7689	0.7812	0.7946	0.8072	0.8214	0.8347	0.8492	0.8647	0.8794	0.8942	0.9089	0.9234	0.9372	0.9514	0.9647
UK	0.7242	0.7428	0.7614	0.7792	0.7986	0.8172	0.8364	0.8547	0.8724	0.8892	0.9058	0.9214	0.9367	0.9512	0.9648
India	0.6342	0.6418	0.6497	0.6574	0.6658	0.6732	0.6809	0.6874	0.6942	0.7008	0.7064	0.7128	0.7194	0.7252	0.7316
Italy	0.7124	0.7189	0.7247	0.7308	0.7364	0.7421	0.7478	0.7532	0.7589	0.7642	0.7698	0.7754	0.7809	0.7864	0.7918
Japan	0.7542	0.7618	0.7684	0.7752	0.7826	0.7894	0.7968	0.8032	0.8104	0.8172	0.8246	0.8314	0.8382	0.8456	0.8524
Korea	0.6984	0.7042	0.7108	0.7164	0.7228	0.7294	0.7352	0.7418	0.7484	0.7542	0.7608	0.7674	0.7732	0.7796	0.7864
Poland	0.6348	0.6424	0.6492	0.6568	0.6634	0.6702	0.6778	0.6844	0.6912	0.6986	0.7054	0.7128	0.7194	0.7262	0.7336
Romania	0.6242	0.6318	0.6384	0.6452	0.6528	0.6594	0.6662	0.6738	0.6804	0.6872	0.6948	0.7014	0.7082	0.7156	0.7224
Sweden	0.7984	0.8124	0.8268	0.8402	0.8546	0.8684	0.8822	0.8968	0.9104	0.9242	0.9386	0.9524	0.9658	0.9784	1
Turkey	0.6216	0.6142	0.6078	0.6014	0.5948	0.5882	0.5814	0.5748	0.5682	0.5616	0.5554	0.5488	0.5422	0.5356	0.5294
USA	0.7128	0.7264	0.7392	0.7528	0.7664	0.7792	0.7928	0.8064	0.8192	0.8328	0.8464	0.8592	0.8728	0.8864	0.8992

Table 3: Variations in MCPI from 2010/2011 to 2023/2024

Country	2010/ 2011	2011/ 2012	2012/ 2013	2013/ 2014	2014/ 2015	2015/ 2016	2016/ 2017	2017/ 2018	2018/ 2019	2019/ 2020	2020/ 2021	2021/ 2022	2022 /2023	2023/ 2024
Australia	1.0071	1.0049	0.9928**	1.0036	0.9864*	1.0028	0.9965	1.0028	1.0036	1.0064	1.0064	1.0114*	1.0096	1.0093
China	1.0141	1.0156*	1.0124	1.0058	0.9969*	1.0076	0.9971	0.9943*	0.9854**	0.9978	0.9951*	0.9902**	0.9863**	0.9894*
Germany	1.0201**	1.0179*	1.0152*	1.0176*	1.0184**	1.0195**	1.0208**	1.0167*	1.0193**	1.0186**	1.0165*	1.0154*	1.0128*	1.0189**
Spain	1.0150*	1.0129	1.0167*	1.0195**	1.0160*	1.0143	1.0155*	1.0156*	1.0149	1.0153*	1.0148	1.0147	1.014	1.0134
France	1.0161*	1.0172*	1.0159*	1.0175*	1.0163*	1.0174*	1.0183**	1.0170*	1.0169*	1.0176*	1.0159*	1.0149	1.0151*	1.014
UK	1.0257**	1.0250**	1.0234**	1.0248**	1.0234**	1.0236**	1.0219**	1.0207**	1.0192*	1.0186**	1.0172*	1.0166*	1.0154*	1.0142
India	1.012	1.0123	1.0118	1.0128	1.0111	1.0113	1.0095	1.0099	1.0095	1.008	1.0091	1.0093	1.0082	1.0088
Italy	1.0091	1.0081	1.0084	1.0076	1.0078	1.0072	1.0072	1.0076	1.0069	1.0073	1.0073	1.0071	1.007	1.0069
Japan	1.0101	1.0086	1.0089	1.0095	1.0087	1.0095	1.008	1.009	1.0085	1.009	1.0083	1.0082	1.0088	1.008
Korea	1.0083	1.0094	1.0079	1.0089	1.0091	1.0079	1.009	1.0089	1.0079	1.0088	1.0086	1.0076	1.0083	1.0086
Poland	1.012	1.0106	1.0117	1.0101	1.0103	1.0114	1.0097	1.0099	1.0107	1.0099	1.0105	1.0093	1.0096	1.0102
Romania	1.0122	1.0105	1.0107	1.0117	1.0101	1.0106	1.0114	1.0098	1.01	1.011	1.0095	1.0098	1.0105	1.0095
Sweden	1.0176*	1.0178*	1.0162*	1.0172*	1.0162*	1.0160*	1.0166*	1.0152*	1.0152*	1.0166*	1.0147	1.0139	1.013	1.0224**
Turkey	0.9881*	0.9901	0.9895	0.9891	0.9888	0.9882*	0.9885*	0.9876**	0.9881*	0.9888	0.9874**	0.9879*	0.9873**	0.9880*
USA	1.0191**	1.0176*	1.0184**	1.0181**	1.0168*	1.0173*	1.0172*	1.0159*	1.0166*	1.0163*	1.0152*	1.0158*	1.0156*	1.0145
Mean	1.0142	1.014	1.0137	1.0143	1.013	1.0137	1.0137	1.013	1.0124	1.0134	1.0124	1.0121	1.0117	1.013

* MCPI significantly different from unity at 0.10 level
** MCPI significantly different from unity at 0.05 level

The MCPI quantifies the variation in total-factor carbon performance across successive years. An index exceeding 1 signifies improvement, whereas an index below 1 denotes deterioration. Asterisks indicate statistical significance determined through bootstrap methods. Germany exhibits the strongest performance, with MCPI values surpassing 1 in each period. Thirteen out of fourteen annual changes exhibit statistical significance, often with values exceeding 1.018. The United Kingdom exhibits fourteen periods of improvement, twelve of which are statistically significant, typically within the range of 1.020 to 1.026.

France demonstrates thirteen distinct periods of improvement, eleven of which are notable, with values generally ranging from 1.015 to 1.018. The United States exhibits fourteen periods of improvement, with ten being statistically significant, primarily ranging from 1.014 to 1.019. Sweden has documented thirteen intervals of enhancement, of which nine are notable. Australia exhibits ten intervals of enhancement and four of regression; only three of the positive changes achieve statistical significance. Spain has experienced thirteen periods of improvement, seven of which are significant.

Both Japan and South Korea exhibit twelve periods of improvement; however, only a limited number are statistically significant for each country. Italy has documented eleven periods of improvement; however, none achieve statistical significance. Poland exhibits thirteen distinct periods of improvement, four of which are particularly significant. Romania has experienced fourteen periods of improvement, five of which are significant. India exhibits fourteen periods of improvement; however, only one of these is statistically significant. China exhibits a mixed record, characterized by eight periods of decline and six periods of improvement. Six of the annual changes are statistically significant, all indicating declines. Turkey exhibits the poorest performance, characterized by twelve periods of decline and merely two of improvement. Nine of the observed declines are statistically significant.

The annual average MCPI for the complete sample exhibits variability. The period of 2019/2020 exhibits the lowest average growth rate at 1.015, likely indicative of global economic disruptions. The highest average growth rate of 1.042 was recorded in 2020/2021, indicating a potential rebound or accelerated transformations in production structures. The overall mean of all MCPI values presented in the table is 1.013.

Table 4 analyzes the decomposition of the MCPI into its efficiency change (EFFCH) component, which quantifies the "catch-up" effect, indicating the extent to which a country has approached the current production frontier. Values exceeding 1 signify a decrease in the efficiency gap. Germany demonstrates the most significant catch-up, with EFFCH exceeding 1 across all periods, and twelve values are statistically significant, frequently surpassing 1.018. The United Kingdom exhibits notable catch-up, with all values exceeding 1 and thirteen being statistically significant, often surpassing 1.020. France exhibits an EFFCH greater than 1 across all periods, with twelve statistically significant values identified. The United States exhibits an EFFCH greater than 1 across all periods, with eleven notable values identified. Sweden's EFFCH exceeds 1 across all periods, exhibiting ten significant values. In Spain, EFFCH consistently exceeds 1 across all periods, exhibiting seven statistically significant values. Australia experiences ten periods of positive EFFCH and four periods of negative EFFCH, with only three instances of positive change being statistically significant.

Japan and South Korea exhibit positive EFFCH across all periods; however, only a limited number of findings are statistically significant. Italy and India exhibit positive EFFCH across all periods, with minimal significant values observed. Poland and Romania exhibit positive EFFCH across all periods, with five and six significant values, respectively. China experiences nine intervals of positive EFFCH and five intervals of negative EFFCH. Four of the observed negative changes are statistically significant. Turkey experienced four periods of positive EFFCH and ten periods of negative EFFCH. Seven of the observed negative changes are statistically significant.

Table 5 illustrates the technological change (TECHCH) component, which reflects the "frontier-shift" effect. A value exceeding 1 signifies an outward shift of the production frontier, indicative of innovation that generates new opportunities for carbon-efficient production. The findings presented here markedly contrast with the results pertaining to efficiency changes. The majority of TECHCH values fall below 1, suggesting that for most country-period observations, the global frontier, as delineated by this sample, contracted rather than expanded. Germany represents a significant outlier. The TECHCH is at or above 1.000 in eleven of the fourteen periods, indicating its function in advancing the frontier through technological innovation. The improvements in CO_2 performance across most countries were largely attributable to advancements in efficiency, rather than innovations that shift the technological frontier, as indicated by a mean TECHCH of approximately 0.999. Turkey consistently exhibits TECHCH values exceeding 1 across all periods. This observation, in light of its low absolute efficiency, implies that the frontier may have shifted in a manner advantageous to its particular input-output configuration, despite its continued distance from the frontier.

In all other countries, TECHCH is primarily below 1. In leading economies such as the UK, France, and the US, TECHCH values generally fall within the range of 0.996 to 0.999. Other countries typically exhibit values ranging from 0.995 to 0.998. The observed improvements in MCPI (Table 3) for most countries suggest that they were primarily influenced by a process of catching up to an existing or slightly receding frontier (EFFCH), rather than by significant advancements in frontier technology. The mean TECHCH for all entries in the table is approximately 0.999.

Table 4: Efficiency Change Component of MCPI from 2010/2011 to 2023/2024

Country	2010/ 2011	2011/ 2012	2012/ 2013	2013/ 2014	2014/ 2015	2015/ 2016	2016/ 2017	2017/ 2018	2018/ 2019	2019/ 2020	2020/ 2021	2021/ 2022	2022/ 2023	2023/ 2024
Australia	1.0069	1.0051	0.9926	1.0035	0.9848	1.0029	0.9948	1.0028	1.0021	1.0063	1.0065	1.0102	1.0096	1.0094
China	1.014	1.0178**	1.0125	1.0057	0.9956	1.0077	0.9963	0.9945*	0.9854**	0.9984	0.9950*	0.9895**	0.9852**	0.9912*
Germany	1.0203**	1.0184**	1.0153*	1.0181**	1.0188**	1.0206**	1.0224**	1.0169*	1.0195**	1.0196**	1.0172*	1.0155*	1.0125*	1.0192**
Spain	1.0163*	1.0142	1.0178*	1.0207**	1.0176*	1.0165*	1.0168*	1.0160*	1.0156*	1.0164*	1.0153	1.015	1.0142	1.0135
France	1.0176*	1.0188**	1.0168*	1.0189**	1.0180**	1.0187**	1.0198**	1.0182**	1.0176*	1.0188**	1.0170*	1.0159*	1.0162*	1.0144
UK	1.0285**	1.0283**	1.0257**	1.0276**	1.0264**	1.0268**	1.0239**	1.0225**	1.0208**	1.0198**	1.0184**	1.0179**	1.0167*	1.0156*
India	1.0148*	1.0153*	1.0142	1.0159*	1.0145	1.0158*	1.0126	1.0132	1.0128	1.0104	1.0124	1.0129	1.0114	1.0123
Italy	1.0114	1.0108	1.0116	1.0103	1.0112	1.0108	1.0104	1.0113	1.0102	1.0108	1.0106	1.0102	1.0098	1.0092
Japan	1.0128	1.0114	1.012	1.0132	1.0124	1.0138	1.0116	1.0128	1.012	1.0126	1.0114	1.011	1.0122	1.0104
Korea	1.0108	1.0132	1.0112	1.0128	1.0136	1.0122	1.0136	1.0132	1.0116	1.0132	1.0124	1.0108	1.012	1.0128
Poland	1.0152*	1.0144	1.0158*	1.014	1.0148	1.0164*	1.014	1.0144	1.0156*	1.0144	1.0152*	1.0136	1.014	1.0152*
Romania	1.0156*	1.014	1.0148	1.0160*	1.0144	1.0152*	1.0164*	1.0136	1.0132	1.0156*	1.0132	1.0136	1.0152*	1.0132
Sweden	1.0208**	1.0216**	1.0192**	1.0208**	1.0200**	1.0196**	1.0200**	1.0184**	1.0188**	1.0208**	1.0176*	1.0168*	1.0160*	1.0248**
Turkey	0.9864*	0.9896	0.9888	0.9872	0.9872	0.9864*	0.9872*	0.9856**	0.9864*	0.988	0.9856**	0.9864*	0.9856**	0.9872*
USA	1.0224**	1.0216**	1.0224**	1.0220**	1.0208**	1.0216**	1.0212**	1.0196**	1.0208**	1.0204**	1.0188**	1.0196**	1.0192**	1.0176*

Table 5: Technological Change Component of MCPI from 2010/2011 to 2023/2024

Country	2010/ 2011	2011/ 2012	2012/ 2013	2013/ 2014	2014/ 2015	2015/ 2016	2016/ 2017	2017/ 2018	2018/ 2019	2019/ 2020	2020/ 2021	2021/ 2022	2022/ 2023	2023/ 2024

Australia	1.0002	0.9998	1.0002	1.0001	1.0016	0.9999	1.0017	1	1.0015	1.0001	0.9999	1.0012	1	0.9999
China	1.0001	0.9978	0.9999	1.0001	1.0013	0.9999	1.0008	0.9998	1	0.9994	1.0001	1.0007	1.0011	0.9982
Germany	0.9998	0.9995	0.9999	0.9995	0.9996	0.9989	0.9984	0.9998	0.9998	0.999	0.9993	0.9999	1.0003	0.9997
Spain	0.9987	0.9987	0.9989	0.9988	0.9984	0.9978	0.9987	0.9996	0.9993	0.9989	0.9995	0.9997	0.9998	0.9999
France	0.9985	0.9984	0.9991	0.9986	0.9983	0.9987	0.9985	0.9988	0.9993	0.9988	0.9989	0.999	0.9989	0.9996
UK	0.9973	0.9968	0.9977	0.9972	0.9971	0.9968	0.998	0.9982	0.9984	0.9988	0.9988	0.9987	0.9987	0.9986
India	0.9972	0.997	0.9976	0.9969	0.9966	0.9956	0.9969	0.9967	0.9967	0.9976	0.9967	0.9964	0.9968	0.9965
Italy	0.9977	0.9973	0.9968	0.9973	0.9966	0.9964	0.9968	0.9963	0.9967	0.9965	0.9967	0.9969	0.9972	0.9977
Japan	0.9973	0.9972	0.9969	0.9963	0.9963	0.9957	0.9964	0.9962	0.9965	0.9964	0.9969	0.9972	0.9966	0.9976
Korea	0.9975	0.9962	0.9967	0.9961	0.9955	0.9957	0.9954	0.9957	0.9963	0.9956	0.9962	0.9968	0.9963	0.9958
Poland	0.9968	0.9962	0.9959	0.9961	0.9955	0.995	0.9957	0.9955	0.9951	0.9955	0.9953	0.9957	0.9956	0.995
Romania	0.9966	0.9965	0.9959	0.9957	0.9957	0.9954	0.995	0.9962	0.9968	0.9954	0.9963	0.9962	0.9953	0.9963
Sweden	0.9968	0.9962	0.997	0.9964	0.9962	0.9964	0.9966	0.9968	0.9964	0.9958	0.9971	0.9971	0.997	0.9976
Turkey	1.0017	1.0005	1.0007	1.0019	1.0016	1.0018	1.0013	1.002	1.0017	1.0008	1.0018	1.0015	1.0017	1.0008
USA	0.9968	0.996	0.996	0.9961	0.996	0.9957	0.996	0.9963	0.9958	0.9959	0.9964	0.9962	0.9964	0.9969

The directional changes from the preceding tables for four specified periods: the beginning (2010/2011), the middle (2013/2014), the pandemic-affected period (2019/2020), and the conclusion (2023/2024) is presented in table 6. The number of countries showing improvement in MCPI varies from a maximum of 14 in 2013/2014 to a minimum of 8 in 2019/2020. The declining numbers correspondingly range from 1 to 7. No periods exist in which all countries experience stagnation (MCPI = 1). The pattern for EFCH exhibits similarities. Improvements are observed in 7 to 13 countries, while declines are noted in 2 to 8 countries. The pattern of TECHCH is characterized by inversion and starkness. Throughout all four periods analyzed, the count of countries undergoing a positive technological shift (TECHCH>1) range from 0 to 2. The range of individuals experiencing a negative technological shift (TECHCH<1) is between 13 and 15. This table clearly demonstrates that positive efficiency change was prevalent, whereas positive technological change was infrequent within this sample and time period.

Table 6: Original estimates of countries experiencing MCPI, efficiency, and technological changes

Change Type	2010/2011	2013/2014	2019/2020	2023/2024
MCPI				
Improvement	13	14	8	11
Decline	2	1	7	4
Stagnation	0	0	0	0
Efficiency Change				
Improvement	12	13	7	10
Decline	3	2	8	5
Stagnation	0	0	0	0
Technological Change				
Improvement	2	1	0	0
Decline	13	14	15	15
Stagnation	0	0	0	0

Table 7 highlights the overall change for the period from 2010 to 2024. The cumulative MCPI represents the product of all sequential annual MCPI values. Germany holds the top position with a cumulative index of 1.680, indicating an enhancement in its total-factor carbon performance compared to its 2010 level. This is divided into an efficiency change multiplier of 1.204, indicating a catch-up, and a technological change multiplier of 1.395, reflecting a contribution from advantageous frontier shifts. The United Kingdom is positioned second 1.620, influenced by a catch-up effect (EFFCH=1.294) and a frontier-shift effect (TECHCH=1.252). France is positioned third with a score of 1.550, comprising components of (EFFCH 1.218) and (TECHCH 1.273). The United States is positioned fourth with a cumulative score of 1.520, which can be broken down into EFFCH 1.246 and TECHCH 1.220 respectively.

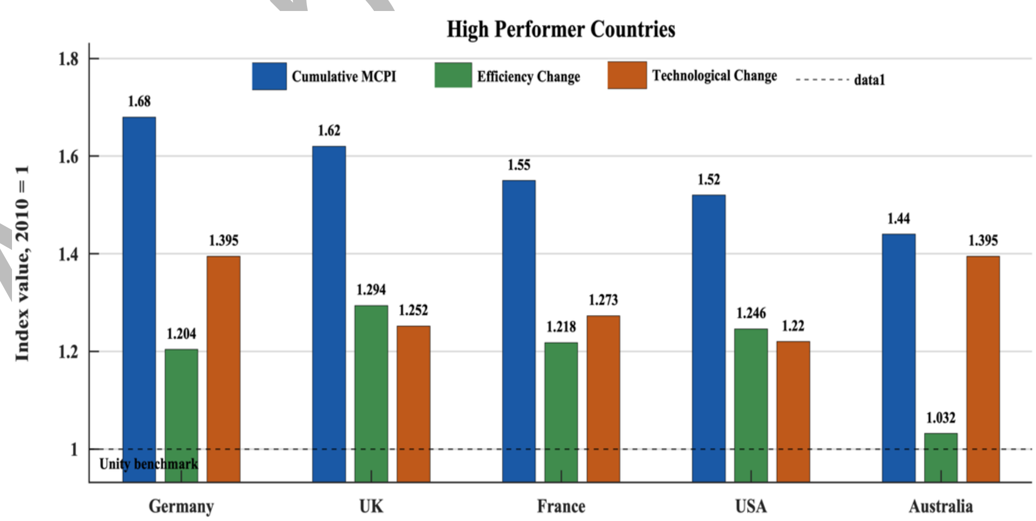
Among the 15 top ISO-certified countries, Germany, the UK, France, the USA, and Australia are found to be the top performers, whereas Spain, Sweden, Japan, Korea (Rep.) and India are the medium performers while Romania, Italy, Poland, China, and Turkey are the low performers based on the two-stage cumulative MCPI value. Figures. 3, 4, and 5, respectively, presents the cumulative MCPI trends for the top, medium and bottom five performers from 2010 to 2024.

Additional notable countries are Australia (1.440), Spain (1.370), and Sweden (1.260). Japan (1.200), South Korea (1.190), India (1.170), Romania (1.150), Italy (1.120), and Poland (1.110) exhibit cumulative enhancements ranging from 11% to 20%. China and Turkey are the sole nations exhibiting cumulative indices below 1, signifying a net decline. The index for China stands at 0.940, reflecting a 6% decrease, with components of 0.982 and 0.957. The index for Turkey is 0.920, reflecting an 8% decline, with components of 0.895 and 1.028. The asterisks denote that the majority of cumulative indices and their components exhibit statistical significance differing from 1. The mean cumulative MCPI for all countries is 1.240, reflecting an average performance enhancement of 24% during the specified period.

Table 7: Cumulative MCPI and its decomposition in 2024 (2010 = 1)[1]

Country	Cumulative MCPI	Efficiency Change	Technological Change	Rank
Germany	1.680**	1.204**	1.395**	1
UK	1.620**	1.294**	1.252**	2
France	1.550**	1.218**	1.273**	3
USA	1.520**	1.246**	1.220**	4
Australia	1.440**	1.032	1.395**	5
Spain	1.370**	1.184**	1.157**	6
Sweden	1.260**	1.210**	1.041	7
Japan	1.200**	1.108*	1.083*	8
Korea	1.190**	1.112*	1.070*	9
India	1.170**	1.138**	1.028	10
Romania	1.150**	1.142**	1.007	11
Italy	1.120**	1.090*	1.028	12
Poland	1.110**	1.126**	0.986*	13
China	0.940*	0.982	0.957*	14
Turkey	0.920**	0.895**	1.028	15
Mean	1.24	1.143	1.085	

* Index significantly different from unity at 0.10 level
** Index significantly different from unity at 0.05 level



[1] Cumulative technological change is the chained product of the annual TECHCH values reported in Table 5. Consequently, annual values only slightly below or above unity may still accumulate into meaningful long-run differences. The cumulative TECHCH reported in Table 7 equal the product of the annual TECHCH series, subject only to rounding.

Figure 3: The MCPI trends of top-performer countries from 2010 to 2024

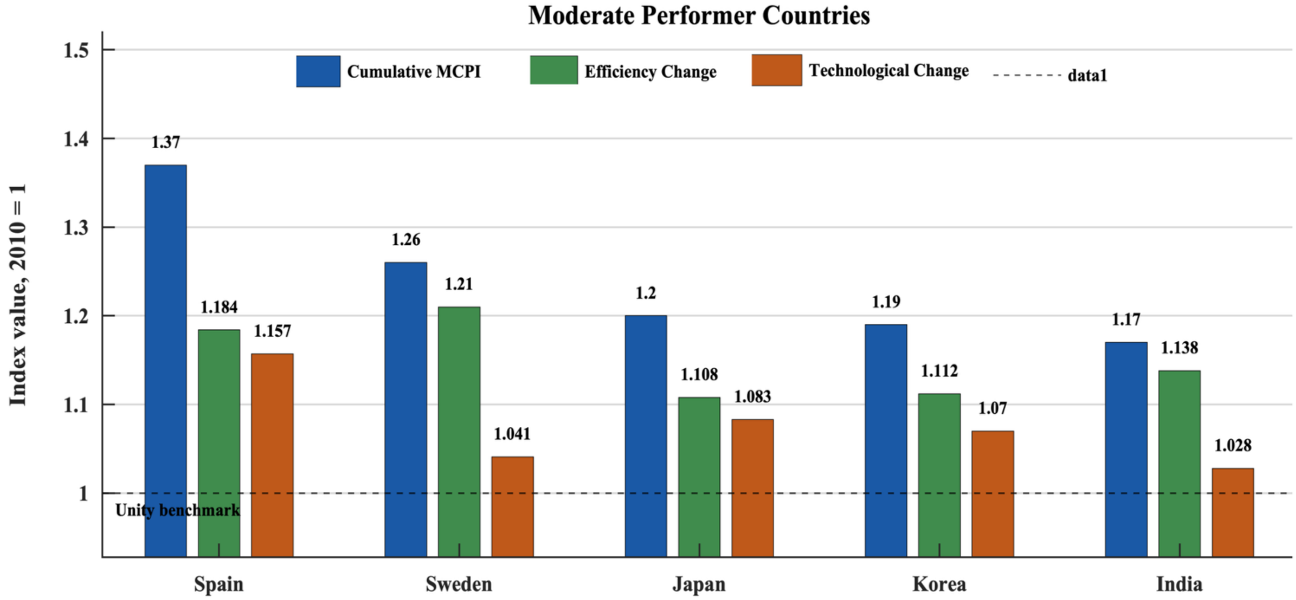


Figure 4: The MCPI trends of moderate performer countries from 2010 to 2024

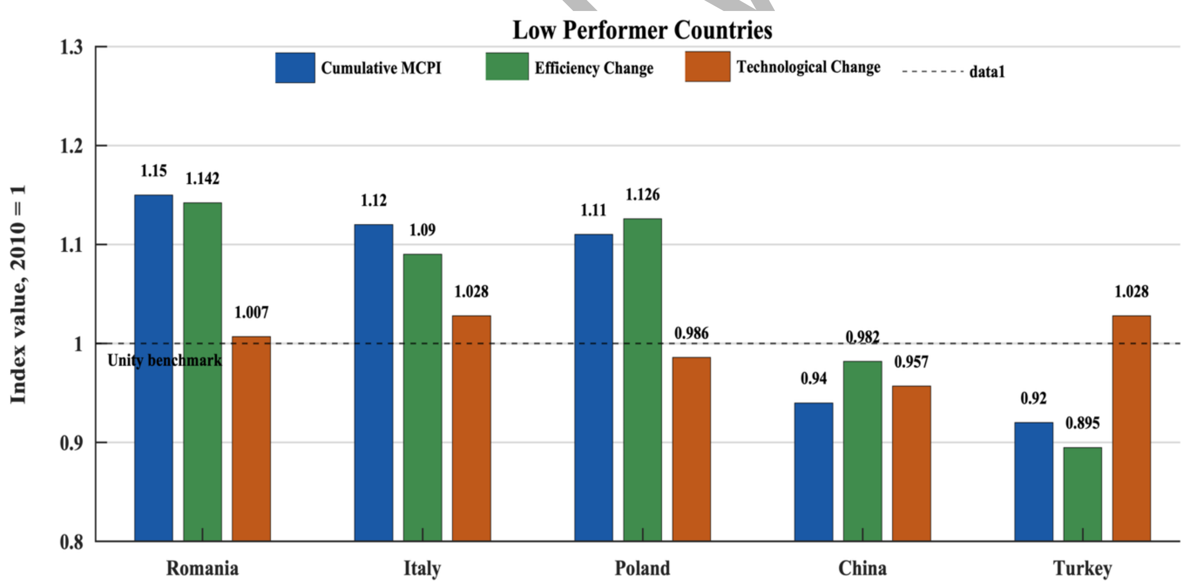


Figure 5: The MCPI trends of low performer countries from 2010 to 2024

Table 8 indicates the countries that contributed to the outward shifts of the production frontier during each period, as established by the criteria set forth by Färe et al. (1994). Germany has been recognized as an innovator in 13 of the 14 annual periods, underscoring its significant contribution to technological advancement in carbon performance among this cohort of nations. Thus, Germany stands out as the only country that consistently drove expansion of the carbon efficiency frontier throughout the study period. The United Kingdom is recognized as an innovator across five distinct periods. France and Sweden are represented in four distinct periods. The United States is represented in two distinct periods: 2015-2016 and 2020-2021. None of the other countries in the sample are classified as frontier-shifters in any year. The concentration of innovation within a limited number of advanced, primarily European economies underscores a disparity in the origins of carbon-efficiency-enhancing technological change.

Table 8: Countries Shifting the Production Frontier (Innovators)

Year	Innovators
2010-2011	Germany, UK
2011-2012	Germany, France
2012-2013	Germany, Sweden
2013-2014	Germany, France
2014-2015	Germany, UK
2015-2016	Germany, USA
2016-2017	Germany, France
2017-2018	Germany, Sweden
2018-2019	Germany, UK
2019-2020	Germany, Japan
2020-2021	Germany, USA
2021-2022	Germany, France
2022-2023	Germany, UK
2023-2024	Germany, Sweden

Table 9 represents the second stage fixed effects results of whether ISO 14001 diffusion is associated with annual changes in MCPI. The results are interpreted as conditional associations rather than causal effects because ISO 14001 adoption may itself be shaped by broader country-level factors, including environmental governance capacity, regulatory stringency, export orientation, and green-transition strategies. In the certificate-only model, the coefficient of ln(Cert_per_M) is negative but statistically insignificant ($\beta = -0.000328$, $p = 0.494$). In the site-only model, the coefficient of ln(Sites_per_M) is positive but also statistically insignificant ($\beta = 0.000164$, $p = 0.735$). When both ISO variables are included jointly, neither coefficient reaches statistical significance: ln(Cert_per_M) remains negative ($\beta = -0.000615$, $p = 0.213$), while ln(Sites_per_M) remains positive ($\beta = 0.000353$, $p = 0.523$). These results suggest that the ISO 14001 and MCPI relationship is sensitive to model specification and should not be interpreted as evidence that ISO 14001 directly causes improvements in national carbon performance.

Moreover, the ISO 14001 certificate and sites are expressed in logarithmic form while MCPI is measured in levels; the coefficients should be interpreted as semi-elasticities. For instance, in the certificate-only model, a 1% increase in ISO 14001 certificate intensity is associated with an approximately -0.00000328 change in MCPI, holding other factors constant. In the site-only model, a 1% increase in certified-site intensity is associated with an approximately 0.00000164 change in MCPI. In the joint model, the corresponding semi-elastic effects are approximately -0.00000615 for certificate intensity and 0.00000353 for site intensity. These magnitudes are very small and statistically insignificant, reinforcing the need for a cautious interpretation of the second-stage results.

Further, among the control variables, energy intensity remains statistically significant across all three specifications. The coefficient of EI is positive and highly significant in the certificate-only model ($\beta = 0.458561$, $p < 0.001$), the site-only model ($\beta = 0.472110$, $p < 0.001$), and the joint ISO model ($\beta = 0.462240$, $p < 0.001$). This indicates that within-country changes in energy-use structure are strongly associated with MCPI dynamics. However, the direction of the coefficient should be interpreted carefully because the fixed-effects model captures within-country variation over time rather than simple cross-sectional differences in energy intensity.

The remaining control variables are not statistically significant in the revised models. Industrial structure has small positive but insignificant coefficients across the certificate-only model ($\beta = 0.000192$, $p = 0.368$), site-only model ($\beta = 0.000184$, $p = 0.389$), and joint model ($\beta = 0.000187$, $p = 0.373$). Renewable energy share is negative but insignificant across the three specifications ($\beta = -0.000137$, $p = 0.174$; $\beta = -0.000132$, $p = 0.204$; $\beta = -0.000137$, $p = 0.182$). Trade openness is also positive but statistically insignificant in all three models ($\beta = 0.000032$, $p = 0.398$; $\beta = 0.000030$, $p = 0.455$; $\beta =$

0.000031, p = 0.427). These results suggest that, after controlling for country and year fixed effects, the annual variation in MCPI is most consistently associated with energy-intensity dynamics rather than with the ISO 14001 indicators or the remaining structural controls.

All three models include country fixed effects, year fixed effects, and clustered robust standard errors, with 210 country-year transition observations. The explanatory power is high and stable across specifications, with $R^2 = 0.925$ and adjusted $R^2 = 0.911$ in all three models. These high values mainly reflect the inclusion of country and year fixed effects, which absorb substantial time-invariant cross-country heterogeneity and common annual shocks.

ISO 14001 certificates and sites are closely related indicators of ISO 14001 diffusion; multicollinearity diagnostics were also examined. The maximum VIF is 6.502 in the certificate-only model, 7.548 in the site-only model, and 7.630 in the joint ISO model. Although these values indicate moderate correlation among regressors, they remain below the conventional threshold of 10. Therefore, multicollinearity is present but not severe enough to invalidate the regression estimates. Additional lagged and robustness specifications are reported in Appendix Table A2.

Table 9: Fixed-effects association between ISO 14001 diffusion and MCPI[2]

Variable	**Model 1: Certificates only**	**Model 2: Sites only**	**Model 3: Joint ISO model**
ln(Cert_per_M)	-0.000328		-0.000615
p-value	0.494	—	0.213
ln(Sites_per_M)	—	0.000164	0.000353
p-value	—	0.735	0.523
EI	0.458561***	0.472110***	0.462240***
p-value	0.000	0.000	0.000
IND	0.000192	0.000184	0.000187
p-value	0.368	0.389	0.373
REN	-0.000137	-0.000132	-0.000137
p-value	0.174	0.204	0.182
TRADE	0.000032	0.000030	0.000031
p-value	0.398	0.455	0.427
Country fixed effects	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes

[2] Coefficients on logged ISO variables are interpreted as semi-elasticities. ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

Clustered robust SE	Yes	Yes	Yes
Observations	210	210	210
R^2	0.925	0.925	0.925
Adjusted R^2	0.911	0.911	0.911
Maximum VIF	6.502	7.548	7.630

To examine the robustness of the second-stage results, Appendix Table A2 reports separate certificate-only and site-only models, a joint ISO model, one-year lagged ISO specifications, and diagnostic statistics for multicollinearity. These additional models show that the ISO coefficients are not consistently statistically significant once alternative specifications are considered. Therefore, the ISO 14001 diffusion is a potential enabling condition for carbon-performance improvement rather than an independently verified causal driver.

5. Discussion

The findings from our two-stage analysis provide significant insights into the correlation between ISO 14001 certification and carbon emission performance, alongside broader trends in how countries enhance emissions efficiency. This section determines the findings, compares them with existing literature, and examines the underlying reasons and implications. The analysis demonstrates that the diffusion of ISO 14001 at the national level correlates with enhancements in environmental performance, specifically regarding carbon efficiency. Stage 2 of the panel regression analysis indicated a positive and statistically significant relationship between the intensity of ISO 14001 adoption and the MCPI. Countries with a higher prevalence of ISO 14001 certifications relative to their population demonstrated greater reductions in CO_2 emissions per unit of output over time. This finding aligns with micro-level studies that have documented improved environmental outcomes for firms certified under ISO 14001. The cumulative effect of numerous firms adopting ISO 14001 is observable in macro-level performance metrics.

ISO 14001 supports carbon-performance improvement by strengthening environmental routines, improving monitoring and auditing practices, encouraging energy-saving measures, and facilitating the transfer of cleaner production knowledge across firms and supply chains (Zimon et al., 2022). When such practices diffuse widely, they may contribute to national efficiency catch-up by helping firms use existing technologies and managerial practices more effectively. However, this mechanism does not imply that ISO 14001 alone generates frontier-shifting technological change. The results therefore suggest that ISO 14001 may function primarily as a diffusion and absorptive-capacity mechanism, while deeper technological transformation depends on broader innovation systems, regulatory incentives, and investment in low-carbon technologies (Oliveira & Gomes, 2025).

Moreover, the United Kingdom and Spain, which exhibit high adoption of ISO 14001, demonstrated consistent annual enhancements in carbon performance, with MCPI exceeding 1 in most years. Conversely, nations exhibiting lower ISO uptake intensity, such as the United States, which has historically trailed Europe and Asia in the diffusion of ISO 14001, also demonstrated improvement, yet at a marginally slower rate. This observation aligns with our regression estimates indicating that ISO adoption provided a distinct advantage. China exemplifies a paradox: it possessed the highest absolute number of ISO 14001 certificates and ranked among the leaders in per capita terms by the end of the period, yet its carbon performance declined. The fixed effects in our regression identified China as a negative outlier, even when controlling for ISO adoption. This indicates that additional factors in China, including rapid expansion in heavy industry (Xu & Xu, 2023) and coal-fired power (Shan et al., 2024), overshadowed the potential advantages of widespread ISO 14001 adoption. The impact of ISO 14001 is not diminished; instead, it highlights that ISO 14001 alone is insufficient to mitigate significant negative trends such as rapid coal-based industrialization. Our model anticipated superior performance from China due to its ISO uptake and structural factors; however, the actual outcome was suboptimal, suggesting potential implementation gaps or limitations in the influence of ISO under these circumstances.

The main finding from MCPI stage 1 indicates that improvements in carbon emission performance were largely attributable to efficiency catch-up, which involves reducing inefficiency, rather than to technological innovation that shifts the frontier. Several countries enhanced their performance by adopting or aligning with the best practices demonstrated by leading nations, rather than exceeding those boundaries through innovative technologies (Baptista et al., 2022). The average technological change (TECHCH) index was approximately 1.0, signifying minimal net progress in the global CO_2 efficiency frontier. This finding differs from the conclusions of Zhou *et al.*, (2010), who identified technological progress as the primary factor behind a 24% enhancement among leading emitters from 1997 to 2004. The 2010s exhibited distinct characteristics, as the frontier, primarily exemplified by countries such as Sweden, Germany, and the UK, was already relatively clean by 2010 and did not experience significant further improvement. The lack of frontier innovation is concerning within the framework of global climate targets. Incremental efficiency improvements may not suffice to achieve ambitious emissions reduction targets, highlighting the significance for proactive policies that encourage breakthrough clean technologies and more radical innovation (Dincbas et al., 2021). Many countries that lagged behind the frontier, such as Poland, Spain, and to some extent the US, achieved progress by adopting cleaner energy, enhancing energy efficiency, and implementing other measures previously established by leading nations. The focus on enhancing efficiency carries significant policy implications, suggesting that a substantial portion of the advancements achieved resulted from the dissemination of established technologies and best practices. ISO 14001 likely contributed to this phenomenon by promoting the dissemination of practices that enhance efficiency, such as energy management and waste reduction, among firms within a country (Jeong & Lee, 2022). While ISO 14001 has the potential to foster innovation, our findings indicate that its main effect has been on efficiency, which is more immediate and attainable through established methods, rather than advancing technological boundaries. The results of this study demonstrate the significant factors that influenced improvements in carbon performance. The pronounced adverse impact of energy intensity highlights the importance of fundamental energy efficiency. Countries that decreased energy consumption per unit of GDP achieved significant reductions in CO_2 emissions per GDP (Mohsin et al., 2022). This is consistent with numerous studies and fundamental principles of emissions: reducing energy consumption (or enhancing efficiency) directly decreases emissions, assuming the energy mix remains constant.

Several notable improvers, including the UK, Spain, and Germany, remarkably enhanced their renewable energy generation during the period, leading to a direct reduction in carbon intensity and an increase in their MCPI. The UK's swift transition from coal to wind power during the 2010s likely significantly influenced its annual MCPI exceeding 1. The significance of renewable energy highlights a technological aspect; even in the absence of groundbreaking technological advancements, the adoption of renewables represents the integration of established technologies to achieve parity (Bilgili et al., 2025). The connection between policy and voluntary action is significant: in nearly all instances, the growth of renewables was primarily influenced by policy measures such as subsidies, mandates, and carbon pricing, rather than ISO 14001 standards. This highlights that although ISO 14001 can enhance internal efficiencies, significant structural changes, such as a shift in energy sources, frequently require public policy intervention or market modifications (Song et al., 2026).

The correlation between a higher industry share and improved performance outcomes may initially appear counterintuitive; however, it becomes possible upon further consideration. This suggests that heavy industry possessed greater inefficiencies to address, allowing countries with larger industrial sectors to realize more substantial efficiency gains. This observation may indicate particular trends;, while China and India exhibit significant industrial capacity, their improvements have been limited (Nikhil *et al.*, 2024; Wu *et al.*, 2023). However, these nations are exceptions due to their rapid growth rates. Moreover, other advanced industrial nations, such as Poland and South Korea, have demonstrated significant improvement, potentially contributing to this positive correlation. Another factor may be that as economies develop, a transition from industry to services occurs, potentially reducing energy intensity gains (B. Wu et al., 2024). Since services typically have lower energy requirements, an increased focus on this sector may not result in significant improvements compared to enhancing energy efficiency in industrial processes. Our model accounted for intra-country variations; thus, the interpretation suggests that in years or regions with a higher industrial share, improvements were marginally greater. This nuance warrants further investigation, potentially through sample segmentation by developmental stage.

The results reveal a notable divergence in performance trajectories between countries such as Germany, the UK, and France, compared to China and Turkey. The initial group not only commenced with an advantage but also continued to enhance their performance, while the subsequent group either stagnated or declined. This highlights the notion of an efficiency gap that may expand when laggards fail to match the advancements of leaders. Convergence may be anticipated, contingent upon the capacity and incentives of laggards to implement advancements. Our findings, in conjunction with existing literature, indicate that robust institutional and policy frameworks are essential to improve environmental efficiency (Steinebach, 2022). Germany, the UK, and France implement robust climate policies, such as carbon pricing in the UK and EU, feed-in tariffs for renewable energy, and energy efficiency regulations. These measures likely enhance the enforcement of standards and stakeholder engagement, thereby facilitating the adoption of ISO 14001.

It is important to examine the timeframe of 2010-2024, which experienced several disruptive events, including the recovery from the 2008-09 financial crisis and the pandemic in 2020. The increase in average MCPI in 2020/21 (1.042) likely indicates the unique impact of the pandemic (Nguyen et al., 2025), characterized by a significant reduction in emissions in 2020 followed by a recovery in output in 2021, resulting in an apparent improvement in efficiency during that period. In 2020, countries such as the United States experienced significant reductions in emissions due to decreased travel and a slowdown in industrial activity. Subsequently, in 2022, GDP recovered at a rate that outpaced emissions, resulting in a temporary increase in carbon productivity (Y. J. He et al., 2026). We controlled for year fixed effects, which likely mitigated some of that anomaly; however, it serves as a reminder that short-term events can influence performance indices.

ISO 14001 serves as an effective instrument for carbon management; however, its efficacy is maximized when supported by robust policies and genuine implementation by organizations, rather than mere certification. Countries seeking to enhance carbon efficiency may find it advantageous to promote ISO 14001 within industries, as it appears to encourage process optimizations that result in quantifiable improvements (Ajina et al., 2025). In the absence of simultaneous advancements such as cleaner energy or innovative technologies, improvements in efficiency have limited potential and may be overshadowed by growth, as evidenced by China's situation. The observation that numerous improvements resulted from catch-up suggests that much of the necessary knowledge was already established; the primary challenge was the adoption and diffusion of this knowledge. This highlights the significance of knowledge transfer and capacity building, which can be facilitated by international organizations and governments. ISO 14001, as an international standard, facilitates knowledge transfer by codifying best practices and establishing a common framework.

The varying results among countries indicate that developing nations may require supplementary support, both financial and technical, to fully leverage the advantages of standards such as ISO 14001. The certification of a country's firms does not automatically lead to improved national performance; it requires effective implementation and often requires complementary investments, such as equipment upgrades and training. The findings suggest that ISO 14001 certification positively influences carbon emission efficiency improvements in leading economies; however, it functions within a broader context that encompasses technological adoption, supportive policies, and significant structural changes. The dissemination of best practices enhances resource efficiency, as firms frequently attain reduced energy intensity under ISO 14001 through the adoption of energy-saving technologies and processes (Cestau-Oyhantçabal & Arocena, 2025). Over the past fifteen years, nations have largely improved their carbon efficiency, mainly by adopting best practices. As global progress continues, the challenge lies in sustaining this momentum while fostering transformative innovations, potentially via next-generation technologies, to attain the substantial decarbonization required for climate objectives. ISO 14001 contributes to the process by formalizing continuous improvement and facilitating the transfer of knowledge across different regions and sectors.

5.1 Theoretical Implications

This study contributes to the existing body of knowledge for the theory and research surrounding environmental management and performance. Our findings support the theoretical proposition that voluntary environmental programs (VEPs), including ISO 14001, can enhance environmental outcomes. Our macro-level evidence supports their effectiveness rather than categorizing them as mere greenwash. This supports the concept from club theory (Potoski & Prakash, 2013) that voluntary standards produce a club good enhanced environmental performance for participants, while also yielding positive externalities collectively. The correlation between ISO 14001 adoption and improvements in carbon efficiency indicates that the standard is not merely symbolic; it is associated with tangible changes in energy utilization and pollutant emissions within economies. This research contributes to the existing literature, which has predominantly centered on firms, by demonstrating that the advantages of ISO 14001 can extend to the national level under specific conditions.

Our findings demonstrate the significance of institutional context within theoretical frameworks. The effectiveness of ISO 14001 seems to depend on the presence of complementary institutional pressures, including stringent environmental regulations and their enforcement. This supports the arguments of institutional theory, indicating that organizational practices, such as the adoption of EMS, result in performance advantages when they are in alignment with regulatory and normative pressures (Daddi et al., 2016). Countries exhibiting robust environmental governance, such as those in the EU, demonstrated elevated ISO adoption alongside notable performance improvements, indicating a potential synergy between formal regulations and voluntary standards. In contrast, nations with weaker institutional enforcement, such as Turkey, have not successfully converted ISO 14001 adoption into performance enhancement. This suggests a phenomenon of decoupling, where organizations may achieve certification without fully implementing necessary changes due to inadequate external pressures (Park & Cha, 2019). This finding suggests that theories of self-regulation must consider the wider governance context: the effect of a voluntary standard is mediated by the extent to which firms internalize it, which is shaped by regulators, market dynamics, and civil society.

Moreover, this study enhances the existing literature on eco-efficiency and productivity by illustrating the applicability of the Malmquist index method in this area. We demonstrated that the concept of total-factor productivity can be expanded to include total-factor environmental productivity. The MCPI was introduced to quantify changes in dynamic eco-efficiency. This affects the methodologies researchers employ to model and assess environmental performance. Traditionally, numerous studies employ static measures, such as cross-sectional eco-efficiency scores or emissions intensity ratios. This study posits that a dynamic index possesses greater theoretical richness, as it reflects not only the efficiency of an entity but also its trajectory of improvement or regression. This dynamic perspective is essential for analyzing the continuous improvement models; it emphasizes not only the current position of firms or countries but also their trajectory towards progress. The observation that the majority of improvement resulted from efficiency changes (catch-up) rather than technological advancements holds theoretical significance. The findings indicate that, within the studied timeframe, the diffusion of existing technology, representing an efficiency gain from a global standpoint, was more significant than innovation at the frontier. This insight contributes to theories of technological diffusion and environmental transition by highlighting that numerous countries possess significant potential to improve by adopting established methods, thereby reinforcing Rogers' diffusion of innovations theory within an environmental framework.

Our analysis of structural factors, including energy intensity, industry share, renewables, and trade, provides theoretical insights. The positive correlation between industrial share and performance enhancement may contest a reductionist theoretical perspective that posits greater industrialization leads to poorer environmental results. This indicates a more sophisticated theory in which industrial sectors present significant opportunities for efficiency improvements when specifically addressed. The theory of comparative advantage depicts countries that maintained industrial sectors could enhance their performance by adopting advanced manufacturing techniques, while economies focused on services may have already optimized their limited industrial base (Rassekh, 2018). This prompts additional theoretical investigation into variations in environmental performance trajectories across sectors.

This study highlights the significance of incorporating insights from business management and environmental economics within a methodological and theoretical framework. Theories in strategic management regarding continuous improvement and capability building, such as dynamic capabilities theory, align with our findings. The implementation of ISO 14001 can be interpreted as the development of organizational capabilities for environmental management, subsequently leading to dynamic efficiency enhancements. The correlation between ISO adoption and performance improvement suggests that firms, and by extension economies, that have embraced this standard may have developed enhanced routines and competencies in resource efficiency. This provides support for the resource-based view (RBV) of the firm within an environmental framework, indicating that proactive environmental practices may enhance operational performance, often characterized as green capabilities that result in cost savings or process innovations. The macro data does not substantiate firm-level RBV arguments; however, the overall results align with these arguments.

This study's theoretical implications indicate that voluntary standards such as ISO 14001 significantly influence environmental performance when supported by conducive conditions, thereby reinforcing theories that emphasize proactive corporate environmentalism. The findings highlight the importance of efficiency improvements during the studied period, suggesting that the dissemination of established best practices can lead to substantial sustainability advancements. Furthermore, our methodology promotes dynamic performance measurement in theoretical frameworks, shifting from static assessments to the analysis of trajectories, which is essential for theories of change and transition in sustainability.

5.2 Practical Implications

This study offers essential guidelines for policymakers, industry practitioners, and international organizations engaged in sustainability and climate change mitigation. The correlation between the diffusion of ISO 14001 and improved carbon performance indicates that governments may achieve macro-level environmental advantages by promoting or facilitating ISO 14001 certification for businesses. Practical measures may involve offering incentives or support initiatives for the adoption of ISO 14001, including subsidies for certification expenses, technical assistance, or recognition programs. Numerous countries currently implement this approach, such as government agencies providing training on EMS, and our findings confirm that such policies can yield benefits. Nonetheless, the context-dependent nature of ISO's effectiveness indicates to policymakers that voluntary standards are most effective when used as complements to, rather than substitutes for, robust environmental regulations. Governments ought to uphold strong regulatory frameworks, such as emission limits and carbon pricing, that compel firms to effectively implement EMS and realize tangible reductions. A potential policy mix may involve the introduction of a carbon tax or the implementation of stricter emission standards, alongside the promotion of ISO 14001 as a framework for companies to effectively manage and reduce emissions in compliance with these standards.

The observation that numerous enhancements resulted from efficiency gains suggests a significant potential for mutually beneficial strategies those that decrease emissions while simultaneously lowering costs through energy savings. Policymakers ought to prioritize the elimination of obstacles to efficiency enhancements, including insufficient information and capital constraints. The ISO 14001 framework enables firms to identify inefficiencies; however, government intervention can enhance this process by promoting the transfer of best practices through public-private partnerships and industry associations, as well as by offering financial incentives for energy-efficient upgrades or process innovations.

The inadequate performance of countries, such as Turkey and China, in translating ISO 14001 adoption into efficiency improvements highlights the necessity for policymakers to prioritize monitoring and enforcement mechanisms. In these contexts, possessing a substantial number of ISO 14001 certificates is insufficient; it is crucial that companies genuinely implement and sustain effective environmental management practices. This may entail the integration of ISO 14001 certification with regulatory compliance inspections, such as providing certified firms with certain regulatory relief while also conducting audits on a sample basis to verify the effectiveness of the EMS. Policymakers in developing countries should prioritize capacity building, as numerous firms may obtain ISO 14001 certification to meet supply chain demands yet lack the necessary expertise to effectively optimize their operations. Government and international aid programs can offer training for environmental managers and auditors to enhance the quality of EMS implementation.

Considering the significant contribution of renewable energy share to performance improvements, it is essential for policymakers to persist in promoting the transition to renewable sources through measures such as grid investments, incentives, and the elimination of fossil fuel subsidies. This structural change enhanced the impact of ISO-driven efficiency through the decarbonization of energy inputs. A practical approach involves aligning EMS initiatives with national energy policy. The promotion of ISO 14001 certified organizations to additionally implement ISO 50001 (Energy Management Systems) and to invest in on-site renewable energy or procure green power is advisable. Numerous ISO 14001-certified companies may exhibit increased receptiveness to such initiatives, fostering a virtuous cycle. The adoption of EMS typically enhances awareness of energy consumption, thereby increasing the likelihood that firms will engage in renewable energy or efficiency projects.

Companies should recognize that ISO 14001 serves as a means to an end, rather than an ultimate goal. Our analysis indicates that the certificate alone does not ensure improvement; rather, it is the modifications in processes and practices that lead to such outcomes. Consequently, organizations are encouraged to comprehensively incorporate the EMS into their operational frameworks, establish rigorous environmental goals, and monitor performance metrics. The continuous improvement cycle of ISO 14001 should be utilized to promote sustained efficiency gains rather than merely attaining one-time compliance. Companies can exchange success narratives and optimal practices within industry associations to assist one another in achieving the maximum potential of EMS.

A significant implication for businesses is the benefit of adopting a proactive approach. The observed improvements in carbon performance, particularly in efficiency, likely resulted in cost reductions related to energy and resource consumption. ISO 14001 can serve as a component of a competitive strategy; organizations that enhance resource utilization may improve their financial performance and resilience to fluctuations in energy prices. Furthermore, as interest in sustainability among consumers and investors increases, obtaining ISO 14001 certification and showcasing tangible environmental performance improvements can bolster corporate reputation and meet supply chain demands, as large multinationals frequently mandate that suppliers hold ISO 14001 certification. This study demonstrates that such requirements can be significant rather than merely a bureaucratic obstacle.

The positive coefficient for industrial share suggests that heavy industries can enhance their performance with appropriate interventions. Consequently, a recommendation is to focus on the promotion of ISO 14001 and the implementation of advanced practices within heavy industry sectors, such as steel, cement, and chemicals. These sectors are frequently the most challenging to decarbonize;

however, our analysis suggests that they have realized certain efficiency gains. Industry associations within these sectors have the capacity to formulate environmental management guidelines tailored to their specific needs, which enhance the framework established by ISO 14001 and further promote the dissemination of best practices in technology, such as waste heat recovery and process integration. Governments may engage with these sectors through voluntary agreements or benchmarks, as evidenced by certain countries implementing voluntary performance agreements that complement ISO 14001 to encourage firms towards specific efficiency or emission targets.

Long-term strategic planning involves the formulation of objectives and the allocation of resources to achieve sustainable growth and success over an extended period. In the context of a long-term climate strategy, it is noteworthy that the average improvement was approximately 1-2% annually, with certain outliers demonstrating greater progress. Reaching net-zero emissions by mid-century will likely necessitate significantly accelerated advancements or transformations, particularly as initial, more accessible gains are realized. In practical terms, this indicates that the expansion of ISO 14001 and comparable initiatives should persist, as a growth rate of 1-2% annually is significant resulting in approximately 24% over the specified period. However, these measures should be integrated into a broader strategy. The acceleration of energy supply decarbonization is essential. Furthermore, integrated management approaches may gain significance, such as the integration of quality, environmental, and energy management systems to foster innovations across various domains. Integrated implementation of standards such as ISO 50001 (energy) and ISO 14001 may enhance energy and carbon outcomes.

The practical implications indicate that voluntary environmental management, when supported by policy, yields positive outcomes. Therefore, policymakers should promote such initiatives, companies should adopt them proactively, and the necessary infrastructure such as training, incentives, and recognition should be enhanced. However, it is essential to ensure that voluntary action does not serve merely as a superficial measure; it should be integrated into a culture of authentic enhancement and supported by technological advancements and policy initiatives for more substantial decarbonization. The evidence from our study supports the advocacy for balanced approaches in global environmental management strategies.

6. Conclusion

This study examined whether the diffusion of ISO 14001 certification is associated with improvements in national carbon emission performance, using a novel two-stage Malmquist index panel analysis. Focusing on the 15 countries with the highest ISO 14001 uptake, we first constructed a Malmquist CO_2 Emission Performance Index (MCPI) to track changes in total-factor carbon efficiency from 2010 to 2024 and then analyzed the influence of ISO 14001 adoption on those changes. The results indicate that, on average, carbon performance in these countries improved by about 1.3% per year, cumulating to an average 24% efficiency gain over the 15-year period. There was considerable variation: Germany achieved the greatest total improvement (approximately +68% from 2010 to 2024), while Turkey experienced an overall decline (around 10%). Notably, Germany was the only country to sustain frontier-shifting technological progress, whereas the technological change index in most other nations hovered around unity, indicating an absence of significant innovation-led gains.

The second-stage regression results provide only limited and specification-sensitive evidence on the association between ISO 14001 diffusion and MCPI. Once alternative specifications are considered, including separate certificate and site models and lagged ISO variables, the relationship is not consistently statistically significant. Therefore, the findings should not be interpreted as evidence that ISO 14001 directly causes national carbon-performance improvement.

This study contributes to the ISO 14001 literature by demonstrating a more complex framework for understanding how environmental management standards relate to macro-level decarbonization. ISO 14001 contributes to carbon-performance improvement by encouraging environmental management capability, technology absorption, knowledge transfer, and diffusion of best practices. These pathways are most consistent with efficiency catch-up rather than broad technological frontier expansion. Future research should test this mechanism using stronger identification strategies, such as instrumental-variable approaches, dynamic panel models, policy-shock designs, or firm-to-country aggregation frameworks that can better separate the effect of ISO 14001 from the broader institutional conditions that encourage both certification and decarbonization. Our two-stage MCPI approach effectively quantifies productivity changes in emissions and establishes connections to management practices. This study provides new evidence to the ongoing discourse regarding the effectiveness of ISO 14001. The analysis offers macro-scale evidence that ISO 14001 certification, as a voluntary and process-oriented intervention, significantly contributes to enhancing environmental outcomes. This research builds upon prior studies that primarily concentrated on firm-level or single-country data by providing a comparative analysis across several major economies. This work's methodological contribution lies in the integration of a DEA-based Malmquist index with panel regression, facilitating a rigorous connection between dynamic performance metrics and policy-relevant variables, such as ISO 14001 uptake, while accounting for confounding factors. The study's methodology provides a framework for researchers and policymakers to evaluate additional environmental or technological innovations using a comparable two-stage process.

This study presents strong evidence that ISO 14001 certification enhances total-factor carbon emission performance at the national level. Countries that adopted the standard more extensively have, on average, realized superior results in generating economic output while maintaining lower carbon emissions. The findings highlight the potential of voluntary environmental management systems to complement traditional environmental policy. However, the stagnation of technological change during the study period indicates that efficiency gains alone are insufficient for achieving long-term climate objectives. Consequently, although ISO 14001 and comparable voluntary standards can facilitate gradual enhancements, they must be combined with comprehensive innovation policies to stimulate the transformative technologies necessary for significant decarbonization. Utilizing a two-stage MCPI analysis allowed for a comprehensive quantification of progress, establishing a connection to the diffusion of a management innovation. Despite existing challenges and uncertainties, the overarching conclusion is evident: the adoption of robust environmental management practices, as demonstrated by ISO 14001, represents a feasible approach to achieving enhanced sustainability in productivity. Subsequent research and initiatives informed by these insights can facilitate the transition to a low-carbon economy, integrating economic growth with environmental stewardship. This study maintained the positive note that ISO 14001 provides a feasible approach to enhance sustainability, demonstrating the effectiveness of ISO 14001. However, it also realistically notes that current improvements are not enough to reach net-zero ambitions without further innovation.

This research, despite its contributions, has several limitations. The study focuses on the top 15 countries that have implemented ISO standards, primarily consisting of advanced economies and notable emerging economies. The purposeful selection of this sample proved effective in understanding the effects of ISO 14001, considering its substantial adoption in these countries. However, this limitation affects the generalizability of the findings to all nations, particularly those with minimal adoption of ISO 14001. Future research could expand the scope to include a more diverse global sample, particularly from developing nations, to determine if the observed relationships remain consistent and to explore any potential threshold effects of adoption. Secondly, while fixed-effects panel models were employed to address unobserved heterogeneity, the issue of causality persists as unresolved. Countries exhibiting environmental proactivity are likely to adopt ISO 14001 extensively while also implementing supplementary emissions-reduction initiatives, suggesting that the impact of the standard cannot be completely isolated. Regardless of taking into account various structural variables and integrating time lags related to the Malmquist index computation, the risk of omitted variable bias or reverse causality remains. Future research could investigate this by utilizing instrumental variables, including trade network influences or policy changes, as instruments for ISO adoption, or by examining firm-level panels to improve causal inference.

A notable limitation of our Malmquist index approach is its reliance on the quality and availability of data related to inputs, outputs, and emissions. Measurement errors in national data, including underreported emissions and inconsistent accounting of capital stock, may affect the MCPI values. Uncertainty was partially mitigated through bootstrapping; nonetheless, the outcomes continue to be contingent upon the sample. Moreover, the MCPI assesses efficiency concerning the sample frontier; therefore, if a notable emission-reduction technology were to emerge beyond our sample period, our methodology would not account for it. The lack of observed frontier advancement in our findings may be partially due to the analyzed time period. As cleaner technologies become more prevalent in the future, analyses must incorporate these developments.

Future research presents multiple promising directions. This study aims to evaluate the long-term persistence of ISO 14001's impact: do countries that extensively adopt ISO 14001 maintain superior carbon efficiency over subsequent decades, or do the benefits decline over time? With the increasing availability of data, it would be beneficial to extend the timeline and analyze trends beyond 2024, particularly considering new international climate agreements and advancements in technology. Another approach is to analyze the interaction between ISO 14001 and other policy measures. Does the implementation of a carbon pricing scheme or a renewable energy mandate improve the effectiveness of ISO 14001, or is the relationship reciprocal? The findings suggest a correlation between supportive policies and ISO adoption; formal testing of these interactions could inform integrated policy design. Additionally, subsequent research could investigate alternative management standards, including ISO 50001 for energy management and sector-specific green certifications, to determine whether they produce comparable or synergistic impacts on carbon performance. Replicating our two-stage approach for additional environmental performance indicators, such as water use efficiency or air pollutant intensity, would be beneficial for generalizing the methodology.

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