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Assessing Carbon Footprint Reduction and Sustainability Strategies Across Major Industrial Sectors: A Comparative Quantitative Analysis

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Abstract: This study quantitatively evaluates carbon emissions from five major industrial sectors—manufacturing, cement, steel, chemical, and food processing—and assesses the effectiveness of ten sustainable environmental management strategies. We employed a comparative quantitative design integrating carbon footprint assessment, Life Cycle Assessment, greenhouse gas inventory analysis, energy auditing, and statistical modeling. A total of 75 industrial facilities were selected via stratified random sampling, with 15 facilities per sector. Primary data were collected through energy audits, fuel consumption records, production reports, and environmental compliance inspections, while secondary data were drawn from national inventories and IPCC emission factors. Statistical analyses included ANOVA, Pearson correlation, Principal Component Analysis, multiple linear regression, and cluster analysis. Implementation of the strategies substantially reduced carbon emissions across all sectors; the steel industry achieved the highest reduction of 26.4%, followed by manufacturing (25.7%) and food processing (25.3%). Industrial energy consumption decreased by 14.7% to 20.3%, renewable energy adoption doubled from 18% to 36%, and waste recycling rates improved from 46% to 71%. Among the strategies, carbon capture and storage achieved the greatest single emission reduction at 38%, whereas energy-efficient equipment demonstrated the highest cost-effectiveness and adoption rate (81%). The principal barriers were high capital investment (mean score 4.63 on a 1–5 scale) and technology constraints. Projection analysis indicated that carbon reductions could increase from 22% in 2025 to 42% by 2035.

Keywords: Carbon Footprint, Industrial Sustainability, Greenhouse Gas Emissions, Comparative Analysis, Sustainable Industrial Strategies.

Introduction

Industrial sector has significant contribution to the global GHGs emission, contributing to approximately one-third of the global anthropogenic carbon footprint (Ghosh et al., 2026). Manufacturing, cement, steelmaking, chemical industry and food processing are sector examples that have a high energy consumption, demand for materials, long supply chains, etc. which leads to a high environmental footprint (Matthews et al., 2008). With the increasing number of regulations and expectations set forth on managing the environment that will force different industries to utilise sustainable solutions across the globe in order to minimise their carbon footprints. However, all of these do not necessarily perform well in all sectors, and all of them must be effectively streamlined in terms of effectiveness and cost-effectiveness in each sector.

The accuracy of the estimation of carbon footprints crucially relies on the boundaries used as well as the methodology. The Life Cycle Assessment (LCA) models are used extensively to trace emissions over the whole supply chain, in particular the input-output LCA (Matthews et al., 2008). The one-point of carbon footprint as a measure of environmentally sustainable production has been documented, however, as one aspect of a broader issue of environmental sustainability as it covers broader environmental effects including resource depletion, toxicity and waste production (Laurent et al., 2012). For this reason, diverse eco-metric measurements relevant to climate change should also be taken into account instead of carbon measurement in any strategy to the industry.

This research aimed at quantitatively measure carbon emission originating from these five major industries and to test the effectiveness of 10 different sustainable environmental management strategies. The technologies used are renewable energy integration, energy efficient equipment usage, waste heat recovery, carbon capture and storage (CCS), circular economy practices, green manufacturing technologies, industrial waste recycling, process optimization, sustainable supply chain management and Environmental Management Systems (ISO 14001) (Zirpe et al., 2025). We assumed that, as these measures are being installed in an integrated way, the GHGs reductions will be significantly lowered, as well as increasing overall sustainability of the facilities.

Our key aim in this study was to go beyond sector-specific analyses to offer a cross-sectoral comparison of CRPs. A total sample of 75 industrial plants (with the 15 industrial plants in each sector) was drawn from 7 strata of industrial plants. We apply comparative quantitative designing method, the method that fused carbon footprints assessment with LCA along with GHG inventory analysis, energy auditing and energy modeling. Measurement of carbon emissions, energy consumption, renewable energy generation ratio, recycling ratio of waste, environmental compliance ratio and environmental sustainable ratio index as a composite index.

The impact of this research can be highlighted as that it has been an all the more empirical research and in addition has contributed to the existing literature concerning the management of the indeterminate carbon impression. Other studies have been focused on specific sectors and given consideration to specific technologies, but our study is a comprehensive assessment over the five high-emission industries that provide solid evidence on what strategy works best and is most feasible (Mahapatra et al., 2021). Our outcomes are in line with this finding: while the greatest single emission reduction per facility is realised with CCS, there are major economic constraints, while our outcomes with the energy-efficient equipment are most cost-effective and adopted, with the greatest cost-effectiveness. The findings will be used to help devise policies and make industrial decisions, including mapping out the main obstacles to the transition towards low-carbon industrial systems such as capital investment and technological constraints. (Lee et al., 2018).

The rest of this paper supports this background through literature on studies relevant to the carbon footprint assessment of industry and measures to manage them sustainably (section 2). In this section, the methodological framework (data collection, sampling and statistical analysis) is described. The quantitative findings, across all sectors and strategies are provided in Section 4. The implications of these findings, as well as other research and barriers to adoption are discussed in Section 5. The main discussion results of this study, its limitation, and recommendation for further study are summarized in the last part, Section 6.

Literature Review

There has been significant scholarly debate on how to quantify industrial carbon footprints, and an ever increasing pressure to cut down carbon footprints related to industry has followed this. In the context of getting the right answer to achieve accuracy and comparative purposes results from carbon footprint studies have been influenced by the boundaries of estimation in particular (Matthews et al., 2008). Indirect emissions from products traded internationally which would not be counted by a narrower-scale analysis can be included and tracked via models that are the study of the product's input-output life cycle. However, there have been a few limitations to CO2 as a stand-alone metric: CO2 does not account for other environmental impacts besides carbon footprint, such as toxicity, resource depletion or change in land-use; and some have argued that a more multi dimensional environmental performance concept (ENV PER) should be used (Laurent et al, 2012).

For these, many publications have been created identifying factors that facilitate and impede companies in decreasing their carbon footprint. Empirical research indicates that motivation is a critical factor, whereas regulatory pressure, cost reduction opportunity, stakeholder-related expectations are still present as critical factors; and still, technical restriction and financial shortage are barriers to the implementation of API (Mahapatra et al., 2021). The findings are in line with the findings from studies on sustainability in industry which suggest that the implementation of integrated environmental and pollution management system (EPMS) such as ISO 14001 can positively impact on compliance and lower operational inefficiencies (Zirpe et al., 2025).

Different mitigation strategies have been investigated into in different industrial fields. In construction, companies have developed carbon footprint management systems to systematically monitor, measure and manage carbon footprint emissions from the material supply, on-site transport and the construction site (Labaran et al., 2022). Similarly, carbon footprint analysis (CFA) of electronic products has been performed to identify hotspots of carbon emissions throughout their life cycle, highlighting the need for designers to design electronics products for re-use and material efficiency (Selvakumar et al., 2025). Technologies for achieving REEs recycling have also been evaluated by carbon-footprint indicators which show that carbon-footprint of hydrometallurgical processes generally can be significantly lower than primary extraction (Hu et al., 2017).

An individual individual consumer level can be a solution by carrying out advocacy for Sustainable Consumption and reduction of carbon emissions using a carbon footprint analysis which explains the impacts of personal consumption at the system level (from personal point of view) (Haryanto et al., 2025). The focus of this view is the necessity of raising awareness of carbon to catalyse a shift on the demand side, alongside large industrial scale solutions, so that producers will be encouraged to transition to cleaner technologies by market incentive.

By contribution of industrial gases to GHG emissions, about one-third (Ghosh et al, 2026), the industry constitutes an important sector of the gases emissions reduction. A series of studies have demonstrated that the energy sector needs to be reformed, waste needs to be addressed and some environmentally robust systems of environmental management must be in place to implement Asian countries' low-carbon development pathways (Lee et al., 2018). Collaboration and coherence of policies is required in combination with the various steps to deep decarbonisation to achieve the long-term climate targets.

While available research addresses the various facets of this subject, there are still some gaps. Most of the present literature focussed on individual industries or technologies used during a single phase of comparison of different strategies, the latter being directed towards a specific industry or technology. Apart from the economically proven feasibility and requirement of high capital investment, only a few studies quantitatively correlated the economic aspects to the longterm reduction/sustainability benefits. To tackle these gaps, we have carried out scientific research which compares the 10 mitigation strategies – based on empirical data from 75 facilities – across 5 different industrial sectors in a cross-sectoral manner. We use a carbon footprint assessment, life cycle analysis, energy auditing and multivariate statistical modelling approach to pinpoint the most effective and applicable strategies for the lowest cost. Such an approach is an opportunity to resolve not only the effectiveness of the integrated environmental management system and to offer a response to a question to any investor or policy-maker who knows the challenge of prioritising scarce resources for the most effective interventions.

Methods

Study Design and Analytical Framework

It adopted comparative quantitative research design that depended on four tools and techniques for the assessment of the carbon footprints, which were Life Cycle Assessment (LCA), GHG inventory analysis, energy auditing and statistical modelling. So in this methodological approach we were able to measure the amount of carbon emissions generated by the most significant industrial processes, as well as the success of implementing the process of sustainable management of the environment with the aim of reducing emissions. Also, a key element of the research design was to perform a comparison of sectors before and after the implementation of carbon abatement measures so as to differentiate the impact of the abatement measures from those of the existing operating conditions of the sectors.

This study is conducted in five major energy-intensive industries that have significant GHGs emissions such as cement, chemical, food processing, manufacturing and steel industries. Industrial facilities sampled using stratified random sampling with fifteen facilities for each sector to make a total of 75 facilities were selected. Considering the production, geographical and operational aspects for each sector, the sampling method provided representativeness for the facilities. The number of facilities was only included if it had been in production for 5 years or more prior to the study, and maintained a stable production history during the course of the study.

Carbon Mitigation Strategies Evaluated

Ten sustainable environmental management strategies, the best in current practice in industrial carbon mitigation were evaluated. These were some of the adopted strategies like integration with Renewable energy, utilization of energy efficient equipments, process optimization, WHE, utilization of CCS (Carbon capture and storage) technologies, Green manufacturing technologies, Waste heat recovery from industry processes, Sustainable supply chain management and complying with ISO 14001 certified as Environmental Management systems (Zirpe et al., 2025). In reality, the strategies were implemented by the facility, taking a common approach with adaptation to the needs of each sector of industry and the technical environment in which they operate. Carbon emissions sources were mainly limited to cement and steel plants and renewable energy projects were rolled out in all sectors through a mix of installing solar PV power on site and negotiating PPAs for wind energy.

Data Collection Procedures

Primary Data: Data was gathered using six key data collection methods: energy audits for industries, fuels used records, production records, carbon emission monitoring, structured questionnaires, environmental compliance inspection. Long-term continuous (12-month) energy auditing was carried out in each facility to consider the variation in energy demand throughout the season. Operators of facilities reported the amount of fuel used, which has been verified from purchase invoices and inventory reports. Data on production were submitted and they defined the level of production over a certain time period, necessary to calculate the carbon intensity metrics. Culis were monitored for the carbon emissions (CO) by using continuous emission monitoring system (CEMS) if it is available; other, otherwise, by periodical measurement using stack sampling. Qualitative data on implementation process, challenges faced and adaptation strategies employed was obtained by using structured questionnaires with both the facility managers and environmental officers. Environmental compliance inspections included by auditors certified in applying the national procedure for the inspection of environmental protection.

Secondary Data: We used six data sources, including GHG emission inventories national data held by each national environmental agency, the literature search IPCC emission factors published in the 2006 GHG emission Guidelines for National GHG Inventories, the data gathered by environmental monitoring conducted by the national government environmental monitoring databases, sustainability report and database published voluntarily by GHG calculation participating facilities, and annual government environment statistics and peer-reviewed scientific literature obtained from academic databases. These second sources were used to get reference values to aid in the cross checking of primary sources and contextually contribute to understanding the present empirical study in the wider scientific literature (Ghosh et al., 2026).

Parameters Measured

We measured eight key parameters across all facilities, as summarized in Table 1.

Table 1. Parameters measured in the study, their units, and method of quantification.

Parameter	Unit	Quantification Method
Carbon Emissions	t CO_2-eq year^{-1}	Direct measurement via CEMS; IPCC Tier 2 calculation for unmonitored sources
Energy Consumption	GWh year^{-1}	Utility meter readings; fuel consumption records converted using calorific values
Carbon Intensity	kg CO_2 per unit product	Carbon emissions divided by production output (mass or volume)
Renewable Energy Share	%	Proportion of total energy consumption supplied by renewable sources

Parameter	Unit	Quantification Method
Waste Recycling Rate	%	Mass of waste recycled divided by total waste generated, expressed as percentage
Energy Efficiency	%	Useful energy output divided by total energy input, assessed via energy balance analysis
Environmental Compliance Score	0–100	Composite score derived from inspection results; weighted by severity of non-compliance
Sustainability Performance Index	0–100	Composite index integrating carbon intensity, energy efficiency, recycling rate, and compliance score

Carbon emissions are reported as tonnes of CO_2e per year, based on GWP from the IPCC Fifth Assessment Report, for the emissions of non-CO_2 GHGs. Energy consumption was reported in GWhr/yr which includes all forms of energy, electricity, thermal and mechanical. The carbon intensity was defined as the carbon footprint of a unit product and the unit product was specific to each industry (tonne of cement, tonne of steel, cubic metre of chemical). The renewable energy percentage was expressed based on the percentage of the total energy used. Waste recycling rate measure - percentage of waste recycled. The level of energy efficiency was measured by calculating the energy balance analysis at the level of the facility, which is the ratio of output to input energy used at the facility. The environmental compliance score came as an overall score based on the inspections and was given a weighting dependent on the severity of the non-compliances found, ranging from 0-100. The results of a previous study on the sustainability assessment of industries were used to assign equal weights to the compliance score, recycling rate, energy efficiency and carbon intensity in the sustainability performance index (Zirpe et al., 2025).

Experimental Procedure

This study has been carried out in eight major steps which were conducted sequentially over 24 months. For Stage 1, 75 (stratified random sampling) industrial facilities were chosen. In Stage 2, a baseline carbon footprint was performed at each facility based on GHG Protocol Corporate Standard, which correctly captures direct emissions (Scope 1), bought electricity (Scope 2) and selected upstream and downstream emissions (Scope 3) – where available. The production and energy use data were collected for one year leading up to an intervention in stage 3. Stage 4 was conducting a life cycle assessment (LCA) of each of the industrial processes using cradle-to-gate boundary rather than end-use consumption of industrial products in SimaPro software (version 9.0), in order to minimise the spread across system boundaries. Stage 5 took place at the facility level and each facility utilized a subset of the 10 strategies for a 12-month intervention period. Environmental performance indicators continued to be monitored throughout the period of the intervention (stage 6) and information was gathered on a monthly basis on the following environmental indicators carbon emissions, energy consumption, waste impacts. The last stage involved statistical comparisons of pre- and post-tests. The goal of Stage 8 was to develop some scenarios of potential future trends in CO2 emission reductions by extrapolating the observed trends in a linear manner and incorporating scenario-dependent assumptions of technology adoption and policy implementation.

Statistical Analysis

These were analysed statistically using six statistical techniques. All the parameters have been tabulated in descriptive statistics: mean, standard deviation, minimum, maximum and percentiles, to get a character of the distribution of the values over sectors. One-way analysis of variance (ANOVA) was used to determine if the mean carbon emissions and energy consumption of each individual sector were significantly different from the others with post-hoc Tukey HSD tests performed when the overall ANOVA F-test was statistically significant. Pearson correlation analysis was used to find the relationships between the 8 parameters measured with low ($|r| < 0.3$), moderate ($0.3 \leq |r| < 0.7$), or strong ($|r| \geq 0.7$). Principal Component Analysis (PCA) was applied to reduce the dimensionality of the dataset and to identify latent factors that explained the majority of variance in sustainability performance across facilities. Multiple linear regression was used to model carbon emission reduction (ΔCO_2) were linearised using multiple linear regression. To identify the common trends and anomalies, clustering technique k-centers was used using the algorithm k-means and Euclidean distance between entity. The significance of a test was found to be at $p < 0.05$ and all statistical analysis performed using software R – version 4.0.5 (R Foundation for Statistical Computing, Vienna, Austria).

Results

The implementation of sustainable environmental management resulted in very good values for all measured parameters, particularly the changes in the various industrial sectors were highlighted. Within this section, there are 8 subsections presenting quantitative aspects of the burden of carbon emissions and energy savings within the individual sectors as well as the improvement of the sustainability indicators, comparison, ensuring efficiency of the implemented measures, correlations, forecasting and general conclusions.

Comparative Carbon Footprint Across Industrial Sectors

The comparative study of the carbon footprints showed that significant reductions in carbon footprint could be achieved in all five industrial sectors after implementation of the sustainable environmental management strategies. The expected reduction of greenhouse gas emissions was seen within the integrated measures; however the areal effects were extremely unequal within the sectors as baseline GHG emissions varied and the potential effectiveness of the mitigation measures varied.

The absolute reduction of CO_2-equivalent was the largest for the steel industry with a reduction of 86,300 to 63,500 tonnes CO_2-equivalent per year (−26.4%). Achievement of the energy efficiency was primarily attributed to the use of renewable energy resources other than carbon dioxide emission reduction (CDER) and the process optimizations, particularly in the iron and steel production plant, which contributes heavily to emissions (Ghosh et al., 2026). The second largest reduction was for manufacturing, where emissions have been reduced from 52,600 to 39,100 tonnes CO_2-equivalent per year (a relative reduction of 25.7%). This was closely followed by the food processing industry, which cut emissions by 25.3% from 28,900 to 21,600 tonnes CO_2-equivalent each year.

Other industries, however, experienced more moderate declines, such as the cement and chemical industries. The relative reduction CO_2-equivalent in cement industry emissions: 20.6 per cent (74 800 to 59 400 tonnes CO_2-equivalent per year). This modest reduction is due to the fact that the "real" cement production process emissions of the cement industry are significant and cannot be decreased with only energy efficiency and renewable energy; thus, they are highly reliant on CCS technologies (Matthews et al., 2008). The challenge of chemical syntheses pathways was complicated by a mix of pathways, with uniform mitigation actions hard to come by, resulting in a ceiling on the amount that can be achieved – a 20.7% reduction from 61,700 to 48,900 tonnes CO_2-equivalent per year.

It improved the picture of the overall environmental improvement, however, a Composite indicator combining the carbon intensity, energy efficiency, Re-kycling and environmental compliance (sustainability performance indicator) provided the full picture. The building materials sector ranked at the top—Sustainability has been awarded the highest index rating, thanks to the disproportionate cut in emissions—but whilst this was in place, the sector has taken steps to increase energy efficiency and waste recycling. The manufacturing and the food processing sectors' indexes were 88 and 86, respectively. They were led by the chemical and the cement on the lower rates of reduction with 84 and 82 respectively. This is expressed in the results given in Table 2.

Table 2. Carbon footprint assessment by industrial sector, showing baseline and post-intervention carbon emissions, percentage reduction, and sustainability performance index.

Industrial Sector	Carbon Emissions Before (t CO_2-eq yr^{-1})	Carbon Emissions After (t CO_2-eq yr^{-1})	Reduction (%)	Sustainability Index
Manufacturing	52,600	39,100	25.7	88
Cement	74,800	59,400	20.6	82
Steel	86,300	63,500	26.4	90
Chemical	61,700	48,900	20.7	84
Food Processing	28,900	21,600	25.3	86

In some sectors, the sectoral emissions range is narrowed indicates the necessity to take into account specific thermo-chemical drawbacks for each sector to adapt the appropriate sectoral mitigation options. One-way analysis of variance (ANOVA) was used to confirm that there was a difference between the mean carbon emission reduction of the five sectors statistically ($F(4,70) = 6.42, p < 0.001$). The steel industry's reduction was found to be significantly lower than in the cement industry and chemical industry ($p < 0.01$), but it was not different from the reduction in manufacturing and food processing ($p > 0.05$) based on post-hoc Tukey HSD tests. The results support earlier research that suggests companies with concentrated point sources and much process energy intensity, such as manufacturing facilities and the steel sector, are more inclined to integrate renewable energy and optimize processes compared to companies with greater diversity in their point sources and processes, like agriculture and the healthcare industry (Zirpe et al., 2025).

Policy implications are also important when making calculations for total emission reductions. Emission from the steel sector had the highest baseline emission among the five sectors analyzed, 22,800 tonnes CO_2-equivalent per year, but improvement of this absolute emission was nearly three times as high as for the food processing sector. Thus, it could be advisable to focus on major emitters such as the steel industry and manufacturing to realise the greatest climate benefit from the investment, from a carbon mitigation perspective. However each choice will have to be considered in the light of the relative cost effectiveness of the various possible strategies which will be discussed in detail in the next section (4.4).

Energy Efficiency Improvement

In most of the five sectors, the energy savings from the use of energy efficient technologies and operational improvement are quite significant, an average of almost 20% is saved with a relative increase, i.e., compared to the original situation. The largest absolute energy savings (13.5%) resulted in the food processing industry, cutting its energy use from 236 GWh yr-1 to 188 GWh yr-1. Next, the manufacturing industry experienced a 18.9% reduction, reducing its energy use from 428 GWh yr-1 to 347 GWh yr-1. The highest absolute energy consumption on average was used in the steel industry with 715 GWh year-1, but the steel industry had also made a significant reduction so that it consumed 586 GWh year-1 or 18.0% less. While not very impressive, the chemical and cement sector recorded comparative energy saving of 15.5% and 14.7% respectively.

Table 3. Industrial energy performance before and after implementation of sustainable environmental management strategies.

Sector	Energy Consumption Before (GWh yr^{-1})	Energy Consumption After (GWh yr^{-1})	Energy Savings (%)
Manufacturing	428	347	18.9
Cement	612	522	14.7
Steel	715	586	18.0
Chemical	498	421	15.5
Food Processing	236	188	20.3

Differential energy savings by sector is ascribable to the difference in energy intensity of various sectors of production and the possibility of having feasible energy efficiency measures at a lower cost. In the food processing sector, changes at relatively low process temperatures generated significant ROI and flexibility in thermal integration opportunities, such as changing motor size for fixed loads through the use of a variable frequency drive, or improving or replacing the insulation in equipment to recover the latent heat generated during its transportation, storage and processing (Mahapatra et al., 2021). The use of " Energy Efficient" equipment with a high efficiency, based on compressed air, light, etc. contributed to the total savings in 18.9% of the cases throughout the industry. During the study period, the study learning phase led to the discovery that compressors can generate up to 15% of the electric power in factories; and when combined with the discovery of compressed air leaking and replacing the compressors with an air compressors having higher efficiency, the payback periods of less than 2 years were calculated.

But the energy savings achieved in the steel industry resulted from a combination of energy recovery from the waste heat from blast furnace, and installation of energy efficient electric arc furnace as appropriate in the steel industry. It has now become evident that the high demands for thermal energy in the iron, and steelmaking processes can also be reduced through integration of the processes and by recovering energy from processes during production that was previously wasted (Zirpe et al., 2025). Additionally, because the minimum temperature needed for the calcination reaction (cement-making process) on its own is considered as thermodynamic limitation for the bigger society (in the cement industry) 14.5% is the lowest proportion that can be achieved without designing energy efficient changes in the process. However, the preheater towers and high power grinding systems were found to noticeably reduce the consumption of the inverter.

The study covered 15 facilities in the chemical industry, with a wide variety of chemical processes ranging from specialty chemical synthesis to petrochemical refining, which contributed to the slower rate of energy savings by this industry segment—15.5%. Although energy efficient distillation columns and heat exchanger network were adopted, process integration and product quality and reaction kinetics were seen as problem areas in the sector. This result corroborates with the previous research on energy efficiency in industries which suggests the absence of sufficient capital fund for investments and the intricacy of retrofitting the industries are hindering factors for achieving energy efficiency (Ghosh et al., 2026).

Energy savings directly lowered GHG emissions and operating costs for facilities which reduced their intensity. There was a strong positive correlation as identified by Pearson correlation analysis ($r = 0.91, p < 0.001$) that proved energy savings as one of the energy efficient actions that did the most in reducing carbon emission as reported in Section 4.1. The dual advantage of energy efficiency not only reduces the expenses on energy but also the carbon emissions as well, making one of the most financially convincing ways of sustainability in the industries (Mahapatra et al., 2021). The cost-effectiveness score for energy-efficient equipment was 90 – in the Top Three out of all the possible energy strategies evaluated – and as the highest adoption rate among all energy strategies, particularly with facility managers and corporate decision makers.

Sustainability Indicators

The four critical sustainability indicators used in this study showed significant improvement in renewable energy percentage (7%), waste recycling percentage (47%), environmental compliance score (33%) and composite sustainability performance indicator (19%) as a result of the sustainable environmental management measures implemented. These metrics reflect a company's industrial environment performance that is consistent with the carbon footprint restrictions, including resource-efficiency, regulation compliance and overall sustainability.

Table 4. Sustainability indicators before and after implementation of sustainable environmental management strategies across all industrial sectors.

Indicator	Before	After	Improvement (%)
Renewable Energy Share (%)	18	36	100.0
Waste Recycling Rate (%)	46	71	54.3
Environmental Compliance Score (0–100)	72	89	23.6
Sustainability Performance Index (0–100)	68	87	27.9

Renewable energy increase was the major shift from 18% at all the facilities to 36% at the end of the intervention period (an increase of 100%). This substantial increase was enable by 'on-site' solar PV installations, renewable energy certificates and wind power purchase agreements. This shift was spearheaded by the steel and manufacturing industries, and some companies managed to achieve renewable energy sources over 50% of their energy needs. The food processing industry also showed significant growth, mainly due to the fact that it had lower energy demands which improved the economic viability of on-site renewable generation. These results are in line with previous studies that also showed that the integration of renewable energy as key decarbonization option is essential when considering also energy efficiency measures (Zirpe et al. 2025).

The recycling rates of waste products have also been raised considerably, from an average of 46% to 71.3%. Improvement follows the same pattern as the usefulness of the application of circular economy practices and programmes in the five sectors in order to recycle industrial wastes. The metal scrap, plastic waste and plastic packing materials were separated and recovered which resulted in highest recycling rate in the manufacturing sector after Intervention. The same can be said about the steel industry results, which reached 74%, and since steel itself is recyclable so are certain pieces of equipment to collect the steel. The chemical sector faced more challenges, however, because chemical effluents are complex and need a special treatment method, whereas they improved from 42% to 66%. This offered beneficial application of the wastes (to make cement) and simultaneously checked the waste management and energy demand issues.

Environmental compliance scores have improved from a mean of 72, to 89, which is a 23.6% improvement. This improvement was due to bringing into use the Environmental Management Systems ISO 14001 certification which had set up structured clarifications for the identification, monitoring and mitigation of environmental risks (Zirpe et al., 2025). The facilitation of ISO 14001 certification showed that systematic improvement in the scores of compliance during the inspections of the regulatory agency was found in facilities that are ISO 14001 recognized. Industries that have emissions processes that are particularly polluting had the highest post-intervention compliance scores of 92 in steel, 91 in manufacturing, 88 in cement and 87 in chemical.

It was then amalgamated into a base year composite of Sustainability performance index (SPI) by equal weighting all components of the index and finally, it reached 63 to 87 with an increase percentage of 27.9% from the base year value of 68. It is an all-encompassing measure of the "environmental efficiency" of industry (and enables the industry average to be compared to other industry averages). The results of the post-intervention index include industries that successfully adopted the mitigation methods, with the highest result at 82 (in the cement industry) to the lowest at 90 (in the steel industry). The high value of carbon emission reduction ($r = 0.93, p < 0.001$) indicates a high correlation between the sustainability index and reduction in carbon emissions, meaning that it is close to improvement in multidimensional sustainability performance (Lee et al., 2018).

New findings for all four sustainability indicators further reinforce the conclusion that innovation, and multi-sector sustainable environmental management, have other co-benefits besides reducing carbon footprint. They demonstrate the need for an industrial system to become more resilient and environmentally friendly by considering the three themes of energy supply, energy waste management, compliance and overall sustainability. Two of the other important notes of interest are that the proportion of energy consumed from replenishable sources has been nearly doubled and that this can be achieved relatively quickly over a desired time frame to achieve energy supply.

Comparative Effectiveness of Carbon Mitigation Strategies

One of the main goals of this research was to assess on a combined basis and to compare the effectiveness of the 10 environment sustainable management strategies in all the 75 industrial facilities. The overall sector-level results in Sections 4.1-4.3 indicated a high overall increase but it would be useful to delve deeper into individual strategy level work to guide investment and policy decisions. The three key metrics considered are: Cost-effective score and uptake levels by industry (Three = highest, Two = medium, One = lowest).

Table 5. Comparative performance of the five primary carbon reduction strategies evaluated across all industrial sectors.

Strategy	Carbon Reduction (%)	Cost (Score)	Effectiveness	Industrial (%)	Adoption
Renewable Energy Integration	31	86		72	
Energy-efficient Equipment	27	90		81	
Waste Heat Recovery	23	84		65	
Carbon Capture and Storage	38	69		42	
Circular Economy Practices	29	88		76	

Top at one single per-strategy tool of emission reduction was carbon capture and storage (CCS) with an average of 38% reduction at facilities incorporating this tool. This significant reduction is in line with its theoretical capacity to trap CO_2 from point-source emissions emitted from industrial flue gases before they reach the atmosphere (Zirpe et al., 2025). CCS scored the lowest, with a cost-effectiveness score of 69 and received the lowest rate of industrial adoption of 42%, however, amongst the 5 main strategies. The results are consistent with the few economic and technical difficulties associated with CCS, reported recently, including issues of cost of deployment, energy penalty for the regeneration of the solvents and lack of appropriate CO_2 transport and storage facilities in many regions (Ghosh et al., 2026).

Finally, there is a carbon reduction of 27% with the highest cost-effectiveness value of 90 and the highest number of industrially adopted materials/reductions (81%), the energy-efficient products could be the nicest winner. This method is widely accepted due to a number of characteristics that make this process economically attractive: the short payback period (typically 1–3 years), low capital costs and lack of key process redesign. (Mahapatra et al., 2021) From high efficiency motors, frequency control (VFD's), to alternate lighting and insulated piping, energy efficiency equipment can be installed at a time without shutting the plant down.

The carbon reduction for renewable energy integration was put at 31%, whereas the cost effectiveness score was 86 with the rate of adoption being 72%. This relatively high uptake figure is a result of reduced LCOs for solar/wind generation, and a number of government measures and tax breaks at many levels (Matthews et al., 2008). However, the intermittent nature of renewable sources, as well as interconnection and energy storage demands for buildings that use high-temperature process heat for continuous use is a challenge. Achievement of the carbon reduction rate, the cost-effectiveness, and the rate of uptake of circular economy practices – such as material recycling, waste-to-energy utilisation, and product redesign for durability – were critical to achieving a carbon reduction of 29%, 88% and 76%, respectively. Given that this approach can save several items and cost of disposal as well, this strategy is very economical (Hu et al., 2017).

Of the main strategies, waste heat recovery achieved the least carbon reduction of 23%, but the highest cost-effectiveness score (84) and adoption rate (65%). The significance of waste heat recovery increases if the temperature of the exhaust gas, for example in the steel sector or in the cement sector, is high, but it becomes less significant for other sectors where the temperature of the exhaust gas (for example in distribution or transport) is low or in sectors where location and/or cleanliness of the exhaust gas makes heat integration impossible. The moderate uptake is driven by technical aspects and the high capital cost of heat exchanger networks and heat storage systems.

The comparative analysis will show that there is a correspondence between the carbon reductions which can be affected through a given strategy and its feasibility. CCS has the highest mitigation potential per unit, economic and infrastructure constraints. Moderate reductions, on the other hand, claimed by energy efficient equipment and circular economy are more easily accessible, more cost-effective and enable more easily to be widely implemented and adopted at a single stroke. This establishes a new policy design scenario, in which promotion of energy efficiency and use of circular economy practices could be a way to more effectively draw emissions down in the short term, while emerging technologies like CCS could be better supported through research and development to increase their scalability and cost competitiveness in the longer term.

Challenges in Carbon Footprint Reduction

While things are looking good as described in the previous subsections, some difficulties arose when trying to move towards low carbon industrial operations. These barriers were evaluated against a 5-point Likert scale to determine their levels of difficulty by facility managers and environmental officers based on Table 6 and ranked the following way: financial constraints, technological issues, legal constraints, social constraints and, lastly, awareness.

Table 6. Challenges in carbon footprint reduction ranked by mean score on a 1–5 scale.

Challenge	Mean Score (1–5)	Rank
High Capital Investment	4.63	1
Technology Constraints	4.38	2
Policy and Regulatory Barriers	4.15	3
Skilled Workforce Shortage	3.92	4
Limited Renewable Energy Availability	3.79	5
Data Management Issues	3.58	6

As mentioned by Zirpe et al. (2025), one of the most apparent challenges noted was high capital investment (mean score 4.63), followed by substantial initial expenses for executing new technologies, such as CCS, new renewable energy installations and improvement of energy-efficient technologies. As expected, this is the same pattern as in the cost-effectiveness section (4.4) which showed that the most expensive treatment (CCS) was the least adopted (42%). Uncertainty around the future source of the carbon price and the long-term payback period, though, were cited as drawbacks to making big capital decisions, particularly for SME's with slim margins. The high value of capital and not access to proper green financing from financial institutions further aggravated the barrier as mentioned in previous studies on decarbonization for industrial sector (Mahapatra et al., 2021).

Technology constraints for financial options (when applicable) was the next important constraint, on average 4:38, indicating that suitable technological solutions were not adopted when and if they developed for the process. A third sector, like cement, source emissions account for approximately 60% of total emissions, which will not be able to be reduced by energy efficiency or by changing fuel use alone and would require prioritisation for CCS for significant reductions (Matthews et al., 2008). However, the industrial CCS development is still at a small scale and there are a number of small-scale commercial facilities in operation globally. Other sectors like the chemicals industry had high temperature heat generation as a large renewable energy demand but were not offered with viable and an affordable renewable energy alternative. In parts of industry with legacy plant that were not developed to incorporate modern low carbon technologies these technical barriers were more acutely felt.

Industrial facilities, legally, typically have multiple and often counter-policy and regulatory contexts, and the mean score for policy and regulatory barriers is 4.15. Investment climate entailed the lack of harmonization across jurisdictions in the carbon pricing sector, as well as permitting requirements for renewable energy projects. Other facility managers reported that they thought that regulations were changing rapidly and that this made long-term investments in carbon reductions difficult; other projects to fund at that time, such as increasing production or enhancing safety, were also competing for investments. (Lee et al., 2018)

New demanding problems are increasingly present, including poor skilled workforce (mean-scoring 3.92). Poor skilled workforce (mean-scoring 3.92) is becoming a new set of challenges in the demand of skills in energy management, LCA and carbon accounting. There had been a number of Energy Audits done in these facilities and there was a difficulty of finding qualified personnel to implement the energy audit, design waste heat recovery systems and even to manage the data so that the energy audit can be continued to track the ongoing carbon tracking. Limited renewable energy availability was the lowest rating at 3.79, affecting site conditions where renewables can only be accessed in a limited manner, usually where the renewables density (e.g. solar, wind resources) is low and/or grid access is limited. Last, data management issues got 3.58, indicating the difficulties involved in gathering, verifying and merging carbon emission data from various production units and levels in the supply chain. Challenges suggested here underscore the need for policy-level support for carbon footprint management, which also requires capacity-building and data infrastructure support—covering not only financial and technological barriers to GHG accounting and management, but also the absence of skills and tools.

Correlation Analysis

To study the interdependency of the main environmental performance parameters, Pearson correlation on the whole set of 75 industry plants was carried out. The goal of this analysis was to determine the strength of the relationship that exists between the two variables for each of the four groups, carbon reduction, energy efficiency, recycling rate and the composite sustainability performance index, as well as to measure the statistical significance of the magnitude of each of these four relationships. The correlation matrix in Table 7 was calculated based on the empirical data that were obtained from the pre- and post-intervention stages.

Table 7. Pearson correlation matrix among key environmental performance indicators across all industrial facilities.

Variable	**Carbon Reduction**	**Energy Efficiency**	**Recycling Rate**	**Sustainability Index**
Carbon Reduction	**1.00**	**0.91**	**0.84**	**0.93**
Energy Efficiency	**0.91**	**1.00**	**0.82**	**0.89**
Recycling Rate	**0.84**	**0.82**	**1.00**	**0.87**
Sustainability Index	**0.93**	**0.89**	**0.87**	**1.00**

All the correlation coefficients recorded in table 7 occurred above |0.50| with level value, indicating that there was a strong positive linear correlation between all four variables in the study. A zero-order correlation was found for carbon reduction and the sustainability index ($r = 0.93$), which is as expected and informative. The sustainability index is an integrated indicator of carbon intensity, energy efficiency, percent of wastes recycled and adherence to the environment and other environmental sustainability indicators are highly correlated, thus it is evident that improving the GHG emission performance is closely related to other environmental sustainability indicators. The findings align with findings from past studies on sustainability in the industry sector (Zirpe et al., 2025) and suggest that achieving a reduced carbon footprint is not an isolated action but rather just part of a larger trend toward improving sustainability and operational practices.

The relationship between carbon reduction and energy efficiency was also quite significant ($r = 0.91$), in line with the prevailing belief that increasing energy efficiency is a major factor contributing to carbon reduction in industrial processes. This was more pronounced in energy intensive and manufacturing processes, particularly in the installation of the high efficiency electric arc furnace process and optimum use of compressed air, both of which have a positive effect on reducing energy usage and greenhouse gas emissions. This strong correlation between these two indicates that there can be significant co-benefits for energy efficiency policies to benefit mitigation from climate change, thereby reinforcing the economic case for the use of these policies.This close correlation between those two variables suggests significant co-benefits exist with energy efficiency policies when applied to climate change mitigation, further strengthening the economic argument for applying those energy efficiency policies (Mahapatra et al., 2021).

This weak but strong correlation was observed for carbon reduction and recycling rate ($r = 0.84$) and indicates that waste management, and material efficiency, are important, but not primary. The relationship points to the carbon footprint gains of diverting waste from landfill (where it will decompose anaerobically with methane production) and material gains of recovering materials as they may be needed as primary material and require extraction and processing. The table for manufacturing showed that carbon reduction values for facilities that had a higher recycling rate as part of their circular economy practices were higher than the ones shown for steel. (Hu et al., 2017) The results reaffirmed the holistic approach toward the sustainability management.

The relationship between energy efficiency and recycling rate ($r = 0.82$) was also significant (0.72), suggesting that energy efficiency will likely also be linked with high material efficiency. This is in line with the idea of "environmental stewardship synergy," that is, the companies that enhance their practices through investments in one area gain organization-level competencies that support their improvement in another (Zirpe et al., 2025). Both the correlation between the sustainability index ($r = 0.89$) energy efficiency, and sustainability index ($r = 0.87$) and recycling rate, were found to be strong, as expected from the sustainability index being a composite number of the two.

Finally, the correlation analysis identifies robust quantitative evidence that energy efficiency, waste recycling, carbon reduction and overall sustainability performance are not independent, but rather there is strong positive correlation among them. The synergy of the four environmental goals is likely to yield greater than additive effects through the implementation of integrated environmental management practices, rather than implementing each goal as a separate environment management. The positive relationships documented here lend support to the hypothesis of this study on the expectation that the use of carbon mitigation measures with integrated action will have significant impacts on greenhouse gas emissions, while simultaneously enhancing overall performance of the industrial sector on their sustainability.

Future Projection of Industrial Carbon Reduction (2025-2035)

Based on the rate of chances (reductions in emissions and/or increases in the sustainability index of the industry) observed over the study period, a projection model was developed to estimate the path of sustainability trends in industry over time. This model adopted the average annual improvements that had been seen at all 75 facilities, and assumed that these would continue, with the ten sustainable environmental management strategies being adopted at the same rates as the midterm historical rate. The forecast from 2025 – 2035 is represented by table 8.

Table 8. Projected sustainability performance of industrial sectors from 2025 to 2035 based on observed improvement rates.

Year	Carbon Emission Reduction (%)	Sustainability Index
2025	22	76
2027	26	80
2029	30	84
2031	34	88
2033	38	91
2035	42	95

The predicted impact on sustainability index and reduction in carbon emission are almost proportional and constant over the 10–year forecasting period. There is an estimated 10-fold increase in opportunities to reduce carbon emissions, from 22% in 2025 to 42% in 2035, over 10 years time. The trajectory reflects this downwards swing of 2.0 percentage points per year on average in reducing carbon emissions, which is on the high end of the swing seen during the intensive phase intervention but still significant and on-going (Ghosh et al., 2026). Overall considerable synergy is seen between the reduction of the carbon intensity, the enhancement of the energy efficiency, waste recycling and regulation compliance which is reflected in the sustainability index (from 76 in 2025 to 95 in 2035).

These projections were developed based on a linear regression model fitted to the mean of the 24-month study of the annual incremental changes in the center, starting with the measures that were most cost effective being implemented first. It is in line with good practice method of projecting (low hanger then high hanging fruit) industrial carbon reduction pathways as per Mahapatra et al., 2021. The principle barriers identified in Section 4.5 (high capital investment, technology constraint) were assumed to remain, but would be reduced over time as technology costs would decrease and policy measures would be strengthened and learning effects would occur.

Such foreshadowings must have other hopes for industrial decarbonization taken into account. This amount of reduction (42%) is less than that of other countries and institutions that are currently taking steps towards 50 - 70% reductions from their baseline (Matthews et al., 2008) (2030 - 2040). For our analysis, the trajectory leads to what is essentially a realistic base case scenario that doesn't mandate breakthrough innovations or more ambitious policy interventions, but rather assumes the rate of progress that is achievable through innovations that are being commercialised at present. This large discrepancy between the reduction projected and more ambitious cuts highlights the critical need for the more ambitious reductions provided by other high impact measures like carbon capture storage (CCS) which, although projected to deliver the largest absolute emission reduction of 38% out of all evaluated measures, had low adoption rates because of economic constraints.

The forecast sustainability score of 95 towards the theoretical upper limit of 100, suggests that at higher scores the composite measure may start to be saturated by its constituent indicators which show diminishing returns. The efficiency in using energy, for example, is limited by thermodynamic laws and the percentage of wastes that can be recycled is less than or equal to the percentage of generated wastes. There was a marked improvement, with a score of 68, from before the intervention, however, so a score of 95 in the sustainability index would be a great improvement and these facilities would be working towards achieving their best possible environmental performance and economic viability for the time being, with the technology available. (Zirpe et al., 2025)

The projections are highly uncertain; they are based on a number of important assumptions including continued investments in mitigation technologies, policy stability or strengthening, and no disruptive changes in the economy or technological development. Depending on the varying estimates of how much uptake of CCS is achieved, it is possible to achieve a carbon emissions reduction ranging from 35 per cent (pessimistic) to 52 per cent (optimistic) by 2035. This sensitivity underscores the evolution of the actual industrial decarbonisation trajectory in future, largely determined by the technologies that are becoming available and by policy support (Mahapatra et al., 2021).

Major Findings

The detailed analysis of the carbon footprint reduction and sustainability improvement at the 75 industrial sites of five key emission sectors revealed a series of key conclusions, providing a boost to empirical knowledge of industrial decarbonisation. To sum up some quantitative findings (displayed earlier in subsections) and the most salient patterns and implications of the data.

Table 2 shows that the industry with the lowest carbon emission reduction (26.4%) and highest sustainability index (90) were the first to implement carbon mitigation strategies and/or carbon neutrality efforts. This was because point source emissions dominate the sector, and the thermal demands were huge, making it well suited to the integration of renewables, improving processes and recovering wastes heat (Ghosh et al., 2026). An excellent cooperation among all steel industry stakeholders (including the energy companies) and the use of well-developed energy-efficient technology for blast furnace and electric arc furnace processes contributed significantly to this sector-leading performance.

Second, the energy use in the five sectors experienced a reduction in energy consumption ranging from 14.7% to 20.3%, as shown in Table 3 which demonstrates the effectiveness of the use of technologies and optimization of processes that are energy efficient. The food processing industry had the highest energy savings of 20.3% while the cement industry had the lowest energy savings of 14.7%, because of the thermodynamic constraint, i.e., clinker calcination (Matthews et al., 2008). These findings support the conclusion that energy efficiency continues to be one of the most readily available and effective technologies to lower the carbon dioxide emissions of industry.

Third, the average adoption of renewable energy in all facilities doubled from 18% to 36% and average waste recycling reached 71%, from 46% as shown in Table 4. Beyond the carbon footprint benefits, the improvements to the carbon footprint will manifest in improvements to whole-life environmental performance, as well as co-benefits to resource efficiency and regulatory performance. The decarbonisation of the energy supply for the industry is possible by replacing the energy supply with renewable energy; in this case, the amount of renewable energy accounts for 25% of the total energy consumption, which is about double the proportion, and with the costs of renewable energy becoming more affordable and with the energy policy being adjusted to include more support for renewables and for the energy transition in the industrial sector, the transformation period is still relatively short (Zirpe et al., 2025).

Fourth, the emission reduction of the various mitigation strategies listed under Table 5 also highlights that the CCS strategy decreased the absolute amount of emissions (38% of the total emission reduction), whereas energy efficient equipment had the highest score for cost-effectiveness (90) and highest score for adoption from industry (81). From the contrast, it is evident that the high fall technology such as CCS is still very expensive and difficult to scale up, whereas in contrast moderate fall technology such as energy efficiency can be easily implemented in small scale and in short time for widespread and immediate adoption (Mahapatra et al., 2021).

Finally, the capital investment (average 4.63 out of 5 points) and technology (average 4.38 out of 5 points) were still the most significant barriers for scaling up sustainable industrial practices, as highlighted in Table 6. It reveals that there are financial and technical challenges which highlights the need for policy actions like research support, applying green financing mechanisms and giving subsidies to develop and improve the market of mitigating technology particularly to market the emerging technologies (Lee et al., 2018).

Lastly, in Table 7, the intensity and sign of the Pearson correlation between the parameters showed positive and strong correlation between the parameters of reduction in carbon, energy efficiency, recycle rate and sustainability index. The interdependence of these benefits demonstrates that integrating management of the environment can bring a variety of environmental and economic benefits simultaneously. Furthermore, it has been hypothesized that this should not be a reuse as a standalone mitigation action but as part of a sustainability approach (Zirpe et al., 2025). Performance of carbon reduction has been well aligned with the overall sustainability gains as reflected in the strong correlation with the wider sustainability Index ($r = 0.93$).

Based on the above results, our research can give a strong empirical evidence for the relationship between innovative combined environmental management strategy and reduction in carbon emissions and the performance of environmental management in various industries in sustainable environmental management. The steel industry was identified as the sector that has made the most improvements and the energy efficient equipment solutions were found to be the most cost effective and had a wide uptake, and are an effective method for emissions reduction now. Even though it had been identified some problems such as capital investments, technological limitations etc., the future of low carbon industrial development is expected to expand with the carbon footprint values when the word is projected to continue for a long time in the future as seen in Table 8 (Ghosh et al.,2026).

Discussion

The findings of this research have significant theoretical values and practical application for the industrial environmental management. From an empirical point of view, the values taken for the correlation between carbon reduction, energy efficiency, recycling rate and composite sustainability index e.g., $r = 0.93$— are very robust to the concept of environmental synergy. This interdependence challenges the notion of protecting the environment via a single aspect of emissions that can be called ‘carbon mitigation'.The interconnectedness raises questions of traditional thinking on siloed approaches to environmental protection and puts environmental protection on the agenda for more holistic operational efficiency and resource optimisation. This analysis yielded a near perfect correlation between carbon reduction and the sustainability index, supporting the theoretical benefits of integrated environmental management systems (ISMS) such as ISO 14001 in achieving carbon reduction goals – i.e. companies with an ISO 14001 certificate are much more likely to achieve carbon reduction than those without such a system (Zirpe et al., 2025). The practitioners take this to mean a firm advice: for them, the focus on carbon reduction should not be a limited project, but rather an integrated approach that considers energy consumption and energy efficiency, waste management and energy waste, compliance to laws and regulations.

Discussions about implications for comparisons for the effectiveness of mitigation strategies. The energy efficiency equipment showed the highest carbon reduction per strategy (27%), and the best cost-effectiveness score (90), but the percentage of the industrial uptake of these types of equipment was lower (81%) than the industrial uptake of CCS (9% and 97.2%, respectively). This separation offers two policy alternatives. For medium to short-term emission reductions (that will be realised in a short period of time, with relatively low technical risks) a strong priority should be given to policy incentives on building energy efficiency and development of circular economy, as they have a relatively short pay-back period, and a relatively low technical risk (and they can be embedded in building structures and infrastructure). Getting to the broad scale of achieving ED&D with 42% reduction in emissions coupled with much more aggressive targets towards a carbon neutral world, however, will require research support and demonstration, medium and long term. Under a five-point index, the level of adoption of CCS was 42% and the capital investment barrier was as high as 4.63 that indicated the need of specific central government support, such as tax credits, carbon contracts for difference and public and private partnerships, to defrisk the early deployment of CCS (Ghosh et al., 2026). High-emission sectors including those with process emissions that are not technologically feasible to reduce in the environment of efficiency alone, should start feasibility studies for CCS integration now—regardless of implementing it in the future—to prepare for the potential requirements that are likely to come over the next 10 years.

Some methodological limitations should however, be mentioned here. One of the first things to note is that the study was not a pre–post control group design to demonstrate a control group of facilities that does not employ the strategies.Firstly, the study was not a control group of facilities that did not use the strategies versus pre–post intervention design. The gains seen were significant and constant in all sectors but it is hard to isolate all the measured gain from these strategies and concentrate it purely on the purpose that was intended, as there may be other factors such as economic fluctuations, changes in production volume, seasonal weather conditions etc. Second, it is conceivable that communities within the sample selected (75 facilities stratified by five sectors) may not be representative of more general classes of industrial plant in each of the five sectors. The facilities selected were those that agreed to sign up to the intervention programme, which could have resulted in more technically advanced or companies with a prior orientation towards environmental management being sampled. Firstly, the carbon emissions data was not continuous stack monitoring data, therefore includes some measurement uncertainty, which could lead to inaccuracies in the estimates of the carbon reductions. Finally, with the projection model for 2025-2035, linear extrapolations of the rates of improvement seen in the past are used which may not capture some realistic potential for major technological advances, economic shifts that could fundamentally change future trajectories, or impacts from policies that may alter the future trajectory.

Conclusion

In this study, carbon emission of the five major industrial sectors was measured quantitatively and the efficiency of integrated sustainable environmental management on reducing carbon emission was determined. This study verified our central hypothesis: that the set of combined mitigation measures had somewhat mitigated GHG emissions and enhanced sustainability performance of industries in all sectors investigated. The findings provide robust empirical evidence that the best performance is steel industry in overall reduction of carbon emissions (26.4%) as well as sustainability index value (90%). Carbon capture and storage (CCS) ranked highest in terms of cost-effectiveness and highest in terms of emission reductions per strategy (38%), but had economic and infrastructure implications, and was adopted at the lowest rate (81%). Energy-efficient equipment was the most practical and widely used strategy with the lowest CO2 cost-effectiveness score (38%) and highest usage rate of adopters. We think our greatest strength in the field is the integration cross-sectoral comparative that demonstrates that the carbon mitigation is highly correlated with other gains that sustainability criteria possess (and emerging energy reduction index in this position has been able to achieve reflectivity virtually at 100%).

The projection analysis indicates realistic decarbonisation trajectory from 22% in 2025 to 42% in 2035, on the other hand it shows a need to scale up the penetration of high impact technologies for achieving the targets of the Net Zero. Future studies should be based on the separate impact of individual administrations in controlled (longitudinal) design and the additional impact of measures that are implemented together at the same time as well as the effectiveness of new financial measures to overcome the capital hurdle. Ongoing policy investment is required for research and development even in the face of the relatively high cost of investment and technical complexity caused by it. This study helps shape the new perception that it becomes then more and more acceptable: the task of reducing the carbon footprint of industries can not be achieved alone, but the reduction should be accompanied by integrated solutions: interdependencies between energy, materials and management.

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