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ENERGY EFFICIENCY ENHANCEMENT IN METALWORKING PROCESSES THROUGH ISO 50001-BASED MANAGEMENT SYSTEMS

J.L. Villa [1,2] **J.A. Fabregas** [3] **C.G. Diaz** [2,3] **J. Fabregas** [2,3,4] **A. Palencia** [4]

1. Department of Civil and Environmental, University of the Coast, Barranquilla, Colombia, jvilla27@cuc.edu.co
2. Postdoctoral Program in Sustainable Project Management, International Research Mexico University, Puebla, Mexico
3. Faculty of Engineering, Autonomous University of the Caribbean, Barranquilla, Colombia,
jairo.fabregas@uac.edu.co, carlos.diaz18@uac.edu.co, jonathan.fabregas@uac.edu.co
4. Department of Mechanical Engineering, Technological University of Bolivar, Cartagena, Colombia
jfabregas@utb.edu.co, argpalencia@utb.edu.co

Abstract- The study explores the implementation of the ISO 50001 standard as an alternative energy management system for the metalworking industry, within the framework of the United Nations' sustainable development goals (SDGs). The main purpose of the research is to enhance the energy efficiency of a metalworking company, contributing both to environmental sustainability and the reduction of operational costs. The primary objective is to identify and apply energy management practices that optimize energy consumption in the plant. This is achieved through the characterization of electrical equipment used in the experimental facility and the analysis of its energy usage. A baseline and a target line were established to measure progress in energy efficiency, evaluating key indicators such as the consumption index and electricity consumption trends. Additionally, the study estimated the critical production point, the critical production rate, and the potential energy savings. The main findings reveal that the company’s lathes consume approximately 1.4 MWh per month on average, accounting for 80% of the total monthly energy consumption during the study period. It was also determined that the critical production parameter is 25.72 units per hour, which could lead to an estimated 7.26% reduction in current energy consumption. The study concludes that implementing recommended energy management practices can significantly improve production efficiency and enhance the company’s financial performance, highlighting ISO 50001 as a key tool for achieving these goals.

Keywords: Energy Efficiency, ISO 50001, Consumption Index, Metalworking Industry.

1. INTRODUCTION

Due to the increasing demand for services and the operational characteristics of processes in the Metalworking Companies’ Sector (MCS), there is a significant energy requirement that must be met with a high-quality and reliable supply. In countries like Colombia, electricity generation is primarily hydroelectric and is currently undergoing a rapid energy transition to mitigate energy security threats caused by extreme climate events [1]. In response to this challenge, Energy Management Systems (EnMS) enable the planning, organization, implementation, and improvement of energy performance in production processes, based on international standards for the rational and efficient use of energy [2]. This has led to a growing number of companies adopting these systems and conducting research under various scenarios [3, 4].

Energy efficiency and rational energy use have become critical topics in global EnMS for two main reasons: the conservation of non-renewable natural resources on which most energy production depends and the environmental pollution resulting from resource exploitation and fossil fuel combustion, both consequences of rising energy demand [5]. As a result, governments and companies are working to implement efficient and environmentally friendly policies and production processes that promote responsible, safe, and sustainable energy consumption, ultimately yielding economic benefits and improved well-being [6].

This concern has inspired scientific initiatives to develop methodologies for rational and efficient energy use aligned with the SDGs, as well as energy management models focused on improving both organizational and operational processes-such as the EnMS proposed by the International Organization for Standardization (ISO). Beyond the application of standards, continuous improvement strategies are highly valued for their effectiveness in manufacturing activities and in reducing occupational risks within occupational health and safety management systems [7, 8]. A literature review by Guillen, et al. [9] analyzed warehouse management techniques in manufacturing dispatch areas, highlighting tools such as the 5S model, Lean Manufacturing, and ABC classification, with a focus on process optimization, time efficiency, and productivity.

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Jesus Rodríguez and Juan Ventura [10] examined how organizational strategies influence human resource management in 120 Spanish manufacturing companies, finding that training and development practices are more sensitive to strategy than compensation practices, positioning human resources as a key source of sustainable competitive advantage. Similarly, Rocio Leon, et al. [11] identified operational risk sources in 73 MCS in Ibarra, Ecuador, focusing on human talent, processes, infrastructure, and environment, and revealing deficiencies in planning, control, and institutional support. These studies aim to design mechanisms for mitigating operational risks.

Recent studies highlight the growing importance of digital tools and intelligent systems in improving energy efficiency. Tyxhari, et al. [12] showed that energy audits supported by specialized software can significantly reduce energy consumption in buildings-up to 31% in heating and cooling-demonstrating the potential of such tools for industrial applications aligned with ISO 50001. Dhriyyef et al. [13] introduced a hybrid algorithm (HFSA) that optimizes the scheduling of energy use in smart homes, achieving over 10% cost savings while maintaining comfort. These algorithmic strategies offer scalable solutions that can be adapted to industrial energy management systems.

Similarly, Umudov, et al. [14] applied AI-driven digital twins in soft drink manufacturing to optimize energy equipment control. Their approach identified production volume as the key factor in energy consumption and demonstrated how predictive maintenance can extend equipment life and reduce downtime-principles that support continuous improvement under ISO 50001. Building on these findings, this study emphasizes the importance of developing tools to implement an integrated management system in energy sustainability management. It focuses on applying ISO 50001 to a MCS to reduce energy consumption, save time, mitigate risks, and promote operational sustainability through efficient energy use [15-17].

2. PROBLEM STATEMENT

Energy management in the metalworking industry faces specific challenges due to the variability in production processes, technologies, and customer-driven demands. While ISO 50001 provides general guidelines for efficient energy use, its effective implementation requires customized approaches that reflect the unique conditions of each facility. One major challenge is establishing a meaningful link between energy consumption and production output. Traditional metrics, such as units produced, are often insufficient due to the diversity of components and services. Instead, using an Equivalent Work Cost (EWC) as a central indicator allows for a more accurate representation of energy performance and supports informed decision-making for continuous improvement.

The goal is to reduce total energy consumption -both primary and secondary- through a flexible energy management system that adapts to different industrial environments and helps identify opportunities for efficiency. In many cases, production is driven by specific customer orders, meaning the type of work and service conditions are not known in advance. This leads to high variability, making it difficult to correlate energy use with production volume. Therefore, understanding the operational behavior of each workstation is essential. By defining an EWC, companies can better assess energy effort and guide improvement actions toward sustainability and efficiency.

Workstations operate on 12-hour shifts, which may be continuous or segmented depending on customer needs. Key areas include lathe, milling, and welding stations, each contributing to energy and input costs. Operator wages must also be distributed across these stations based on task assignments. Analytical methods such as the baseline and target line approach are crucial in energy management. The baseline establishes a reference point for energy consumption under normal conditions, while the target line sets specific efficiency goals. This method enables organizations to track progress, evaluate the impact of energy-saving measures, and identify areas for improvement. It also fosters a culture of continuous improvement by providing clear metrics that support strategic and informed decisions.

2.1. Limitations of the Energy Management Model

This model establishes a relationship between energy consumption and the equivalent energy cost of a variable derived from an average tariff that reflects the operational cost of manufacturing processes involved in the production, reconstruction, or repair of metal components. To formulate this variable, the most representative or frequent operation within the plant is used as a reference, and values are extrapolated to other activities.

However, its application presents significant limitations. Each company must have a detailed understanding of its production processes to identify a variable directly linked to output, that significantly affects energy consumption. In companies where production is highly customized and driven by specific client requirements, it is essential to understand the operational dynamics in order to adapt the model effectively. This involves adjusting calculation parameters and refining energy indicators so that the model can be contextualized as a methodological framework applicable across different industrial settings, provided the unique characteristics of each plant are acknowledged.

3. DIAGNOSIS OF THE MCS's OPERATIONAL ACTIVITY

3.1. Energy Management Systems

An EnMS is defined as a set of interrelated elements that operate sequentially through a process of planning, development, verification, and control to enhance an organization’s energy performance. It provides tools and guidelines for companies or users to systematically improve energy indicators associated with production processes, increase the use and self-consumption of renewable energy, and ensure compliance with the organization's energy policy. The EnMS consists of an organizational structure, procedures, processes, and resources required for its implementation [18, 19]. These elements are introduced through methodologies based on international standards and are structured into the following stages, as shown in Figure 1.

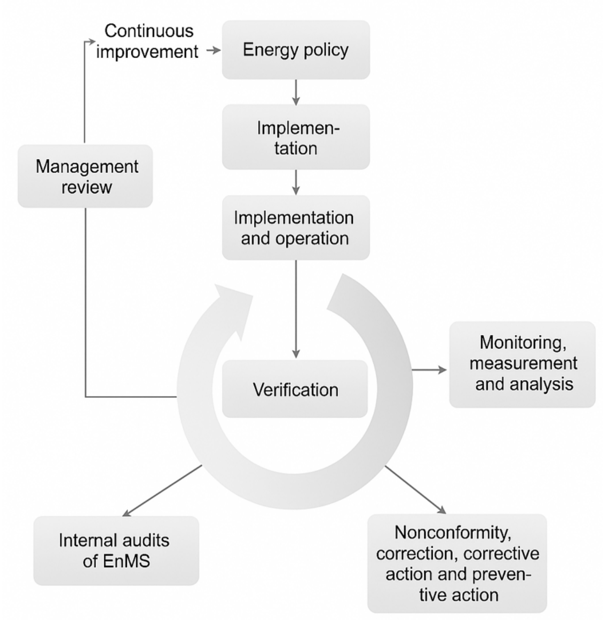

Figure 1. Energy management model for ISO 50001 [20]

The planning phase begins with an energy review, which establishes the baseline, energy performance indicators, objectives, targets, and action plans. The implementation phase involves executing the previously defined plans. The verification phase includes monitoring processes and controlling variables related to the energy study, following the guidelines of the standard and the organization. Information in this phase is typically presented in reports. The Act phase is based on the feedback received, where corrective actions are taken to drive continuous improvement within the company.

3.2. Energy Diagnosis in an MCS

The process begins with the energy characterization of the technologies, machines, and tools used in the company's production operations. To achieve this, a site visit was conducted, and information was recorded using a custom-designed format for documenting the facilities. This format included the operating ranges of variables for different processes, as well as the technical specifications of the equipment.

Figure 2. Machining operations production area

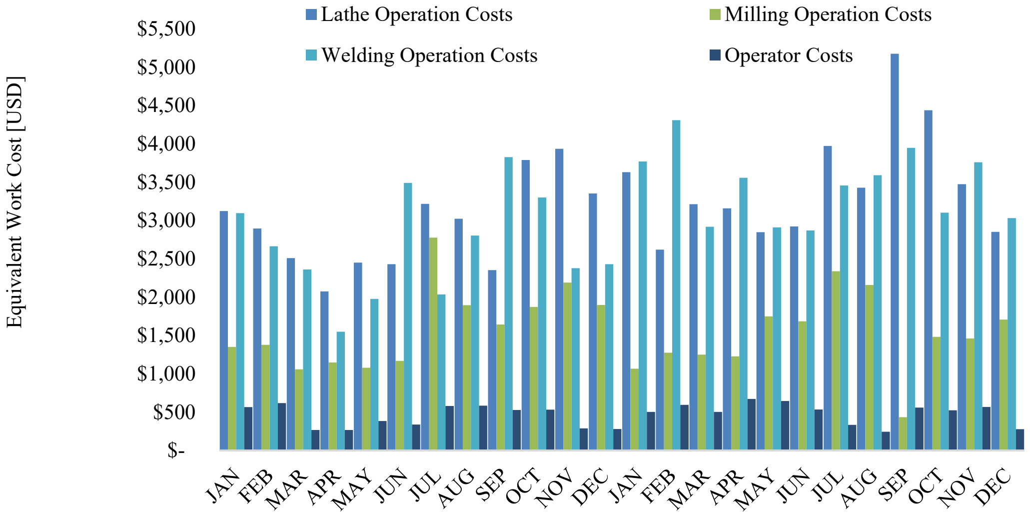

Figure 3. Historical equivalent work cost by activity

The company will provide the environment for validating the mathematical model. Subsequently, the standard is applied by adjusting the model according to the parameters and operational dynamics of both the sector and the company. This allows for the identification of energy not directly associated with production processes. This value will be analyzed concerning the company's work habits, methods, and practices to establish energy improvement policies and promote the rational use of energy through the proposed tool.

3.3. Baseline and Target Line Method

To implement the ISO 50001 methodology, it is important to identify a variable related to the production process that allows for analyzing energy consumption. Since individual costs for each process are available, they have been combined into a representative total cost for the overall process. This method helps apply the methodology by providing a strong historical foundation for analysis (Figure 4).

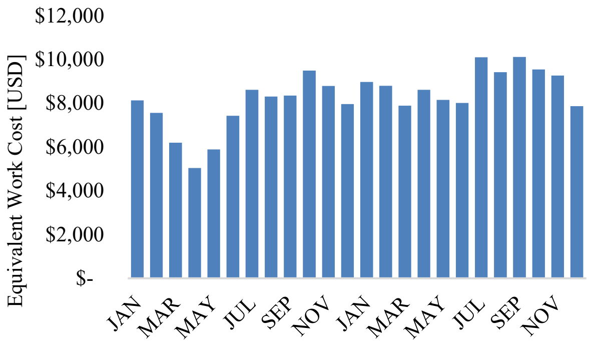

Figure 4. Equivalent total labor cost in USD

Figure 5 presents the monthly electrical consumption as a function of production units, highlighting a coefficient of determination (R^2) of 0.522. This value indicates a strong correlation, consistent with the standards established by the ISO methodology.

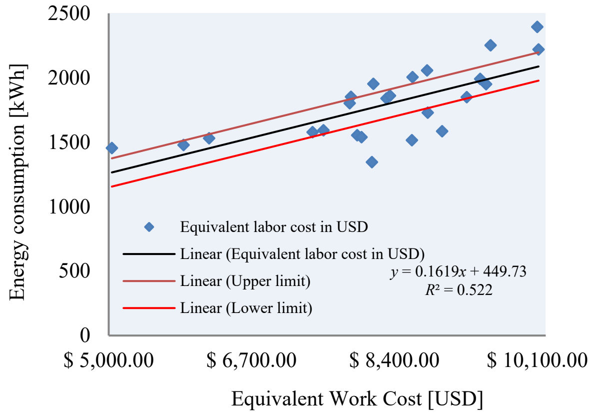

Figure 5. Baseline graph - relationship between energy consumption (kWh) and EWC (USD)

From the analysis of the correlation data, Equation (1) is obtained [16].

$$E_{elect} = (0.1619C_{Eq} - 449.73)\,\text{kWh/month} \qquad (1)$$

where, C_{Eq} represents the EWC cost of the MCS services provided monthly, E_{elect} denotes energy consumption expressed in kWh per month, and the value 449.73 refers to Non-Process-Associated Energy (NPAEn).

This value corresponds to the operation of equipment whose E_{elect} is independent of the plant's monthly production level. It suggests that NPAEn is linked to devices not directly involved in production, such as fans, work lamps, and other factors like operational delays.

A data filtering process is required, beginning with the calculation of the standard deviation of the dataset. Values that fall 0.7 times above or below the calculated mean from the original baseline data are removed. This results in a new correlation, referred to as the Filtered Data Baseline. As shown in Figure 6, the correlation of the filtered data reaches a value of 0.85, reflecting a highly accurate fit and a very strong correlation according to the standard. It also indicates that 35% of the E_{elect} is not associated with production, for a new NPAEn of 646.07 kWh/month.

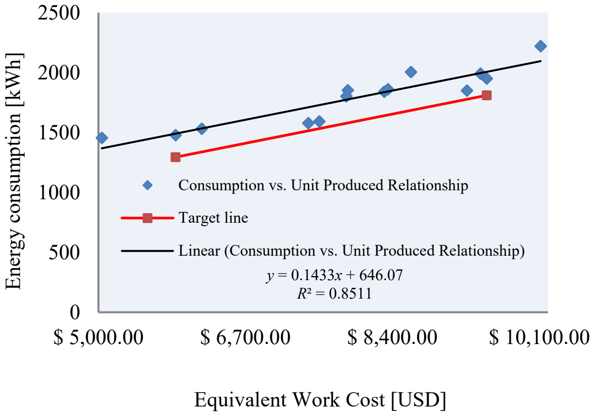

Figure 6. Target line - electrical consumption vs EWC

The baseline and target line models were calibrated using operational data from the case study company following ISO 50001 methodology. Calibration involved tuning coefficients based on variations in EWC and production rate, aligning with recommended engineering methodologies for ISO 50001 implementation in industrial contexts [21]. A numerical sensitivity analysis was performed to quantify how changes in operational parameters affect energy consumption. The results show that a 5 % increase in EWC leads to approximately 3.2 % higher energy consumption, while a 5 % increase in production rate causes around 2.7 % increased consumption. This emphasizes the model's sensitivity to operational variations and its applicability in operational planning [22].

To assess robustness, the model was applied to a milling process. The resulting $R^2 = 0.83$ closely matches the welding process's $R^2 = 0.85$, confirming high model reliability and measurement accuracy. These high R^2 values are consistent with outcomes reported in technical evaluations of ISO 50001 implementations, where energy model fit indices range between 0.80 to 0.90, indicating strong predictive validity. From a practical perspective, these insights enable metalworking firms to forecast energy demand under different production and EWC scenarios-facilitating data-driven energy policy decisions. The integration of sensitivity analysis into ISO 50001 frameworks enhances process stability and guides improvements in energy performance and production planning.

4. RESULTS AND DISCUSSION

4.1. Obtaining the Consumption Index

The Consumption Index (CI) represents the ratio between energy consumption and the C_{Eq}, highlighting the variability of E_{elect}, as illustrated in Figure 7. The CI was calculated by dividing energy consumption by the C_{Eq}, allowing for an analysis of the plant's energy performance throughout the study period. This analysis identified the months with the highest E_{elect} and helped determine the causes behind energy inefficiency peaks that increased the company's billing costs.

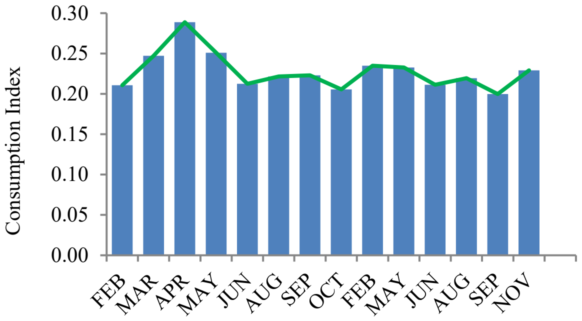

Figure 7. Variation of the energy consumption index

Based on the baseline concept, the baseline CI is defined. This represents the energy consumed per USD generated by production processes, as shown in Equation (2) [16]:

$$IC = \frac{E_{elect.}}{C_{Eq}} = \frac{(0.1433C_{Eq} - 646.07)\text{ kWh/month}}{C_{Eq}} \qquad (2)$$

The increase in energy costs per unit produced is calculated by dividing the NPAEn by the C_{Eq}. Therefore, as production increases, the monthly CI per unit decreases, reflecting improved energy performance.

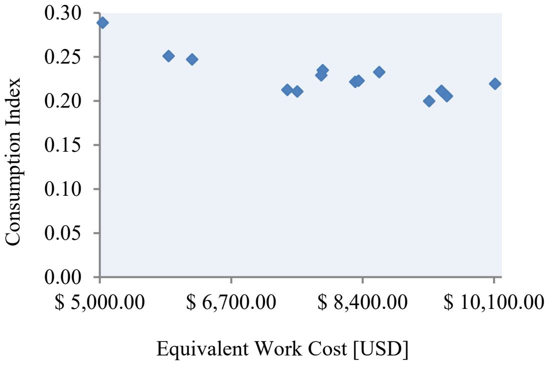

Figure 8. Actual consumption index vs EWC

Figure 8 shows how the CI was lower in certain months relative to the C_{Eq}, indicating higher efficiency in those months compared to others. The minimum CI recorded was 0.20, and the maximum was 0.29, due to variations in NPAEn.

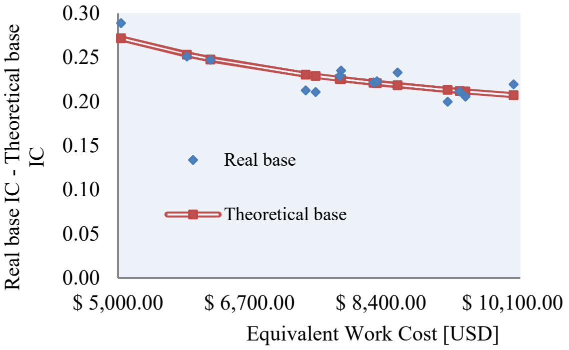

Figure 9. Actual vs theoretical consumption index vs EWC

In Figure 9, a decreasing slope in the data indicates a correlation between the actual and theoretical CI for C_{Eq} values below $10,000 USD. However, by applying the second derivative, it is possible to determine the critical C_{Eq} and the Potential Energy Savings (PES). Figure 10 shows that when the C_{Eq} exceeds $10,000 USD per month, a potential energy saving of 129.72 kWh/month could be achieved, equivalent to 7.26% of current consumption, as indicated in Table 1.

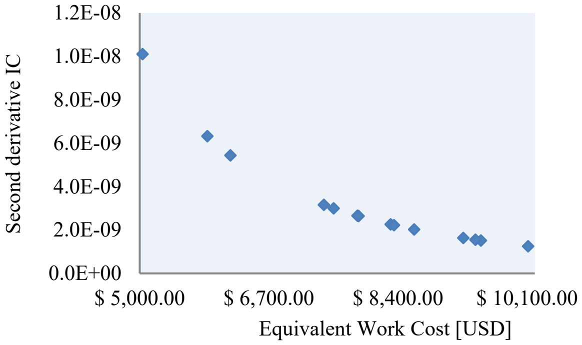

Figure 10. Second derivative of the consumption index vs EWC

Table 1. Critical EWC parameters

Critical Production Parameters	Value	Units
Average Current EWC	$ 7.957.53	Units Produced / Month
Current Critical EWC Rate	22.10	Units Produced / Hour
Average Actual CI	0.23	kWh / Unit Produced
Estimated Critical EWC Point	$ 9.260.49	Units Produced / Month
Estimated Critical EWC Rate	25.72	Units Produced / Hour
Potential Energy Savings	129.72	kWh / Month
% Savings	7.26%	

4.2. Energy Consumption Trends

The E_{elect} behavior of the MCS system is analyzed in relation to the C_{Eq}. By applying the actual C_{Eq} to the baseline equation, the theoretical E_{elect} is determined. The difference between actual and theoretical consumption allows for the identification of months with higher and lower profitability. The increasing and decreasing trend in the cumulative sum shown in Figure 11 demonstrates that the MCS operating mode is not stable, as it exhibits peaks of energy inefficiency. These peaks indicate months in which E_{elect} was high despite producing the same or fewer units.

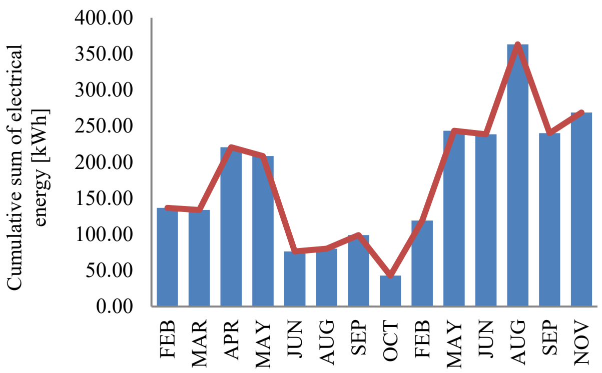

Figure 11. Cumulative sum of the difference between actual and theoretical energy consumption

Figure 11 illustrates the fluctuating nature of operations throughout the year, with both upward and downward trends in the cumulative sum. The inefficiency peaks highlight the months in which the services provided were equal to or below the previously recorded EWC.

4.3. Implementation Roadmap for ISO 50001 in MCS

Figure 12 illustrates the stepwise roadmap for implementing ISO 50001 in MCS, structured under the Plan–Do–Check–Act (PDCA) cycle. The diagram summarizes the key stages: Energy Review, Baseline Definition, Target Setting, and Implementation, along with continuous verification and improvement. This visual guide provides a practical framework for aligning operational actions with ISO 50001 clauses, enabling replicability and systematic energy management.

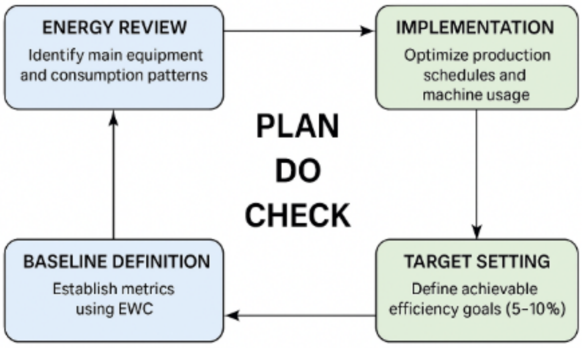

Figure 12. Implementation roadmap for ISO 50001 in MCS

4.3.1. Energy Review

The first step involves conducting a comprehensive energy review to identify major energy-consuming equipment and operational patterns. This diagnostic phase enables companies to map energy flows and prioritize areas with the highest potential for savings. Studies emphasize that systematic energy audits are critical for MCS to uncover inefficiencies and establish a foundation for ISO 50001 compliance [23].

4.3.2. Baseline Definition

Defining an energy baseline is essential for tracking performance improvements. In MCS, the EWC metric provides a robust indicator by correlating energy consumption with production variability. Recent research highlights that accurate baseline improves decision-making and facilitate predictive modeling for energy performance [23].

4.3.3. Target Setting

Setting realistic targets-typically 5-10% efficiency gains-is recommended to ensure feasibility and maintain operational stability. Literature suggests that incremental goals aligned with ISO 50001 clauses foster continuous improvement and reduce resistance to change [24].

4.3.4. Implementation

This stage focuses on executing action plans, such as optimizing production schedules, reducing idle times, and upgrading to energy-efficient technologies. Integration of digital tools for real-time monitoring has proven effective in enhancing ISO 50001 adoption in MCS [24].

4.3.5. Verification

Verification involves continuous monitoring, internal audits, and performance reviews under the PDCA cycle. Research confirms that systematic verification ensures compliance and sustains energy savings over time [25].

4.3.6. Staff Training and Engagement

Human factors are critical enablers of success. Training programs aligned with ISO 10015 standards improve awareness and technical competence, fostering a culture of energy efficiency. Evidence shows that employee engagement significantly influences the effectiveness of ISO 50001 systems [24].

4.3.7. Alignment with ISO 50001 Clauses

Each roadmap stage corresponds to specific ISO 50001 requirements (Table 2).

Table 2. Roadmap Clause for ISO 50001 in MCS

Roadmap Step	ISO 50001 Clause
Context and Energy Review	Clause 4 and 6.4
Energy Review and Baseline	Clause 6.4
Targets and Action Plans	Clause 6.2
Support and Implementation	Clause 7 and 8
Monitoring and Improvement	Clauses 9 and 10

4.4. Energy Utilization Strategies

- Routine Establishment: Implement regular maintenance and operational routines to enhance equipment performance and prevent failures.
- Technological Modernization: Replace outdated equipment with energy-efficient technologies to reduce consumption and improve reliability.
- Staff Training: Educate personnel on energy-saving practices and efficient equipment usage to foster a culture of sustainability.
- Production Planning: Optimize production schedules to avoid energy consumption peaks and improve overall efficiency.
- Energy Monitoring: Use performance indicators to track, control, and adjust energy usage in real time for better decision-making.

- Renewable Energy Integration: Assess the feasibility of clean energy sources like solar or wind to reduce environmental impact and enhance energy independence.

4.5. Energy Utilization Strategies

Figure 13 presents a comparative evaluation of the EWC under two scenarios: actual operational conditions and projected performance assuming the implementation of energy-saving and efficiency strategies. The analysis indicates that applying these measures would have resulted in an estimated cost reduction of $14,407.88 USD over the study period, highlighting the significant economic impact of structured energy management practices.

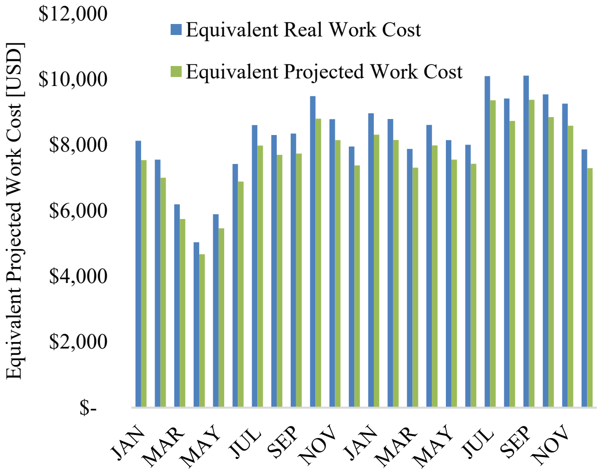

Figure 13. Comparison of equivalent work cost

4.6. Alignment with SDGs and Carbon Reduction Targets

The estimated energy savings of 7.26%, equivalent to 3,116.6 kWh/year, translates to approximately 0.582 tCO_2e (tons of carbon dioxide equivalent) avoided annually, using the national emission factors of 0.187 $kgCO_2/kWh$ provided by the Colombian Mining and Energy Planning Unit (UPME) for 2024. This reduction supports SDG 7 (Affordable and Clean Energy) and SDG 12 (Responsible Consumption and Production) by promoting efficient resource use and lowering carbon intensity. Similar ISO 50001 implementations in MCS worldwide report energy savings between 5-12%, reinforcing the global relevance of this approach.

5. CONCLUSIONS

The energy characterization revealed that the company's metalworking machines consume an average of 1,789 kWh per month, with lathes accounting for approximately 80% of total energy consumption. A critical production parameter of 25.72 units per hour was established, enabling an estimated 7.26% reduction in energy consumption compared to current levels. The energy consumption index graph confirmed that the company's energy usage was generally stable, with opportunities for further optimization.

To enhance energy performance and align with international best practices, the implementation of the ISO 50001 EnMS is strongly recommended. This standard provides a structured framework for continuous improvement in energy efficiency, cost reduction, and environmental impact mitigation. The key benefits of ISO 50001 implementation include establishing a clear baseline and defining a target line. This allows the company to systematically monitor progress, identify deviations, and implement corrective actions. The approach promotes data-driven decision-making and supports long-term strategic planning.

ISO 50001 promotes the integration of energy performance into daily operations. Through documented procedures and performance indicators, the company can optimize machine usage, reduce idle times, and prevent energy waste. Adopting ISO 50001 helps meet regulatory requirements and enhances the company's reputation in the market. It demonstrates a commitment to sustainability, which can be a differentiating factor in client acquisition and retention. The estimated energy savings of 7.26%, equivalent to approximately 0.582 tCO_2e avoided annually. This reduction supports SDG 7 and SDG 12 by promoting efficient resource use and lowering carbon intensity. For Latin America, adopting this methodology can accelerate industrial decarbonization and enhance competitiveness in sustainable markets.

NOMENCLATURES

1. Acronyms

SDGs	Sustainable Development Goals
MCS	Metalworking Companies' Sector
EnMS	Energy Management Systems
ISO	International Organization for Standardization
NPAEn	Non-Process-Associated Energy
CI	Consumption Index
PES	Potential Energy Savings
EWC	Equivalent Work Cost
UPME	Colombian Mining and Energy Planning Unit

2. Symbols / Parameters

C_{Eq}: Equivalent work cost
E_{elect}: Energy consumption

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BIOGRAPHIES

Name: **Jennifer**
Middle Name: **Luz**
Surname: **Villa**
Birthday: 09.10.1988
Birthplace: Barranquilla, Colombia
Bachelor: Mechanical Engineering, Department of Mechanical Engineering, Faculty of Engineering, Autonomous University of the Caribbean, Barranquilla, Colombia, 2011
Master: Mechanical Engineering, Faculty of Engineering, Autonomous University of the Caribbean, Barranquilla, Colombia, 2016
Doctorate: Project Management, Benito Juarez G. University, Puebla, Mexico, 2024
Doctorate: Student, Project Management, Research and

Innovation University of Mexico, Cuernavaca, Mexico, Since 2025
Post Doctorate: Student, Sustainable Project Management, International Research Mexico University, Puebla, Mexico, Since 2025
The Last Scientific Position: Lecturer, Department of Civil and Environmental, University of the Coast, Barranquilla, Colombia, Since 2018
Research Interests: Materials, Energy and Manufacturing Processes, Project Management
Scientific Publications: 8 Papers, 3 Projects
Scientific Memberships: GINS Research Group

Name: **Jairo**
Middle Name: **Alfonso**
Surname: **Fabregas**
Birthday: 26.10.1979
Birthplace: Barranquilla, Colombia
Bachelor: Systems Engineering, Faculty of Engineering, Autonomous University of the Caribbean, Barranquilla, Colombia, 2007
Master: Student, Management Systems, Faculty of Engineering, Autonomous University of the Caribbean, Barranquilla, Colombia, Since 2025
Research Interests: Telematics Systems, Industrial Automation, Technology Management

Name: **Carlos**
Middle Name: **Gabriel**
Surname: **Diaz**
Birthday: 07.08.1985
Birthplace: MA Gangue, Colombia
Bachelor: Electronic Engineering, Department of Electronic Engineering, Faculty of Engineering, University of the North, Barranquilla, Barranquilla, Colombia, 2007
Master: Mechatronic Engineering, Polytechnic School of Engineering of Gijon, University of Oviedo, Gijon, Spain, 2010
Doctorate: Project Management, Benito Juarez G. University, Puebla, Mexico, 2023
Doctorate: Student, Project Management, Research and Innovation University of Mexico, Cuernavaca, Mexico, Since 2025
Post Doctorate: Student, Sustainable Project Management, International Research Mexico University, Puebla, Mexico, Since 2025
The Last Scientific Position: Strategic Coordinator of the Academic Vice-Rector's Office, Autonomous University of the Caribbean, Barranquilla, Colombia, Since 2024
Since 2024 Research Interests: Renewable Energy, Robotics and Automation, Mechatronic Design, Project Management
Scientific Publications: 16 Papers, 11 Theses, 15 Projects
Scientific Memberships: GINS Research Group

Name: **Jonathan**
Surname: **Fabregas**
Birthday: 10.11.1987
Birthplace: Barranquilla, Colombia
Bachelor: Mechanical Engineering, Department of Mechanical Engineering, Faculty of Engineering, Autonomous University of the Caribbean, Barranquilla, Colombia, 2012
Master: Mechanical Engineering, Faculty of Engineering, Autonomous University of the Caribbean, Barranquilla, Colombia, 2015
Doctorate: Project Management, Benito Juarez G. University, Puebla, Mexico, 2024
Doctorate: Student, Engineering, Technological University of Bolivar, Cartagena, Colombia, Since 2024
Post Doctorate: Student, Sustainable Project Management, International Research Mexico University, Puebla, Mexico, Since 2025
The Last Scientific Position: Lecturer, Department of Mechanical-Electronic, Autonomous University of the Caribbean, Barranquilla, Colombia, Since 2016
Research Interests: Computational mechanics, Renewable Energy, Project Management
Scientific Publications: 49 Papers, 11 Theses, 7 Projects
Scientific Memberships: IMTEF Research Group

Name: **Argemiro**
Surname: **Palencia**
Birthday: 14.01.1981
Birthplace: MA Gangue, Colombia
Bachelor: Mechanical Engineering, Department of Mechanical Engineering, Faculty of Engineering, University of the Atlantic, Barranquilla, Colombia, 2005
Master: Mechanical Engineering, Department of Mechanical Engineering, Faculty of Engineering, University of the North, Barranquilla, Colombia, 2011
Doctorate: Engineering, Department of Mechanical Engineering, Faculty of Engineering, National Autonomous University of Mexico, Mexico City, Mexico, 2019
The Last Scientific Position: Assist. Prof., Department of Mechanical Engineering, Faculty of Engineering, Technological University of Bolivar, Cartagena, Colombia, Since 2022
Research Interests: Energy Conversion, Renewable Energy, Biomass Gasification
Scientific Publications: 15 Papers, 10 Master's and Doctorate Theses
Scientific Memberships: ASME Member