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Review

Energy Efficiency Benchmarking in Industrial Plants: A Structured Review and Framework Synthesis

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Abstract

The global industrial sector is one of the main sources of consumer demands that drive the global economy, but it also represents roughly 37%-40% of the total energy demands worldwide, which makes it the largest contributor to emissions of greenhouse gases. As the price of energy keeps increasing and the environmental regulations are becoming stricter, it has been crucial for companies to set up energy efficiency as one of their top priorities. This study is a structured review of industrial energy-efficiency benchmarking literature, complemented by a synthesized framework derived from existing standards and prior studies. Namely, reviewing standards, such as ISO 50001, the U.S. Environmental Protection Agency-established program "Energy Star", and the Indian scheme Perform, Achieve, and Trade, which is cited by various authors in the scientific literature. The study synthesizes key implementation stages reported in the literature to illustrate how benchmarking programs are commonly structured in industrial practice, which is the essence of the PDCA cycle, thorough data collection and the choosing of the most appropriate key performance indicators are being indicated. This research paper can be seen to comprehend efforts on external benchmarking for this wide range of industrial sector dependent on energy-intensive industries dealing with cement and steel. Besides, the authors depict complicated nature of performance by such technological tools as digital technologies and Artificial Intelligence facilitating on-the-spot, predictive optimization. By examining various case studies from all over the world, the paper is able to show that a well-organized method of benchmarking can bring substantial monetary savings, strengthen the market position, and also be in line with various sustainable development and decarbonization objectives of the industry. Lastly, it also talks about the planned research which is about predictive benchmarking practice, the degree of consonance with net-zero roadmaps while extending these activities to small-and medium-sized enterprises.

Keywords

Industrial energy efficiency, Energy benchmarking, Energy management systems, Key performance indicators, Sustainability, Industrial decarbonization

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1. Introduction

Industrial facilities form the basis of the modern economy, are the main suppliers of such goods as cement, steel, chemicals, textiles, and automobiles, which are the main goods of global development. Nevertheless, the industrial output of these goods is leading to a high environmental cost. The industrial sector accounts for approximately 37%-40% of global energy consumption [1,2]. Most of this energy demand is supplied by fossil fuels, which in turn makes the sector a major source of greenhouse gases and climate change. In several developing economies, including India, China, and countries in Southeast Asia, industrial energy demand is projected to increase by up to 200% by 2040 under current policy and technology trajectories, which will make it increasingly difficult to meet international climate targets established under the Paris Agreement, including limiting global temperature rise to well below 2 °C, pursuing efforts toward 1.5 °C, and achieving net-zero greenhouse-gas emissions by mid-century [3-5]. Consequently, energy efficiency has become a strategic necessity in industrial planning [6-8]. Energy efficiency often described as the "first fuel" reduces fossil fuel demand, lowers operating costs, and decreases greenhouse gas emissions. Overlapping descriptions emphasizing cost savings, the concept of energy efficiency as the "first fuel," and its economic benefits have been merged into a unified statement that highlights its strategic, economic, and environmental importance [9,10]. Energy efficiency benchmarking is among the most practical tools for achieving reduced energy costs and improved operational performance. Effective energy conservation practices enhance organizational performance by improving cost efficiency, increasing resilience to energy price fluctuations, and supporting compliance with increasingly stringent environmental regulations. These practices also contribute to regulatory compliance, lower greenhouse gas emissions, and enhanced industrial competitiveness, as discussed earlier in this section [11]. Benchmarking stands for the regular and obligatory testing of a plant's energy efficiency followed by comparing the results with the industry average, the best performing plants, or companies of a similar nature. Energy audits on the other hand, are mere snapshots, whereas benchmarking is a continuous improvement process [12-14]. It brings to light resource-intensive inefficiencies, encourages investment in improved equipment, and supports progress toward long-term sustainability goals. The present study provides an in-depth review of benchmarking literature, including conceptual frameworks, international standards, and global case-study evidence [15,16].

In this context, industrial energy efficiency plays a central role in achieving international climate and sustainability commitments. It directly supports the Paris Agreement, which aims to limit global temperature rise well below 2 °C and pursue efforts toward 1.5 °C through long-term decarbonization pathways. Furthermore, energy efficiency benchmarking contributes to multiple United Nations Sustainable Development Goals (UNSDGs), particularly SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation and Infrastructure), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action), by promoting resource efficiency, emissions reduction, and sustainable industrial growth [17-19]. Accordingly, this paper is positioned as a structured review rather than an experimental or methodological study. Its objective is to critically review existing industrial energy-efficiency benchmarking practices, analyse relevant standards and case-study evidence, and synthesize a literature-based benchmarking framework to support understanding and application in industrial plants.

The paper introduces a structured and integrative energy efficiency benchmarking framework that systematically combines established standards with implementation-oriented guidance. This framework advances existing approaches by bridging the gap between theoretical benchmarking models and practical industrial application. A comprehensive review of relevant standards, benchmarking methodologies, and prior studies has been conducted. The synthesized evidence is now explicitly discussed to demonstrate how the proposed framework is grounded in and extends existing research. The study highlights how the proposed framework can support industries, energy managers, and policymakers in implementing effective benchmarking practices, improving energy performance, and aligning with national and international energy efficiency standards.

2. Literature Survey

Benchmarking is a very powerful tool through which energy consumption can be reduced to save energy in a more efficient way. The evidence to that statement is provided by various sources, and one of the influences of benchmarking is that energy management practice changes [20-22]. Examples of such changes are international standards like ISO 50001, the Energy Star program in the USA, and Perform, Achieve, and Trade (PAT) Scheme of India. While these initiatives share the objective of improving industrial energy performance, they differ significantly in scope, geographic applicability, sectoral coverage, and the degree of prescriptiveness in performance benchmarking. A growing number of multinational companies have adopted the ISO 50001 standard to define the way a company can both establish its energy baselines and measure its energy savings. The U.S. ENERGY STAR program, which is sustained by the Environmental Protection Agency (EPA), offers various sectors performance metrics and also publicly identifies and certifies the highest-performing facilities [23-25]. The concept of market-based interventions implemented in the PAT system of India where the industries operating beyond the set targets can obtain tradable energy savings certificates (ESCerts) is presented; single-cycle PAT was the major contributor to nearly 9 million tonnes of CO_2 emissions reduction. Positive influence of benchmarking is also referred to in the literature [26-28]. For example, the iron and steel sector, which by systematic benchmarking introduced the process of identifying inefficiencies in blast furnace operations that were energy-intensive and thus managed to achieve energy intensity reduction of substantial amounts. In the cement industry, benchmarking has supported the adoption of waste heat recovery systems, contributing to energy efficiency improvements of up to 20% [29]. This is similar to the situation described by where the combined use of high-efficiency motors and good maintenance practice led to the reduction of energy consumption by 10%-15% in motor systems [30]. Benchmarking is correlated with changes in corporate culture, which has been confirmed both for the case of the individual industries as well as overall [22]. The most common effect of benchmarking is the introduction of accountability and transparency in energy management practices, which is usually the case. Despite these reported benefits, several studies have identified persistent limitations in energy efficiency benchmarking practices [31]. SMEs are in such a position that it is difficult for them to manage as they do not have enough money, and lack of proper technical expertise makes it impossible for them to carry out benchmarking tasks. There are still problems with data quality and the standardization of data since different industries usually have different metrics and methods for measurement; therefore, they are not easily comparable. Environment-friendly policy instruments, skill-development programs, and digital technologies were the three main factors that helped to get over the difficulties. Nevertheless, the overall perception is that the benefits of benchmarking are measurable, if done properly [32].

3. Proposed Methodology

This methodology is synthesized from existing literature to illustrate commonly reported approaches for benchmarking energy efficiency in industrial plants Benchmarking is a powerful tool for improving energy efficiency by enabling organizations to systematically evaluate and reduce energy consumption. Numerous studies have demonstrated that benchmarking influences energy management practices and supports continuous improvement [20-22]. International initiatives such as ISO 50001, the U.S. ENERGY STAR program, and India's PAT scheme illustrate how benchmarking frameworks contribute to improved industrial energy performance.

Although these initiatives share a common objective of enhancing energy efficiency, they differ in terms of geographical coverage, sectoral applicability, and the degree of prescriptiveness in performance evaluation. ISO 50001 has been widely adopted by multinational companies as a structured framework for establishing energy baselines and monitoring energy performance improvements. The U.S. ENERGY STAR program, administered by the EPA, provides sector-specific performance metrics and publicly recognizes high-performing facilities [23-25].

In India, the PAT scheme represents a market-based mechanism in which industries exceeding assigned efficiency targets can trade Energy Saving Certificates (ESCerts). During the initial PAT cycle, this approach contributed to an estimated reduction of nearly 9 million tonnes of CO_2 emissions. Several studies have reported similar positive outcomes associated with benchmarking practices [26-28]. For example, in the iron and steel sector, systematic benchmarking has enabled the identification of energy-intensive processes in blast furnace operations, leading to substantial reductions in energy intensity. In the cement industry, benchmarking has supported the adoption of waste heat recovery systems, resulting in energy efficiency improvements of up to 20% [29].

Likewise, studies on industrial motor systems have shown that the combined use of high-efficiency motors and improved maintenance practices can reduce energy consumption by approximately 10%-15% [30]. Beyond technical improvements, benchmarking has also been linked to positive organizational changes, including enhanced transparency, accountability, and energy-conscious corporate culture [22].

Despite these benefits, several challenges remain. SMEs often face financial constraints and limited technical expertise, which hinder effective benchmarking implementation. Additionally, inconsistencies in data quality and a lack of standardized performance metrics across industries limit comparability [31]. Nevertheless, supportive policy instruments, capacity-building programs, and digital technologies have been shown to mitigate these barriers. Overall, the literature confirms that when implemented systematically, energy benchmarking delivers measurable and sustained performance improvements [32].

4. Energy Efficiency in Industrial Benchmarking

Figure 1 illustrates the global distribution of industrial energy consumption by sector. Table 1 provides a comparative overview of major benchmarking frameworks. Benchmarking in the industrial sector can differ in several ways. Internal benchmarking means comparing the performance between the departments or factories of one organization. Through this, Benchmarking enables organizations to identify optimal operating practices. While external benchmarking is the process of comparing the performance of the company with the best-performing peer companies in the same sector, competitive benchmarking is solely based on competitors [22]. Functional benchmarking is a shift in the assessment of certain processes or systems, for instance, compressed air or HVAC, without consideration of the industry [33]. Strategic benchmarking links the long-term energy goals with the company & sustainability initiatives. One of the most significant changes in benchmarking is the impact of the various technological innovations. The real-time monitoring of energy consumption in different facilities has become feasible due to the deployment of Energy Management System (EMS) software [11,34]. Meanwhile, smart meters and IoT devices gather the consumption data in detail; AI and ML algorithms can even predict energy needs, detect wastages, and provide optimization suggestions [11,33]. Besides, digital twins are virtually recreating the industrial processes, and therefore, they can be used for the energy-saving strategies' rehearsal before the actual implementation. All these instruments are making the benchmarking program more accurate, lower the costs, and make it easier to spread across different sectors [34].

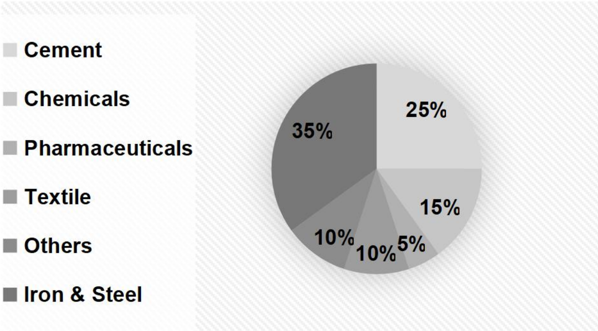

Figure 1. Global industrial energy consumption share by sector.

Table 1. Comparative analysis of major benchmarking frameworks [35,36].

Feature	ISO 50001	U.S. EPA ENERGY STAR for Industry	India's PAT Scheme
Governing Body	International Organization for Standardization	U.S. EPA	Bureau of Energy Efficiency (BEE), Government of India
Core Mechanism	Management System Standard (Process-based)	Performance Benchmarking (Outcome-based)	Market-Based Mechanism (Cap-and-Trade for Energy)
Nature	Voluntary (globally); Mandatory for large consumers in the EU	Voluntary	Mandatory for Designated Consumers (DCs)
Key Metric	Organization-defined Energy Performance Indicators (EnPIs)	1-100 ENERGY STAR Score based on national peer comparison	Specific Energy Consumption (SEC) reduction targets
Primary Incentive	Certification, operational efficiency, regulatory compliance	Public recognition, brand value (ENERGY STAR label)	Issuance of tradable Energy Saving Certificates

5. Comparative Analysis

Benchmarking in the industrial sector may be different in several aspects. One of them is internal benchmarking which essentially means comparing between, for example, the performances of two departments or factories of one organization. A company can then unmask the most effective methods through this. When it comes to external benchmarking, the focus is on comparing the company with the best-performing peer companies in the same sector. In contrast, competitive benchmarking is just about competitors. Functional benchmarking is a change of focus in the evaluation of certain processes or systems, e.g. compressed air or HVAC, without regard to the industry [35]. As a result, strategic benchmarking connects the long-term energy goals of the company with its sustainability initiatives. One of the major changes with benchmarking is the effect of various technological innovations. Through the implementation of EMS software, it has become possible to carry out real-time monitoring of energy consumption in the different facilities [11,33]. On the other hand, smart meters and IoT devices collect the consumption data in detail; AI and ML algorithms not only can predict energy needs but also detect wastages and provide optimization suggestions [11,33]. Moreover, digital twins are merely the virtual recreations of the industrial processes and thus, they can be used for energy-saving strategies' rehearsal before the actual implementation. All these instruments are making the benchmarking program more accurate, lower the costs, and make it easier to spread across different sectors. A cross-sectoral comparison of energy efficiency is illustrated in Figure 2. Key performance indicators for selected industries are summarized in Table 2.

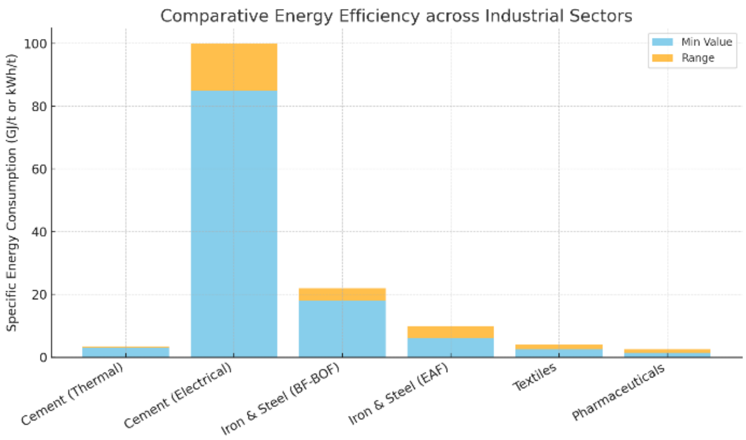

Figure 2. Comparative energy efficiency across industrial sectors.

Table 2. KPIs for selected industries [37].

Industry	Primary Energy-Intensive Process	Key KPI	Definition	Typical Industry Benchmark Range
Cement	Clinker Production (Kiln) & Grinding	Specific Thermal Energy Consumption (STEC)	Thermal energy used per unit of clinker produced (GJ/t)	3.0-3.5 (Dry Process)
		Specific Electrical Energy Consumption (SEEC)	Electrical energy used per unit of cement produced (kWh/t)	85-100
Iron & Steel	Blast Furnace / Basic Oxygen Furnace (BF-BOF)	SEC	Total energy used per unit of crude steel produced (GJ/tcs)	18-22
	Electric Arc Furnace (EAF)	SEC	Total energy used per unit of crude steel produced (GJ/tcs)	6-10

6. Conclusion

Energy efficiency benchmarking is an instrumental tool to achieve sustainable industrial development. With the precise measuring and comparing of energy performance, industries can uncover energy inefficiencies, lower their expenses, and at the same time, have a positive impact on the environment. The verdict from case studies, frameworks, and declarations of international organizations is consistent with the finding that benchmarking generates substantial benefits not only for the cement industry but also for the steel sector. Despite the presence of many challenges such as the poor quality of the data, the high initial cost, and the low level of understanding of SMEs, the adoption of digital technology, the introduction of government incentives, and the setting of international standards are very helpful in facilitating the benchmarking process. The future pathway is to move to the use of artificial intelligence for predictive benchmarking, integration with net carbon emissions targets, and development of sector-specific frameworks. Presently, benchmarking is functional in the transition toward missions for sustainable industries under the Paris Agreement and the UNSDGs which require 2050 net-zero emissions targets. In conclusion, energy benchmarking indeed is not just a technical measure but also a strategy for companies to remain competitive in the future. By means of it, they become a part of the triple bottom line process which is economic resilience, environmental stewardship, and long-term advantage in a world that is increasingly recognizing the synergy of efficiency and sustainability.

7. Future Work

Energy management in the industry is a tale of keeping pace with almost daily changes. Most of the changes are inspired by the setting up of very high targets for climate and, at the same time, by technological innovations. Initially, future activities in the energy benchmarking area will be largely devoted to opening new frontiers. One of these is the forecasting benchmarking; we can move from basing the present state on historical data to a more foresight and predictive approach. The AI-powered EMSs will provide us with the capability to render benchmarks which are not only in line with a plant's real-time performance but also tailored for that specific performance taking into account a limitless number of variables. Thus, benchmarking will be totally different from a periodical report card and will become a platform for ongoing and real-time optimization guide. The other angle of expansion maybe the link between the zero-emission roadmaps and the substantial change needed in benchmarking frameworks if they are to go beyond energy intensity and integrate a full range of decarbonization metrics. Simply put, future places will be obliged to track all aspects of decarbonization, for instance, carbon intensity, fuel replacement, consumption of renewable energy, and some of the necessary technologies that facilitate the transition to a low-carbon economy are CCS, utilization, and storage of carbon. Hence, the operations will be the fundamental platforms in achieving carbon neutrality goals. The problem of SMEs accessibility, which has been around for a long period and still needs solving in the future, is one of the main issues that the future campaigns must address. SMEs generally have financial and technical skill shortages compared to large corporations. Future campaign strategies will likely have to rely on the creation of cheap, large-scale, and user-friendly benchmarking solutions that can potentially be achieved through cloud-based platforms and government-funded technical assistance programs. The untold story about policy reforms and markets is that their evolution will forever be the cause of landscape change. Meanwhile, we would still see the trend of more severe government intervention, which in the future might concentrate on the production of intensified market signals aided by some market-oriented mechanisms such as the further development of the PAT scheme, the coming into existence of "white certificate" markets for accomplished energy-saving activities getting closer to reality, in addition to the setting up of standards for green purchases by public authorities.

Conflict of Interest

The authors declare no conflict of interest.

Generative AI Statement

The authors declare that no Gen AI was used in the creation of this manuscript.

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