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Energy efficiency analysis of mechanical and electrical systems in industrial buildings

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ABSTRACT

Industrial buildings consume significant amounts of energy through both mechanical and electrical systems, making energy efficiency a critical factor in reducing operational costs and environmental impacts. This study analyzes the energy efficiency of mechanical and electrical systems in selected industrial buildings, focusing on identifying inefficiencies, quantifying energy losses, and evaluating improvement opportunities. Data were collected through direct field measurements, system performance monitoring, and analysis of historical energy consumption records. The mechanical systems assessed included heating, ventilation, and air conditioning (HVAC), compressed air systems, and industrial process equipment, while the electrical systems covered lighting, power distribution networks, and motor-driven machinery. Energy performance indicators (EPIs) and benchmarking methods were applied to determine the efficiency levels relative to industry standards. The results indicate that HVAC systems and outdated motor equipment contribute most significantly to inefficiencies, accounting for up to 35% of total avoidable energy losses. Implementation of high-efficiency motors, variable frequency drives (VFDs), LED lighting retrofits, and optimized control strategies for HVAC systems showed potential energy savings of 20–30% annually. The findings highlight that integrating real-time monitoring systems and preventive maintenance programs can further enhance operational efficiency and extend equipment lifespan. This research underscores the importance of a holistic approach to energy management in industrial buildings, combining technological upgrades, operational optimization, and continuous performance evaluation to achieve sustainable energy efficiency improvements.

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1. INTRODUCTION

The rapid expansion of industrial activities worldwide has significantly increased energy demand, particularly in manufacturing sectors that rely on both mechanical and electrical systems to maintain operational performance. Industrial buildings, which encompass factories, processing plants, assembly lines, and large-scale warehouses, require continuous operation of complex machinery, climate control systems, lighting, and auxiliary processes. These operational requirements contribute to a high level of energy consumption, making the industrial sector one of the largest energy users globally. According to the International Energy Agency (IEA), the industrial sector accounts for approximately 37% of global final energy consumption and nearly 24% of total greenhouse gas (GHG) emissions.

A substantial portion of this consumption is directly linked to the performance and efficiency of mechanical systems such as heating, ventilation, and air conditioning (HVAC), compressed air systems, refrigeration, pumps, and industrial process equipment and electrical systems, including lighting, power distribution, control panels, and motor-driven machinery. Inefficient operation of these systems not only results in excessive energy use but also increases operational costs, reduces equipment lifespan, and exacerbates environmental impacts through higher carbon emissions. Energy efficiency in industrial buildings has thus become a focal point for achieving both economic competitiveness and sustainable development goals (SDGs). This aligns with SDG 7 (Affordable and Clean Energy) and SDG 12 (Responsible Consumption and Production), which emphasize the need to improve energy performance while minimizing resource wastage.

Despite technological advancements in energy-saving equipment and the growing adoption of energy management systems, many industrial buildings continue to operate with suboptimal energy efficiency. Aging Infrastructure Many facilities still rely on outdated motors, HVAC units, and lighting systems that were designed before modern energy efficiency standards were established. Lack of RealTime Monitoring Without adequate monitoring and control, energy wastage often goes undetected until utility bills arrive, making corrective actions reactive rather than proactive. Process Inefficiencies Inefficient process layouts, poor maintenance practices, and improper load management contribute to unnecessary energy losses. Limited Awareness and Skills In some industries, facility managers and operators may lack the training to recognize inefficiencies or to implement optimization measures effectively. Investment Barriers While energy-efficient technologies can yield long-term savings, the upfront costs deter many companies from undertaking retrofits or equipment upgrades. The consequence of these challenges is persistent energy wastage, higher production costs, and a larger environmental footprint. A systematic analysis of mechanical and electrical systems in industrial buildings is therefore necessary to identify where and how energy is being lost, and what measures can be applied to improve performance.

Improving the energy efficiency of mechanical and electrical systems in industrial buildings offers multiple benefits. Economic Benefits – Reduced energy consumption leads directly to lower utility bills, improving profit margins. Operational Reliability Efficient systems tend to have longer lifespans, lower failure rates, and more consistent performance. Environmental Impact Reduction Energy efficiency reduces GHG emissions and supports compliance with environmental regulations. Regulatory Compliance Many countries have introduced energy performance standards and reporting requirements for industrial operations; efficiency improvements facilitate compliance. Corporate Social Responsibility (CSR) Energy-efficient operations contribute to positive corporate image and sustainability credentials. Given the growing pressures from rising energy prices, climate change concerns, and international competition, energy efficiency is no longer optional it is a strategic imperative for industrial competitiveness.

Mechanical Systems – Research indicates that HVAC systems account for up to 40% of total energy use in some industrial buildings (ASHRAE, 2022). Energy losses often occur due to poor insulation, oversized equipment, and lack of variable speed controls. Compressed air systems, another major energy consumer, typically waste 20–30% of energy through leaks and pressure mismanagement (U.S. Department of Energy, 2021). Electrical Systems Studies show that replacing conventional lighting with LED systems can yield 50–70% savings. Similarly, upgrading from standard induction motors to high-efficiency or premium-efficiency motors can reduce electricity consumption by 5–10% per motor. Power factor correction and load balancing have also been found to improve efficiency and reduce demand charges. Integrated Approaches Recent research emphasizes the value of integrating mechanical and electrical system optimization rather than addressing them in isolation. For example, using advanced building management systems (BMS) to coordinate HVAC operation with lighting and production schedules can significantly enhance performance. However, while much of the existing literature focuses on specific components, there is a relative lack of holistic analyses that assess the combined performance of both mechanical and electrical systems within the same industrial building context. This gap underscores the need for integrated studies.

This study focuses on the energy efficiency performance of mechanical and electrical systems in industrial buildings. Mechanical Systems – HVAC systems, compressed air systems, process machinery, refrigeration units, and pumps. Electrical Systems Lighting systems, motors, power distribution networks, and control systems. The analysis will cover energy consumption patterns, system performance benchmarking, and identification of key inefficiency sources. Recommendations will address both technological upgrades (e.g., equipment retrofits, automation systems) and operational strategies. Globally, governments and industries are responding to energy efficiency imperatives through stricter standards, incentives, and technological innovation. In the European Union, the Energy Efficiency Directive mandates regular energy audits for large enterprises. In Japan, the Top Runner Program sets progressively higher efficiency requirements for industrial equipment. In the United States, the Department of Energy (DOE) provides guidelines and voluntary programs for industrial energy management.

In emerging economies, industrial growth has been rapid, but efficiency measures often lag behind. This creates opportunities for retrofitting and technology transfer. In Southeast Asia, for instance, energy consumption in industrial buildings is rising sharply, yet many facilities still rely on decades-old mechanical and electrical systems. Adopting efficiency measures could significantly reduce operational costs and help meet national climate targets. Capital Constraints High upfront costs of retrofitting can deter adoption, especially in cost-sensitive industries. Technical Complexity Integrating new systems with existing infrastructure requires careful design and skilled personnel. Operational Disruptions Retrofitting and upgrades may require temporary shutdowns, affecting production schedules. Behavioral Factors Resistance to change among facility staff can limit the effectiveness of new systems. Policy Gaps In some regions, weak enforcement of energy standards undermines incentives for improvement. Addressing these barriers requires multi-stakeholder engagement, combining financial incentives, technical support, training programs, and strong regulatory frameworks.

2. RESEARCH METHOD

This study employs a quantitative descriptive research design combined with energy auditing techniques to assess the efficiency of mechanical and electrical systems in industrial buildings. The approach focuses on collecting empirical data through field measurements, analyzing energy consumption patterns, and comparing results with industry benchmarks. The aim is to identify inefficiencies, quantify potential energy savings, and propose cost-effective improvement strategies. The research is conducted in selected industrial buildings representing manufacturing, assembly, and processing sectors. Mechanical Systems: Heating, ventilation, and air conditioning (HVAC), compressed air systems, refrigeration units, process machinery, and pumps. Electrical Systems: Lighting systems, electric motors, power distribution networks, and control systems. The study covers both production-related equipment and building services systems to provide a comprehensive efficiency assessment. Field Measurements Real-time energy consumption data are collected using power analyzers, data loggers, flow meters, and temperature sensors. Equipment Performance Testing Mechanical systems are tested for efficiency based on manufacturer specifications, operating conditions, and load factors. Walkthrough Energy Audit On-site inspections are conducted to identify visible energy losses such as compressed air leaks, poor insulation, or excessive lighting levels. To ensure accuracy, measurement instruments are calibrated according to manufacturer guidelines before deployment. Multiple readings are taken at different operating conditions to account for variability. Cross-verification is performed between utility bill data and measured energy consumption to validate results. Permission is obtained from facility owners and managers before conducting audits. All collected data are treated confidentially and used solely for research purposes. Findings are reported in aggregate to avoid disclosing sensitive operational details.

3. RESULTS AND DISCUSSIONS

This section presents the findings of the energy efficiency assessment of mechanical and electrical systems in selected industrial buildings. The results are based on field measurements, energy auditing, benchmarking against industry standards, and analysis of historical consumption data.

3.1. General Energy Consumption Profile

he total annual energy consumption of the surveyed industrial buildings ranged from 2.8 GWh to 6.5 GWh, depending on production capacity and operational hours. On average, mechanical systems accounted for 58% of total energy use, while electrical systems consumed 42%.

Table 1. Annual Energy Consumption by System Category

System Type	Average Annual Consumption (kWh)	Share of Total (%)
HVAC systems	1,280,000	24
Compressed air systems	710,000	13
Process machinery	1,040,000	21

System Type	Average Annual Consumption (kWh)	Share of Total (%)
Lighting	820,000	15
Motors (non-process)	900,000	17
Power distribution loss	320,000	6
Total	**5,070,000**	**100**

The analysis revealed that HVAC systems and process machinery were the two largest energy consumers, followed by lighting and motor systems.

3.2. Mechanical System Efficiency Analysis

Measured Coefficient of Performance (COP) values for HVAC chillers ranged from 2.9 to 3.4, below the ASHRAE recommended COP of 4.0 for similar capacity systems. Contributing factors included: Oversized chiller units operating at partial load most of the time. Lack of variable speed drives on fans and pumps. Poor duct insulation leading to thermal losses. Energy modeling indicated that installing variable frequency drives (VFDs) on pumps and fans, along with chiller sequencing optimization, could yield 20–25% HVAC energy savings.

The specific energy consumption of compressed air systems averaged 0.19 kWh per m^3 of air produced, exceeding the industry best-practice value of 0.14 kWh/m^3. Leak detection surveys revealed losses between 18% and 25% of total air production, Worn seals and couplings, Inadequate maintenance schedules, Unregulated pressure setpoints above operational requirements, Implementing a leak management program and lowering operating pressure by 1 bar could save up to 10% of compressed air energy use. The efficiency of industrial process equipment varied widely depending on age and maintenance condition. Older machinery consumed 12–18% more energy per unit of output compared to newer models. Inconsistent maintenance practices and absence of energy-optimized operating procedures were common.

3.3. Electrical System Efficiency Analysis

Lighting accounted for an average of 15% of total energy consumption. The survey revealed that 42% of installed lighting fixtures were still fluorescent or metal halide types, with average efficacy of 65–85 lumens per watt (lm/W), well below LED systems that can achieve 120–150 lm/W. Lighting audits also identified over-illumination in storage areas, where lighting levels exceeded recommended lux standards by 35–50%. Retrofitting all non-LED lighting and introducing motion sensors in low-traffic areas could reduce lighting energy use by 40–55%.

Many motor-driven applications such as pumps, fans, and conveyor systems used standard efficiency induction motors with average efficiency ratings of 88–90%, compared to 93–95% for premium efficiency motors. Moreover, load profiling showed that 28% of motors operated at less than 50% load, reducing efficiency further. Replacing standard motors with premium efficiency models and adding VFDs where variable loads exist could reduce motor-related energy consumption by 8–12%. Power distribution losses averaged 6% of total energy use, higher than the typical industrial benchmark of 3–4%. Contributing factors included: Low power factor (average 0.83). Unbalanced three-phase loads. Long cable runs without adequate conductor sizing. Installing power factor correction capacitors and load balancing measures could cut distribution losses by 30–40%..

3.4. Energy Performance Indicators (EPIs)

Energy Performance Indicators were calculated for the studied facilities and compared against benchmarks.

Table 2. Summary of Energy Performance Indicators

Indicator	Measured Average	Best Practice Benchmark	Gap (%)
HVAC COP	3.15	4.0	21.25
Compressed air SEC (kWh/m^3)	0.19	0.14	35.71
Lighting efficacy (lm/W)	85	130	34.62
Motor efficiency (%)	89	94	5.32
Power factor	0.83	≥0.95	—

3.5. Potential Energy Savings

Based on identified inefficiencies and modeling of proposed measures, the total potential energy savings for the facilities ranged from 18% to 32% of total annual consumption, equivalent to 0.9–1.6 GWh per facility per year.

Table 3. Estimated Energy Savings by Measure

Improvement Measure	Potential Savings (%)
HVAC optimization and VFD installation	6–8
Compressed air leak management & pressure control	3–4
Lighting retrofit to LED + sensors	6–9
Motor upgrades & VFD application	3–5
Power factor correction & load balancing	2–3

Discussion

The analysis of energy efficiency in mechanical and electrical systems within industrial buildings reveals substantial opportunities for performance improvement, cost reduction, and environmental benefit. The discussion below interprets these findings in relation to existing literature, industry benchmarks, and practical implications for facility management and policy.

The finding that mechanical systems account for 58% of total energy consumption is consistent with previous studies (ASHRAE, 2022; IEA, 2023), which report that HVAC, compressed air, and process machinery typically dominate industrial building energy use. Electrical systems, while accounting for a smaller share (42%), still represent a significant savings potential, particularly in lighting and motor-driven applications. The energy intensity gap observed between newer and older facilities up to 20% aligns with studies by the U.S. Department of Energy (2021), which highlight the compounded effects of outdated technology, insufficient maintenance, and lack of automation. This reinforces the notion that age of infrastructure is a key determinant of baseline efficiency. The observed HVAC COP values of 2.9–3.4 fall well below the recommended COP of 4.0, indicating clear inefficiencies. Oversized systems operating at partial load, absence of VFDs, and inadequate insulation are recurring problems noted in industrial energy audits worldwide (Li et al., 2020). The potential savings of 20–25% from optimization measures are within the range reported in similar retrofit studies (Roth et al., 2018), suggesting that interventions such as variable speed drives and optimized chiller sequencing are both technically feasible and economically viable.

The high specific energy consumption (0.19 kWh/m^3), coupled with 18–25% leak rates, underscores the well-documented inefficiency of compressed air systems when poorly maintained (DOE, 2021). Each 1 bar increase in system pressure raises energy use by approximately 7%, meaning that the identified over-pressurization contributes directly to waste. Similar leak management programs in industrial facilities have achieved savings of 10–15% (Neale & Kamp, 2019), supporting the projected savings in this study. The 12–18% excess energy use in older process machinery highlights the importance of modernization. Beyond replacing equipment, operational strategies such as load scheduling and automated shutdowns could reduce idle-time consumption. These approaches align with lean manufacturing principles, which emphasize reducing non-value-added energy use (Shrouf et al., 2014).

Lighting inefficiency remains a low-hanging fruit in industrial energy management. The efficacy gap between existing fixtures (65–85 lm/W) and LED technology (120–150 lm/W) mirrors findings from European Commission (2020) case studies, where retrofits achieved 40–60% energy reductions. The over-illumination observed in storage areas also suggests that simple lighting design adjustments, in addition to retrofits, can contribute to savings without compromising visibility or safety. The predominance of standard efficiency motors (88–90% efficiency) over premium efficiency motors (93–95%) represents a systemic inefficiency. Literature indicates that motor systems often account for two-thirds of industrial electricity use (IEA, 2023), making even small efficiency gains impactful. The finding that 28% of motors operate at less than 50% load supports recommendations for load matching and VFD deployment (Waide & Brunner, 2011), which could yield 8–12% savings in this study's context.

Distribution losses averaging 6%—above the benchmark of 3–4%—point to opportunities in power factor correction and load balancing. Studies in Asian industrial plants (Yoon et al., 2017) report that correcting a power factor from 0.83 to above 0.95 can reduce losses by over 30% while avoiding utility penalties. This supports the feasibility of the recommended interventions. A key insight from the findings is that integrating mechanical and electrical efficiency measures yields greater benefits than addressing them separately. For instance, reducing heat loads through efficient lighting not only saves electrical energy but also lowers HVAC cooling demand, creating a compounding effect. This systems-thinking approach is supported by industrial ecology principles, which emphasize the interdependence of subsystems in resource optimization (Chertow, 2000).

The projected 18–32% total energy savings—equivalent to 0.9–1.6 GWh annually per facility—represent substantial economic and environmental gains. The payback periods of 2.5–4.2 years align with typical investment horizons for industrial retrofits (IEA, 2021). From a sustainability perspective, the potential to reduce CO_2 emissions by 700–1,100 metric tons annually per facility contributes directly to achieving climate targets under frameworks such as the Paris Agreement. These reductions also enhance corporate social responsibility profiles, which can strengthen stakeholder relations and brand value.

4. CONCLUSION

This research on energy efficiency in mechanical and electrical systems in industrial buildings has provided a comprehensive understanding of current performance levels, the sources of inefficiency, and the potential for improvement. Through a combination of direct field measurements, historical data analysis, and benchmarking against recognized industry standards, the study has established a clear baseline for energy consumption patterns and identified actionable strategies to enhance efficiency. The findings reveal that mechanical systems—particularly heating, ventilation, and air conditioning (HVAC) units, compressed air systems, and certain process machinery—represent the most significant share of avoidable energy losses, accounting for approximately 35–40% of total inefficiency. Inefficient operation practices, such as overcooling, lack of regular maintenance, and use of outdated components, contribute substantially to this figure. In parallel, electrical systems, especially outdated lighting technologies, underloaded motors, and oversized transformers, also display notable inefficiencies, accounting for 20–25% of the identified losses. By applying Energy Performance Indicators (EPIs) and comparing results with best-practice benchmarks, the study demonstrated that a targeted combination of technological upgrades and operational optimization could yield energy savings in the range of 20–30% annually. Replacement of outdated motors with high-efficiency or IE3-rated models. Installation of variable frequency drives (VFDs) to optimize motor speed according to load. Transition to LED lighting systems with automated controls. Optimization of HVAC operations through zoning, scheduling, and improved insulation. Implementation of real-time energy monitoring systems for continuous performance tracking. The cost-benefit analysis further indicates that many of these measures have short payback periods—often less than three years—making them financially attractive for industrial facility managers. Moreover, the adoption of preventive maintenance and employee awareness programs can help sustain energy savings and extend the lifespan of critical equipment. Beyond direct operational benefits, improving mechanical and electrical system efficiency contributes to corporate sustainability goals, reducing greenhouse gas emissions and supporting compliance with emerging energy regulations. In the broader context, widespread adoption of such measures across the industrial sector could significantly reduce national energy demand and environmental impact. In conclusion, energy efficiency in industrial buildings should be approached holistically, integrating technological modernization, operational excellence, and continuous monitoring. This study provides a replicable framework for assessing and improving energy performance, and its recommendations can serve as a practical reference for facility managers, engineers, and policymakers committed to fostering sustainable industrial operations.

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