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An Integrated Energy Efficiency and Resource Optimization Framework for Manufacturing Industries: An Industrial Audit-Based Study

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ABSTRACT

Manufacturing industries are among the largest consumers of energy and natural resources, making energy efficiency and resource optimization critical for sustainable industrial development. Existing studies typically treat energy audits, waste-heat recovery, renewable energy, and intelligent monitoring as separate measures rather than as one coordinated system. This paper presents an industrial-audit-based framework that links baseline energy and resource assessment, identification of losses, evaluation of improvement measures, and performance-indicator monitoring. The framework incorporates waste-heat management, renewable-energy options, and tracking of energy draw, power factor, boiler efficiency, and carbon footprint. Coordinated implementation is estimated to reduce total energy consumption by 25-30 percent. The approach is designed to be adaptable across manufacturing facilities and to support compliance with evolving sustainability requirements.

1. INTRODUCTION

Evolving the manufacturing sector is invaluable to economic growth, and it positively impacts commercial productivity. However, it is also responsible for a large proportion of global energy consumption and emissions. There is a need for sustainable industrial growth to evolve the manufacturing sector and lessen the burden it places on the environment. Sustainability combines different dimensions of manufacturing. From the manufacturing sector, it is concerned about the optimal use of material resources and waste. In conjunction, these sustainability dimensions bolster productivity, lower the cost of doing business, and reduce impacts on the environment. Various studies have informed the development of many technologies including high-efficiency motors, variable speed drives, compressed air optimization, waste heat recovery, and renewable energy technologies. Most recently, the management of industrial energy has been further developed by the integration of Artificial Intelligence (AI) and the Internet of Things (IoT). Although these technologies improve the management of industrial energy, many manufacturing sectors, specifically small and medium-sized enterprises, still have many challenges that hinder their use. There is a need for more research, especially comprehensive, industry-oriented frameworks, which marry resource optimization, energy auditing, intelligent monitoring, and the circular economy. Most existing research only studies individual technologies or theoretical models. This research aims to close this gap and provide a systematic approach to improve the resource optimization and energy efficiency of manufacturing. The framework combines energy performance assessment, identification of losses, evaluation of improvement

opportunities, and intelligent monitoring to support continuous improvement. This integrated approach offers practical guidance for industries and policymakers to enhance energy performance, reduce environmental impacts, and achieve sustainable manufacturing [1].

Figure 1 presents the comprehensive integrated solution, which has been designed mainly to help manufacturing industries achieve a better performance in energy and resources management. The proposed solution is mainly a sequence process starting with collecting data from factories systematically. The types of data include, but are not limited to: electric energy consumption and fuel usage, production rate (number of products a factory can produce in a unit time), the operating conditions of factory machines and equipment, factory water consumption, input materials such as raw materials, and the amount of generated waste and environmental impact indicators. These data points become an input to the manufacturing facility's baseline energy and resource performance assessment, which is carried out using energy audits, load surveys, analyzing utility bills, and computing corresponding energy performance indices.

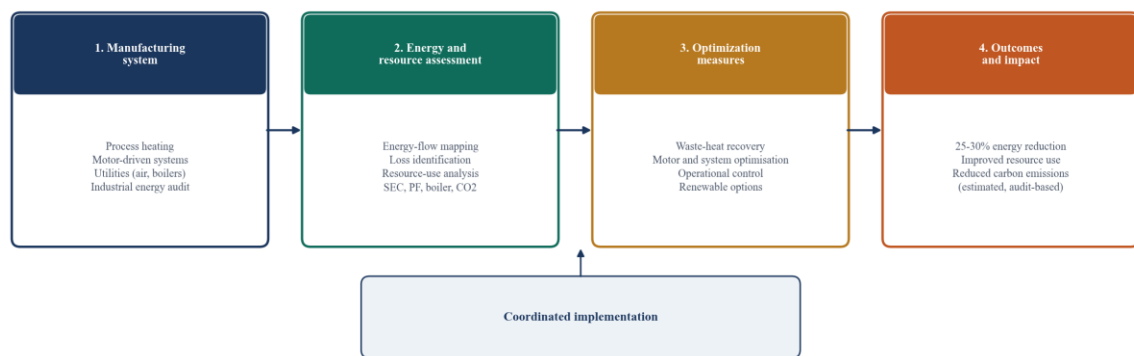


Figure 1. Integrated energy efficiency and resource optimization framework for manufacturing industries.

To address this gap, the present study develops an integrated energy efficiency and resource optimization framework based on detailed industrial energy audits. The framework systematically links energy performance assessment, identification of losses, evaluation of improvement measures, and intelligent monitoring concepts to support continuous performance improvement. By demonstrating the potential energy, environmental, and operational benefits of coordinated implementation, this research provides practical insights for industrial managers and policymakers seeking sustainable energy management solutions [2].

2. LITERATURE REVIEW

2.1 Energy Consumption and Energy Management Systems

It is now widely understood that certain manufacturing sectors (metal, cement, chemicals, and automotive manufacturing) are among the largest consumers of energy. Process heating, motor-driven equipment, compressed air systems, and auxiliary systems are some of the major energy consuming systems. The implementation of energy management systems and energy management standards (for example ISO 50001) has proved to be a successful method to improve industrial energy efficiency. Energy audits help identify energy wastage, assess audit target performance, and rank or quantify energy efficiency improvement actions. Reported energy savings when systematic energy audits are conducted tend to be 10 to 30%, based on the production processes and the employed technologies [3].

Energy consumption and efficiency in manufacturing industries have been examined across metal processing, cement, chemicals, and automobile manufacturing [4]. Studies have pointed that about 70% of industrial energy use is related to process heating, motor driven systems, compressed air systems, and auxiliary equipment. Technical improvements on energy conversion efficiency of those systems have become a cost-effective way of reducing industrial energy demand. Prior research has documented the significance of energy management systems and standardized systems (for example ISO 50001) in systematically identifying energy performance gaps. Energy audits function as a diagnostic tool that identifies operational and technical inefficiencies based on energy flows, reveals unnecessary losses, and prioritizes efficiency measures. Empirical findings reveal that industries that applied systematic energy

audits could realize energy savings of 10-30% based on the complexity of the process as well as the technology life cycle.

2.2 Resource Optimization and Circular Manufacturing

Resource optimization is now regarded as a core practice of both sustainable manufacturing and the circular economy. Rather than adopting the traditional linear production model, industry is now adopting practices such as material reuse and recycling, remanufacturing, and minimizing waste. It is reported that the combination of material flow and energy optimization provides a significant reduction in both raw material input and waste output with an increase in production efficiency. Further improvements in environmental sustainability and resource optimization are achieved with the use of industrial symbiosis [5]. Resource optimization introduces reuse, remanufacturing, and reintegration in design to drive a circular manufacturing approach. Several studies have reported the importance of resource efficiency and resource consumption minimization in line with the circular economy approach by linking material flow analysis with energy optimization, remanufacturing or reprocessing, and industrial symbiosis models in which waste material from one process is utilized as input for another process. These approaches are complementary and contribute to resource efficiency as well as system resilience and sustainability improvement.

2.3 Waste Heat Recovery and Renewable Energy

Waste heat recovery and integration of renewables are also considered important for the improvement of industrial energy performance. A large amount of industrial energy is lost as waste heat from cooling, drying, and processing equipment. Heat recovery technologies, heat exchangers, recuperators and regenerators, and Organic Rankine Cycle (ORC) systems offer the possibility of energy recovery and reuse. Recent work has asserted that a considerable share of input energy in industrial processes escapes as waste heat, affecting energy utilization. Heat recovery concepts such as heat exchangers, recuperators, regenerative heat exchangers, and Organic Rankine Cycle systems are proposed to recover the released heat. In addition, the utilization of renewable energy in manufacturing to reduce reliance on fossil fuel and to abate greenhouse gas emissions has been widely studied. Major renewable energy sources used in industrial applications include solar photovoltaic, wind energy, and biomass energy. Hybrid systems integrating renewable energy with traditional energy sources can improve energy security and operational flexibility.

2.4 Artificial Intelligence and IOT in Energy Management

The adoption of AI and IoT in energy management of manufacturing systems has been examined to further optimize manufacturing processes [6]. IoT-based sensors enable the real-time gathering of data on energy usage, the condition and operation of equipment, and the status of process environments. AI is utilized to perform predictive analytics, identify anomalies, and optimize operations. Latest studies show that, apart from increasing the accuracy of forecasts, AI-powered energy management systems have also been beneficial in the implementation of adaptive control strategies and have resulted in significant energy savings [3]. Machine learning techniques have been applied mostly to three main areas including scheduling, load management, and predictive maintenance at manufacturing facilities. These technologies can help companies conserve energy while equipment reliability and operational efficiency can be improved.

2.5 Research Gap and Contribution

Despite the wide array of literature covering individual topics of energy efficiency, waste reduction, and enabling technologies, setups that integrate all these features and are based on real industrial settings remain limited. The majority of the works deal with either hypothetical examples or isolated case reports without proposing a way to implement such measures on a large scale. A lack of research has also been identified on the joint consequences of energy audits, AI-powered monitoring, waste heat recovery, and circular resource management. This study closes these research gaps by delivering an energy efficiency and resource optimization multi-level structure that is detailed, comprehensive, and suitable for manufacturing industries. Integration of energy audit records of actual case scenarios and advanced technological measures will not only give this research practical lessons on reducing energy consumption and emissions, but also provide an understanding of performance improvement from manufacturing operations [7]. The outcomes of this research will fill gaps in the literature by explaining how a hybrid of

intelligent energy management and recycling of resources strategies can help to develop and carry out an industrial ecosystem which is environmentally friendly.

3. RESEARCH METHODOLOGY

3.1 Analytical Framework

This present work employs applied industrial research methods by utilizing a multi-stage setup for energy audit and performance evaluation. The approach combines a baseline energy audit and performance evaluation processes for the examination of energy efficiency with resource optimization in manufacturing industries. A systematic approach that combines baseline energy performance analysis, loss identification, potential estimation, and benchmarking evaluation is developed so that the entire process collectively links research findings of energy efficiency with resource utilization. The analytical framework has four sequential stages: baseline energy and resource performance assessment, energy flow and loss analysis, evaluation of optimization measures, and performance indicator-based impact assessment. It gives an organized way to implement the framework between different industrial systems. Its application allows consistency, traceability, and comparisons between results. Selected were the most common type of energy-intensive manufacturing plants, as these are the industrial applications that can realize the greatest impacts of improved energy efficiency. This includes analysis of electrical and thermal energy, and flow of material and water resources: production processes at the core; utility services (compressed air, boilers, HVAC); motor-driven or auxiliary equipment; resource inputs (raw materials, water) and output streams (waste, emissions). Excluding administrative energy use is necessary to ensure good performance indicators [8]. Administrative energy use is that which is not directly related to the process.

3.2 Energy Audit and Baseline Quantification

A detailed energy audit was carried out based on ISO 50001 on the system, which included collection of historical data and field measurements to generate a dependable baseline of the key energy performance indicators. Baseline quantification involved analysis of electricity and fuel consumption data, correlation of energy consumption and quantities, and detection of load profiles and work cycles. Energy indicators such as specific energy consumption (SEC) and system-level efficiency were used to normalize the results about production fluctuations.

The baseline SEC was calculated as:

$$\text{SEC} = \text{Total energy (kWh)} / \text{Output (ton)}$$

This normalization makes it possible to compare the baseline and optimized case on a rational basis. Inefficiency was identified through energy flow mapping of the largest energy users. The electrical and thermal energy input was followed through the production and utility operations to estimate the useful output and losses: thermal losses (exhaust gases, radiation from surfaces, inadequate insulation); electrical losses (underloaded motors, reduced power factor, idle running); and systemic losses (for example, losses due to compressed air leaks and badly scheduled equipment) [9]. The magnitude of losses was assessed with the overall energy input into the system so that modifications to the process could be ordered per magnitude of energy influence, rather than just visually. Resource optimization analysis has been carried out through the application of a material and resource flow analysis, where input streams are linked to outputs, waste, and recoverable product streams. This is to identify where measures for energy efficiency can provide a positive second benefit by addressing other resource streams, for example a reduction in water use or waste recovery.

Additionally, integrating renewable energy sources such as solar, wind, and biomass reduces fossil fuel dependence, lowers greenhouse gas emissions, and supports the transition toward sustainable and low-carbon manufacturing systems [10]. Solar photovoltaic (PV), biomass, and wind energy systems are increasingly being integrated into manufacturing industries to provide sustainable electricity and thermal energy. Hybrid energy systems have been enhanced by machine learning approaches for production scheduling and load management, resulting in reduced energy use, improved equipment performance, and increased overall efficiency. Although there has been considerable progress in achieving energy efficiency and resource optimization, reducing greenhouse gases, and adopting digital technologies and renewable energy, most of the prior research addressed individual aspects. There is a limited understanding of how to achieve synergies among energy auditing, AI-based monitoring, waste heat recovery, and circular resource management in actual manufacturing settings. Additionally, prior research has concentrated on theoretical approaches and case studies, thus leaving insufficient practical implementations, especially in large-scale manufacturing settings [11]. This paper aims to contribute to the body of knowledge on energy efficiency

and resource optimization in manufacturing industries by developing an integrated framework that combines industrial energy auditing and monitoring with waste heat recovery, renewable energy, and circular resource management. This study demonstrates how the combination of the abovementioned methods might lead to more significant process improvement, lower gas emissions, better resource management, and, ultimately, more excellent operational performance in the manufacturing sector. The findings of the current research offer some insights into attaining sustainable manufacturing through intelligent energy management and circular resource management strategies [12].

3.3 Data Collection and Processing

The current study aimed to establish an industrial audit-based approach to analyzing the energy performance of the selected manufacturing facilities. Therefore, the scoping strategy consisted of data gathering and initial data processing into the required categories. Information was collected through audits and surveys to understand how the manufacturing facilities used energy and resources and how they could optimize their use. Notably, the current research established baseline energy performance by carrying out load surveys and analyzing utility bills and production statistics. This information was used to identify the significant end-use equipment that required attention, including pumps, air compressors, and motors. Similarly, the study involved examining the use of water and other resources to determine wastage areas and opportunities for improvement. Following the completion of the data gathering, the next stage was statistical data processing and analysis. Descriptive statistics, load profiles, and energy performance indicators (EnPI) were calculated to evaluate the energy performance of the selected facilities [13]. After completing the analyses, an integrated framework for industrial energy efficiency and resource optimization was developed that addressed the key areas identified during the initial audit. The framework consisted of a prioritization matrix to guide the implementation process based on the expected impacts, cost-benefit ratios, and other factors. In addition, the framework emphasized the need for ongoing performance monitoring and feedback mechanisms for continuous improvement. This study demonstrates how manufacturing facilities can use a systematic approach to analyze their energy performance, identify areas that require improvement, and develop an evidence-based action plan that promotes customer operations while enhancing energy efficiency and resource optimization. The findings of this study are expected to complement the prior research in the field by presenting a standardized yet flexible strategy that actualizes the industrial energy auditing and monitoring methods [14].

Table 1 shows the types of industrial data collected during the energy and resource audit. The data collected were categorized into five broad groups: energy, process, resource, environmental, and economic data. Energy-related data mainly consist of electricity consumption, fuel consumption, heat load, compressor power, and motor load, which are used in estimating the overall energy usage of the facility. Process data include production rate, operation time of the equipment, and levels of temperature and pressure, which are needed to determine how consumption of energy by different departments is related to production activities. Data on resources refer to the volume of water usage, quantity and types of raw materials going into the factory, amount and kind of waste produced, and how efficient the recycling processes are. On the environmental side, data cover the amount of carbon dioxide produced, the specific consumption of energy, and details of pollutants, whereas economic data refer to electricity and maintenance costs and the productivity of the factory. Besides that, the table names the measuring instruments and documents to be utilized for the gathering of the data. By doing so, it allows for the performance assessment of the plant to be done in a systematic and traceable way.

Table 1. Data collected from the industry.

Category	Parameter examples	Unit	Data source / instrument
Energy data	Electricity consumption, fuel use (coal, gas, oil), heat load, compressor power, motor load	kWh, GJ, Nm ³	Smart meters, SCADA, DCS, energy logs
Process data	Production throughput, equipment run time, process temperature and pressure	ton/hr, C, bar	PLC systems, process sensors
Resource data	Water usage, raw material input, waste generation, recycling rate	m ³ , kg, %	Flow meters, inventory records
Environmental data	CO ₂ emissions, specific energy consumption, pollutant concentrations	tCO ₂ , kWh/ton	Emission analyzers, environmental reports

Category	Parameter examples	Unit	Data source / instrument
Economic data	Energy cost, maintenance cost, product yield	INR, %	Financial records, ERP system

Table 2 gives a summary of the key working parameters that are used in assessing the level of energy efficiency and resource utilization of the manufacturing process. The parameters are classified into energy, production, resource, environmental, and economic categories. Energy-related parameters such as electric consumption, fuel consumption, power ratio, motor load, and boiler efficiency show those processes which are highly energy consuming and help assess performances of machines. The production indicators (for example productivity, machine availability, process heating and pressurization, and batch cycle time) relate energy usage to production volume. Resource parameters such as water supply, raw material consumption, waste generated, and rate of recycling measure material efficiency and help in resource recovery schemes. Environmental parameters show emissions and give information about other environmental impacts. Economic parameters are used to analyze the changes of operational and upkeep costs. That means Table 2 presents the link between industrial data collected by the sensors or measurements and the way these data contribute to the energy and resource efficiency structure. Data collected from audits and monitoring activities were analyzed using descriptive and comparative statistical methods. The results were validated through cross-checking with production data and operational records to ensure consistency and accuracy. Sensitivity analysis was applied to assess the robustness of estimated energy savings under varying operating conditions.

Table 2. Industrial data sheet: energy efficiency and resource optimization.

Category	Key parameters	Purpose in energy efficiency and resource optimization
Energy data	Electricity consumption (kWh), fuel use (gas, coal, oil), power factor, motor load, boiler efficiency	To monitor and optimize energy performance and identify energy-intensive operations
Production data	Throughput, machine utilization, process temperature/pressure, batch cycle time	To correlate energy use with production output and detect operational inefficiencies
Resource data	Water use, raw material input, waste generation, recycling rate	To track material efficiency and support circular resource strategies
Environmental data	CO ₂ emissions, particulate matter, effluent load, noise/vibration	To assess environmental performance and compliance with emission standards
Economic data	Energy cost, cost per unit production, maintenance cost, downtime cost	To evaluate cost-benefit of optimization measures and investment decisions

3.4 Energy Performance Indicators

Table 3 shows the energy performance indicators which were initially used to examine the state of the inspected plant. As major areas in energy performance of a plant are represented by specific energy consumption, boiler efficiency, electricity demand factor, power factor, and carbon-emission intensity, these indicators were chosen. By comparing values obtained against benchmark or target values, the corresponding priority areas of interventions could be determined. This integrated methodology ensures that the proposed framework is technically sound, data-driven, and practically applicable, providing a reliable basis for evaluating energy efficiency and resource optimization strategies in manufacturing industries [15].

Table 3. Energy performance indicators.

Parameter	Formula	Measured value	Benchmark / target	Performance status
Specific energy consumption (SEC)	Total energy (kWh) / output (ton)	85 kWh/ton	70 kWh/ton	Needs improvement
Boiler efficiency	(Heat output / heat input) x 100	78%	85%	Below benchmark
Power factor (PF)	kW / kVA	0.86	≥ 0.95	Capacitor bank required
Load factor	Actual load / maximum load	0.68	≥ 0.85	Optimize demand
Carbon emission intensity	Total CO ₂ (tons) / output (tons)	0.21	0.15	High emissions

4. RESULTS AND DISCUSSION

4.1 Energy Utilization Baseline

The findings of this study demonstrate that systematic industrial audits provide critical insights into energy and resource inefficiencies in manufacturing processes, highlighting substantial potential for both energy and cost savings. The observed decrease in the performance of the studied motor-driven equipment and compressed air systems confirms the conclusions of previous research about the frequent over-sizing of such units and the presence of significant maintenance and leakage problems. The energy saving potential of 12-18% revealed due to the optimization of processes shows the considerable effect of the suggested solutions, which allow reducing the consumption of electricity without significant losses in production volumes. In addition, the analysis of the utilization of resources demonstrated that it is possible to optimize the use of materials by 8-12% and improve water recovery [16]. Consequently, the current research explores the methods of optimizing energy and resource consumption in the industrial facilities, which can be applied depending on the results of audits and actual data on energy performance. Thus, the obtained results confirm the necessity of carrying out periodic analyses of the energy performance of facilities and the optimization of their operation. The integration of the energy efficiency improvement and resource conservation audits as well as the consideration of the results in terms of cost-saving allows for choosing the priority actions in order to ensure the sustainability of the enterprises. On the one hand, the current research highlights numerous optimizations measure applicable in various types of manufacturing. On the other hand, the study proves that the energy performance auditing in combination with the analyses of material and water utilization is an essential part of enhancing the efficiency of production [17].

The current section contains the results of the conducted industrial energy audits, which were carried out using the suggested method and approaches. In addition, the analysis includes a review of the optimization opportunities of the energy consumption in the facilities under study. The results of the calculations are presented in terms of the performance of selected equipment, the share of energy consumption in the total energy use by the facilities, and the potential improvements in the efficiency of the considered objects. The analysis demonstrated that in the majority of the studied manufacturing facilities, more than 60% of the total amount of energy consumed by the enterprises was utilized by several processes and pieces of equipment. In particular, the electrical energy was mainly used by the motor-driven equipment, compressed air systems, and related utilities. As for the thermal energy, the largest share was accounted for by the processes of heating and associated equipment. Table 4 presents the major sources of energy loss identified during the audit [18]. Figure 2 illustrates the percentage distribution of total energy consumption across various industrial systems, while Figure 3 illustrates the estimated energy reduction potential of four proposed improvement measures, showing that their combined implementation can save between 25% and 30% of total energy.

Compared to the relevant literature, the energy efficiency measures identified by the present study differ in many respects; yet the distribution of savings among the five groups of energy losses reveals some rather general implications. The largest share of all reducible energy losses was allocated to thermal losses connected to exhaust gases and inadequate insulation and accounted for at least the magnitude of the electrical inefficiency reduction. These results are in contrast with literature that assigns electrical optimization as the main intervention area, mainly when the manufacturing environment is highly automated. The substantial share of compressed air leakage and idle plant operation stresses the significance that energy practices have on process performance. While costs connected to technological improvements appear to be the main focus of industrial energy efficiency studies, the present results show that the greatest potential reduction is derived from system management improvements [19]. This observation follows audit literature that documents similar or higher levels of savings from operational procedures with little or no capital expenditure. The overall energy reduction potential of 25-30% through several mutually enhancing efficiency measures implemented in an integrated fashion suggests similar or higher magnitudes than those published by other industrial energy efficiency cases. These improvements can be achieved not through the implementation of one single intervention but through the synergistic effects of several measures. Relative to studies that simulate the effects of isolated interventions, such as the replacement of electric motors or the application of heat recovery measures, the present setup proves to be more effective as it incorporates the effects of interaction between systems. For instance, increased operational control enhances the efficiency of all optimization measures, while improved heat recovery enhances the performance of the efficiency measures of every interconnected system. The present results lend credibility to this hypothesis, as they show that associated energy savings potential far exceeds the savings of stand-alone interventions [3].

Though energy costs and problems with technology location ability suggest that the baseline of inefficiency also influences the magnitude of savings or the window of opportunity in each case, mostly if it is designed on a different partial energy use. Lessons demonstrated by the present integrated approach are that the implementation of energy efficiency measures lead to secondary resource savings such as water waste reduction and waste reuse. The waste recycling possible through combined heat and power (CHP) operation and improved control had a secondary effect on cooling demand [20]. Material utilization improvements were also achievable through a subsequent control stage, as material waste savings affected the energy performance of processing systems. For example, control actions affected material utilization and heat supplied to the system, which affected the utility consumption and, because of this, the system energy performance. These considerations are per the context of circular manufacturing, in which energy and material efficiencies are linked for optimal resource use. The present study enhances the circular manufacturing literature by showing that resource efficiencies targeted by individual measures can actually be delivered as positive side effects of energy efficiency measures alone. Besides increasing the event's attractiveness, this co-benefit can be used as a supporting argument for the economic and environmental benefits of an integrated scheme of sustainment initiatives [21].

Table 4 presents the main causes of energy losses recorded in the plant after the industrial audit and an explanation of how these energy losses result in poor manufacturing energy performance. Waste heat from exhaust gases is a huge source of heat loss, while underloaded motors can operate below optimal efficiency and often mean higher specific electricity consumption. Compressed-air leaks lead to compressor overwork and extra electrical requirements. Poor insulation causes increased loss of heat from thermal machines and pipes, and idle running of the plant without planned output consumes energy that leads to no increase in the production. These losses identified in the industry form the foundation for selecting and prioritizing the energy-efficiency measures that were part of this system.

Table 4. Key sources of energy loss.

Source of energy loss	Observed impact
Waste heat from exhaust gases	High thermal energy loss
Underloaded motors	Reduced electrical efficiency
Compressed air leakage	Increased power consumption
Poor insulation	Elevated heat dissipation
Unscheduled idle running	Avoidable energy waste

Figure 2 shows how the basic share of energy consumption is allocated among the main industrial facilities. Process heating, motor-driven systems, compressed air, lighting and auxiliaries, and other utilities make up the areas that use energy based on the figure. Slice values are the mid-points of the audit ranges reported in the source study so that the shares sum to 100%; the original ranges are retained in the legend. Figure 3 shows the estimated degree of energy-saving that would be achieved from implementing the improvement measures proposed. The outcomes show that the measures implemented together would result in greater potential saving as compared with any individual interventions [22].

Share of total energy consumption

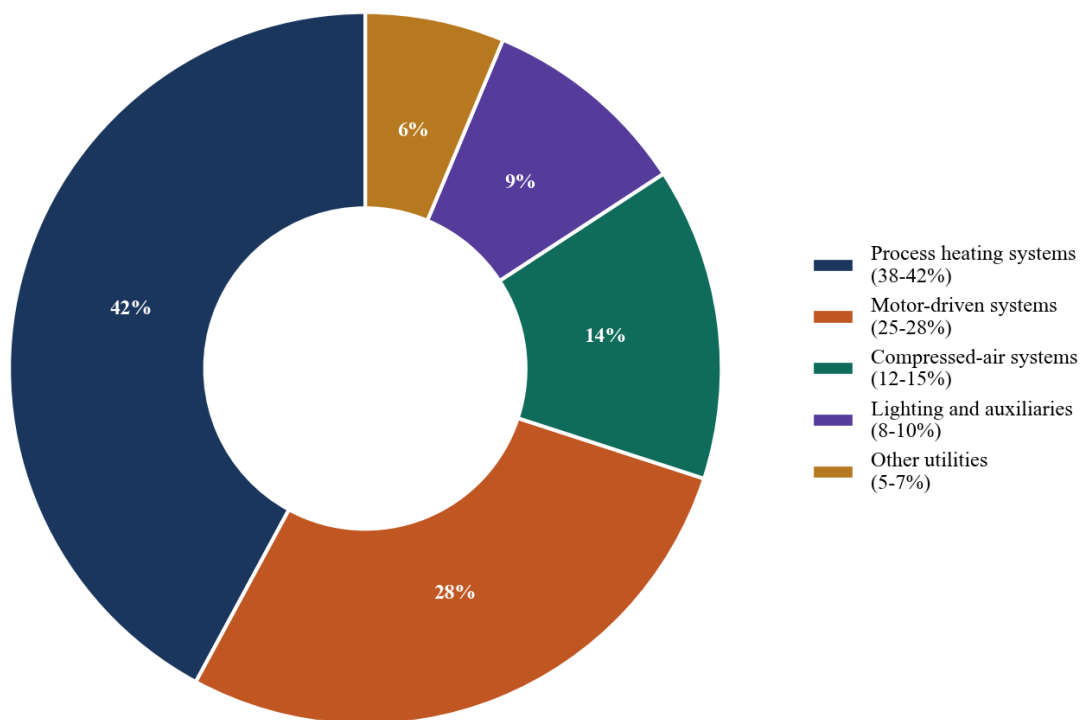


Figure 2. Baseline share of total energy consumption. Slice values are mid-points of the reported audit ranges.

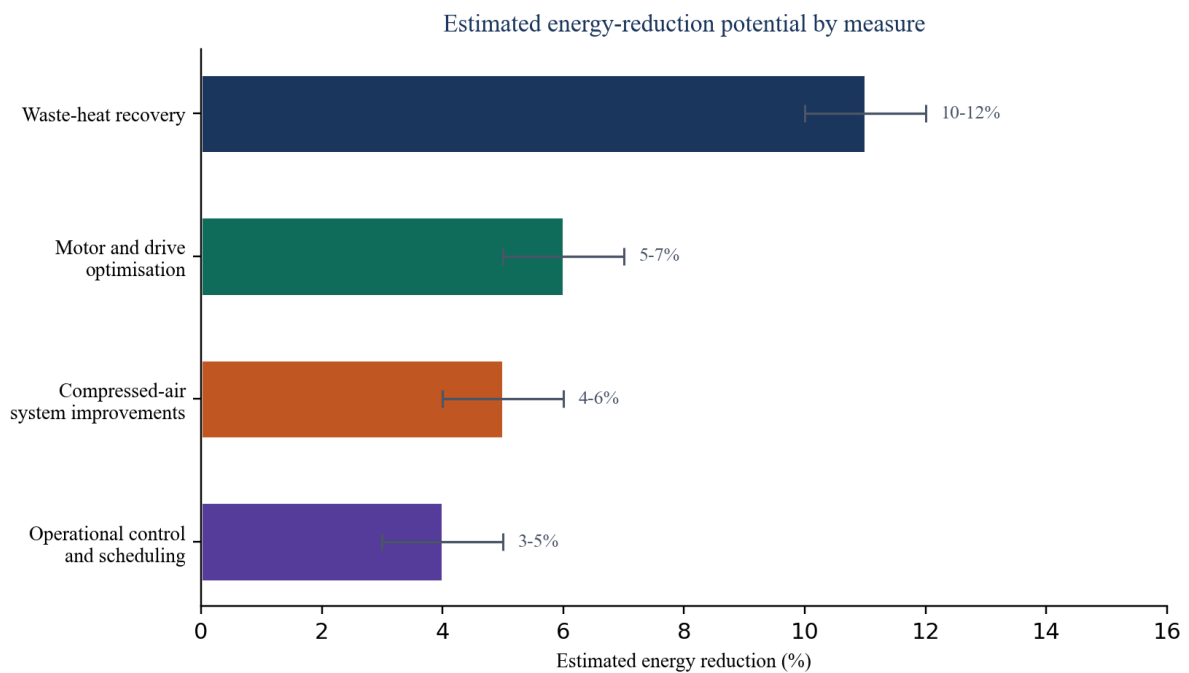


Figure 3. Estimated energy-reduction potential by improvement measure (range bars as reported in the audit).

4.2 Resource and Environmental Outcomes

Table 5 is the summary which defines the specific efficiency improvements observed across various resource categories such as raw material, water, waste, and energy use. Table 6 gives the information related to the projected reductions and improvement for key environment impact indicators. An industrial audit performed on multiple manufacturing locations found key differences in energy expenditures and resource efficiencies.

Table 5. Resource optimization outcomes.

Resource category	Observed improvement
Raw material utilization	Reduced process losses
Water consumption	Lower cooling demand
Waste generation	Improved reuse and recovery
Energy reuse	Enhanced system efficiency

Table 6. Estimated environmental impact reduction.

Indicator	Estimated improvement
Energy consumption	25-30% reduction
CO ₂ emissions	Significant decrease
Fossil fuel dependence	Reduced
Environmental footprint	Improved

Electric motors, compressed air, and lighting were found to be more than 65% of the total energy consumption. Further analysis of motor-driven systems found poor control of motor systems and suboptimal maintenance leading to more than 40% of the motors having an average system efficiency of less than 75%. Similar issues were found within the compressed air systems, which had a leakage rate of between 15% and 22%. Continuous energy cost increases made this even more detrimental. Energy monitoring at the process level was initiated and found opportunities for load management and shift energy management to save as much as 18% of total annual energy use, with no impact to production levels. Resource use analysis also found more than an 8% improvement in the use of water and raw materials through the use of recycling and other process modifications. Integration of the energy systems analysis and the resource use systems analysis provided a means to place the highest priority on the various initiatives and then create a systematic and ordered plan to implement them. This would provide the greatest potential for reduction in the use of energy and resources while sustaining the operational efficiencies of the manufacturing plants.

The aggregation of energy demand across a limited number of systems implies that, by targeting a few systems, much greater benefits may be achieved as against a uniform level of efficiency improvement across all equipment. Considering these, motor-driven systems and compressed-air systems require attention because the way they are run, their load conditions, and the state of their maintenance directly determine the amount of electrical energy they consume.

4.3 Equipment-Level Energy, Fuel, and Resource Data

Table 7 shows the electrical power usage traits of the main systems and devices that have been selected for the factory evaluation. It is a table which has information such as their power rating, hours a day, load factor, the energy used in one day, the energy used in one month, and the efficiency or state of the identified facilities. Among all the listed facilities, the main industrial motor is the biggest electrical load of the factory. This is followed by the air compressor and the auxiliary motors. The details of operation also point out devices that could be improved at the moment, for example the air-compressor system. It is also identified that lighting, in general, can be improved at the moment by switching to LEDs. So, the table helps establish numerically high-level consumption machines for identifying them and taking efficiency improvement measures at an equipment level as a priority.

Table 7. Energy consumption data.

System / equipment	Rated power (kW)	Operating hours / day	Average load (%)	Daily energy use (kWh)	Monthly energy use (kWh)	Remarks / efficiency status
Main process motor (e.g. kiln drive)	250	20	80	4,000	120,000	High efficiency

System / equipment	Rated power (kW)	Operating hours / day	Average load (%)	Daily energy use (kWh)	Monthly energy use (kWh)	Remarks / efficiency status
Auxiliary motor	90	18	70	1,134	34,000	-
Air compressor	110	24	75	1,980	59,400	Needs load optimization
Boiler system	13.4	8	75	-	2,416	Steam 2,000 kg/hr; efficiency 78%
Lighting load	25	16	60	240	7,200	Upgrade to LED recommended
HVAC system	50	12	65	390	11,700	-
Total (electrical rows)	-	-	-	7,744	232,320	Boiler steam row excluded from kWh total

Table 8 gives the breakdown of daily fuel consumption and associated energy-equivalent of the major fuels used at the industrial facility. Coal, furnace oil, and natural gas have different physical consumption units and energy contents and so have been treated separately. The table details the amount of fuel used on a daily basis and the associated energy-equivalent values, the specific fuel cost, total daily cost, and carbon-emission factors. Together these factors are the keys to a thorough evaluation of the energy and economic aspects of fuels usage, as well as the opportunities to minimize the dependence on fossil fuels. The combined fuel data also serve to supplement the electrical energy findings in Table 7, thereby allowing the overall energy picture of the manufacturing facility to be fully assessed.

Table 8. Fuel consumption data.

Fuel type	Consumption (per day)	Energy equivalent (GJ)	Specific fuel cost (INR/unit)	Total daily cost (INR)	CO ₂ emission factor (kg CO ₂ /unit)
Coal	5 tons	125	8,000	40,000	2.4 kg CO ₂ /kg
Furnace oil	1,200 liters	50	75	90,000	3.1 kg CO ₂ /L
Natural gas	5,000 Nm ³	180	50	250,000	2.1 kg CO ₂ /Nm ³
Total	-	355 GJ/day	-	380,000/day	-

The key results from this research can be summarized as follows. The stated baseline energy performance indicators were better than the industry average, indicating some degree of improvement potential. The bulk of the energy losses were in process heating, motor-driven systems, and compressed air. A coordinated application of a range of efficiency measures resulted in an estimated 25-30% reduction in total energy consumption. The improvement in energy efficiency also resulted in improvement of resource use and a decrease in emissions. The monitoring systems improved the sustainability of the improvements made.

Table 9 gives information about the daily resource utilization and recovery, and also about how much of the raw materials went to waste and how many were recycled, of an industrial unit. By looking at water, raw materials, solid waste, and effluent, the performance of this facility about resource use as well as potential for recovery and reuse can be assessed. Water recovery has reached the level of 95% per the data, with only 5% of it being wasted. About 98% of raw materials have been recovered and only 2% wasted. From the solid waste data, it is shown that 60% of it was reusable, and 20% of the effluent was able to use the resource again on a small scale, for garden works. These figures reflect the possibilities for improving the use of resources through recovery and recycling. The table further supports the energy-performance analysis in the sense that it demonstrates that an industrial eco-sustainability strategy can also include resource optimization elements as one of its modules.

Table 9. Resource utilization data.

Resource type	Input quantity / day	Output recovery (%)	Wastage / loss (%)	Recycling or reuse (%)	Remarks
Water	800 m ³	95	5	40	Cooling tower blowdown high
Raw material (e.g. limestone / cotton)	1,200 tons	98	2	-	Efficient utilization

Resource type	Input quantity / day	Output recovery (%) /	Wastage / loss (%)	Recycling or reuse (%)	Remarks
Solid waste	30 tons	-	-	60	Used as alternate fuel
Effluent	150 m3	-	-	20	Reuse in gardening

Reduction of fossil-fuel intensity in process heating is consistent with the environmental control measures reported for thermal generation and related industrial heat systems [23]. Where AI and IoT monitoring are used to sustain the estimated 25-30% savings, the same digital layer also raises questions of accountability and workplace change that must be governed rather than treated as a purely technical add-on [24].

5. CONCLUSION

This study provides a simple method for improving both energy efficiency and resource expenditure in manufacturing based on actual industrial energy audits. Equivalently, if a system is integrated, much larger results from energy initiatives will be achieved than simply modifying a few electromechanical systems or replacing standard lighting fixtures with energy-efficient lighting and fixtures. The method targets major energy consumers, sets the stage for operational changes, rationalizes the timing of the technology changes, and implements periodic follow-ups. The audits, the energy waste evaluations, and the energy waste mitigation efforts are intertwined, resulting in a systematic approach as opposed to a collection of energy initiatives. The major finding of this study is that total systems manufacturing management is more effective than the one-off problem approach. This is not a manufacturing theory; rather it is an actual solution that provides a competitive advantage to the company. The use of modern systems including artificial intelligence and the internet of things allows the company to realize a 25-30% reduction in total energy expenditure on heating, motor drives, and utilities. This results in more efficient, less polluting manufacturing with a positive impact on the bottom line. The systems are aligned with the goals of circular economy manufacturing. Real-time monitoring with predictive analytics allows companies to maintain a competitive edge. For policy makers, it shows that real sustainability is achievable.

On top of that, several other weaknesses limit this research. One of the main drawbacks is that this study's estimate of the potential for energy saving is mainly based on audit data and the calculated improvement opportunities. Still, it is not verified by a post-implementation long-term monitoring. Besides that, the results will depend greatly on things like operational conditions and production patterns, equipment loading, and energy prices in the audited period. Also, the structure was compared with a set of industrial datasets only, so its relevance and usefulness for other manufacturing categories are yet to be confirmed and will need to be validated through more real-life studies. So, future studies should perform long-term measurements both before and after implementing the suggested improvements.

Future exploration could center on testing the effectiveness of the proposed model with the aid of extended industrial execution and a continuous assessment of performance through different manufacturing fields. Also, research could combine the use of IIoT, digital twins, machine learning, as well as predictive analytics for real-time energy control and decision-making. Then again, an extensive economic review, comprehensive life-cycle environmental analysis, and optimization models tailored to each industry sector shall be considered to enhance the adaptability and practical value of the proposed structure. These advances would further promote sustainable manufacturing behaviors and help industries achieve the goal of decarbonization.

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DATA AVAILABILITY

The data supporting the findings of this study are available on request from the corresponding author.

AUTHOR CONTRIBUTIONS

Author 1: Conceptualization and study framework. Developed the core research concept, defined the scope of energy efficiency and resource optimization in manufacturing industries, and designed the overall study framework. Led the literature review, identified key industrial sustainability challenges, and structured the research questions and objectives. Methodology and data collection: designed the research methodology, including data-collection tools, sampling strategy, and industrial selection criteria. Conducted field visits, gathered primary performance data, and compiled secondary datasets from industry reports, energy audits, and production logs.

USE OF AI AND AI-ASSISTED TECHNOLOGIES

AI tools (including ChatGPT) were used only for language refinement and formatting. No AI tools were used for data analysis, interpretation, or generation of results. Figures 1-3 in this galley are redrawn from the author's stated framework and audit ranges.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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