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Research Article

Energy Efficiency Assessment in a Textile Dyeing Facility: A Case Study

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ABSTRACT

This study presents the results of a comprehensive energy audit conducted at an industrial textile dyeing facility in Türkiye, aimed at evaluating its energy performance and identifying potential energy efficiency improvements. Electricity and natural gas consumption patterns were analyzed using historical production and energy data, field measurements, and onsite observations. The audit focused particularly on thermal energy systems, including steam boiler operation, heat distribution lines, and auxiliary equipment, as well as electrical systems such as lighting. Flue gas analysis, thermal imaging, and energy monitoring were employed to determine system efficiencies and quantify energy losses. Based on the audit findings, three main energy efficiency measures were proposed: recovery of waste heat from boiler flue gases, insulation of uninsulated piping and installation elements, and conversion of conventional lighting systems to high efficiency LED luminaires. The results indicate that natural gas accounts for more than 90% of total energy consumption, highlighting the critical importance of improving thermal systems. The proposed measures demonstrate energy savings and economic benefits, with simple payback periods ranging from 0.6 to 3.9 years. The findings confirm that systematic energy audits are an effective and cost effective approach to reducing energy consumption, operating costs, and greenhouse gas emissions in energy intensive textile dyeing facilities.

Introduction

Climate change has emerged as one of the most critical global challenges of recent decades, posing severe environmental, economic, and social risks worldwide. Rising average global temperatures, the increasing frequency and intensity of extreme weather events, and the growing occurrence of droughts and floods clearly demonstrate that the impacts of climate change are accelerating at an unprecedented rate [1-3]. Scientific assessments consistently warn that, without substantial reductions in greenhouse gas emissions, global temperature increases may exceed critical thresholds by the end of the century, leading to irreversible consequences for natural ecosystems, water resources, and human activities [4,5].

Energy production and consumption patterns lie at the core of this challenge. Fossil fuels continue to dominate the global energy mix, accounting for a significant share of carbon dioxide emissions and reinforcing dependence on finite energy resources [6,7]. In this context, improving energy efficiency has been widely recognized as one of the most effective and economically viable strategies for mitigating climate change while sustaining industrial productivity and economic growth [8-10]. Energy efficiency improvements are particularly crucial in energy-intensive industries, where even marginal efficiency gains can yield substantial reductions in energy consumption, operational costs, and associated emissions [11]. The industrial sector represents a considerable portion of total energy consumption in Türkiye, with the textile industry ranking among the leading contributors [12,13]. Within this sector, fabric dyeing and finishing processes are especially energy intensive due to their high demand for both thermal and electrical energy. Significant quantities of steam and hot water are required for dyeing, washing, and drying operations, while pumps, compressors, fans, lighting systems, and auxiliary equipment extensively consume electricity [14-16]. Consequently, textile dyeing plants are characterized by high operating costs and notable greenhouse gas emissions, making them a priority sector for energy efficiency improvement initiatives.

Recent studies have demonstrated that systematic energy management practices can significantly enhance energy performance in textile and dyeing facilities. In particular, energy audits have proven to be a powerful tool for identifying inefficiencies, quantifying energy losses, and developing feasible energy saving measures tailored to facility specific conditions [17, 18]. Reported case studies indicate that optimization of boiler systems, reduction of thermal distribution losses, recovery of waste heat from exhaust gases, implementation of efficient lighting systems, and improved control of electrical drives can result in considerable energy savings and emission reductions in textile plants [19-21]. These findings highlight the critical role of detailed energy audits as a prerequisite for sustainable operation in energy intensive manufacturing sectors.

In Türkiye, increasing energy demand, high dependence on imported energy resources, and rising energy prices further intensify the need for efficient energy use in industrial facilities [22]. National energy strategies and regulatory frameworks increasingly emphasize energy efficiency as a key instrument for reducing external energy dependency and minimizing environmental impacts. Within this framework, energy audits are promoted as an essential decision support tool for identifying energy saving potentials and prioritizing energy investments in industry [23].

This study presents the results of a comprehensive energy audit conducted at a textile dyeing plant in Türkiye. The analysis focuses on evaluating electricity and heat energy consumption patterns, identifying the main sources of energy loss, particularly in boiler operation and auxiliary systems, and assessing opportunities to improve overall energy performance. Based on the measured data and audit findings, potential energy efficiency measures are proposed, and their technical, economic, and environmental impacts are discussed. The results of this study aim to contribute to the development of energy efficiency practices and to the transition to more sustainable industrial processes in the Türkiye textile dyeing sector.

Material and Methods

In this study, a systematic energy audit approach was adopted to evaluate the energy performance of the industrial facility under investigation. Energy audits are considered one of the most effective and economical methods for revealing the energy efficiency potential by enabling detailed analysis of energy flows throughout an enterprise and on a process basis [24]. In this context, energy consumption points are identified, energy losses are quantified, and technically feasible improvement suggestions are developed.

When examining standards for energy management, it is seen that the ISO 50001 Energy Management System has significant similarities with the ISO 14001 Environmental Management System in terms of structure, implementation process and monitoring mechanisms. Both standards are based on the continuous improvement approach and aim to systematically improve energy and environmental performance in businesses [25,26]. In the literature, it is emphasized that audit and certification processes based on such management systems contribute not only to reducing energy consumption but also to improving production performance, reducing environmental impacts, and increasing economic benefits [27,28].

Energy audits can be conducted at different levels of scope and detail depending on the size of the enterprise, the energy consumption structure, and the analysis objectives. These audits are generally classified as walk-through, mini-audit, and maxi-audit [17]. Similarly, some researchers have classified energy audits as basic, medium level, and comprehensive audits [29]. However, these classifications mostly focus on the plant or process level, and the need to adopt a broader systems approach for the holistic management of material and energy flows and the systematic improvement of environmental performance is particularly emphasized in the literature [30].

Table 1 presents the facility's annual energy consumption, expressed both in quantity and as a proportion of total consumption, for natural gas and electricity. As the results show, natural gas is the dominant component of total energy consumption across all years studied, accounting for more than 90% of total energy use. In comparison, electricity accounts for less than 10%. This consumption pattern demonstrates that the facility is largely dependent on thermal energy, primarily for steam and hot water production. In this study, energy consumption values are expressed in ton of oil equivalent (TOE), which is a standardized unit commonly used to compare different energy sources on a common basis.

Table 1. Energy consumption data and percentage rates

	Type of Energy (TOE)		Percentage Rate	
Years	Natural gas	Electricity	Natural gas	Electricity
2020	652.13	70.87	% 90.2	% 9.8
2021	514.91	54.14	% 90.49	% 9.51
2022	730.77	73.66	% 90.84	% 9.16

Table 2 illustrates the monthly distribution of electricity and natural gas consumption for the year 2022. The results indicate a pronounced seasonal variation in total energy consumption, with significantly higher values during winter and early spring. This trend is primarily driven by increased natural gas consumption, which is associated with higher thermal energy demand for steam and heating processes. In contrast, electricity consumption remains relatively stable throughout the year, exhibiting only minor fluctuations. The lowest total energy consumption is recorded during the summer months, particularly in July and August, reflecting reduced thermal demand. Overall, the monthly consumption profile confirms that natural gas use is the dominant factor influencing the facility’s total energy demand and underscores the importance of targeting energy efficiency measures to thermal energy systems.

Figure 1 presents the monthly relationship between production output and total energy consumption of the facility. Although both parameters exhibit similar trends in certain periods, the overall relationship is weak and non-linear. In particular, energy consumption remains relatively high during some months with lower production levels, indicating the influence of base thermal loads and auxiliary energy demands independent of production volume. Conversely, periods of increased production do not always correspond to proportional increases in energy consumption. This behavior suggests that energy use in the facility is strongly affected by seasonal conditions and fixed process-related energy requirements, rather than solely by production output.

Table 2. Monthly energy consumption (TOE) for 2022.

Months	Electricity	Natural gas	Total
January	7.19	79.88	87.07
February	7.43	84.69	92.12
March	9.08	106.44	115.52
April	4.53	59.36	63.89
May	5.81	51.35	57.15
June	6.13	55.34	61.46
July	4.68	36.68	41.36
August	4.33	31.65	35.99
September	4.07	33.08	37.15
October	5.67	51.82	57.48
November	6.9	65.68	72.58
December	7.85	74.79	82.64
Total	73.67	730.76	804.41

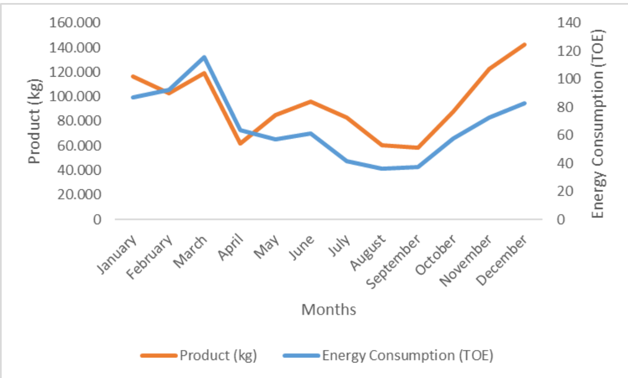

Figure 1. Production and energy consumption relationship

The energy audit also included an examination of the facility's mechanical and electrical installations and a detailed analysis of the energy-consuming equipment on the production line. Accordingly, the operating conditions, load states, and energy consumption of steam boilers, insulation, and lighting elements were evaluated. The equipment's efficiency was examined, and potential areas for improvement were identified. The study also addressed the lighting systems used throughout the facility, examining existing lighting levels, types of luminaires used, and energy consumption. Energy-saving potentials for the lighting system were assessed, and improvement suggestions were developed. Finally, a general evaluation was conducted based on all analyses, and technical, economic, and operational recommendations to increase energy efficiency were presented. These recommendations were considered in line with the objectives of reducing the facility's energy consumption, lowering operating costs, and minimizing environmental impacts. In the energy audit studies, devices calibrated and labeled by accredited national or international organizations were used. Table 3 summarizes the measurement periods and methods applied during the energy audit at the facility. Momentary measurements such as flue gas emissions, thermal imaging, indoor temperature, indoor air quality, and lighting levels were conducted at multiple time points to ensure representative and reliable results. In contrast, electrical energy consumption of electric motors was continuously recorded at two minute intervals using an energy analyzer, enabling detailed monitoring of operational energy use. This combined approach allows both instantaneous performance assessment and time dependent energy behavior to be accurately evaluated within the scope of the study.

Table 3. Measurement Periods and Methods.

Measurement	Period	Method
Flue gas emissions	Momentarily	Flue gas analyzer at 2 different times
Thermal Images	Momentarily	Thermal Camera
Indoor Temperature	Momentarily	Temperature measurement at 3 different times, constant values.
Indoor Air Quality	Momentarily	Air quality meter with constant values at 3 different times
Electric Motors	Recording every 2 minutes	Energy analyzer
Light Intensity	Momentarily	4 different moments, lux meter

Systems

Steam Boilers

The facility has one natural gas fired steam boiler to meet its steam needs. It supplies steam to the drying, painting, and washing machines in different sections of the facility. The label information for the steam boilers is given below.

Table 4 Steam Boiler Labeling Information

Fuel Type	Natural gas
Capacity	2000 kg/h
Operating Pressure	6 bar
Operating Temperature	165 °C
Test Pressure	10 bar

Flue gas, surface temperature, and natural gas consumption data were collected from the steam boiler. Table 4 presents the technical labeling information of the steam boiler operating at the facility. The boiler, fired by natural gas with a nominal capacity of 2000 kg/h, operates at 6 bar pressure and 165 °C, typical values for industrial steam generation systems. These parameters indicate that the boiler is designed to meet medium-pressure process steam requirements under stable operating conditions.

Table 5 summarizes the flue gas analysis results obtained from the steam boiler. The measured oxygen concentration of 4% and excess air coefficient of 1.24 indicate an adequate air fuel ratio and proper combustion control. The low carbon monoxide concentration (1 ppm) confirms complete combustion, while the combustion efficiency of 93.8% reflects a relatively high thermal performance. However, the flue gas temperature of 159 °C and a net heat loss rate of 6.2% suggest that a portion of the thermal energy is lost through the exhaust gases, highlighting the potential for improving efficiency through waste heat recovery or further combustion optimization.

Table 5. Flue Gas Analysis Measurement Results of the Steam Boiler

Flue Gas Temperature	159 °C
Boiler Outlet Temperature	56.8 °C
Ambient Temperature	30.4 °C
Oxygen	% 4
Carbon Dioxide	% 9.71
Carbon Monoxide	1 ppm
Excess Air Coefficient	1.24
Combustion Efficiency	% 93.8
Net Heat Loss Rate	% 6.2
Flue Draft	-0.049 mbar

In addition to the measurements above, thermal imaging was performed using a thermal camera to detect potential heat losses from the boiler surfaces, as shown in Figure 2. Accordingly, the heat loss potential of the boiler's front surfaces was observed. Heat losses from the boiler surface, along with flue gas measurements, are crucial for determining the overall boiler efficiency. Thermal camera images of the boilers are shown in the figures below.

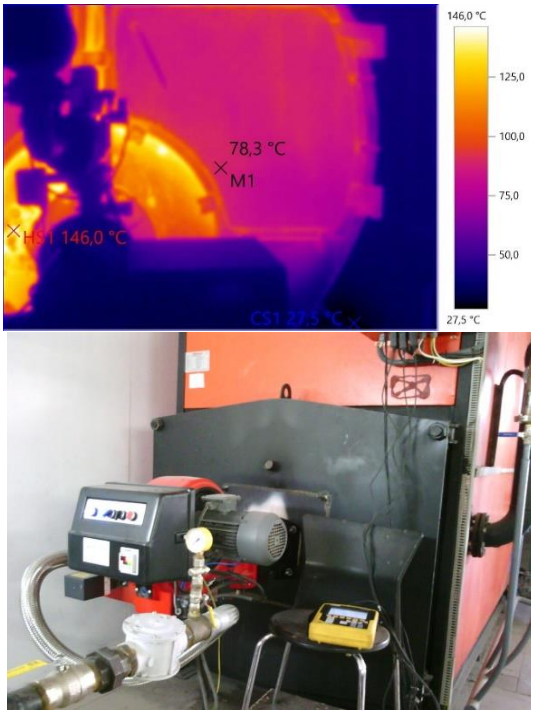

Figure 2. Thermal camera image of the boiler.

Examination of the thermal images of the boiler located at the facility reveals that the average temperature on the front surface is 75°C, while on the side surfaces it is 58°C.

Table 6. Natural gas meter measurement

Meter Value (Sm^3)	
First reading	400.754
Final reading	401.710

Thermal camera and flue gas measurements were taken from the plant's boilers as part of the study. Flue gas data and other boiler measurements (surface and ambient temperature, natural gas consumption, boiler dimensions) were added to this measurement to calculate the boiler's current efficiency. Average values of these flue gas measurements were considered in the calculations; taking multiple measurements is crucial for obtaining the most accurate results. Boiler efficiency calculations were performed based on the measurements taken from the boilers. The boiler efficiency formulas are given below, along with the resulting values for the boilers.

Heat loss due to dry flue gas (L_1):

$$L_1 = \frac{m * C_p(T_f - T_a)}{GCV\ of\ fuel} 100 \quad (1)$$

where, L_1 is the % heat loss due to dry flue gas, m is the mass of dry flue gas in kg/kg of fuel, C_p is the specific heat of flue gas in kj/kg, T_f is the flue gas temperature in ℃, T_a is the ambient temperature in *℃,* GCV is the gross calorific value of the fuel in kj/kg.

Heat loss due to moisture in flue gas(L_2):

$$L_2 = \frac{9 * H_2\left((584 + C_p\ (T_f - T_a)\right)}{GCV\ of\ fuel} 100 \quad (2)$$

where H_2 is kg of the hydrogen in fuel on 1 kg basis, 584 is the latent heat corresponding to partial pressure of water vapour.

Heat loss due to unburned carbon monoxide in flue gas (L_3):

$$L_3 = \frac{\%CO * C * 5744}{(\%CO + \%CO_2) * GCV\ of\ fuel} * 100 \quad (3)$$

L_3 is the heat loss due to partial conversion of C to CO (%), CO is the volume of unburned CO in the flue gas, CO_2 is the actual volume of CO_2 in the flue gas (%), C is the carbon content kg/kg of fuel.

$$L_4 = (U_r + U_c) * A(T_s - T_0) \quad (4)$$

where, U_r is the radiation coefficient, U_c is the convection coefficient, A is the surface area, T_s is the boiler surface temperature, and T_0 is the ambient temperature.

$$L_5 = \frac{m_b * h_b}{m_f * GCV\ of\ fuel} * 100 \quad (5)$$

where, m_b is the mass of blowdown water (kg/h), h_b is the enthalpy of blowdown water (kJ/kg), m_f is the fuel flow rate (kg/h), and GCV is the gross calorific value of the fuel in kJ/kg. The total heat loss rate was calculated using Eq.

$$L_{tot} = L_1 + L_2 + L_3 + L_4 + L_5 \tag{6}$$

$$\eta = 100 - (L_{tot}) \tag{7}$$

η represents the boiler's efficiency.

Insulation of the Systems

The system includes lines for conveying superheated steam. Insulation is the critical factor for energy efficiency in piping systems. The reason why the insulation of the equipment in the system is so important is that superheated steam is carried in these lines. When the insulation between the superheated steam in the lines and the surrounding environment is insufficient, heat is lost to the environment. Within the scope of the study, the piping system, boiler rooms, and the piping lines of the machines were examined. There are valves, pumps, and some lines in the system that are not insulated. An efficiency study was conducted to determine the energy efficiency achievable by insulating uninsulated valves and lines. Images of the lines were captured with a Testo 868 thermal camera. An example thermal image of the uninsulated points detected by thermal measurements is given in Figure 3.

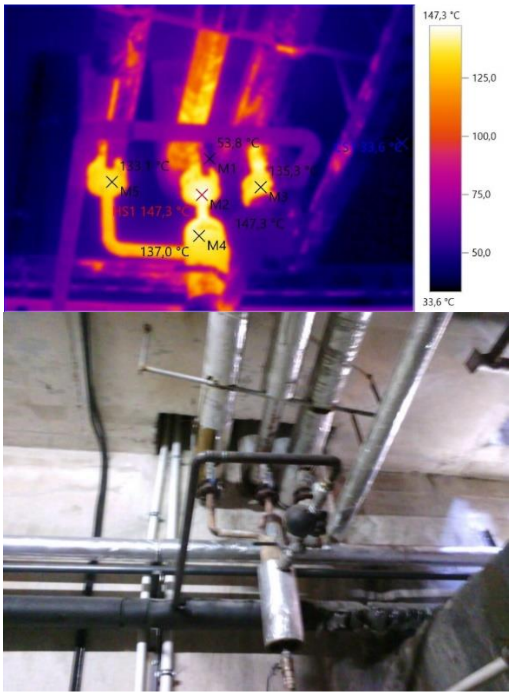

Figure 3. An example of thermal camera measurement photo

CO_2 emission Analysis

In this study, the grid electricity emission factor for Türkiye was taken as 0.435 kg-CO_2/kWh based on national power sector intensity data [31]. The natural gas emission factor was assumed as 0.202 kg CO_2/kWh according to IPCC default values [32]. The avoided emissions were obtained by multiplying the annual savings by the emission factor.

Results and Discussion

As a result of the detailed energy audit conducted at the examined facility, three different energy efficiency measures were proposed. These are, respectively, recovery of waste heat from the boiler flue, application of insulation to uninsulated installation elements, and conversion of lighting elements. First, the current efficiency of the steam boiler is calculated and presented in Table 7. Based on calculations using field measurements and fuel consumption data, the total heat losses in the boiler were determined component by component. Heat loss due to dry flue gas was calculated as 5.81%, and heat loss due to moisture in the flue gas was calculated as 2.03%. Since CO formation in the combustion process is negligible, heat loss from unburned carbon monoxide remained at a low value of 0.11%. Heat loss from radiation and convection through the boiler surfaces was determined to be 0.11%, indicating that the boiler insulation is generally sufficient. Heat loss due to blowdown was calculated as 1.67%. Taking all these losses into account, the total heat loss was 10.73%, and the boiler efficiency was 89.27%. This calculated efficiency value is consistent with the 85–92% range reported in the literature for natural gas fired industrial steam boilers, indicating that the boiler has an acceptable energy performance under current operating conditions [30].

Table 7. Boiler heat losses

Heat Loss Due to Dry Flue Gas (L_1)	%5.81
Heat Loss Due to Moisture in Flue Gas (L_2)	%2.03
Heat Loss Due to Unburned Carbon Monoxide in Flue Gas (L_3)	%0.11
Heat Loss Due to Radiation and Convection from Boiler Surface (L_4)	%0.11
Heat Loss Due to Blowdown (L_5)	%1.67
Total Heat Loss (L_{tot})	%10.73
Boiler Efficiency (η)	%89.27

Regular periodic maintenance of the boiler should be performed. Measurement equipment (such as thermocouples) that controls automation should be calibrated periodically, and equipment found to be inaccurate should be replaced. Periodic measurements of boiler water conductivity should be taken, and conductivity values should be kept under control so as not to exceed the upper limit. Periodic flue gas analysis should be performed, flue gas components should be checked, and combustion rates should be monitored.

Energy Efficiency Measures

Boiler Flue Gas Waste Heat Recovery

Measurements taken at the boiler chimney showed a flue gas outlet temperature of 179.9 °C. By utilizing the heat in the flue gas, the boiler feed water can be preheated, the hot water needs of another section can be met with this project, and the plant's natural gas consumption will be reduced. The flue gas velocity, chimney area, specific heat of flue gas and density for this application are given in Table 8, and the amount of useful energy to be obtained from the flue gas has been calculated.

Table 8. Net Energy Obtainable from Boiler Flue

Average Flue Gas Temperature	179.9°C
Flue Gas Specific Density	0.78 kg/m³
Flue Gas Mass Flow Rate	0.65 kg/s
Flue Gas Specific Heat	1.088 kj/kg°C
Predicted Flue Gas Temperature After Application	130°C
Predicted Flue Gas Temperature Difference After Application	49.9°C
Amount of Heat Recoverable	35.23 kW
Economizer Efficiency	90%
Net Energy Transferable to Water	31.71 kW

The savings that can be achieved through flue gas recycling are given in Table 9.

Table 9. Savings to be Achieved with Flue Gas Recycling

Current Boiler Efficiency	%89.27
Natural Gas Savings	16.22 kW
Annual Operating Hours	3456 h
Annual Energy Savings	56056.76 kWh
Unit Cost of Energy	0.0779 $/kWh
Annual Cost Savings	4366.9 $/year
Investment Cost	17000 $
Simple Payback Period	3.9 year

Insulation of the System

Table 10 presents the energy, fuel, and economic impacts of the proposed insulation measures in different process lines of the textile plant on a system basis. The evaluation for the total line length of 192 m revealed a potential annual energy saving of 115,800 kWh. These savings resulted in a total annual financial gain of $3,898.1, while the total investment cost was calculated as $2,239.8. Thus, the average payback period for the proposed insulation applications was determined to be 0.6 years. When examined on a system basis, drying lines stand out as the system with the highest savings potential, saving 61,700 kWh of energy. These lines alone account for approximately 53% of the total energy savings. However, the relatively low investment cost ($1,209.7) and a payback period of 0.6 years indicate that insulation applications in drying lines are the most important measure in terms of both energy and economic benefits. Boiler lines and scrubbing lines also offer significant savings potential. Annual energy savings of 24,300 kWh are achieved in boiler lines, with a payback period of 0.6 years. In scrubbing lines, energy savings are 28,900 kWh/year, and although the payback period is slightly longer than for other systems at 0.9 years, it is still acceptable and feasible. Although the savings determined for the condensate tank and other auxiliary equipment are relatively low (940 kWh/year), insulation applications in these systems help reduce heat losses throughout the facility. However, the payback period of this group, at 1.4 years, is longer than that of other systems, indicating that its application priority should be considered secondary.

Table 10. Insulation project for the system

System	Total Line Length (m)	Surface Temperature Range (°C)	Annual Energy Savings (kWh)	Annual Financial Savings ($/year)	Total Investment Cost ($)	Average Payback Period (year)
Boiler Lines	37	83 – 150	24300	811.8	392.5	0.6
Washing Lines	45	77 – 140	28900	983.9	591.4	0.9
Drying Lines	104	80 – 150	61700	2069.9	1209.7	0.6
Condensate Tank and Others	6	80	940	32.5	46.2	1.4
Total	192	-	115840	3898.1	2239.8	0.6

Lighting Conversion Application

Table 11 presents the results of energy efficiency measures implemented in the facility, specifically the transition from traditional fluorescent fixtures to high efficiency LED fluorescent lamps, including the amount of electricity saved and costs, the investment costs of the measures, and the payback periods. While the total number of fixtures and annual operating hours remained unchanged, the average power demand per fixture decreased by approximately 50%, from 25 W to 12 W. As a result, annual electricity consumption decreased from 31,468 kWh to 14,452 kWh, corresponding to an annual energy saving of 17,016 kWh. This reduction leads to a significant decrease in annual electricity costs. Furthermore, energy savings can be achieved by using sensor controlled lighting in general use areas. With a total investment cost of $4,483.6, the proposed lighting improvement provides a simple payback period of approximately 0.7 years, demonstrating that this measure is highly cost effective and economically feasible for industrial applications.

Table 11. Lighting conversion data

Type	Current Situation	Proposed Situation	Change / Savings
	Fluorescent / Lamp	LED Fluorescent (Osram)	High efficiency system
Total Number of Luminaires	354	354	No change
Average Luminaire Power (W)	25	12	50%
Annual Operating Time (h/year)	3120	3120	No change
Annual Electricity Consumption (kWh)	31468	14452	17016
Annual Electricity Cost ($/year)	627.6	288.2	339.4 kWh
Total Investment Cost ($)	-	4483.6	-
Simple Payback Period (year)			0.7

CO_2 Emission Reduction

The results of the emission analysis are presented in Table 12. Accordingly, the waste heat recovery project is expected to reduce CO_2 emissions by 13.11 t-CO_2/year, while the insulation improvements provide 27.09 t-CO_2/year of reduction. The lighting retrofit contributes an additional 7.40 t-CO_2/year decrease.

Overall, the combined implementation of the proposed measures can achieve a total emission reduction of 47.6 t-CO_2/year, clearly demonstrating the environmental effectiveness of the energy audit based improvement strategy.

Table 12. Amount of CO_2 reduction

Energy Efficiency Measures	Energy Saving (kWh/year)	Emission Factor (kg-CO_2/kWh)	CO_2 Reduction (t-CO_2/year)
Waste heat recovery-natural gas	56056.76	0.234	13.11
Thermal insulation-natural gas	115800	0.234	27.09
Lighting retrofit-electricity	17016	0.435	7.40
Total			47.6

When the results of the present study are compared with the results of similar studies in the literature, Ozer and Guven [33] reported that comprehensive energy efficiency practices, including waste heat, flash steam and coolant recovery and insulation improvements, in a fabric dyeing factory in Turkey can reduce total energy consumption by up to 49% and specific energy consumption by up to 25%. The same study also highlighted that effective production planning and operating dyeing machines at full load can provide an additional energy saving potential of approximately 23%. These findings underscore the critical role of thermal energy management and process optimization in improving the energy performance of textile dyeing plants.

Conclusion

This study evaluates the energy performance of an industrial textile dyeing plant and identifies potential areas for improvement as a result of an energy audit conducted at the facility.

Electricity and natural gas consumption patterns were analyzed using historical production and energy data, field measurements, and on-site observations. The audit focused particularly on thermal energy systems such as steam boiler operation, heat distribution lines, and auxiliary equipment, as well as electrical systems such as lighting. Flue gas analysis, thermal imaging, and energy monitoring methods were used to determine system efficiencies and measure energy losses. Based on the audit findings, three main energy efficiency measures were proposed: recovery of waste heat from boiler flue gases, insulation of uninsulated pipes and fittings, and conversion of conventional lighting systems to high efficiency LED fixtures.

Three energy efficiency measures were evaluated in detail: boiler flue gas waste heat recovery, insulation of uninsulated process elements, and conversion of the lighting system to LED technology. Among these, the insulation application provided the highest annual energy saving, 115,840 kWh, and the shortest payback period, 0.6 years, demonstrating that low cost thermal loss prevention measures should be prioritized in similar facilities. The waste heat recovery project yielded moderate savings of 56,056.76 kWh/year with a longer payback period of 3.9 years, while the lighting retrofit achieved 17,016 kWh/year electricity savings with a payback of 0.7 years.
The combined implementation of the proposed measures is estimated to reduce total emissions by approximately 47.6 t-CO_2/year, demonstrating the environmental effectiveness of a systematic energy audit approach. In addition, the weak and nonlinear relationship between production and energy consumption indicates the presence of significant loss of thermal loads independent of production volume.

Ethics committee approval and conflict of interest statement

There is no need to obtain permission from the ethics committee for the article prepared. There is no conflict of interest with any person / institution in the article prepared.

Author Contributions

Study conception and design; Acquisition of data; Analysis and interpretation of data; Drafting of manuscript; Critical revision.

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Not applicable.

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