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e-ISSN: 3062-2743

The impact of energy efficiency measures on carbon reduction: An integrated LCA-exergy approach

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Cite this study: İlgin Beyazit, N. (2025). The impact of energy efficiency measures on carbon reduction: An integrated LCA-exergy approach. WAPRIME, 2(2), 32-45.

https://doi.org/10.5281/zenodo.18299861

Keywords

Energy Efficiency
Waste Heat Recovery
Exergy Analysis
Carbon Reduction
Life Cycle Assessment

Research Article

Received: 08 November 2025
Revised: 05 December 2025
Accepted: 06 December 2025
Published: 31 December 2025

Abstract

In this study, the technical, environmental, and economic impacts of waste heat recovery (WHR)–based energy efficiency measures implemented in industrial facilities are evaluated using an integrated energy–exergy–carbon footprint–life cycle assessment (LCA) framework. Pre- and post-implementation scenarios are compared for three textile plants. The energy analysis results indicate a 9.8–11.7% reduction in total energy consumption, corresponding to an annual natural gas saving of approximately 4,858 MWh, while no significant change is observed in electricity consumption. The exergy analysis reveals that exergy efficiency increases from 36–41% to 44–50%, accompanied by a substantial reduction in system exergy losses. Carbon footprint calculations demonstrate a total emission reduction of approximately 981 t CO_2 per year. Assuming a carbon price of 80 € per ton of CO_2, the annual economic benefit is estimated at approximately 78,500 € per year, with a payback period of 2–3 years. Cradle-to-gate LCA results show a 9.6–11.7% decrease in Global Warming Potential (GWP), along with consistent improvements in Acidification Potential (AP) and Eutrophication Potential (EP) indicators. The findings demonstrate that waste heat recovery is a technically feasible, environmentally effective, and economically attractive energy efficiency strategy for thermally intensive processes commonly used in the textile industry.

1. Introduction

Energy efficiency is widely recognized as a key instrument in mitigating climate change due to its potential to reduce energy demand and, consequently, greenhouse gas emissions [1, 2]. Indeed, recent studies conducted for G7 countries demonstrate that improvements in energy efficiency lead to significant reductions in carbon emissions [3]. These findings are consistent with other empirical studies focusing on OECD countries, which indicate that, under appropriate governance and policy frameworks, energy efficiency measures can substantially reduce environmental degradation and carbon-based indicators [4-6]. The International Energy Agency (IEA) defines energy efficiency as the “first fuel” and considers it one of the most cost-effective and rapidly deployable mitigation options, particularly for reducing energy demand and fossil fuel consumption in industrial processes [1, 7, 8].

The literature clearly highlights that industrial processes account for a significant share of global energy consumption and carbon emissions, with process-based energy use being a dominant contributor to total industrial emissions [9]. In Türkiye, the industrial sector represents a substantial portion of final energy consumption, and both national energy outlook reports and climate change mitigation strategies emphasize process-based energy efficiency policies as a priority intervention area for achieving 2030 targets [10-12]. Furthermore, empirical evidence indicating that energy consumption and greenhouse gas emissions in the manufacturing sector increase in parallel with economic activity further reinforces the importance of implementing such policies [12]. Consequently, efforts aimed at enhancing energy efficiency in industrial processes are of strategic importance for energy security, reducing import dependency, and strengthening industrial competitiveness [8].

A significant share of the existing literature on energy efficiency applications evaluates savings primarily based on operational energy use; however, studies that systematically examine the environmental impacts of these measures throughout their life cycle using life cycle assessment (LCA) remain relatively limited [13, 14]. In industrial systems, a considerable portion of energy losses originates from low-temperature waste heat sources, equipment inefficiencies, or process mismatches. Identifying these losses through exergy analysis enables a more accurate assessment of both the actual improvement potential and the associated carbon footprint impacts [15-17]. Exergy-based analyses go beyond quantifying energy savings by capturing improvements in the "quality of usable energy," thereby enhancing resource use efficiency and providing deeper insights into system performance improvements [18-20].

Moreover, it is increasingly emphasized that the environmental impacts of energy efficiency measures are not limited to operational energy consumption alone but should be evaluated through a life cycle assessment (LCA) that also accounts for material production, equipment lifetime, maintenance processes, and end-of-life stages [21]. The LCA approach enables the identification of "hidden emissions" associated with energy efficiency investments, allowing for a more comprehensive assessment of environmental performance. In parallel with rising carbon costs in the industrial sector (e.g., EU-ETS, CBAM), the economic benefits of energy efficiency projects should be evaluated not only in terms of energy savings but also from the perspective of avoided carbon costs [22-24]. However, the existing literature generally addresses energy efficiency, LCA, and carbon pricing within separate analytical frameworks, and studies that integrate these three components in a holistic manner remain scarce [13, 14, 21]. This gap highlights the need for combined assessments that simultaneously consider hidden emissions and carbon cost implications of energy efficiency investments.

In this context, analytical models that comprehensively examine the interactions between energy efficiency, exergy performance, CO_2 emissions, LCA indicators, and carbon costs are extremely limited in the literature. This study addresses this gap by analyzing the impacts of energy efficiency measures implemented in selected industrial facilities using the integrated assessment framework presented in Figure 1. The technical (energy and exergy), environmental (CO_2 emissions and LCA indicators), and economic (carbon costs and savings) outcomes of energy efficiency applications are evaluated simultaneously, thereby contributing to the literature by providing a comprehensive and integrated assessment framework. Accordingly, the study offers an inclusive perspective that captures not only operational energy reductions but also the environmental and economic impacts of energy efficiency strategies across the entire life cycle of industrial systems.

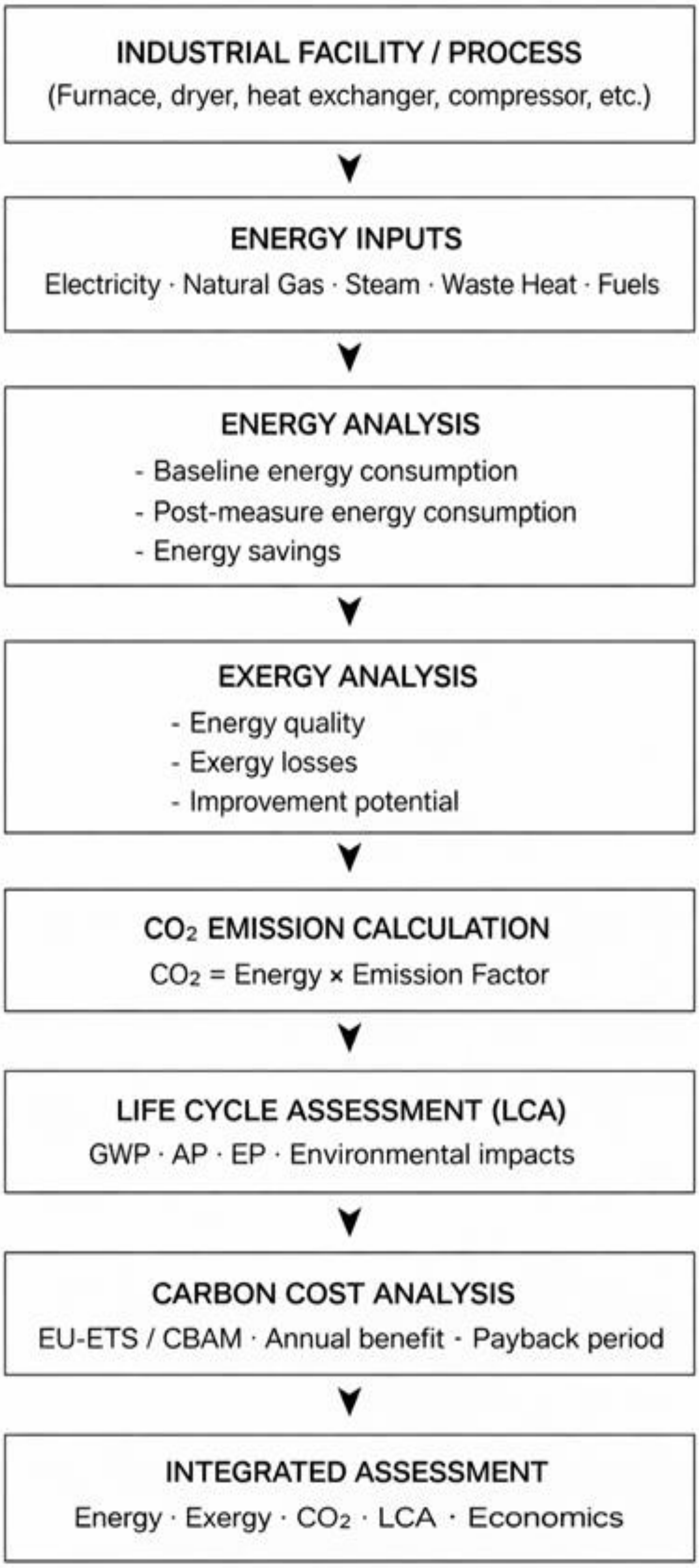

Figure 1. Integrated assessment framework for energy efficiency measures in industrial facilities.

2. Materials and Methods

In this study, pre- and post-implementation scenarios of energy efficiency measures were comparatively evaluated for a representative industrial process. The analysis framework consists of four main components: energy analysis, exergy analysis, carbon footprint assessment, and life cycle assessment (LCA).

2.1. Energy Analysis

The annual energy consumption of the process was calculated by considering both electricity and natural gas components. This approach is widely adopted in industrial systems for energy balance calculations and primary energy analyses [25-28].

The electricity energy consumption was calculated using Equation (1) [29]:

$$E_{el} = \sum_i P_{el,i} t_i \quad (1)$$

The annual natural gas energy consumption was calculated using Equation (2) [29]:

$$E_{NG} = \sum_j \dot{m}_{NG,j} * LHVE \quad (2)$$

The total annual energy consumption of the system was determined as the sum of electricity and natural gas consumption, as expressed in Equation (3) [29]:

$$E_{year} = E_{el} + E_{NG} \quad (3)$$

The annual energy savings achieved through the implementation of energy efficiency measures were calculated as the difference between the baseline and post-implementation energy consumption, as given in Equation (4) [29]:

$$E_{savings} = E_{baseline} + E_{after} \quad (4)$$

In this context, P_i denotes the electrical power of the i_{th} equipment (kW), while t_i represents its annual operating time (h year^{-1}). The mass flow rate of natural gas is expressed by $\dot{m}$ (kg s^{-1}), and the lower heating value of natural gas is denoted by LHV (kJ kg^{-1}). The annual electricity consumption is defined as E_{el} (kWh year^{-1}), whereas the annual natural gas consumption is expressed as E_{ng} in terms of its electrical energy equivalent (kWh year^{-1}). The total energy consumption prior to the implementation of energy efficiency measures is represented by $E_{baseline}$, while Eafter denotes the total energy consumption after the implementation. Accordingly, the annual energy savings are calculated as $E_{savings}$ (kWh year^{-1}), corresponding to the difference between the baseline and post-implementation energy use. The adopted energy consumption models are consistent with standard methodologies widely recommended in the literature for the evaluation of energy savings and performance in industrial processes.

2.2. Exergy Analysis

The physical exergy of the process fluid was calculated using the classical h–s (enthalpy–entropy) formulation. This approach is internationally recognized as a standard method for energy- and exergy-based performance assessments [30].

The physical exergy was calculated using Equation (5) [26, 31]:

$$ex = (\mathrm{h} - \mathrm{h}_0) - \mathrm{T}_0\,(\mathrm{s} - \mathrm{s}_0) \quad (5)$$

The exergy flow rate for mass flow was calculated using Equation (6) [32, 33]:

$$\dot{Ex} = \dot{m} * ex \quad (6)$$

The exergy loss was calculated using Equation (7) [28, 34]:

$$\dot{Ex}_{loss} = \dot{Ex}_{in} - \dot{Ex}_{out} \quad (7)$$

The exergy efficiency was calculated using Equation (8) [27, 35]:

$$\eta_{ex} = \frac{\dot{Ex}_{out}}{\dot{Ex}_{in}} \quad (8)$$

In this formulation, h represents the specific enthalpy of the working fluid (kJ kg^{-1}), while h_0 denotes the specific enthalpy evaluated at the reference environmental conditions. Similarly, s and s_0 correspond to the specific entropy of the fluid and the specific entropy at the reference state, respectively (kJ kg^{-1} K^{-1}). The reference environmental temperature is denoted by T_0 (K). The mass flow rate of the fluid is expressed as $\dot{m}$ (kg s^{-1}). Based on these thermodynamic properties, the specific physical exergy is defined as ex (kJ kg^{-1}), and the total exergy flow rate is given by $\dot{Ex}$ (kW or kJ s^{-1}). Accordingly, $\dot{Ex}_{in}$ and $\dot{Ex}_{out}$ denote the exergy rates at the inlet and outlet of the system, respectively. The exergy efficiency of the system, η_{ex} (%), is defined as the ratio of the useful exergy output to the exergy input, providing a measure of the thermodynamic performance and irreversibility within the system.

2.3. Carbon Footprint Calculation

The impact of energy savings on carbon emission reductions was quantified using the emission factor method, which is widely adopted in the literature. In this approach, the amount of saved energy is multiplied by the corresponding emission factor to estimate the associated CO_2 reduction. The CO_2 reduction was calculated using Equation (9) [36]:

$$CO_2 = E_{savings} \times EF \tag{9}$$

where EF denotes the emission factor (kg CO_2 kWh^{-1}). Energy-related emission factors were obtained from standardized sources, such as the IPCC emission factor guidelines and the IEA emissions database. Emission estimation methodologies based on these references are widely applied in the literature [37,38]. The CO_2 reduction from electricity savings was calculated using Equation (10) [39]:

$$CO_{2_{el}} = E_{\ savings,el} \times EF_{el} \tag{10}$$

The CO_2 reduction from natural gas savings was calculated using Equation (11) [40]:

$$CO_{2_{dg}} = E_{\ savings,NG} \times EF_{NG} \tag{11}$$

The total CO_2 reduction was calculated using Equation (12) [41]:

$$CO_{2_{total}} = CO_{2_{el}} \times CO_{2_{NG}} \tag{12}$$

In addition, the economic benefit associated with avoided carbon emissions was calculated by incorporating the carbon price under the European Union Emissions Trading System (EU ETS). The carbon cost savings was calculated using Equation (13) [41]:

$$M_{\text{carbon}} = CO_{2_{\text{total}}} \times F_{\text{carbon}} \tag{13}$$

In this framework, $E_{savings,el}$ represents the annual electricity savings (kWh year^{-1}), while $E_{savings,ng}$ denotes the annual natural gas savings expressed in equivalent electrical energy (kWh year^{-1}). The electricity and natural gas emission factors are defined as EF_{el} and EF_{NG} (kg CO2 kWh^{-1}), respectively. Accordingly, the reductions in carbon dioxide emissions resulting from decreased electricity and natural gas consumption are expressed as $CO_{2,el}$ and $CO_{2,NG}$. The economic valuation of the avoided emissions is calculated using the carbon price, F_{carbon} (€/ton CO2), leading to the annual economic benefit associated with emission mitigation, denoted as M_{carbon} (€/year). The adopted methodology is fully consistent with internationally recognized carbon accounting frameworks, including the guidelines established by the Intergovernmental Panel on Climate Change (IPCC) and the ISO 14064 standard [42].

2.4. Life Cycle Assessment (LCA)

In this study, life cycle assessment (LCA) was conducted under a cradle-to-gate system boundary [43,44]. Within this framework, the effects of energy efficiency measures on process-related energy consumption and the associated environmental impacts during the operational phase were comparatively evaluated. Accordingly, the LCA focuses on the fuel and energy inputs required to deliver the functional performance of the process under pre- and post-energy efficiency scenarios. The production, installation, maintenance, and end-of-life phases of the waste heat recovery (WHR) equipment were excluded from the system boundary. This approach is widely adopted in industrial energy efficiency studies to isolate the environmental benefits attributable specifically to operational energy savings [21,44]. The functional unit was defined as "1 ton of final textile product" for each facility. This definition is considered appropriate for comparative LCA studies in energy-intensive industries, as it enables normalization of results and ensures comparability across different facilities [44,45]. LCA calculations were performed using the openLCA software, with background data sourced from the Ecoinvent database. The environmental impact categories assessed in this study include:

- Global Warming Potential (GWP, kg CO_2-eq),
- Acidification Potential (AP, kg SO_2-eq),
- Eutrophication Potential (EP, kg PO_4-eq).

The environmental impacts of energy efficiency measures were calculated for both baseline and post-implementation scenarios using identical system boundaries and methodological assumptions. This approach ensures that the observed differences in environmental impacts are attributable solely to changes in energy consumption. The applied methodological framework is consistent with the ISO 14040–14044 standards and the European Commission JRC-ILCD guidelines [45,46].

3. Results and Discussion

In this section, the impacts of waste heat recovery (WHR)–based energy efficiency measures implemented in industrial facilities are evaluated within a comprehensive framework encompassing energy consumption, exergy performance, carbon emissions, economic outcomes, and life cycle environmental impacts. The findings demonstrate that this integrated energy–exergy–carbon–LCA approach provides a more comprehensive assessment of system performance in technical, environmental, and economic terms compared to conventional single-dimensional analyses.

3.1. Energy Savings Results

Following the implementation of waste heat recovery measures (boiler feedwater and drying air heat recovery), significant reductions in total final energy consumption were achieved across the three textile facilities. Prior to the implementation of the measures, the total annual energy consumption was determined as 8,000 MWh/year for Facility 1, 14,700 MWh/year for Facility 2, and 22,500 MWh/year for Facility 3. These energy consumption levels are consistent with facility scales, specific energy consumption values, and field-based measurement data reported in the literature for the Turkish textile sector [47–49]. Previous studies indicate that energy consumption in textile production—particularly in thermal processes such as dyeing, drying, and finishing—is predominantly driven by steam and fuel use, while electricity accounts for a relatively smaller share of total energy consumption [48, 49]. Indeed, a recent field-based study involving measurements from 150 textile facilities across Türkiye reported an average specific electricity consumption of 7 ± 5.3 kWh/kg product and a specific steam consumption of approximately 20 ± 11 kg steam/kg product for dyeing and drying processes [47]. These findings indicate that annual total energy consumption reaching the GWh scale is a sectorally expected outcome for textile facilities.

Within this context, the baseline energy consumption levels of the facilities examined in this study are consistent with sectoral benchmarks. The total energy consumption of Facility 1 (8,000 MWh/year) falls within the lower-to-middle range reported for medium-scale textile facilities, while Facility 2 (14,700 MWh/year) corresponds to the upper range of medium-scale facilities. The energy consumption of Facility 3 (22,500

MWh/year) aligns with values reported for large-scale, integrated dyeing–drying facilities . Based on total energy consumption (electricity + natural gas), the calculated energy savings ratios were 11.7% for Facility 1, 9.8% for Facility 2, and 11.0% for Facility 3. When the three facilities are evaluated collectively, an overall reduction of approximately 10.7% in annual total energy consumption was achieved.

The majority of these savings resulted from reductions in natural gas consumption, reflecting the high thermal energy demand of dyeing, drying, and finishing processes in the textile sector. This observation is consistent with the literature, which identifies thermal loads as the dominant component of energy consumption in textile processes, with electricity playing a secondary role [48, 49]. Accordingly, no significant change was observed in electricity consumption, as the implemented measures directly targeted thermal energy requirements. The annual natural gas savings were calculated as approximately 936 MWh/year for Facility 1, 1,440 MWh/year for Facility 2, and 2,482 MWh/year for Facility 3, resulting in a total annual saving of approximately 4,858 MWh/year. These savings magnitudes are consistent with field-based performance results reported for waste heat recovery applications in the textile sector, confirming the high effectiveness of WHR systems in thermally intensive industrial processes [48, 50]. The calculated energy consumption values and savings ratios are presented in Table 1, clearly demonstrating that waste heat recovery applications provide substantial improvements in thermal energy performance in textile facilities.

Table 1. Energy consumption values before and after energy efficiency measures (MWh/year).

Facility	Scenario	Electricity (MWh/year)	Natural Gas (MWh/year)	Total Energy (MWh/year)
Facility 1	Baseline	2,800	5,200	8,000
	After implementation	2,800	4,264	7,064
Facility 2	Baseline	5,100	9,600	14,700
	After implementation	5,100	8,160	13,260
Facility 3	Baseline	7,900	14,600	22,500
	After implementation	7,900	12,118	20,018

Table 1 presents a comparative overview of the annual electricity, natural gas, and total energy consumption of the three textile facilities before and after the implementation of the energy efficiency measure. As shown in the table, electricity consumption remained unchanged in all three facilities, while significant reductions were observed in natural gas consumption. This indicates that the waste heat recovery application considered in this study directly targets thermal energy demand, and that the reduction in total energy consumption is primarily driven by savings in thermal energy use.

3.2. Improvement in Exergy Performance

Following the implementation of the waste heat recovery (WHR) application, a significant improvement in the exergy efficiency of the processes was observed. The literature clearly demonstrates that WHR systems reduce exergy losses particularly in heat exchange processes and low-temperature waste heat zones, thereby enhancing the quality of usable energy (exergy) within the system [15–17]. Compared to conventional energy analyses, exergy-based assessments provide a clearer identification of the sources of thermodynamic losses and make the actual improvements achieved by sustainable technologies more visible [35].

In this context, the improvements in exergy performance obtained in the present study are consistent with the general trends reported in the literature and indicate that the reduction of losses occurring in equipment with intensive thermal interactions—such as heat exchangers and drying lines—has a direct impact on overall system performance. The recovery of waste heat generated at low temperature levels plays a critical role not in increasing the quantity of energy, but in improving its quality [15, 17].

Table 2. Results of the exergy analysis.

Facility	Condition	Exergy input (MW)	Exergy output (MW)	Exergy efficiency (%)	Exergy loss (MW)
Facility 1	Baseline	3.20	1.31	41	1.89
	After measure	3.00	1.50	50	1.50
Facility 2	Baseline	5.80	2.20	38	3.60
	After measure	5.30	2.44	46	2.86
Facility 3	Baseline	8.50	3.06	36	5.44
	After measure	7.80	3.43	44	4.37

As shown in Table 2, significant increases in exergy efficiency were achieved in all facilities following the implementation of the waste heat recovery application. In Facility 1, exergy efficiency increased from 41% to 50%, while exergy losses decreased from 1.89 MW to 1.50 MW. Similarly, in Facility 2, exergy efficiency improved from 38% to 46%, accompanied by a reduction in exergy losses from 3.60 MW to 2.86 MW. In Facility 3, exergy efficiency increased from 36% to 44%, while exergy losses declined from 5.44 MW to 4.37 MW.

These results demonstrate that the use of exergy analysis allows the system's improvement potential to be identified more clearly and distinctly compared to conventional energy analysis. As emphasized in the literature, exergy analysis not only quantifies overall efficiency improvements but also enables the identification of equipment and processes where thermodynamic losses are concentrated, thereby supporting critical decision-making in system design and optimization [35]. The findings of this study confirm that the optimization of thermally critical components—such as heat exchangers and drying lines—plays a fundamental role in enhancing the exergy performance of WHR applications [15, 17].

3.3. Performance of optimization methods reported in the literature

In this study, the impact of energy efficiency measures on carbon emissions was evaluated based on the marginal CO_2 emission reductions associated with the energy savings achieved through the implemented waste heat recovery (WHR) measure, rather than by calculating the total carbon footprint of the facilities. This approach is widely recommended for measure-based assessments, as it enables direct policy- and decision-support analyses without requiring the expansion of system boundaries or detailed knowledge of the overall emission inventory of the facility [23, 36–38]. Accordingly, the reduction in natural gas consumption achieved after the implementation of the WHR application was taken as the basis for the analysis. For each facility, the annual energy savings were multiplied by standard CO_2 emission factors for natural gas to estimate the annual CO_2 reduction potential attributable to the implemented measure. This method is recognized in the literature as a measure-based emission reduction approach that does not require comprehensive facility-level emission inventories when assessing the impacts of energy efficiency projects [36, 38].

The obtained results indicate that even a single energy efficiency measure can lead to CO_2 emission reductions on the order of several hundred tons per year in industrial facilities. These magnitudes are consistent with previous studies that have investigated the carbon reduction potential of industrial-scale energy efficiency and waste heat recovery projects [23, 39]. The economic impacts of energy efficiency investments were evaluated by considering carbon price scenarios commonly adopted in the literature within the framework of the European Union Emissions Trading System (EU ETS) and the Carbon Border Adjustment Mechanism (CBAM). Recent studies frequently assume carbon prices in the range of 70–100 €/ton CO_2 or higher under EU ETS and CBAM scenarios [23, 24, 39]. Under this assumption, the annual economic benefits resulting from avoided carbon costs associated with emission reductions were calculated.

Table 3. Marginal CO_2 reduction and carbon cost savings associated with the waste heat recovery measure.

Facility	Natural gas savings (MWh/year)	CO_2 reduction (t/year)	Carbon price (€/t)	Annual carbon cost savings (€/year)
Facility 1	936	189	80	15,126
Facility 2	1,440	291	80	23,270
Facility 3	2,482	501	80	40,109
Total	**4,858**	**981**	–	**78,505**

As shown in Table 3, the annual CO_2 emission reductions resulting from the WHR application were estimated to be approximately 189 tt/year for Facility 1, 291 t/year for Facility 2, and 501 t/year for Facility 3. When the three facilities are considered collectively, the total carbon reduction achieved through the implementation of a single energy efficiency measure reaches approximately 981 t CO_2/year. This result demonstrates that process-based energy efficiency measures implemented in industrial facilities can have a significant and quantifiable impact on carbon emissions. Under the assumed carbon price of 80 €/ton CO_2, the annual economic benefits obtained through avoided carbon costs were calculated to be approximately 15,100 €/year for Facility 1, 23,300 €/year for Facility 2, and 40,100 €/year for Facility 3. The total annual carbon cost savings for the three facilities amount to approximately 78,500 €/year. When these values are considered together with the direct reduction in energy costs, the results indicate that the payback period of the waste heat recovery investment may decrease to the range of 2–3 years when carbon costs are taken into account, in line with industrial-scale energy efficiency projects reported in the literature.

The obtained economic performance indicators are consistent with previous studies demonstrating that incorporating carbon costs into the evaluation of energy efficiency and waste heat recovery projects significantly enhances their financial attractiveness [23, 24, 39]. In this context, the results clearly show that energy efficiency projects should be regarded not only from an energy savings perspective but also as strategic instruments for avoiding carbon costs and reducing regulatory risks.

3.4. LCA Results

In order to evaluate the environmental impacts of the energy efficiency measure from a life cycle perspective, a comparative Life Cycle Assessment (LCA) was conducted in this study under a cradle-to-gate system boundary. The analyses were performed using the openLCA software in conjunction with the Ecoinvent database, and the methodological framework was defined in accordance with ISO 14040–14044 standards and the ILCD (International Reference Life Cycle Data System) guidelines [45, 46]. This approach enables the assessment of not only the operational impacts of energy efficiency applications, but also the indirect environmental effects associated with fuel consumption, auxiliary materials, and process-related inputs within the defined system boundary.

The functional unit of the study was defined as “1 ton of final textile product” for each facility. This definition is consistent with the recent literature emphasizing the importance of clearly and consistently defining the functional unit in LCA applications for energy-intensive industries to ensure comparability of results [44, 45]. Similarly, the cradle-to-gate approach is widely adopted in industrial LCA studies, as it allows the environmental impacts associated with production and process stages to be evaluated in an isolated manner. This methodological choice also provides a robust basis for isolating the production- and process-related environmental impacts of energy efficiency applications [21, 44]. Within this framework, Global Warming Potential (GWP), Acidification Potential (AP), and Eutrophication Potential (EP) indicators were calculated for both the pre- and post-energy efficiency scenarios, and the effects of the energy efficiency measure across different environmental impact categories were quantitatively assessed. The literature indicates that the impact of energy efficiency measures on

LCA results is generally most pronounced in the GWP category, whereas improvements in other impact categories, such as AP and EP, are reported to vary depending on the energy carrier and the defined system boundaries [13, 21].

Table 4. Summary of LCA results.

Facility	Scenario	GWP (kg CO_2-eq/ton)	AP (kg SO_2-eq/ton)	EP (kg PO_4-eq/ton)
Facility 1	Baseline	120	0.45	0.085
	Post-measure	106	0.40	0.076
Facility 2	Baseline	115	0.43	0.082
	Post-measure	104	0.39	0.074
Facility 3	Baseline	110	0.42	0.080
	Post-measure	98	0.37	0.071

As shown in Table 4, significant reductions in Global Warming Potential (GWP) values were achieved across all facilities following the implementation of the energy efficiency measure. In Facility 1, the GWP decreased from 120 kg CO_2-eq/ton to 106 kg CO_2-eq/ton, corresponding to an approximate reduction of 11.7%. Similarly, the GWP value declined from 115 to 104 kg CO_2-eq/ton (9.6%) in Facility 2, and from 110 to 98 kg CO_2-eq/ton (10.9%) in Facility 3. These results demonstrate that energy efficiency measures can substantially reduce the carbon footprint at the life cycle level. In addition to the observed reductions in GWP, consistent improvements were also achieved in Acidification Potential (AP) and Eutrophication Potential (EP) indicators across all facilities. The reductions in AP and EP reveal that energy efficiency applications not only mitigate greenhouse gas emissions but also decrease environmental impacts associated with fuel combustion, auxiliary chemical use, and process-related emissions. These findings are consistent with recent studies emphasizing the importance of integrating energy efficiency with LCA and highlighting the need to make "hidden emissions" visible in environmental assessments [13, 21, 44].

Overall, the results indicate that the environmental benefits of energy efficiency measures are not limited to operational emissions alone; rather, improvements are achieved across multiple environmental impact categories throughout the life cycle via indirect reductions in fuel and resource use associated with production processes. The literature, particularly studies focusing on energy-intensive industries, underscores the dominant role of operational energy efficiency in reducing GWP, while also highlighting that improvements in AP and EP indicators are critical for comprehensive sustainability assessments [21, 44, 45]. In this context, the LCA results obtained in this study clearly demonstrate the necessity of evaluating the environmental performance of energy efficiency investments from a holistic life cycle perspective.

3.5. Comparison with the Literature

The energy, exergy, carbon reduction, and life cycle assessment (LCA) results obtained in this study exhibit a strong overall agreement with findings reported in the existing literature. In particular, the savings achieved through waste heat recovery (WHR) and process-based energy efficiency measures implemented in industrial facilities are consistent with the typical performance ranges documented in previous studies. From an energy consumption perspective, the total energy savings of approximately 10–12% achieved across the three textile facilities are in line with the efficiency levels commonly reported for WHR applications at the industrial scale. Numerous industrial case studies have demonstrated that WHR-based systems can deliver substantial energy savings, with particularly high benefits observed in thermally intensive sectors [15, 16, 29]. In this regard, the savings achieved in the present study can be considered both technically realistic and well aligned with the literature.

The exergy analysis results also reveal a similar level of consistency with previous research. The observed increase in exergy efficiency parallels thermodynamic studies indicating that the recovery of low-temperature waste heat can effectively reduce exergy losses [17, 35]. The literature further emphasizes that exergy-based assessments provide a clearer identification of the true improvement potential within a system compared to conventional energy analysis, highlighting the critical role of optimizing heat exchange equipment [15, 35]. The findings of this study corroborate these conclusions by confirming that WHR applications enhance system performance primarily by improving energy quality rather than merely increasing the quantity of recovered energy. The results obtained in this study further demonstrate that WHR applications significantly improve overall system performance. From a carbon mitigation perspective, the total emission reduction of approximately 1,000 tons CO_2/year is consistent with previous studies reporting that energy efficiency measures implemented in industrial facilities can deliver substantial carbon savings. The literature indicates that, depending on the scale of the facility and the scope of the implemented measure, single energy efficiency projects can achieve emission reductions on the order of several hundred tons of CO_2 per year [51, 52, 53]. Considering the emission factors applied and the magnitude of energy savings achieved, the calculated carbon reduction levels in this study fall well within the ranges reported in the literature.

The life cycle assessment (LCA) results also exhibit trends consistent with previous research. The improvements observed in Global Warming Potential (GWP), Acidification Potential (AP), and Eutrophication Potential (EP) indicate that energy efficiency measures reduce not only operational emissions but also indirect environmental impacts associated with fuel use and process-related inputs. These findings align with recent studies emphasizing the importance of integrating energy efficiency with LCA and demonstrating that improvements can be achieved across multiple environmental impact categories [13, 21, 44, 45]. In particular, LCA studies conducted in energy-intensive industries highlight the dominant influence of operational energy efficiency on GWP, while also reporting meaningful reductions in AP and EP indicators [21, 44]. Finally, the compatibility of the dataset used in this study and the resulting findings with real industrial facilities is supported by both national and international industrial energy indicators. When field data related to the textile sector—such as specific energy consumption values and process-based energy distribution—are taken into account, the baseline energy consumption levels of the analyzed facilities and the achieved savings magnitudes appear consistent with typical values reported in the literature [15, 25, 29, 54]. This consistency strengthens the generalizability and practical applicability of the study's results.

4. Conclusion

In this study, the carbon mitigation and economic impacts of energy efficiency measures in the industrial sector were evaluated within an integrated analytical framework that jointly considers energy, exergy, CO_2 emissions, life cycle assessment (LCA), and carbon cost components. The analyses conducted based on waste heat recovery (WHR) measures implemented in selected textile facilities demonstrate that energy efficiency investments generate multidimensional benefits extending beyond operational energy savings to include significant environmental and economic performance improvements. The energy analysis results indicate that WHR applications can substantially reduce natural gas consumption, particularly in thermally intensive processes. When the three facilities are evaluated collectively, an overall reduction of approximately 10.7% in total energy consumption was achieved, with the majority of the savings attributable to decreased natural gas use. The absence of any notable change in electricity consumption confirms that the implemented measures directly target thermal energy demand.

The exergy analysis clearly reveals that energy efficiency measures enhance the quality of usable energy within the system. Across all facilities, exergy efficiency increased by approximately 7–10 percentage points, while significant reductions in exergy losses were observed. This finding highlights the critical role of exergy analysis in identifying the true improvement potential of energy efficiency projects and in guiding system design decisions regarding which equipment should be prioritized for optimization. Carbon footprint calculations show that the achieved energy savings correspond to an annual emission reduction of approximately 981 tons of CO_2. When carbon price assumptions under the EU Emissions Trading System (EU ETS) and the Carbon Border Adjustment Mechanism (CBAM) are considered, the resulting economic gains from avoided carbon costs reach a substantial level. When combined with reductions in energy costs, the payback period of the waste heat recovery investment is estimated to decrease to the range of 2–3 years. This outcome indicates that energy efficiency projects are becoming a strategic investment option for industrial facilities in the context of rising carbon costs.

The life cycle assessment (LCA) results further demonstrate that the environmental benefits of energy efficiency measures are not limited to operational emissions alone. The observed improvements in Global Warming Potential (GWP), Acidification Potential (AP), and Eutrophication Potential (EP) indicate that indirect emissions associated with fuel use and process inputs can also be effectively reduced. This underscores the indispensable role of the LCA approach in evaluating the environmental performance of energy efficiency projects and highlights the importance of accounting for so-called "hidden emissions." Overall, this study presents an integrated analytical framework that comprehensively evaluates the technical, environmental, and economic impacts of energy efficiency strategies applied in industrial facilities. The findings confirm that energy efficiency projects not only reduce energy consumption but also lower carbon emissions, improve economic performance, and mitigate environmental impacts across the life cycle. In this context, the results of the study are considered to provide valuable guidance for both industrial applications and the design of energy and climate policies.

Author contributions
Nesrin İlgin Beyazit: Conceptualization, Methodology, Data curation, Software, Writing-Reviewing and Editing.

Conflicts of interest
The author declares no conflicts of interest.

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