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THE EVALUATION OF THE IMPACT OF INDUSTRIAL ENERGY CONVERSION APPLICATIONS ON ENERGY CONSUMPTION THROUGH CRITICAL ELEMENTS

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Abstract

Energy expenses and carbon emissions from energy production are increasing today due to rising energy demand. One of the sectors that uses the most energy is industrial facilities. Industrial plants are among the sectors with the highest energy needs. In these facilities, energy requirements are essential for maintaining operational and manufacturing activities. Within the scope of this study, the energy consumption of a steel pipe production facility is analyzed and classified. Investigations were carried out covering the years 2021, 2022 and 2023. High energy consumption elements within the facility were identified as a result of field measurements. The reasons for excess energy consumption in the identified production elements were revealed through further investigations. As a result, inefficiency and poor maintenance have become the primary causes of excessive energy use. The analyses indicated how the use of renewable energy sources, maintenance activities, and energy conversions would change energy consumption levels compared to the current situation. Numerical analyses have determined that energy transformation will increase energy efficiency, reduce carbon emissions, and lower energy costs. Through an analysis of current site conditions, this study offers a technical perspective on the energy demand challenge, aiming to quantify the consumption levels of critical production elements.

Keywords: Energy efficiency, Energy consumption, Energy transformation, Carbon emission

KRİTİK ELEMANLAR ARACILIĞIYLA ENDÜSTRİYEL ENERJİ DÖNÜŞÜMÜ UYGULAMALARININ ENERJİ TÜKETİMİNE ETKİSİNİN DEĞERLENDİRİLMESİ

Özet

Enerji giderleri ve enerji üretiminden kaynaklanan karbon emisyonları, artan enerji talebi nedeniyle modern çağda artmaktadır. En çok enerji ihtiyacının olduğu sektörlerin başında sanayi tesisleri gelmektedir. Bu tesislerde enerji gereksinimi işletme ve imalat faaliyetlerini sürdürebilmek için şarttır. Bu çalışma kapsamında, bir çelik boru üretim tesisinin enerji tüketimi analiz edilip sınıflandırılmıştır. Endüstriyel tesis bünyesinde 2021, 2022 ve 2023 yıllarını kapsayacak şekilde incelemeler yapılmıştır. Tesis içerisindeki yüksek enerji tüketim elemanları saha ölçümleri sonucunda tespit edilmiştir. Tanımlanan üretim elemanlarında fazla enerji tüketiminin nedenleri daha ileri ölçümler ve değerlendirmelerle ortaya konulmuştur. Sonuç olarak, verimsizlik ve zayıf bakım, aşırı enerji kullanımının birincil nedenleri olarak ortaya çıkmıştır. Yapılan analizlerde yenilenebilir enerji kaynaklarının kullanımı, bakım faaliyetlerinin ve enerji dönüşümlerinin gerçekleştirilmesinin mevcut duruma kıyasla enerji tüketim miktarlarını nasıl değiştireceğini ifade edilmiştir. Sayısal analizlerde, enerji dönüşümlerinin enerji verimliliğini artıracağı, karbon emisyon değerlerini azaltacağı ve enerji maliyetlerini düşüreceği belirlenmiştir. Gerçekleştirilen çalışma ile günümüzün temel problemlerinden olan enerji gereksinimi sorununa güncel fiziksel değerlendirmeler açısından teknik bir inceleme sunularak kritik üretim elemanlarının sarfiyatları belirlenmiştir.

Anahtar Kelimeler: Enerji verimliliği, Enerji tüketimi, Enerji dönüşümü, Karbon emisyonu

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1. Introduction

Industrial facilities are expanding in scale and capability as technology advances across manufacturing sectors. To sustain interconnected operations such as production, storage, and transportation, these facilities require substantial amounts of energy. Whether derived from renewable or non-renewable sources, the majority of generated energy is ultimately consumed by industrial systems.

The combustion of fossil fuels for energy generation releases carbon emissions into the atmosphere, elevating the global carbon footprint and contributing significantly to climate change. High energy demand not only exerts environmental pressure but also imposes considerable financial costs on manufacturers, with economic impacts propagating throughout the supply chain from producer to end-user.

Implementing energy efficiency improvements within industrial facilities presents a key strategy for concurrently reducing production costs and carbon emissions. To maximize effectiveness, such energy transformation initiatives must be designed and evaluated on a plant-specific basis. Each production facility exhibits a unique energy consumption profile and operates at distinct levels of efficiency. Consequently, it is essential to characterize the specific operational identity of each building through facility-specific audits and to formulate tailored, energy-centric solutions based on the resultant data. This methodology is fundamentally grounded in the comprehensive assessment of an operational production facility.

In this study, the energy anatomy of a steel pipe manufacturing plant was examined through detailed on-site measurements and systematic physical observations. Components and processes with high energy consumption or low operational efficiency were identified. An energy map for the years 2021, 2022, and 2023 was created to quantitatively present the facility's energy use and associated costs. Furthermore, a scenario analysis was conducted in which alternative energy-efficient technologies—whose effectiveness, cost-benefit potential, and environmental advantages are well documented in previous studies—were hypothetically integrated into the plant. The pre- and post-transformation states were compared in terms of energy consumption and financial impact. The findings demonstrate that replacing low-efficiency equipment, implementing appropriate maintenance strategies, and increasing the integration of renewable energy sources can significantly improve energy performance. From minor digital enhancements to comprehensive system upgrades, a wide range of improvements offer measurable benefits in the short, medium, and long term.

2. Literature Review

The escalating global demand for energy has precipitated a significant increase in academic research focused on energy efficiency, the development of alternative energy sources, and digital energy transformations. Within this discourse, it is critical to distinguish between the interrelated yet distinct concepts of energy conservation and energy efficiency, which share a common objective of reducing energy-related impacts. Energy conservation primarily seeks to curtail energy use through behavioral or operational changes, whereas energy efficiency aims to maximize output or service level from a given unit of energy input. Fundamentally, efficiency is achieved by performing more work with the same, or even less, energy [1]. Recent studies highlight that efficiency gains are strongly dependent on technological advancements, including high-performance equipment and digital monitoring systems [2, 3]. Increasing energy efficiency is explained through current technological devices [4]. Energy efficiency has been widely recognized as a cornerstone of sustainable industrial production [5]. Several global studies emphasize that improving energy efficiency and reducing reliance on fossil fuels are fundamental to achieving sustainability targets [6, 7]. Global policies targeting energy efficiency for the existing energy demand worldwide are included in the studies in the literature [8]. According to the International Energy Agency [9], energy efficiency represents the single most cost-effective pathway for addressing increasing energy demand and reducing emissions worldwide. National studies similarly indicate that Turkey's energy efficiency agenda has historically concentrated on high-consumption sectors such as industry, electricity generation, transportation, and residential buildings [10].

Industrial operations exhibit substantial potential for reducing energy use while maintaining production levels. Planned and correctly implemented energy efficiency measures can yield improvements of up to 20–25% in industrial plants [11, 12]. However, these improvements must be tailored to sector-specific and facility-specific characteristics [13]. Despite variations in production methods, many industries share common process elements, allowing the transfer of best practices across facilities [14, 15]. In particular, the iron and steel sector remains one of the world's most energy-intensive industries, where process optimization, waste-heat utilization, and digital transformation have emerged as priority research areas [16, 17].

The environmental consequences of energy production based on non-renewable sources continue to be central to academic and policy discussions. Fossil-fuel combustion releases carbon emissions that intensify the greenhouse effect and contribute to long-term climate change [18]. In contrast, renewable energy sources such as solar, wind, and geothermal energy significantly reduce emissions and offer environmentally sustainable alternatives [19, 20]. Empirical studies in countries with high industrial activity, such as China and Australia, demonstrate that increasing the share of renewables leads to a measurable decrease in carbon intensity and supports national emission-reduction strategies [7, 21, 22].

Recent literature also underscores the importance of developing detailed energy profiles for industrial facilities. Indicators such as specific energy consumption (SEC)—for example, energy use per ton of steel produced—are regarded as more meaningful metrics for evaluating industrial performance than aggregate economic indicators [19, 17]. Moreover, the integration of variable frequency drives (VFDs), advanced control strategies, and data-driven monitoring has proven effective in reducing energy consumption in motor systems, compressors, and cooling towers [23, 24, 25]. These technologies enhance process adaptability and enable real-time energy optimization, which is increasingly relevant for energy-intensive industries.

Overall, the existing body of research highlights the necessity of conducting detailed energy analyses in industrial facilities and implementing targeted energy transformation strategies. The present study contributes to the growing literature by providing a quantitative and plant-specific assessment of energy consumption in a steel pipe manufacturing facility in Turkey's heavy industry sector. By combining on-site measurements with scenario-based improvement evaluations, the study offers empirical evidence that supports the broader academic findings on energy efficiency and industrial transformation.

3. Material and Methods

3.1. Study Area

The industrial plant serves in the production of spiral welded steel pipes. The steel pipe production facility consists of 25.000 m2 closed area and has 5 production lines. The annual production capacity of the production facility is approximately half a million tons.

The production process within the steel pipe manufacturing facility commences with the introduction of steel coil sheets as the primary raw material. These sheets are subsequently formed into pipes of the specified thickness, length, and diameter using spiral pipe milling machines. In the subsequent stage, any welding imperfections are remediated, after which the integrity of the pipes is verified through a hydrostatic pressure test.

3.2. Methods

The research infrastructure was built upon quantitative data obtained from the study area, an industrial production facility. A comparative analysis was conducted on key performance indicators—including energy consumption, cost, losses, and leakage—before and after the energy transformation to enable a robust quantitative assessment.

In the steel pipe production plant, which is the study area, various measurement equipment is used to evaluate energy efficiency. Flue gas analyzers are used to measure the combustion efficiency and carbon emission values of the fuels used in the plant. Thus, information is obtained about energy use and the possible impacts of the facility on the environment. Thermal cameras are used to determine the surface temperatures of the machinery and structures within the facility. Insulation deficiencies and overheating that may occur on surfaces are determined by thermal cameras. The temperature and humidity levels of the working environment are carried out using devices that detect temperature and humidity. Pressure differences and fluid velocities of ventilation systems are measured with manometers and pitot tubes. To reveal the efficiency of ventilation systems, anemometers that measure air flow rate and volume are used. For the efficiency of the electrical systems in the plant, current, voltage and consumption values are provided by using energy analyzers and multimeters. Table 1 shows the usage areas of the devices used for measurements.

Table 1. Plant measuring instruments

Device Name	Measurement Area
Energy Analyzer	Energy Measurements
Multimeter	Electrical Measurements
Thermal Camera	Thearmal Measurements
Flue Gas Analyzer	Flue Gas Measurements
Anemometer	Air Flow Rate
Pitot Tube	Flue Gas Measurements
Thermometer	Temperature Measurements
Luxmeter	Light Intensity Measurements

In this case, flue gas analyzer and pitot tube readings were used to determine the combustion rates from the boiler used for heating. The specific energy consumption (SEC) Equation (1) was used to determine how much energy was needed to generate air in the compressors [26].

$$SEC = \frac{Average\ Power\ Consumption\ (kW)}{Avg.Compressed\ Air\ Flow\ Rate\ (\frac{m^3}{min})} \quad (1)$$

Utilizing Equation (2), the power loss values (PL) resulting from compressed air leaks are computed [26]. Here, N is the number of stages, Po is the compressor outlet pressure (kPa), E_a is the compressor adiabatic efficiency, E_m is the motor efficiency, and V_f is the escaping air flow rate (m^3/s) and, k is the specific heat rate of air (taken as 1.4).

$$PL = \frac{P_i * V_f * \left[\frac{k}{k-1}\right] * N * [\frac{\left(\frac{P_0}{P_i}\right) * (k-1)}{k * N} - 1]}{E_a * E_m} \quad (2)$$

Equation (3) was used to determine the new system efficiency values because of the pump motors utilized in cooling systems being revised within the context of energy conversion [27]. P_1 denotes the initial power value, P_2 the power value (kW) following the revision, N_1 the initial speed (rpm) value, and N_2 the speed value following the revision in the provided equation.

$$\frac{P_2}{P_1} = \left(\frac{N_2}{N_1}\right)^3 \quad (3)$$

The energy consumption amounts of the lighting systems were calculated from the consumption values specified in the product catalogs by taking an inventory of lighting through physical observation. The analysis of the efficient systems to be applied to the areas to be revised as a result of the energy transformation of the facility was obtained as a result of market research.

4. Results and Discussion

Energy-oriented analyses were conducted on an operational industrial facility to validate the premise that energy transformations can significantly reduce both energy consumption and carbon emissions. In this regard, a plant involved in the fabrication of steel pipes was chosen as the study area.

With the study, energy efficiency evaluations in the plant cover the 3-year period from 2021 to 2023. Analyses were carried out for the stages and situations where energy is used in the production processes of the steel pipe production facility. Boilers, the facility's compressed air system, cooling towers, pumps, and lighting were all examined in this regard.

Results should be clear and concise. Discussion should explore the significance of the results of the work, not repeat them. A combined Results and Discussion section is often appropriate. Avoid extensive citations and discussion of published literature.

4.1. Quantities of Production and Consumption

For the years 2021, 2022, and 2023, the steel pipe production facility's electricity, natural gas, diesel fuel, and LPG consumption amounts were gathered and examined. The cost and energy usage figures for 2021, 2022, and 2023 are displayed in Table 2. Consumption values are presented in "Tons of Oil Equivalent (TOE)" for standard evaluation purposes.

Table 2. Energy consumption and costs for three years

Year	Energy Type	Consumption Amount	Unit	TOE	%	Cost ₺	%	Unit Cost ₺/TOE
2021	Electricity	8740154.10	kWh	751.65	68,23	4463342.20	86.46	5938.05
	Natural Gas	377040.00	Sm³	311.05	28.23	452097.10	8.75	1453.45
	Diesel	36.86	Ton	37.60	3.41	235955.20	4.57	6275.40
	LPG	1188.00	Kg	1.29	0.11	10692.00	0.20	8288.37
2022	Electricity	7607008.50	kWh	654.20	61.35	4086635.20	80.55	6246.76
	Natural Gas	443560.00	Sm³	365.93	34.32	728184.00	14.35	1989.95
	Diesel	41.80	Ton	42.63	3.99	228228.00	4.49	5353.69
	LPG	3156.20	Kg	3.44	0.32	29983.90	0.59	8716.25
2023	Electricity	4111951.20	kWh	353.62	64.59	3387827.90	82.48	9580.41
	Natural Gas	215369.00	Sm³	177.67	32.45	588633.00	14.33	3313.06
	Diesel	15.30	Ton	15.60	2.84	124848.00	3.03	8003.07
	LPG	550.00	Kg	0.59	0.10	6050.00	0.14	10254.24

The energy consumption in Tons of Oil Equivalent (TOE) and cost distributions for the years 2021, 2022 and 2023 are given in Fig. 1 as a pie chart. When the distributions for the years are analyzed, electricity consumption has the largest share in consumption distributions for 68%, 61% and 64%, respectively. Therefore, the largest costs were incurred for electricity consumption.

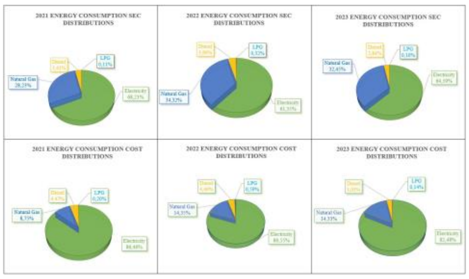

Figure 1. Consumption and cost breakdowns for three years (2021-2022-2023)

For 4 different consumption classes, unchanged consumption and cost rankings for the years 2021, 2022 and 2023 have been formed. Accordingly, consumption and cost values for electricity, natural gas, diesel fuel and LPG are ranked from the highest to the lowest for the relevant years, respectively. Quantifying costs and consumption is very important for creating an energy identity.

The annual gross production output of the steel pipe production facility was analyzed for the years 2021, 2022, and 2023. The total production was 99,847.70 tons in 2021, 97,917.10 tons in 2022, and 53,077.60 tons in 2023. Fig. 2 illustrates the monthly distribution of this output across the three-year period.

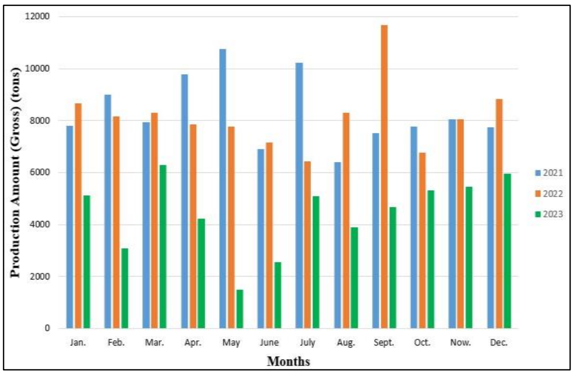

Figure 2. Monthly pipe production quantities (2021-2022-2023)

4.2. Trend Analysis Focused on Production and Consumption

In order to show the relationship between the production quantities in the industrial production facility and total energy consumption, the three years studied were analyzed. The monthly relationship between total energy consumption and total steel pipe production for 2021 is depicted in Fig. 3.

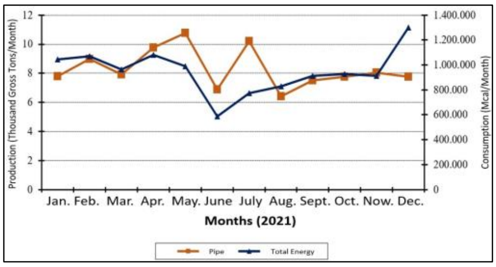

Figure 3. 2021 monthly production-consumption relationship

The relationship between 2022 total steel pipe production and total energy consumption monthly is shown in Fig. 4.

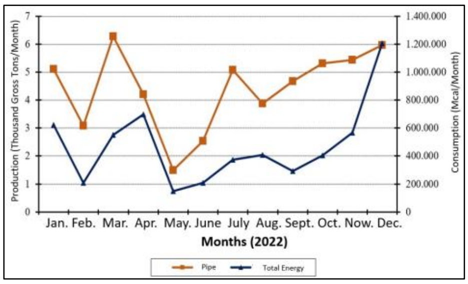

Figure 4. 2022 monthly production-consumption relationship

In Fig. 5, the comparison of steel pipe production with total energy consumption in 2023 is expressed graphically.

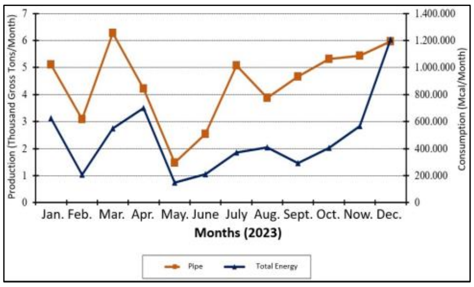

Figure 5. 2023 monthly production-consumption relationship

The comparative analysis of monthly steel pipe production and total energy consumption over a three-year period reveals a distinct correlative pattern. This relationship is quantified in the scatter plot presented in Fig. 6, which displays the corresponding energy consumption for all production volumes, alongside a mathematical expression that models their interdependence.

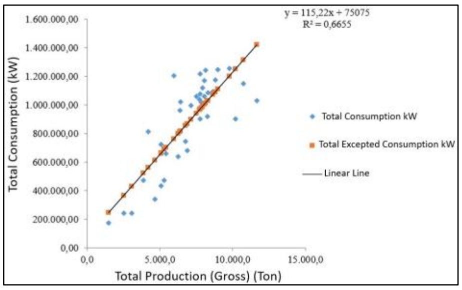

Figure 6. Mathematical relationship between consumption and production

The production amounts and energy consumption amount of the steel pipe plant for the base years are analyzed by modeling. The main purpose of revealing this bidirectional relationship is to understand the effect of production on the energy consumption of the plant.

4.3. Specific Energy Consumption (SEC)

Specific energy consumption is an important variable in energy consumption assessments of industrial facilities. SEC values generated for the past periods constitute a prediction for the consumption amounts of the next years. Three-year SET graphs for the steel pipe production plant are given in Fig. 7, Fig. 8 and Fig. 9 respectively.

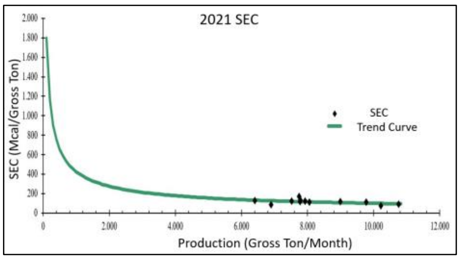

Figure 7. SEC curve for 2021

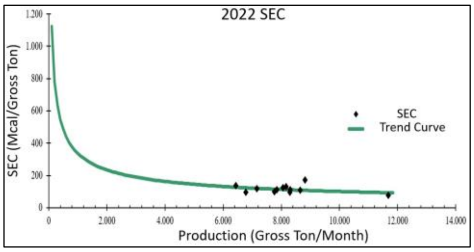

Figure 8. SEC curve for 2022

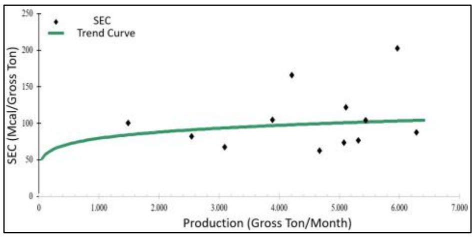

Figure 9. SEC curve for 2023

Analysis of the energy consumption graphs reveals that the figures vary greatly. This demonstrates how SEC-only projections might be deceptive when it comes to expectations for future consumption.

4.4. Consumption in Plant Critical Equipment and Improvement Methods

The investigation to this point has involved a thorough examination of the facility's integrated energy and production trends. Subsequent on-site inspections enabled the identification of both the primary energy-intensive areas and key sections with high potential for expedited digital transformation.

4.4.1. Boiler Equipment

Water heating and heating of common social areas within the facility is provided by a natural gas fuel-based boiler. Investigations and measurements were carried out to reveal the energy efficiency status of this boiler in the facility. The results obtained are given in Table 3.

Table 3. Boiler measurement

Measurement	Unit	Value
O_2	%	6.00
CO	ppm	84.00
CO_2	%	8.39
Flue-Gas Temperature	°C	257.10
Ambient Temperature	°C	27.60

Heat losses were calculated to determine the boiler efficiency numerically. Heat losses in the boiler are divided into heat loss through dry flue gas (L_{KBG}), heat loss due to moisture in the flue gas (L_{BNG}), heat loss due to unburned carbon monoxide in the flue gas (L_{COBG}), heat loss by radiation and convection from the boiler surface (L_{RK}). L_{KBG} is calculated by Equation (4). In the equation, K is the coefficient depending on the flue gas (0.311), T_{BG} is the Flue-Gas Temperature, and T_O is the Ambient Temperature. Gross Calorific Value (GCV) and Net Calorific Value (NCV) are fuel-dependent calorific values and are 13,459.13 and 12,132.35, respectively.

$$L_{KBG} = \frac{K * (T_{BG} - T_O)}{CO_2} * \frac{(GCV)}{(NCV)} \tag{4}$$

L_{NBG} is calculated by Equation (5). In the given equation, H represents the percentage of hydrogen in the fuel by weight (24.57 %).

$$L_{NBG} = \frac{(9 * H) * (50 - T_O + (0.50 * T_{BG}))}{GCV} * \frac{GCV}{NCV} \tag{5}$$

L_{COBG} is calculated by Equation (6). In the equation, K is the coefficient for natural gas (taken as 32).

$$L_{COBG} = \frac{K * CO}{CO_2 + CO} * \frac{GCV}{NCV} \tag{6}$$

These values are calculated separately and expressed in Table 4.

Table 4. Boiler heat losses

Heat Loss	Unit	Value
L_{KBG}	%	9.43
L_{NBG}	%	2.75
L_{COBG}	%	0.04
L_{RK}	%	1.65
L_{Total}	%	13.87

Blowdown, which is an application that prevents the formation of scale and sediment in the boilers, causes heat loss in the boilers. There is no blowdown-induced heat loss in the boiler in the facility.

Boiler efficiency within the steel pipe manufacturing plant is quantified as the percentage exclusion of total heat loss. The calculated efficiency for the boiler in question is 86.13%. While this figure approaches ideal levels, potential remains for further reducing energy consumption through the implementation of alternative heating methods.

This section analyzes the impact of integrating solar collectors for water heating on overall energy use. The efficacy of such a solar thermal system is intrinsically linked to the solar irradiance profile of the plant's geographical location. Fig. 10 presents the monthly averages of daily sunshine hours for the region, derived from historical data spanning the period from 1961 to 2023.

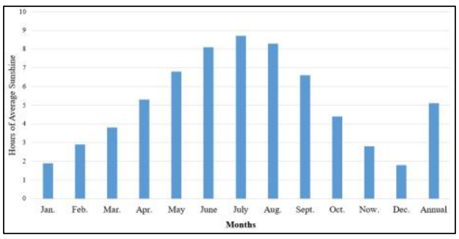

Figure 10. Monthly average sunshine hours (1961-2023)

When the insolation periods on the graph are analyzed, it will be beneficial to use solar panels in hot water supply due to the high insolation periods in summer months. System features for the solar collector considered as an alternative energy source are given in Table 5. Since the measurements in the boiler were made at 50 °C, this value was taken as reference in the calculations to be made in the collector.

Table 5. Features of solar collectors

Features	Unit	Value
Collector Gross Area	m^2	1.77
Collector Radiation Field	m^2	1.62
Number of Collectors	Number	10
Design Temperature	°C	50
Collector Efficiency	%	0.73
System Efficiency	%	0.90

Fig. 11 shows the monthly energy amounts obtained by using solar collectors. As can be seen in the graph, the months of May, June, July and August, which are the months with the longest sunshine hours, are the months with the highest amount of solar energy generated.

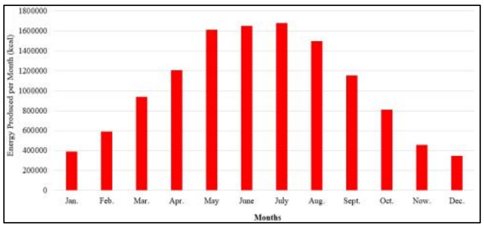

Figure 11. Monthly amount of energy produced from solar energy

The cumulative natural gas savings are calculated as the sum of the monthly savings. The thermal energy supplied by the solar system is converted into a natural gas equivalent using Equation (7). In this equation, the constant 8,250 kcal represents the standard lower heating value (LHV) of natural gas, as stipulated by the Turkish Ministry of Energy. The parameter η denotes boiler efficiency, which is assigned a value of 92% for this analysis.

$$NG_{saved} = \frac{E_{solar}}{8250 * \eta} \quad (7)$$

To illustrate, the solar collector's energy output for January, measured at 391,645.20 kcal, was applied to Equation X. This calculation corresponds to a natural gas saving of 51.60 m^3. The monthly savings values were summed to obtain the annual natural gas reduction of 1625.65 m^3. The annual financial savings from natural gas were determined to be ₺7,481.25, based on the prevailing unit cost of ₺4.60.

In environmental terms, using a conversion factor of 1.90 kg CO_2 per m^3 of natural gas, the initiative also mitigates 3.09 tons of carbon dioxide emissions annually.

With the renewable energy source study to be applied to the steel pipe production facility, natural gas consumption used in the boiler will be reduced. As a result of the analysis, the natural gas savings to be achieved on a monthly basis are given in Fig. 12. Accordingly, as a result of the solar collector application, 1625.65 m^3 of natural gas consumption will be saved annually.

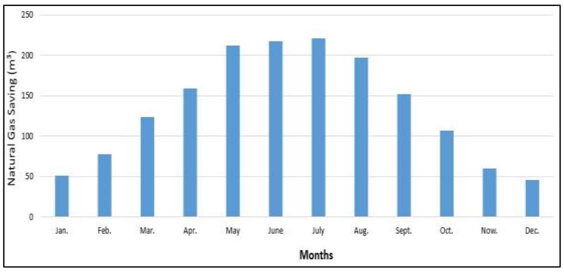

Figure 12. Amount of natural gas saved

4.4.2. Compressor Equipment

Compressors, one of the most energy consuming system equipment in industrial plants, are used to increase the pressure of fluids. Due to its high energy consumption potential, compressors in the plant are included in the scope of the study.

There is a total of 3 compressors in the steel pipe production facility and the power of the compressors ranges from 75 kW to 136 kW. Depending on the intensity of steel pipe production, the compressors can be used individually or together.

One of the most important factors affecting the efficiency of compressors is air leaks occurring in the system. It is necessary to detect these leaks and measure the amount of leakage. In the steel pipe production facility, compressed air lines were scanned with ultrasonic detectors, and the amount of air leakage was determined. Air leaks are recorded by the device in decibels (dB), which is a unit of sound intensity. The sections where leakage was detected in the measurements made on the compressed airlines in the facility are given in Fig. 13 and Fig. 14.

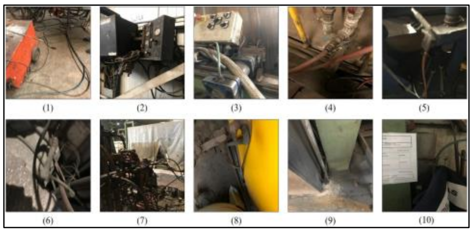

Figure 13. System leakage zones (1-10)

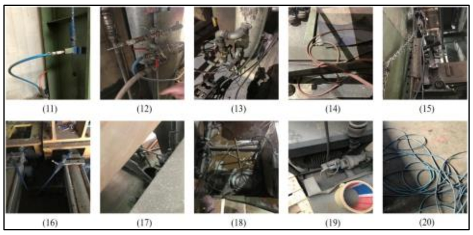

Figure 14. System leakage zones (11-20)

The leakage measurement values of the numbered sections are shown in Table 6 in decibels (dB).

Table 6. Leakage zones measurements

No	Location	Measurement (dB)
1	Final Nozzle	48
2	Plasma Unit	59
3	Plasma	53
4	Machine Air Line Inlet	47
5	Air Gun Next to Internal Weld	55
6	Ultrasonic Lower Zone	51
7	Top of Epoxy Cart	40
8	Epoxy Side Air Tank	53
9	Pipe Outlet Corner Behind Internal Sandblasting	77
10	Curing Oven Operator Panel Side Pipe Exit Area	81
11	Electrical-Mechanical Workshop Hall Entrance	43
12	Curing Oven Pipe Outlet Air Line	63
13	Internal Sandblasting 1-2 Air Collector Valve Output	66
14	Internal Sandblasting 1-2 Air Hose	45
15	Internal Sandblasting 1	52
16	Upper Deck of the End-Stripping Trolley	50
17	Powder Coating Unit	47
18	Induction Under	76
19	Polyethylene Raw Material Suction Lower Region	69
20	Hose Behind Cure Outlet	45

As a result of the measurement of air leakages, power loss values due to leakages were calculated using Equation (2). Power loss values and annual energy losses caused by leakages are evaluated specific to leakage zones and given in Table 7.

Table 7. Local energy losses due to air leaks

Location No	Power Loss (kW)	Annual Energy Loss (kWh/year)
1	0.238	1884.960
2	0.307	2431.440
3	0.276	2185.920
4	0.277	1797.840
5	0.286	2265.120
6	0.266	2106.720
7	0.149	1180.080
8	0.276	2185.920
9	0.590	4672.800
10	0.661	5235.120
11	0.182	1441.440
12	0.349	2764.080
13	0.386	3057.120
14	0.205	1623.600
15	0.271	2146.320
16	0.261	2067.120
17	0.227	1797.840
18	0.568	4498.560
19	0.422	3342.240
20	0.205	1623.600

Energy losses due to leaks are expressed graphically in Fig. 15. As can be seen from the graph, the leakage areas with the highest energy losses are the 9th, 10th and 18th regions.

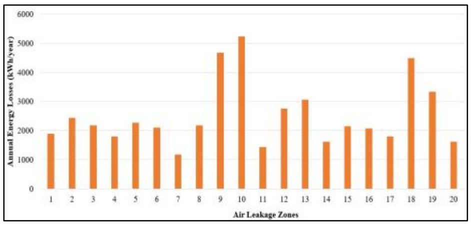

Figure 15. Energy losses due to local air leaks

After determining the air leaks within the facility, the amount of energy consumed by the compressors was calculated in terms of specific energy consumption (the amount of energy spent to produce 1 Nm^3 of compressed air). SEC values and other parameters of the 3 compressors used are given in Table 8.

Table 8. Existing compressor consumption values

No	Working Pressure (Bar)	Unit Energy Consumption (kW)	Air Flow (m^3/min)	SEC (kW/(m^3/min))
Compressor-1	7.00	149.06	21.43	6.95
Compressor-2	7.00	74.75	11.50	6.51
Compressor-3	7.00	147.50	23.24	6.34

As a result of the calculation of SEC values, compressor number 1 consumes 149.06 kW of energy for an average compressed air production of 21.43 m^3/min. On the other hand, the SEC value is 6.95. The values given show that the relevant compressor does not provide sufficient efficiency.

For energy efficiency, a high efficiency compressor is planned to replace compressor number 1. The values of the high efficiency compressor are given in Table 9.

Table 9. Alternative compressor consumption values

No	Working Pressure (Bar)	Unit Energy Consumption (kW)	Air Flow (m^3/min)	SEC (kW/(m^3/min))
Alternative	7.00	157.90	28.09	5.62

The SEC value of the new compressor is 5.62 kW/m^3/min). Since the operating average air flow rate in the plant is 21.43 m^3/min, the energy consumed by the new compressor is 120.44 kW. The savings values obtained as a result of energy efficiency are presented in Table 10.

Table 10. Energy savings in compressor usage

Parameters	Existing	Alternative	Unit
Compressed Air Consumption	21.43	21.43	m3
Measured Power Consumption	149.06	120.44	kW
Operating Pressure	7.00	7.00	Bar
Specific Energy Consumption	6.95	5.62	kW/(m^3/min)
Unit Energy Savings	28.62		kW
Annual Operating Time	7920.00		Hours
Annual Energy Savings	226760.40		kWh/years

4.4.3. Cooling Systems

Water cooling towers contribute to the efficient operation of the system by removing heat from the system. During the application, some of the water gives excess heat in the system to the atmosphere as a result of evaporation. The remaining part of the water is rejoined to the cycle within the system.

There is 1 cooling tower in the facility. The cooling processes of the coated pipes are carried out with the water cooled in the cooling towers. The operation of the system is provided by 2 pumps, 1 active and 1 spare. Pump motors use star-delta connection and energy efficiency is IE2.

Within the scope of energy assessments, measurements were made on pump motors. The instantaneous consumption value of 28.21 kW was measured on the existing pump motor. The label information of the motor is given in Table 11.

Table 11. Details of engine label

Parameters	Value
Power (kW)	45
Rated Speed (rpm)	1470
Current Drawn (A)	70

Two 45 kW motors and AC motor speed control drivers will be put on the pumps as part of the energy transformation project, and the speed will be adjusted. Lowering the speed levels will result in ideal operating conditions. The 45-kW motor is lowered from 50 Hz to 32 Hz in the scenario under investigation. Equation (3) is used to determine the motor's power consumption in the new scenario, which comes to 7.09 kW. The figures in Table 12 were derived from 7920 annual operating hours.

Table 12. Status of using an AC drive

Parameters	Value
Drawn Power (kW)	28
Existing Engine Speed (rpm)	1470
Alternative Engine Speed (rpm)	928
Alternative Engine Power Consumption (kW)	7.09
Hourly Savings (kW)	20.90
Annual Savings (kWh)	165528

When speed is decreased, power is reduced according to the speed's cube, increasing the system's energy efficiency.

The plant's cooling tower incorporates two identical mechanically-driven fan motors. The electrical energy consumption of these fans is determined through the application of the standard three-phase motor power equation. In addition to the parameters provided in Tables 11 and 12, the analysis utilizes a supply voltage of 400 V, a power factor of 0.85 for the IE-2 motor class, and an annual operational duration of 7,920 hours per year. The electrical power drawn by the fan motors was determined using the standard three-phase power by Equation (8) [28, 29].

$$P = \sqrt{3} * V * I * \cos\phi \qquad (8)$$

The application of the relevant values to the Equation (8) indicates a power draw of 41.2 kW for each individual fan. The aggregate power demand (P_{total}) for the two units is therefore calculated to be 82.4 kW. The calculations demonstrate that the cooling tower fans account for a substantially larger share of energy usage compared to the operational data obtained for the cooling water pumps in the field.

4.4.4. Test Engine Equipment

Using electric motors, electrical energy is converted into mechanical energy for various purposes. While electric motors account for 36% of Turkey's electricity consumption, this rate can reach 80% in industry [30]. These consumption rates reveal the importance of increasing energy efficiency in electric motors.

In this part of the study, the efficiency status of the motors with high energy consumption in the plant and the savings values to be achieved as a result of the transformations were examined. The values of the engine of the hydro-test machine used to pressure test the steel pipes produced in the plant and the values of the engine recommended for efficiency increase are given in Table 14. The term IE used in Table 13 indicates the International Efficiency class. Here, IE-2 refers to medium efficiency and IE-4 refers to a very high efficiency class.

Table 13. Hydro-test engine efficiency comparison

Parameters	IE-2 Engine Consumption (Current)		IE-4 Engine Consumption (Alternative)	
	Value	Unit	Value	Unit
Engine Consumption	95.60	kW	93.80	kW
Monthly Consumption	29827.20	kWh	29269.70	kWh
Annual Consumption	357926.40	kWh	351236.20	kWh

High energy consumption is also attributed to the turbine motors powering the external sandblasting process for steel pipes. The four installed motors, characterized by IE-2 efficiency, are targeted for replacement with IE-4 models to enhance energy efficiency. Table 14 provides a comparison of the consumption profiles between the current state and the proposed scenario.

Table 14. Turbine engine efficiency comparison

Parameters	IE-2 Engine Consumption (Current)		IE-4 Engine Consumption (Alternative)	
	Value	Unit	Value	Unit
Engine Consumption	49.80	kW	48.90	kW
Monthly Consumption	15537.60	kWh	15247.20	kWh
Annual Consumption	186445.20	kWh	182966.10	kWh

Last but not least, the hydraulic line motor utilized for lifting and moving the generated pipes is the facility's most energy-intensive motor. The steel pipe production plant has a single central hydraulic unit with two IE-2 efficiency class motors. Table 15 lists the current consumption and values for the IE-4 efficiency class motor that was taken into consideration in place of the current motor.

Table 15. Comparison of hydraulic line motor efficiency

Parameters	IE-2 Engine Consumption (Current)		IE-4 Engine Consumption (Alternative)	
	Value	Unit	Value	Unit
Engine Consumption	33.00	kW	32.34	kW
Monthly Consumption	24780.00	kWh	21344.40	kWh
Annual Consumption	261360.00	kWh	256132.80	kWh

4.4.5. Lighting Equipment

Lighting in the industrial facility is carried out using lamps. There is a total of 407 lamps used for lighting within the facility. Due to the high number of lamps, the lighting system was evaluated in terms of efficiency. During the field observation, the sections and luminaire types of the lamps were determined. Accordingly, the lamps in the facility are distributed in 9 different sections as given in Table 16 and contain a single type of luminaire. Due to the presence of a single type of luminaire, power consumption on a single sample was performed with an energy analyzer.

Table 16. Number of lighting and its location

Location	Number of Lamb
Hall A1	55
Hall A2	85
A-Intersection	15
Hall B1	58
Hall B2	85
Hall C2	47
Hall C3	36
Carding Hall	14
Maintenance Department	12

In the measurements made on the luminaire, it was determined that a single luminaire consumes 163.50 W power. The luminaires in the facility operate 12 hours a day and 310 days a year. Within the scope of energy transformation, energy saving was targeted by using LED luminaires with 77 W power consumption instead of old halogen lamps. The priority here was to ensure that the working comfort and occupational safety standards in the facility were not adversely affected while ensuring energy efficiency. In the evaluations made in this context, the comparison for the current situation and energy efficiency is given in Table 17.

Table 17. Lighting conversion results

Parameters	Existing Case		Alternative Case	
	Value	Unit	Value	Unit
Number of Lamb	407	Number	407	Number
Total Hourly Consumption	66.34	kW	31.33	kW
Total Daily Consumption	796.09	kWh	376.06	kWh
Total Monthly Consumption	20698.39	kWh	9777.76	kWh
Total Annual Consumption	248380.70	kWh	117333.20	kWh

When all the energy transformations included in the scope of the study are realized in the steel pipe production facility, the total amount of savings to be achieved annually in terms of TOE is 15.3105 TOE/Year. The amount of CO_2 released into the environment as a result of production was reduced by 21966.26 tons/year in comparison to the existing scenario as a result of the efficiency studies that were conducted.

5. Conclusıons

Energy has remained a fundamental requirement throughout history, although the areas in which it is consumed have evolved alongside technological development and industrial expansion. As global energy demand continues to rise, the increasing reliance on finite resources has intensified the need for energy efficiency, savings, and renewable energy integration. Within this context, the industrial sector—one of the largest energy-consuming segments—must undergo systematic and facility-specific energy transformation to ensure sustainable production. This study evaluated three years (2021–2023) of production and energy consumption data from an operational steel pipe manufacturing plant. Critical subsystems with high energy use were identified, and improvement scenarios were developed to enhance efficiency and reduce costs. The energy reductions to be achieved by energy transformations are expressed numerically. Boilers, compressors, cooling towers, pumps, and lighting systems were determined to be the primary contributors to energy consumption. The analyses showed a direct relationship between production volume and energy use, reflecting the load-dependent characteristics of industrial processes. The corresponding relation is shown by corelation.

By analyzing the energy consumption data, the regions where consumption is high and critical were identified. Accordingly, boilers, compressors, cooling towers and lighting are the points with high energy consumption for the plant.

Based on on-site measurements and detailed evaluations, several improvement strategies were proposed, including the substitution of boilers with renewable-based heating options, leak reduction in the compressed air system, motor replacement and speed control for cooling systems, and the adoption of high-efficiency LED lighting technologies. Scenario analyses demonstrated that these transformations can yield substantial reductions in energy consumption and associated costs.

The projected benefits are significant across all time horizons. Depending on the subsystem, the payback periods of the proposed investments for different range years, indicating that both rapid-return and long-term strategic actions are feasible within the plant. Moreover, the transformation scenarios collectively lead to a substantial reduction in the facility's carbon footprint. The results indicate that electricity-related energy savings can reach 92%, while natural gas consumption can be reduced by approximately 8%, contributing to both environmental sustainability and operational efficiency.

Overall, the study confirms that well-planned energy improvements in industrial facilities not only reduce energy consumption and emissions but also strengthen economic performance. The findings provide a practical roadmap for energy transformation in similar manufacturing environments and highlight the long-term value of integrating high-efficiency equipment and renewable energy technologies into industrial operations.

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