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Original Research

Performance, exergy, and environmental analysis of blast furnace top pressure turbine in an iron-steel factory

Furkan İrşat Albayrak[1], Alper Ergün[2], Gökhan Yıldız[3]
[1] Department of Alternative Energy Sources Technology, Vocational School, Hacettepe University, Türkiye
[2] Department of Energy Systems Engineering, Faculty of Technology, Karabük University, Türkiye
[3] Department of Electronics and Automation, Düzce Vocational School, Düzce University, Türkiye

ABSTRACT

The iron-steel industry, which has a large part of its energy consumption, strives to stay at the targeted level in the competition race and to hold on in the field in which it operates. For this purpose, production capacity turned to different energy saving methods due to the effort to reach the relevant standards and high quality low cost strategies. But, energy prices are constantly variable and energy costs are high. In this study, the Blast Furnace Top Pressure Turbine system (TRT), which is one of the important energy saving methods of the iron and steel industry, was examined. Considering the importance of the TRT system, operating conditions, operating parameters, and factors affecting energy recovery, the effect of various operating parameters on the operation of the TRT system was evaluated. Considering the annual operating time of 8000 hours, the annual production amount is 42400000 kWh, the value in terms of tons of oil equivalent is 3640 toe, the investment cost of the plant in 2018 is $400000 and the annual savings amount is $2755900. The amount of carbon emission reduction due to this production amount was calculated as 10888 $kgCO_2/h$ on average, and this amount of carbon emission was prevented every year with the commissioning of the facility. When the cost and energy calculations related to the system are examined, the payback period of the project is calculated as approximately 0.15 years. The obtained data showed that the TRT system is a suitable method for energy saving in the iron and steel industry.

Keywords: TRT, Blast furnace, Iron-Steel industry, Energy, Exergy, Environmental.

Corresponding Author:

Gökhan Yıldız
Department of Electronics and Automation
Düzce University
Address
E-mail: gokhanyildiz@duzce.edu.tr

1. Introduction

Today, energy plays the most significant role in the improvement of countries by becoming an indispensable phenomenon in human life, whose importance is enhancing day by day. In developing Turkey, in addition to the developing economy and welfare level, population growth along with industry causes an increase in energy consumption. Energy has become a major economic factor in terms of the ever-increasing energy prices and the high cost of energy. This case causes the energy saving of the industry and iron-steel sector, which has a large part of the world's energy need, and accordingly the beginning of the period when every consumer is a producer. Energy efficiency is the reduction of energy consumption per unit or amount of product without causing a decrease in the standard of living and service quality in buildings, and the quality and quantity of production in industrial enterprises. In addition to new investments made to increase energy efficiency, the use of new energy resources is more important in terms of decreasing energy costs and reducing dependence on energy resources. For this purpose, making expensive investments to obtain the energy that can be gained by saving reveals the need for longer time, and it is possible to obtain cheaper and faster with the energy savings to be made [1]. Although integrated iron-steel factories are large energy consuming factories, they also produce energy.

Combustible gases produced as a by-product in these factories can be used to recover some of the spent energy [2]. However, the recovery of these gases by combustion has environmental effects that cannot be underestimated [3]. For this purpose, the blast furnace gas also has the energy potential that can be obtained by keeping the pressure at the blast furnace outlet under control with the peak pressure modulating turbine.

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In the economies of growing and developing countries, the iron-steel industry has a significant share of the economies of the countries and is among the sectors that consume the most energy. However, the carbon emission that negatively affects the air quality created by the iron-steel industry should not be ignored. The need for energy is also increasing due to the acceleration in production and exports of the sector, which has an important contribution to the country's economy. However, the high level of energy consumption necessitates the iron-steel industry to turn to energy recovery solutions in order to compete. In recent years, because of research conducted by local governments, it is considered that there is a serious saving potential opportunity because of energy saving studies implemented in factories. In Integrated Iron-Steel Factories, the unit that uses the most energy is the blast furnaces [4]. For this reason, various applications have been developed for the recovery of the energy consumed in the blast furnaces in the factories. One of these applications is the Blast Furnace Top Pressure Turbine (TRT) system and this system is a turbine system that provides energy recovery while keeping the top pressure of the blast furnaces at the operating pressure of the furnace. As a result of the difference created between the pressure of the blast furnace gas, the outlet pressure and the turbine outlet pressure, electrical energy is produced by the movement of the turbine-generator system. Depending on the working performance of the blast furnaces, there is a reduction in carbon emissions at the same rate, as well as saving for the energy purchased from outside in exchange for the energy produced. TRT system is a turbine-generator system based on the principle of generating electrical energy without combustion by utilizing the pressure energy of the gas, as an alternative to reducing the pressure by expanding the blast furnace gas, which is obtained as a by-product as a by-product in the blast furnace, with pressure reducing valves. National and international studies on the Blast Furnace Top Pressure Turbine System are limited.

Oda et al., (2007) evaluated the potentials of reducing carbon dioxide (CO_2) emissions depending on regions in the world iron-steel industry and the minimum costs of technological possibilities. Existing steel production facilities are modeled by examining energy saving technologies and the global energy system model. Two types of objectives were considered, top-down and bottom-up. In the bottom-up type targets, energy efficiency targets in the steel industry, effective technological response-cost correlation and emission reduction ways were investigated. In order to make improvements in modelling, studies on the analysis and modeling of high-scale energy efficient systems such as coke dry quenching, coke gas recovery, low-scale energy efficiency, TRT system and plastic waste recovery in the steel industry in the 2020s were carried out. It has been stated that energy efficiency will increase by an estimated 15% in 2030 and the TRT system, the construction of new generation coke ovens, oxygen gas recovery facilities; coke dry extinguishing facilities play a major role in achieving the energy efficiency target in the steel production industry [5]. Guo and Fu (2010), in order to evaluate China’s specific energy consumption rate per ton of coal-sourced crude steel, compared the average data of iron and steel production with Japan (656 kg/t) in 2004, with a specific energy consumption of 705 kg/t. They found that its consumption was 7.5% higher than that of Japan. It has been stated that up to 30% of the energy consumption in the blast furnaces can be recovered by using the TRT system and the energy consumption value is reduced by 11 kg/t [6]. Wu and Yang (2012) stated that 70% of the energy consumption in the current industry is in the iron-steel sector 39% of this consumption is for blast furnaces, 11.9% for coke plants, 7.77% for steelworks, 17.5% for electric furnaces, and 5.55% for sinter factories. It was stated that blast furnaces have a large share in energy consumption and high pressure and temperature are released during the production of liquid raw iron, and this pressure energy is lost in septum (reducing) valves. It was obtained that 20% of the energy consumption of the blast furnaces can be recovered with the TRT system used for the recovery of this pressure energy in the blast furnaces, and it is a system that can be installed in any blast furnace with a volume greater than 1000 m^3 [7]. Arens et al., (2012) emphasized that the CO_2 global emission rate of Germany, which is one of the largest steel producing and CO_2 emitting countries in the world, is 3-5%. The amount of steel production in 2010 reached approximately 44 million and it was stated that it is the best steel producer country in Europe and the seventh largest steel producer country in the world with this production. The importance of reducing CO_2 emissions and energy consumption in increasing energy efficiency was mentioned [8]. Cai et al.

(2016) stated that the TRT system is one of the second most valuable energy recovery systems in the iron-steel industry and that up to 30% of the energy consumption can be recovered in the generator rotating on the turbine demand. In addition, in this study, it was determined that the total pressure loss in the blades was 0.7% due to the low gas velocity, and the turbine performance was 90.1% due to the uniform distribution of the gas flow in the turbine stages [9]. Liu and Gao (2016) stated that the energy costs of medium and large enterprises in the Chinese iron-steel industry increased from 20% to 30% and their CO_2 emissions were estimated to be 1232.9 Mt in 2007. At the end of 2008, 60 wet type TRT systems and 91 dry type TRT systems were installed out of 158 blast furnace facilities with a volume greater than 1000 m^3. In addition, dry type was installed in 70% of 530 medium and large scale blast furnaces in 2011, and it was stated that this rate reached 100% in 2014 [10]. Priya and Patil (2014) performed a simulation based on various parameters such as turbine output power, turbine inlet pressure, turbine outlet pressure, temperature and flow rate of Blast Furnace gas for a TRT system and determined the optimum values at which the turbine should be operated [11]. Jianqi et al. (2016), dynamic mathematical model of high pressure and pre-TRT pressure was created based on the mechanism analysis of the blast furnace upper pressure system and gas flow equation. Then, the upper pressure model and the pressure before TRT were simulated with a closed-loop identification method based on Recursive Least Squares (RLS) [12].

In this study, the place of the TRT system in the world, its benefits to the businesses it operates and its technological advantages are examined. The implementation and financial analysis of the TRT system in the integrated iron and steel factory, its effect on the specific energy consumption per ton of raw steel produced, its effect on energy costs and the positive effect of the amount of energy obtained on carbon dioxide production compared to coal etc. fueled processes were examined.

2. Material and method

TRT can be defined as a system that can be used instead of furnace gas pressure reducing valves in order to convert the top pressures of blast furnaces operating in integrated iron-steel factories into useful energy. In the blast furnaces operating in integrated iron-steel factories and at the beginning of the liquid raw iron process, the blast furnace gas obtained as a by-product due to the process should be expanded to certain top pressure values by means of septum (expansion) valves in order to ensure the operating conditions of the blast furnace. The TRT system is a turbine-generator system based on the principle of generating electrical energy without consuming and burning any additional fuel by utilizing the pressure energy contained in the blast furnace gas.

Liquid raw iron is obtained by charging sinter, pellets, lump ore and metallurgical coke into the blast furnaces, which are at the beginning of the liquid raw iron process in integrated iron-steel factories. Blast furnace gas, which is released because of chemical reactions during the production of liquid raw iron, is a flammable gas because it contains CO and H_2. Blast furnace gas, which has low calorific value, can be used as fuel in consumer units such as coke ovens, steam boilers, furnace stoves and some annealing furnaces by being transferred to the blast furnace gas network after cooling and cleaning the dust it contains in the gas cleaning units in the blast furnace process.

Figure 1. TRT (Top Pressure Recovery Turbine)

The top pressure required by the blast furnaces during the production of liquid raw iron is provided by the top pressure reducing valves (septum valves) under the control of the furnace, and there is approximately 25-30 times the difference between the inside of the furnace and the gas collector network pressure. In general, if a blast furnace with a top pressure of 200 kPa is compared with a blast furnace gas network pressure of approximately 6-8 kPa, this ratio is approximately 30 times.

The TRT system is used in the iron-steel industry in countries such as Brazil, Italy, China, Japan, South Korea, Germany and Türkiye. These facilities have been widely used in the integrated iron-steel industry in Europe and especially in Japan, which is dependent on foreign energy in terms of energy, after the oil crisis in the 1970s. All of the integrated facilities in Japan and Korea and the integrated iron-steel facilities in China have a TRT system in general.

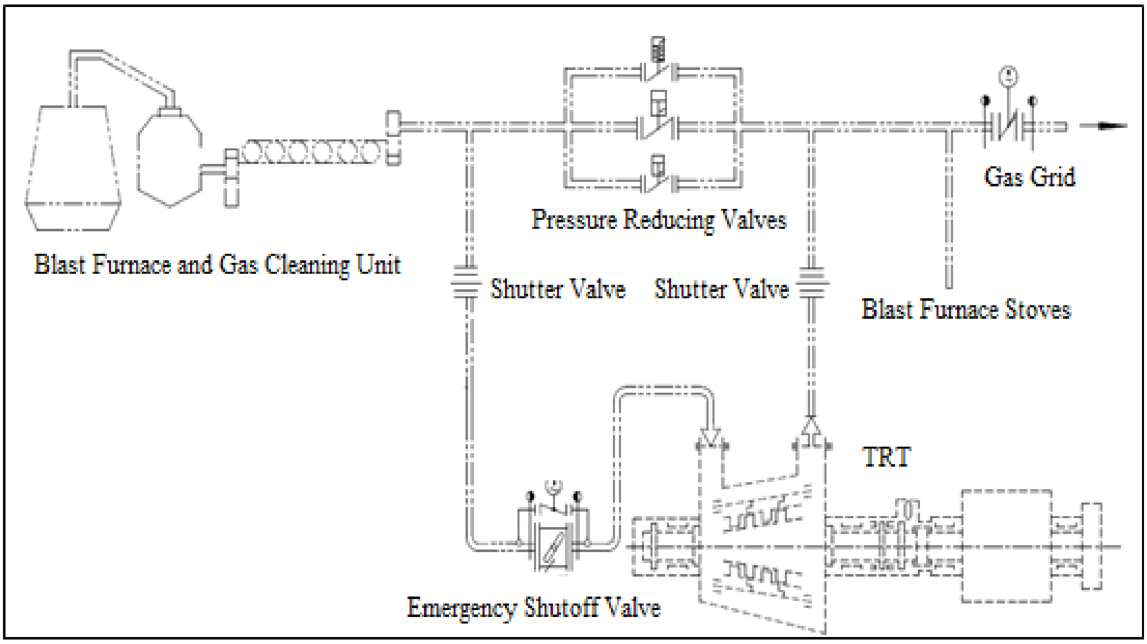

Figure 2. Dry type TRT system

Dry type TRT systems can recover approximately 45-50% of the energy need generally spent for turbo blowers. This turbine system is installed for blast furnaces with a dry type blast furnace gas cleaning system. Dry type TRT system is more efficient than wet type TRT system. The turbine inlet gas temperature of the TRT system considered in this study is maximum 250 °C and the working design temperature is 150 °C on average. It also requires less water and electricity than wet type TRT systems.

In the installation of the TRT system, the current hourly, daily and monthly electrical energy consumptions of the blast furnace it is connected to, the blast furnace production capacity, the air flow obtained from the turbo blower used for production in the blast furnace and its technical features are taken into account. It is also important to examine technical features such as the technical features and capacity of the blast furnace gas cleaning unit, the amount of dust in the clean and blast furnace gas in the line, the dirty and clean gas temperatures, the gas cleaning unit inlet and outlet line pressures, the amount of moisture in the gas. The design parameters of the existing TRT system and the actual operating parameters are given in Table 1.

Table 1. Specifications and production capacity of the TRT system

Blast Furnace Volume	1650 m^3
Inlet Gas Flow Rate	243750 kg/h
TRT Inlet Gas Pressure	230 kPa (g)
TRT Inlet Gas Temperature	150 °C

TRT Outlet Gas Pressure	10 kPa (g)
TRT Input Gas Dust Content	<5 mg/Nm^3
TRT Electricity Production Capacity	8.48 MW
Blast Furnace Gas Content	CO: 22.98% N_2: 56.35% CO_2: 18.69% O_2: 0% H_2: 1.98% Q: 680-700 (kcal/m^3)

2.1. Performance evaluations based on TRT design

Performance calculations depending on the design of the TRT system were calculated by considering the minimum, average and maximum production capacities depending on the operating conditions of the blast furnace, and the amount of power that the TRT system can produce is given in Table 2.

Table 2. Design parameters of TRT system

Parameter	Unit	Minimum	Design	Maximum
Turbine Inlet Gas Flow Rate	kg/h	168000	297000	427000
Turbine Inlet Gas Pressure	kPa (g)	110	230	260
Turbine Inlet Gas Temperature	℃	100	150	250
Turbine Outlet Gas Pressure	kPa (g)	10	10	8
Turbine Inlet Relative Humidity	%	56	--	74
Turbine Inlet Gas Dust Content	mg/Nm^3	5	5	5
Turbine Electricity Production Power	MW	--	8.48	10.5
Turbine Rotation Speed	rpm	3000	3000	3000

2.2. Evaluations based on blast furnace performance

During the process of obtaining liquid raw iron of the blast furnace, the top pressure, main collector pressure, dirty gas temperature, clean gas temperature depending on the operating conditions and the generator output power of the TRT system can be evaluated as a result of these data.

Depending on the operating conditions of the blast furnace, there may be planned and unplanned stoppages throughout the year, and electrical energy production will not be possible due to the maintenance work to be carried out on the TRT system during the shutdown processes. In addition, in order to operate the TRT system and obtain electrical energy from the system, production will not be possible at low top pressure due to turbine operating criteria, and the blast furnace top pressure will be provided through the by-pass line. The monthly average operating data of the blast furnace in 2018 are given in Table 3. Experiments were carried out by taking into account the data of the process, including the TRT system examined in this study, in hourly, daily and monthly periods in 2018.

Table 3. Blast furnace operating parameters for 2018

2018	Blast Furnace		
	Top Pressure (kPa)	Pressure After Reducing Valve (kPa)	Gas Temperature (°C)
January	117	4-5	108
February	117	4-5	120
March	117	4-5	125
April	114	4-5	125
May	115	4-5	128
June	117	4-5	131
July	121	4-5	125
August	127	4-5	140
September	121	4-5	144
October	116	4-5	137
November	125	4-5	130
December	122	4-5	130

2.3. Evaluations of performance

While the process of converting the energy contained in the blast furnace gas into useful power by reducing the pressure in the TRT system, the change of the inlet and outlet gas temperature difference in relation to the conversion of this energy has a direct effect on the useful energy obtained.

In the turbine, the fluid does work against the blades placed on the shaft as it passes. Thus, the turbine does work by rotating the shaft. In the turbine, the work is positive because it is done by the fluid. Although there is heat transfer between the machines and the environment during normal operation, continuous flow machines can be considered to operate near adiabatic operating conditions. Therefore, the model process for turbines is assumed to be adiabatic. The adiabatic expansion in the turbine is shown in Figure 3. Here, it is Reversible Isentropic Expansion: 1-2' and Irreversible Adiabatic Expansion: 1-2'.

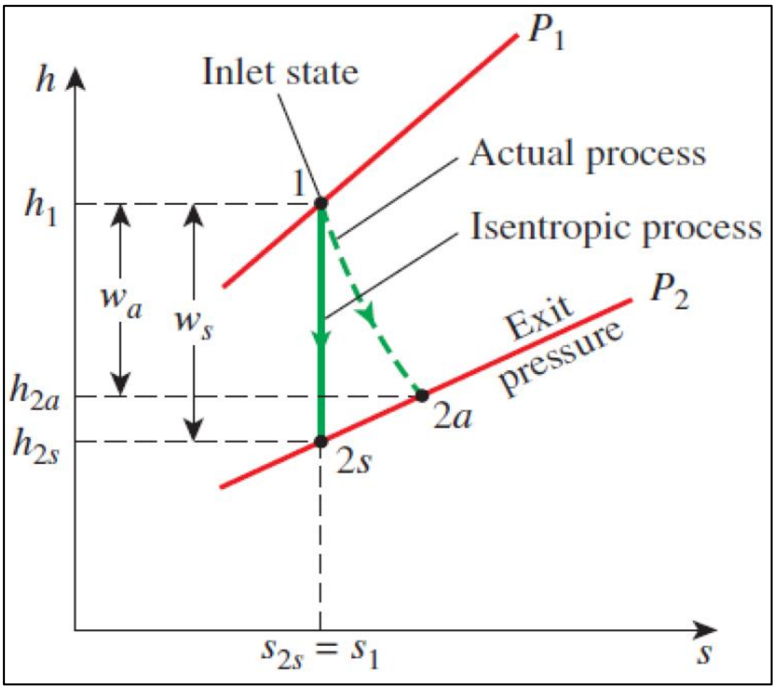

Figure 3. The h-s diagram for the actual and isentropic processes of an adiabatic turbine

In the TRT system, the maximum work that can be achieved under the ideal reversible isentropic expansion (kJ/kg);

$(W_{\mathrm{s}}) = h_1 - h_{2\mathrm{s}} = \Delta h_s$ (1)

Work obtainable under irreversible adiabatic expansion conditions (kJ/kg);

$(W_{\mathrm{a}}) = h_1 - h_2 = \Delta h$ (2)

Work loss due to isentropic expansion (kJ/kg);

$W_v = (W_{12\mathrm{s}}) - W_{\mathrm{a}} = h_2 - h_{2\mathrm{s}}$ (3)

Isentropic turbine efficiency;

$\eta_{s\mathrm{T}} = W_{\mathrm{a}} / W_{\mathrm{s}} = W_{\mathrm{a}} / W_{\mathrm{a}} + W_v = (h_1 - h_2) / (h_1 - h_{2\mathrm{s}}) = \Delta h / \Delta h_s$ (4)

Isentropic turbine power (kW);

$P_{12} = \dot{m}\, W\, \eta_{s\mathrm{T}} = \dot{m}\, W_{\mathrm{a}}$ (5)

Turbine power on the shaft (kW);

$P_{\mathrm{W}} = \dot{m}\, W_{\mathrm{a}} \eta_{\mathrm{sT}} = P_{12} \eta_T$ (6)

Generator terminal power (kW);

$P_G = P_{\mathrm{Wa}} \eta_G = \dot{m}\, W_{\mathrm{a}} \eta_T \eta_G$ (7)

Here, Ws is the maximum work that can be obtained under the ideal reversible isentropic expansion (1--2') (kJ/kg), Wa is the work that can be obtained under the conditions of irreversible adiabatic expansion (kJ/kg), Wv is the work loss due to isentropic expansion (kJ/kg). Δh_s isentropic enthalpy curve in reversible expansion (kJ/kg), Δh isentropic enthalpy curve in irreversible expansion (kJ/kg), η_{sT} isentropic turbine efficiency, η_G Generator efficiency, $\dot{m}$ mass gas flow rate (kg/s), P12 isentropic turbine power (kW), P_{W} is the turbine power on the shaft (kW), P_G is the generator terminal power (kW).

As a result of using the flow rate, density, heat storage capacity, pressure and temperature parameters affecting the power to determine the power of the TRT system, the power converted into useful electrical energy is obtained in Equation 8 [11].

$$W = \dot{V}.\rho.c_p.\Delta T.\eta_{\mathrm{T}}.\eta_{\mathrm{G}} \quad (8)$$

Depending on the temperature and pressure of the gas coming from the blast furnace to the TRT system, the functional change of the temperature difference resulting from the work done in the TRT system and the outlet temperature it reaches is obtained from Equation 9.

$$\Delta T = T_g.\left[1 - \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}}\right] \quad (9)$$

In irreversible processes, exergy is not conserved and is always destroyed. Accordingly, the exergy equivalence for open systems is expressed as it shows in Equation 10.

$$\frac{dE_{CV}}{dt} = \sum_k 1 - \left(\frac{T_0}{T_k}\right)\dot{Q}_k - \left(\dot{W}_{CV} - P_0 \frac{dV_{CV}}{dt}\right) + \sum \dot{m}_{in} e_{in} - \sum \dot{m}_{out} e_{out} - T_0 S_{gen.} \quad (10)$$

dE_{KH}/dt and dV_{KH}/dt in this equation are defined as the exergy and volume change of the control volume, respectively. Since E_{KH} / dt = 0 and dV_{KH} / dt = 0 in continuous flow open systems, Equation 11 is written as follows.

$$\sum \dot{m}_{in} e_{in} - \sum \dot{m}_{out} e_{out} - T_0 S_{gen.} = \dot{W}_{CV} - \sum_K 1 - \left(\frac{T_0}{T_k}\right)\dot{Q}_k \quad (11)$$

During the economic examination of the relevant system, the parameters of the sinking fund factor (SFF), annual salvage value (ASV), annual maintenance cost (AMC) and annual interest rate (i) should be taken into account. The cost of capital (investment) (B), capital recovery factor (CRF) is calculated as Equation 12 and the life of the system (n) is calculated [13], [14].

$$CRF = \frac{i.(1+i)^n}{(1+i)^n - 1} \tag{12}$$

Fixed annual cost is calculated as in Equation 13.

$$FAC = B(CRF) \tag{13}$$

The investment cost of the plant is calculated as (B), and in Equation 14 the salvage value (S) is calculated as one fifth of B.

$$S = 0.2(B) \tag{14}$$

SFF and ASV are calculated as in Equation 14 and Equation 15 [15].

$$SFF = \frac{i}{(1+i)^n - 1} \tag{15}$$

$$ASV = S(SFF) \tag{16}$$

The annual maintenance cost of the system is Equation 17 (AMC); is the cost arising from cleaning, periodic and emergency maintenance. Here, 15% of the fixed annual cost (FAC) is considered as the fixed annual maintenance cost.

$$AMC = 0.15(FAC) \tag{17}$$

As a result, the annual cost is expressed as Equation 18.

$$AC = FAC + AMC + ASV \tag{18}$$

Enviroeconomic (environmental cost) analysis is done using the carbon price (or CO_2 emission price) or the amount of carbon released. Setting a carbon price is an important method for reducing national greenhouse gas emissions. The carbon price is an approach that calculates the cost of the emission of greenhouse gases that cause global warming. Paying the price of carbon (CO_2) released into the atmosphere will encourage people and countries to reduce their carbon emissions. At the same time, this case will reveal the importance of renewable energy technologies that do not emit carbon into the atmosphere. In the article published by Sovacool in 2008, the average CO_2 equivalent density for electricity production from coal is given as approximately 960 g CO_2/kWh. In fact, this value will be 2.08 kg CO_2/kWh, considering 40% transmission and distribution losses and 20% losses due to inefficient electrical appliances used [16], [17], [18]. Therefore, the actual CO_2 reduction is given in Equation 19:

$$\phi_{CO_2} = \Psi_{CO_2}.W \tag{19}$$

ϕ_{CO_2} indicates the amount of CO_2 reduced per hour (kg CO_2/h) and Ψ_{CO_2} indicates the average amount of CO_2 emissions released during energy production from coal (2.08 kg CO_2/kWh). Studies show that the price of CO_2 is between 13 \$/tCO_2 and 16 \$/tCO_2.

$$Z_{CO_2} = P_{CO_2}.\phi_{CO_2} \tag{20}$$

Z_{CO_2} expressed in Equation 13 is the environmental cost (hourly CO_2 reduction price, ¢/h), P_{CO_2} is the carbon price per kg CO_2 and is taken as 1.45 ¢/kg CO_2.

3. Results and discussion

It has been determined that the blast furnace, where TRT is fed, will operate for an average of 8000 hours during the year, except for the planned and unplanned shutdowns that may occur throughout the year. With the data of 2018, the useful energy that can be obtained by using the inlet pressure, temperature and flow rate of the TRT was calculated. In addition, the power that can be obtained at different pressures, temperatures and flow rates, which may be different from the data realized in 2018, was evaluated. The outlet pressure of TRT is taken as 10 kPa in all calculations. During the year, according to the operating performance of the blast furnace, the turbine inlet pressure was between 114 kPa and 127 kPa, the turbine inlet temperature was between 108 ℃ and 144 ℃, and the blast furnace gas production was between 213500 kg/h and 243750 kg/h. Turbine outlet pressure is 10 kPa, blast furnace gas density is 1.25 kg/m^3, k value is 1.41 and c_p value is 1.03 kJ/kgK. In line with this information, adiabatic work, thermodynamic power, entropy generation, exergy efficiency and loss, TRT power and energy efficiency of the blast furnace were calculated.

As a result of using the design data of TRT in Equation 14, the equivalence of the produced energy was obtained and sample performance calculations were made and because of this equation, the design power of 8480 kW was obtained.

With the obtained equivalence; TRT's monthly average performance data calculations were made using the blast furnace gas production values in 2018, which vary according to the liquid raw iron production need of the factory.

The payback period of the plant was calculated by considering the investment cost of the plant in 2015 and the dollar exchange rate in April. The annual average operating time of the power plant is assumed to be 8000 hours. According to data in 2018, an average of 220000 kg/h blast furnace gas enters TRT at most. The annual interest rate is 10%, the annual regular increase rate is 4%, the repayment rate is 8% and the operational life of TRT is accepted as 20. The initial investment cost of the plant is $400000, the annual spare parts cost is $15000, the leveled operating and maintenance cost is $5.8 per hour, and the electricity supply price is $0.054/kWh. Assuming that the facility will operate for 8000 hours excluding maintenance stops, the total income and total expenses have been determined, and the annual earnings have been proportioned to the investment cost in 2015 and the payback period has been calculated as 0.15 years.

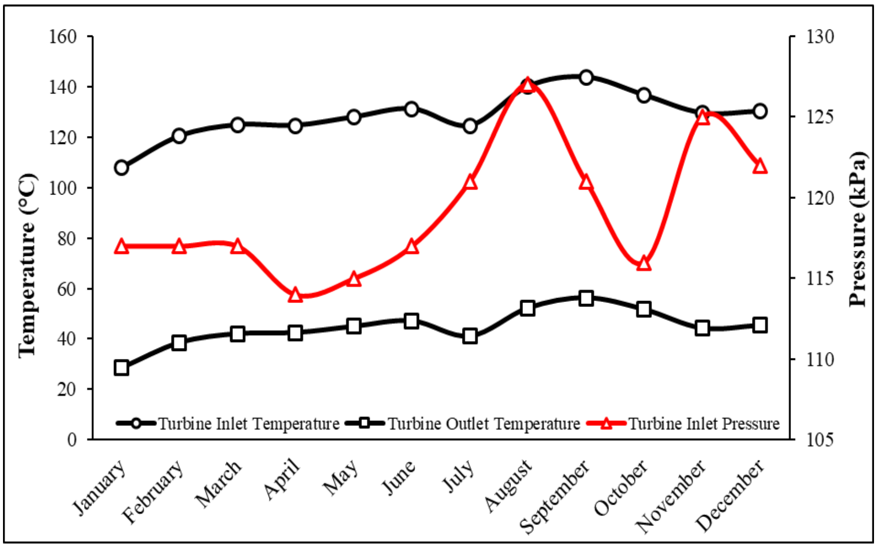

Figure 4. Changes of turbine operating parameters according to months

Figure 4 shows the variation of the changes inlet temperature, inlet pressure and outlet temperature parameters according to months. It was observed that the turbine inlet temperature varies between 108 °C and 144 °C, the outlet temperature varies between 28 °C and 56 °C, while the inlet pressure varies between 117 kPa and 127 kPa.

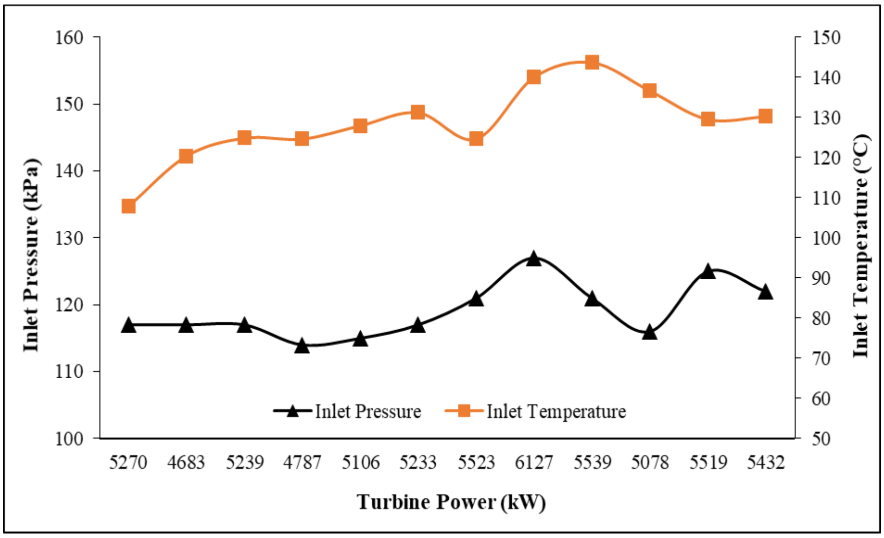

Figure 5. Changes in turbine power according to inlet pressure and temperature

Figure 5 shows the change in turbine power according to the inlet temperature and pressure. The power value produced in the turbine varies between 4683 kW and 6127 kW. While the temperature and pressure curves increase in parallel with each other, it is seen that the power produced in the turbine increases when the temperature and pressure increase.

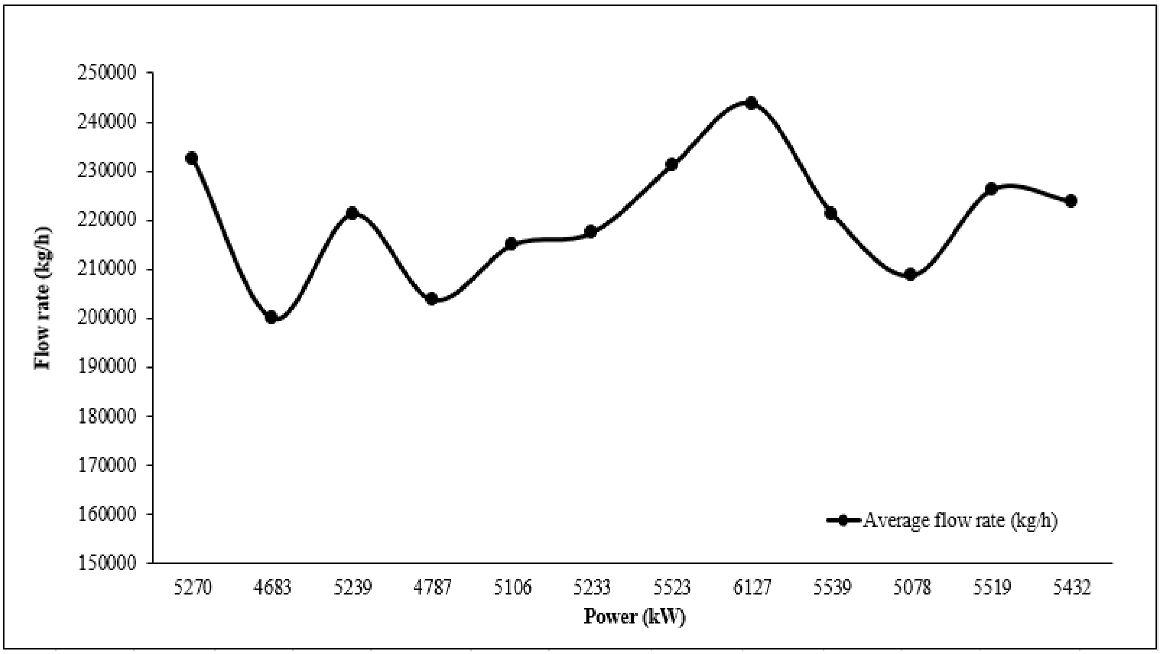

Figure 6. Flow rate dependent power variation

Figure 6 shows the change in turbine power depending on the flow rate. The flow rate ranges between 200000-243750 kg/h and the power produced increased depending on the increase in the flow rate.

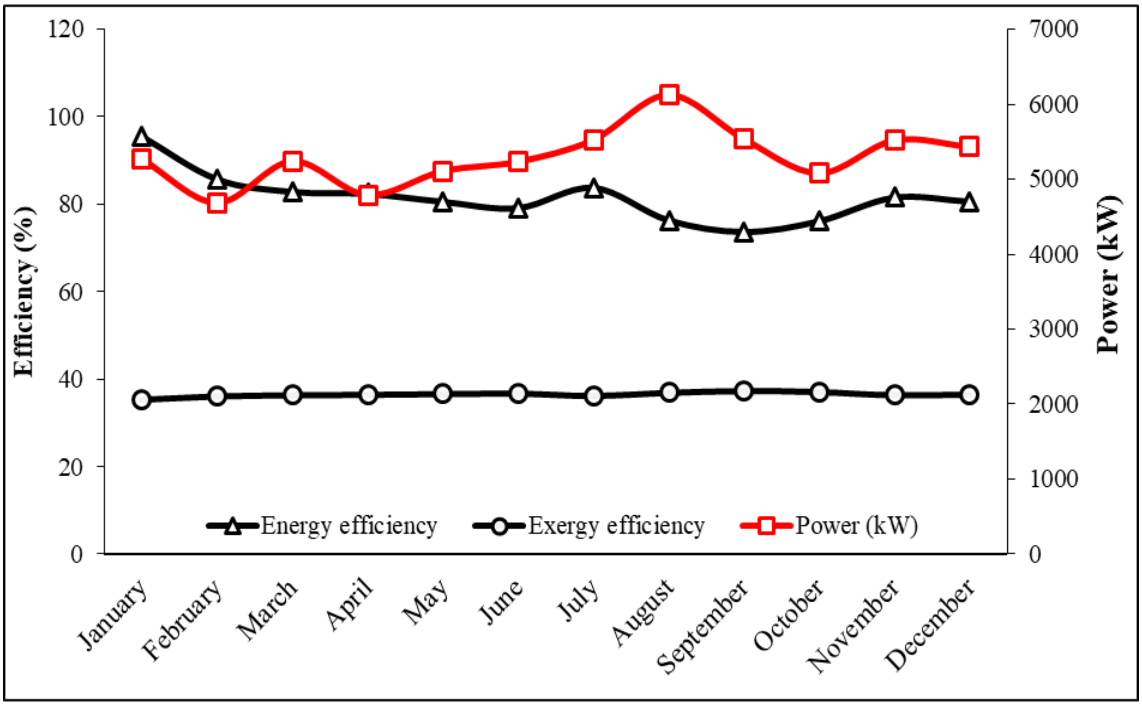

Figure 7. Performance values by month

Figure 7 shows the change in energy efficiency, exergy efficiency and generated power values by month. It has been observed that the energy efficiency varies between 73% and 95%, while the exergy efficiency varies between 35% and 38%. It is observed that turbine performance values are higher in July, August and September.

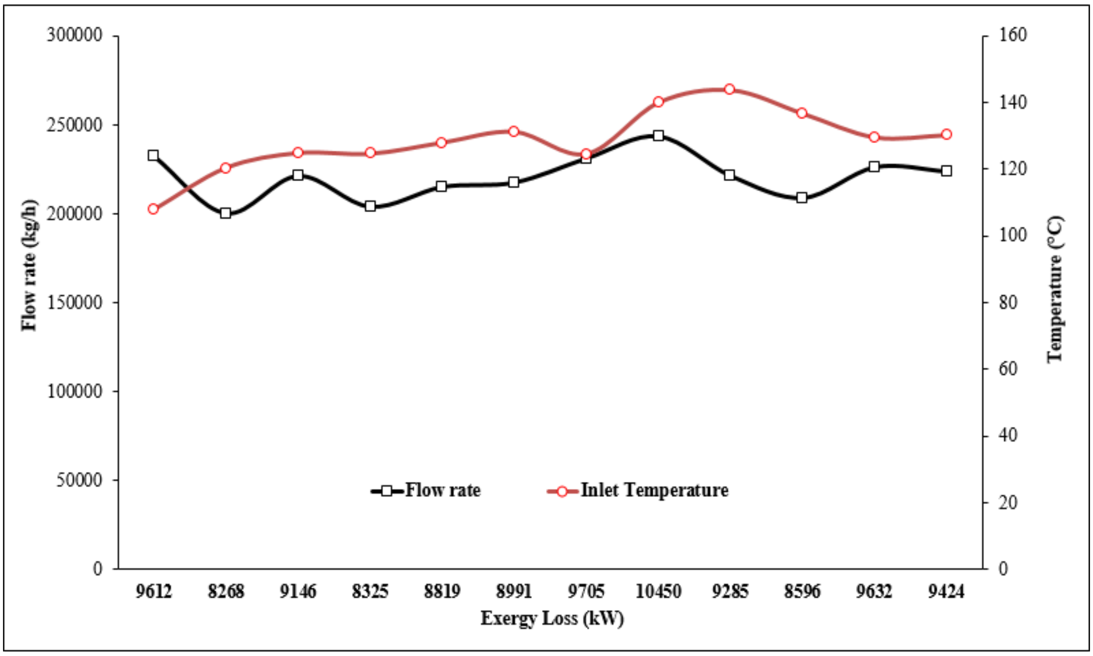

Figure 8. Exergy losses due to temperature and flow rate

Figure 8 shows exergy losses depending on turbine inlet temperature and flow rate. The value of exergy losses varies between 8300 kW and 10 450 kW values.

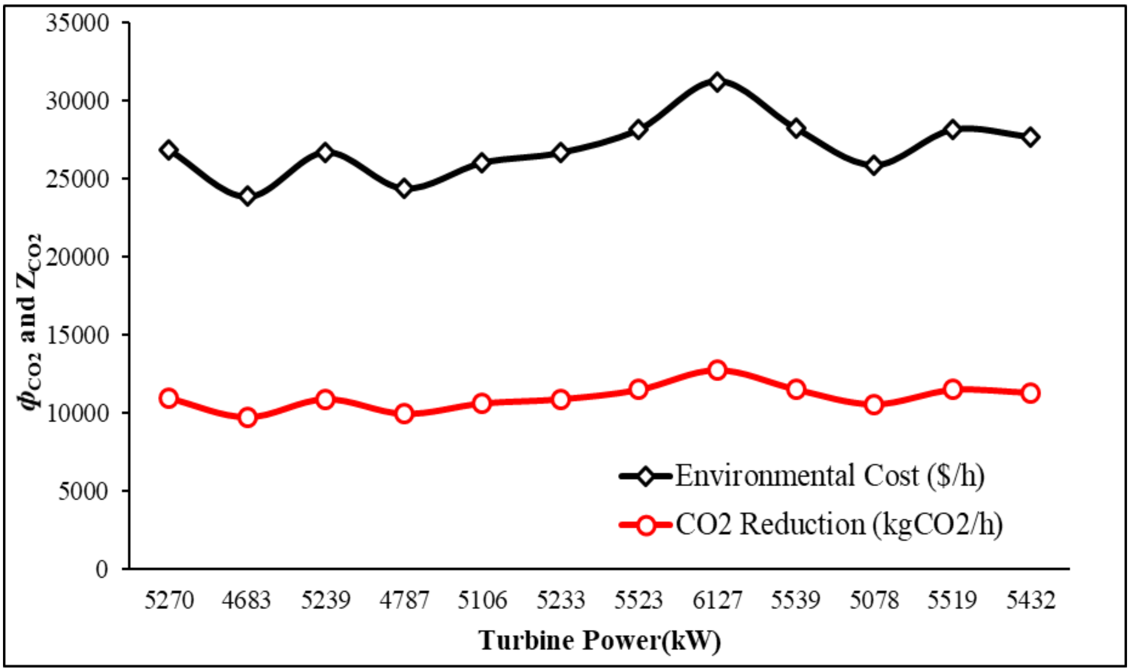

Figure 9. Environmental cost analysis results

The results of environmental cost analysis are shown in Figure 9. As a result of the analyzes made, approximately 132 tons of CO_2 emissions will be reduced annually with the use of TRT. However, the environmental cost parameter has been calculated around $16000 per month.

The payback period of the plant was calculated by considering the investment cost of the plant in 2015 and the dollar exchange rate in April 2019. The annual average operating time of the power plant is assumed to be 8000 hours. The annual interest rate is three percent (i=0.03), the salvage value is twenty percent of the investment cost (S=0.2), and the annual maintenance cost is fifteen percent of the investment cost (AMC=0.15). In addition, the operational life of the system is accepted as twenty (n=20) years. After the calculations, the annual earnings of 2,755,900 $ and the payback period depending on this income are calculated as 0.15 years.

4. Conclusions

The TRT system plays a very important role for businesses with blast furnaces. The fact that it is used extensively in countries such as Brazil, Italy, China, Japan, South Korea and Germany reveals the importance of this system in terms of energy saving. In this study, the TRT system, which will be fed by the blast furnace connected to the iron-steel factory, is discussed. The monthly and annual top pressure of the blast furnace facility in 2018, the inlet temperature of the gas entering the TRT system after the cleaning process of the blast furnace gas coming out of the blast furnace, the blast furnace gas density, the blast furnace gas flow rate were examined and the data were recorded. Considering the operating parameters of the blast furnace, planned and unplanned downtimes were observed throughout the year, along with the variable iron and steel production of the factory, and the production interruptions and maintenance requirement of the TRT system were also taken into account. In these processes, energy production calculations of the system were made when energy production could not be made from the TRT system, and in the decrease and increase experienced due to the top pressure of the blast furnace. According to the analyzed data, the amount of power produced in the TRT system, the average blast furnace gas flow rate was between approximately 213500-243750 kg/h, while the blast furnace gas temperature was between approximately 108-144 ℃. The gas pressure under these conditions is approximately 114-127 kPa.

Considering the actual work data, based on the monthly average of the TRT system in 2018, depending on the liquid raw iron production of the blast furnace, the highest electricity production was realized in August and the lowest electricity production was realized in February, and the year average was approximately 5300 kWh.

- Considering the annual operating time of 8000 hours, the annual production amount is 42400000 kWh, the value in terms of tons of oil equivalent is 3640 toe, the investment cost of the plant in 2018 is $400000 and the annual savings amount is $2755900.
- The amount of carbon emission reduction due to this production amount was calculated as 10888 kgCO_2/h on average, and this amount of carbon emission was prevented every year with the commissioning of the facility.
- When the cost and energy calculations related to the system are examined, the payback period of the project is calculated as approximately 0.15 years.
- It is observed that TRT production increases with increasing inlet gas pressure, and TRT production increases slightly with increasing inlet gas temperature. TRT production decreased with the increase of the outlet gas pressure and it is seen that the increase in the gas flow rate causes more power generation at the same turbine outlet pressure.
- Investigation of the solid particle erosion characteristic of TRT under variable operating conditions, numerical research on the aerodynamic characteristics and optimal design of the TRT prototype with protective chrome material coating for the elimination of wing failures, researches on energy recovery from the condensate fluid formed in the wet type TRT system and reduction of CO_2 emissions.

Declaration of competing interest

The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.

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Abbreviations

CV	Control volume
in	Inlet
gen	Generation
out	Outlet
0	Dead state

Nomenclature

AC	Annual cost	P_{CO_2}	Carbon price
AMC	Annual maintenance cost	RLS	Recursive Least Squares
ASV	Annual salvage value	S	Salvage value
B	Cost of capital investment	SFF	Sinking fund factor
CO_2	Carbon dioxide	t	Tone
CRF	Capital recovery factor	TRT	Top Pressure Recovery Turbine
c_p	Specific heat (kJ/kgK)	W	Power (W)
i	Annual interest rate	Z_{CO_2}	Environmental cost (¢/h)
FAC	Fixed annual cost	ρ	Density (kg/m^3)
k	Thermal conductivity (kJ/kgK)	η_T	Efficiency of turbine (%)
$\dot{m}$	Mass flow rate (kg/h)	η_G	Efficiency of generator (%)
n	System life	ϕ_{CO_2}	Amount of CO_2
P	Pressure (kPa)	Ψ_{CO_2}	Average amount of CO_2 emissions from coal

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