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An applied study on energy analysis of a coke oven

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Abstract. In this study, the energy view of an oven of a 70-oven coke battery in an iron and steel plant was evaluated based on operating parameters and recommendations for improving efficiency were made. A mass and energy balance per coking period (p) was created for a coke oven. It was found that during each coking period, 51.2% of the energy input was used as coking heat. It is predicted that approximately 6.91% of the input energy can be recovered from flue gas into the combustion air. By recovering the heat from the flue gas into the combustion air, the efficiency of the coke oven can be increased to 58.11%. The heat of the coke oven gas can be recovered and converted into usable form, which accounts for 6.53% of the total energy input. With the dry quenching process, it is possible to recover around 24% of the energy used from coke. Improved oven insulation, heat recovery from coke and flue gases, and the dry quenching process can recover energy worth more than 25.19 GJ/p. The energy efficiency of the furnace was predicted to rise to 82.11% with coke dry quenching and to more than 88.64% with coke gas heat recovery and insulation upgrades. The potential economic savings are $2578, equivalent to a reduction in CO_2 emissions of 2.45 tons per coking period. The financial equivalent of emissions reductions from carbon trading could be $233 per coking period. Through the processes of dry coke quenching, coke gas (CG), and flue gas heat recovery and thermal insulation improvements of the coke battery, the total amount of recoverable energy can exceed 617,294 GJ/year.

Keywords: Coke oven, Energy, Efficiency, Saving, Emission.

1 Practical applications

The main objective of this study is to raise industry awareness of potential energy recovery opportunities and system improvements by conducting an energy analysis within the operating parameters of the coking plant of an integrated iron and steel plant. Furthermore, the number of applied studies in literature is rather small. The indirect contribution of this study is to create additional resources for young researchers and engineers new to the industry and to raise awareness among iron and steel investors of the level of returns that can be achieved by investing in energy-intensive equipment. A mass and energy balance of a coke oven was performed, the performance of the oven during operation was evaluated, and recommendations were made for possible energy recovery and system upgrades.

2 Introduction

A large part of the world's iron and steel production comes from China and India. In 2019, Turkey accounted for 1.8% of global production and ranked eighth with 33.7 million tons of production [1]. The steel industry consumes a lot of energy because it requires numerous melting, cooling, heating, and solidification processes [2]. The annual share of steel production in global energy consumption and CO_2 emissions is 5% and 4%, respectively [3]. In Turkey, the sectoral shares of energy consumption and emissions of the steel industry are 25% and 40%, respectively [4, 5]. Turkey's production is expected to increase significantly by 2030 [6]. The proportion of energy consumption and CO_2 emissions is expected to increase dramatically as production increases. A key to increasing industry awareness is identifying potential savings and system improvements in operational facilities through energy analysis. The by-products of the steel industry include tar, coke oven gas, blast furnace gas (BFG), etc. Significant energy savings can be achieved by evaluating these products. Improving system efficiency can be achieved through both heat recovery and heat loss prevention [7]. Turkey can cut its energy consumption by at least 20% (45 million tons of oil) by implementing regular and effective energy efficiency measures [8]. Increasing the energy efficiency of the industry will increase competitiveness, secure energy supplies, and mitigate climate change [9]. The iron and steel production process consists of numerous subunits that carry out a series of operations from raw

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(a)

(b)

Figure 1. Coke battery image; (a) top view and (b) side view.

materials to semi-finished steel products. Coking plants, sinter plants, blast furnaces, steel workshops, rolling mills, and power generation plants are some of the most important subunits of integrated iron and steel plants. Furthermore, contingent on product requirements and corporate policies, there might be intermediate production facilities. One of the primary energy sources for the iron and steel industry is metallurgical coke, which is produced by heating coal to temperatures above 1100 °C in oxygen-free coke ovens [10, 11]. This process results in the release of volatiles in the coal through a series of reactions, leaving behind high-carbon coke that contains no volatiles [12]. A coking plant is connected to an integrated steel production network [13]. Coal preparation, batteries, crushing and screening plants, and by-product plants form the four main subunits of coking plants built to supply metallurgical coke to blast furnaces. The coking plants produce metallurgical coke, cast coke, walnut coke, coke powder and gas, raw tar, raw benzene, naphthalene, and ammonium sulfate.

3 Introduce of the coking plant

To make it easier for practitioners to understand the energy relationships and loss points of the coking plant, the production conditions of a specific coking plant were examined, and the data collected was evaluated. There are three different coke batteries in the iron and steel plant where this study is conducted. The facility comprises three batteries: 1–2 batteries with 44 ovens, 3–4 batteries with 56 ovens, and 5–6 batteries with 70 ovens. The oven is approximately 4.5 m high, 0.45 m wide and 13.59 m deep. The coal capacity of the oven for one cooking period is approximately 20 tons. The coking temperature ranges from 1200 °C to 1300 °C, and the coking period is nearly eighteen hours. An energy analysis was performed on 5–6 batteries with 70 ovens. Coke gas at 2820 Nm^3/h and blast furnace gas at 35,200 Nm^3/h are supplied to battery ovens as fuel. Figure 1a and 1b shows the top and side views of the coke oven that is the subject of this paper.

Figure 2 illustrates the coke oven material flow diagram.

In a coking plant, the coke oven is where coal is coked. Figure 2 illustrates how the reaction energy released during the coking process supports the process, while the heat released by the reaction of the mixed gas (MG) fed to the combustion chamber and the combustion air ensures the coking of the coal in the coke chamber.

4 Literature review

Few recent studies have been published in the literature that assess a coking plant's energy analysis with its operating conditions. The following is a summary of some of them.

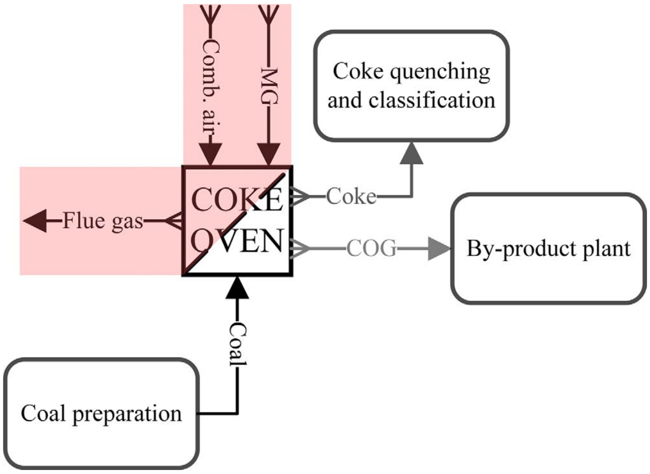


Figure 2. Coke oven material flow diagram.

In a study conducted by Larsson *et al.*, an assessment was made of the connections and interrelations among coking plants and other associated facilities in terms of mass and energy. It was asserted that the material and energy costs allocated to the various production units within a steel production facility are roughly 28–30% for the coke oven plant, 56–59% for the blast furnace, and 14% for the basic oxygen furnace [14]. Approximately 59.5% of the heat applied to the coke oven was applied to coal to produce coking, according to a study on energy analyses conducted by Ertem and Ozdabak on a coking plant [15]. The research conducted by Sultanguzin *et al.* examined the production of metallurgical coke, the coal fuel-energy balance, and the optimization of steel production based on energy and environmental standards [16]. The energy efficiency of an industrial furnace was studied by Ajah *et al.* They recommended some ways to make the furnace more energy-efficient. They claim that increasing the temperature of the combustion air, recovering energy from the flue gas, and improving the insulation properties of the refractory wall increase the energy efficiency of the furnace from 57% to 78% [17]. As demonstrated by Nogami *et al.* examined the material and energy balances of an integrated iron and steel facility that includes a blast furnace, hot stove, coke oven, and coke dry quenching. They provided diagrams to illustrate the mass and energy flow boundary conditions for a coke oven in their study [18]. Zhao *et al.* attempted to optimize the control of coke gas in real time using an echo states network system based on Gaussian processes in order to support energy optimization in a practical study [19]. The temperature distribution and heat transfer of the coke chamber, heating wall, and combustion chamber of a coke oven were examined numerically by Xiao *et al.* using the multi-compartment coupling mathematical model that was developed. According to the data, using regular silica bricks could result in a 60-minute reduction in coking time and a 49% decrease in fuel gas consumption during a single cycle [20]. Liu and Guo claimed that coking consumes between 40% and 50% of an oven's energy input [21]. The research that Casemiro *et al.* carried out an energy analysis study to ascertain the coke oven's potential for heat recovery. According to their analysis, there was an energy loss of 3.47 GJ per unit ton of coke produced [22]. In their numerical investigation, Lin *et al.* created numerical models to look into the coke chamber's gas flow, volatile evolution, and temperature profile [23]. The research that Magrinho *et al.* carried out an energy analysis study using the ECLIPSE software to provide a coking plant's environmental impact and energy requirements characterization and optimization [24]. Mahato *et al.* attempted to do an optimization study on a coke oven to lower the gas consumption of the coke oven and boost coke production more effectively. They successfully reduced the cycle time and the amount of coke oven gas consumed after conducting a number of studies [25]. Buczynski *et al.* numerically assessed the energy performance of an industrial coking plant by using a one-dimensional time-dependent mathematical model. The moving boundary conditions were taken into consideration in the study in order to establish the system energy balance [26]. In their numerical study, Neto *et al.* used Aspen Plus software to simulate and examine the impact of a coke oven battery's combustion chamber temperature on fuel consumption. They claim that a new set of regulations can save the amount of gas used in coke ovens by 12% [27]. A numerical study conducted by Veinskii developed a couple of equations for the energy balance of a coke oven as well as the material balance of the coking process. Therefore, exergetic efficiency was determined at 57.78% for the oven [28]. Das *et al.* created predictive models to characterize the thermo-physical properties of the oven charge by taking the chemical composition and structural factors into account [29]. Tiwari *et al.* examined the coking process's rate of heat utilization. The coal cake's heat penetration rate was found to be 60% [30]. This study assessed the energy performance of a coke oven in operation at a coking plant. Coking plants are divisions of iron and steel production plants, and there are a few recent practical studies assessing the energy performance of these plants in the literature.

Global economic issues, wars, and power struggles following COVID-19, and notable increases in energy costs have resulted in an industrial contraction and increased difficulty for commercial competition. To obtain an advantage in product pricing in the market, it is crucial to minimize production costs. In an energy-intensive iron and steel facility, this study made recommendations for improvement and cost savings by analyzing the energy savings that can be achieved through system upgrades and investments. The study seeks to mitigate the effects of the current economic challenges on the production sector in this regard. The study's widespread effects include establishing a resource for young researchers and engineers who are just starting out in the iron and steel industry and raising awareness among investors about the amount of money that can be saved by making investments in energy-intensive facilities. The method and content of the study are intended to contribute to the literature as well as the iron and steel industry.

5 The coke oven's thermal characteristics

This study determines the mass and energy balance of a coke oven and assesses the oven's performance in its current configuration. Improvements to the system and prospects for energy recovery were suggested. Table 1 shows the lower heating value (LHV) and chemical composition of the MG fed into the combustion chamber.

Table 1 illustrates that the MG's LHV is roughly equivalent to 3161 kJ/Nm³. The combustion reaction in the coke oven of MG takes place with an air–fuel ratio (AFR) of 9.74.

Table 1. Chemical composition of fuel burned in the coke oven.

Content (%)	CG	BFG	MG
H_2	60.19	1.82	6.16
O_2	0.08	–	0.03
N_2	6.64	54.38	50.73
CH_4	21.75	–	1.6
CO	6.48	21.09	20.01
CO_2	2.7	22.71	21.31
C_2H_4	0.42	–	0.03
C_2H_6	1.74	–	0.13
MG LHV (kJ/kg)			3161

6 Governing equations

Equation (1) can be used to establish the general mass balance.

$$\sum m_{\text{in}} = \sum m_{\text{out}}, \tag{1}$$

where the symbols for the inlet and outlet mass are m_{in} and m_{out}. Equations (2) and (3) can be used to determine the mass balance for the combustion chamber and coke oven [31].

Equation (2) provides the mass balance for the coke oven.

$$m_{\text{coal}} = m_{\text{coke}} + m_{\text{ash}} + m_{\text{tar}} + m_{\text{COG}} + m_{\text{others}}. \tag{2}$$

In equation (2), m_{coal} is the mass of fed coal to the oven; m_{coke} is the mass of coke; m_{ash} is the mass of ash; m_{tar} is the mass of tar; m_{COG} is the mass of COG; and m_{others} is the mass of volatile gases; etc. gained per coking period. Equation (3) can be used to calculate the mass balance of the combustion chamber.

$$m_{\text{MG}} + m_{\text{comb. air}} = m_{\text{flue gas}}. \tag{3}$$

In equation (3), the mass input of the MG and combustion air into the combustion chamber is represented by m_{MG} and $m_{\text{comb. air}}$, respectively. The amount of flue gas released during a coking period is represented by $m_{\text{flue gas}}$.

The energy balance general equation is denoted by equation (4).

$$\sum E_{\text{in}} = \sum E_{\text{out}}. \tag{4}$$

The input and output energies are expressed by E_{in} and E_{out} in equation (4), respectively. Equation (5) can be used to represent energy balance.

$$Q_{\text{CMG}} + Q_{\text{SEMG}} + Q_{\text{R}} = Q_{\text{SEc}} + Q_{\text{SECOG}} + Q_{\text{SEt}} + Q_{\text{SEa}} + Q_{\text{SEfg}} + Q_{\text{shl}} + Q_{\text{ol.}} \tag{5}$$

In equation (5), the combustion energy of MG is represented as Q_{CMG}, the sensible energy of MG as Q_{SEMG}, the reaction energy as Q_R, the sensible energy of coke as Q_{SEc}, the sensible energy of COG as Q_{SECOG}, the sensible energy of tar as Q_{SEt}, the sensible energy of ash as Q_{SEa}, the sensible energy of flue gas as Q_{SEfg}, the surface heat loss by convection (Q_{cv}) and radiation (Q_r) as Q_{shl} and other losses such as openness, leakages, etc. are designated as Q_{ol}. Equations (6)–(8) can be used to estimate the surface heat loss from the surfaces of the coke oven [15, 32].

$$Q_{\text{shl}} = Q_{cv} + Q_r, \tag{6}$$

$$Q_{cv} = C_1 \sum A_s (T_s - T_a)^{1.25}, \tag{7}$$

$$Q_r = C_2 C_3 \sum A_s \left[\left(\frac{T_s}{100} \right)^4 - \left(\frac{T_a}{100} \right)^4 \right]. \tag{8}$$

The variables in equations (7) and (8) are A_s, T_s, and T_a, which represent the surface area, surface, and ambient temperatures, respectively. Also, C_1, C_2 and C_3 are constant values.

7 Energetic view of the coke oven

Equations (6)–(8) were used to compute the surface heat losses of the coke oven by applying the average surface temperatures recorded by the oven thermal camera system, which is depicted in Figure 3.

The upper section of the oven has the highest loss rate based on the heat losses shown in Figure 3. Despite the equal upper and lower surface areas of the oven, the temperature differences cause a difference in heat loss of about 1,034,892 kJ/p. The rates of heat loss from the pusher and the coke sides are fairly similar. There is 2,234,842 kJ/p in total thermal loss from the surfaces. 98.26% of the surface heat loss is lost by convection or about 2,195,989 kJ/p, and 1.74% is lost by radiation, or 38,853 kJ/p. The combustion chamber and coke oven mass balances are shown in Figure 4.

As can be seen in Figure 4, to coke the 18,625 kg of coal loaded into the coke oven during coking period, 12,044 kg of MG and 117,308 kg of air were burned in the combustion chamber. Flue gas emissions totaling 129,352 kg were released by combustion. Upon completion of the coking of 18,625 kg of coal, the following products were produced: 11,994 kg of coke, 2720 kg of coke oven gas, 1415 kg of tar, 1490 kg of ash, 1006 kg of volatile gases, etc. were

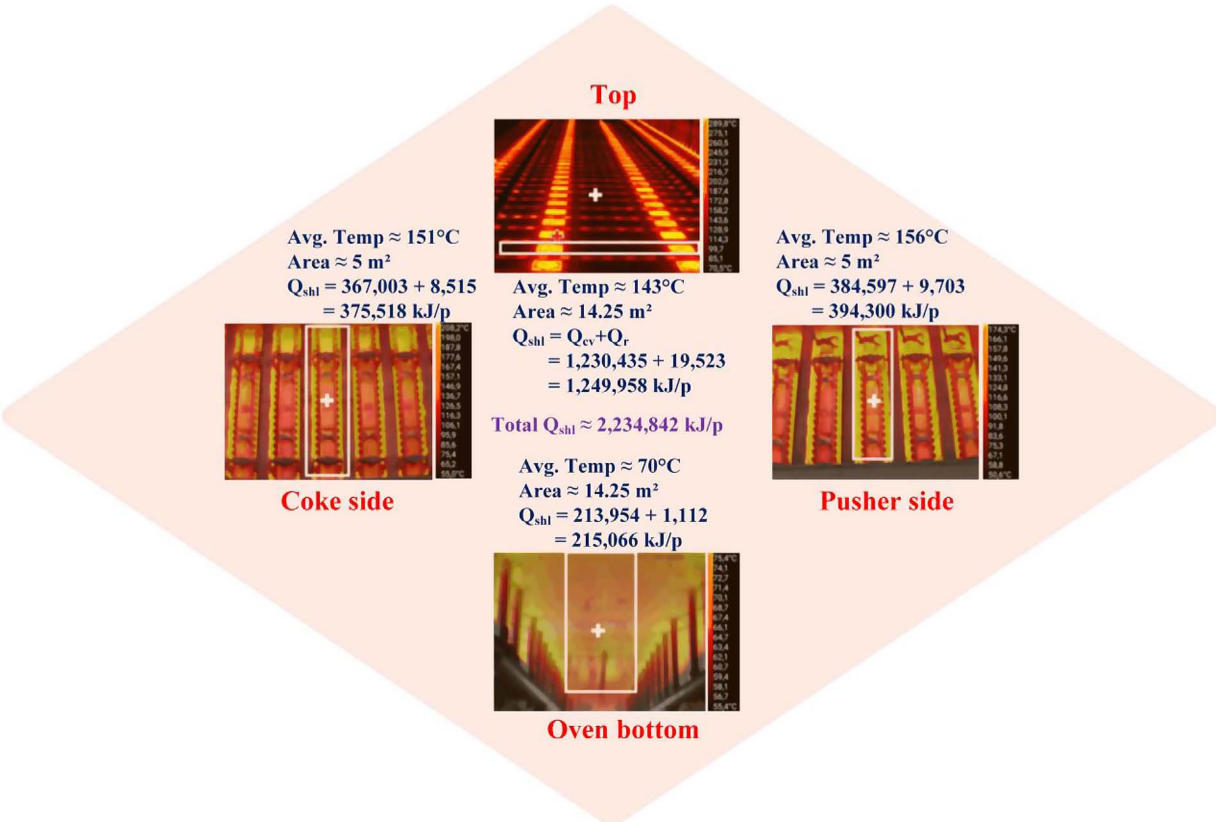
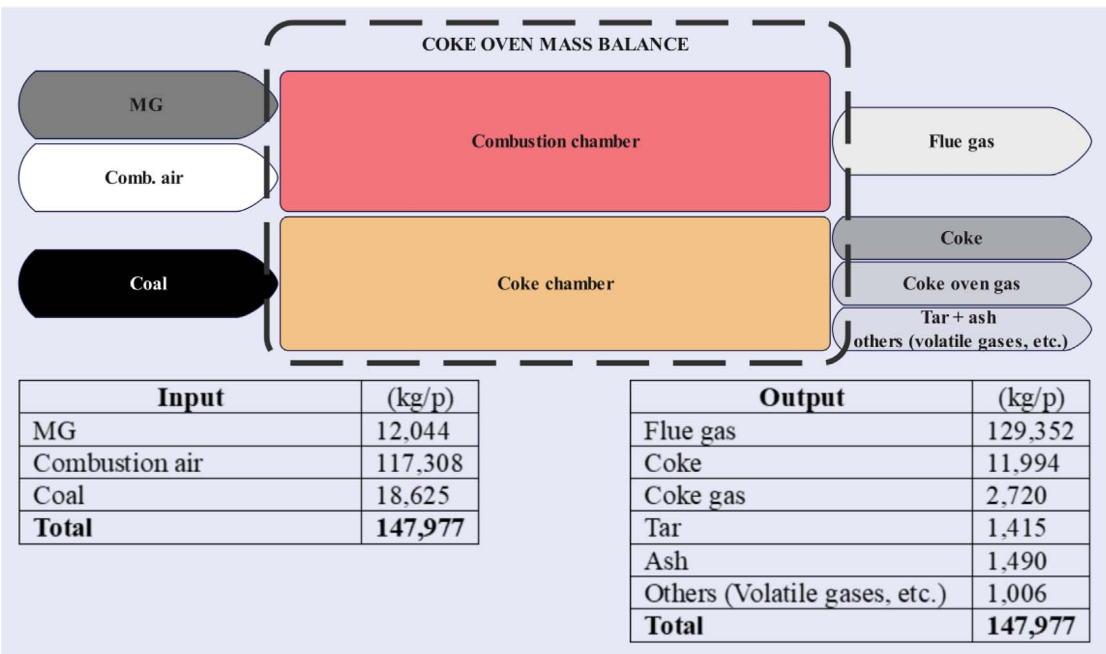


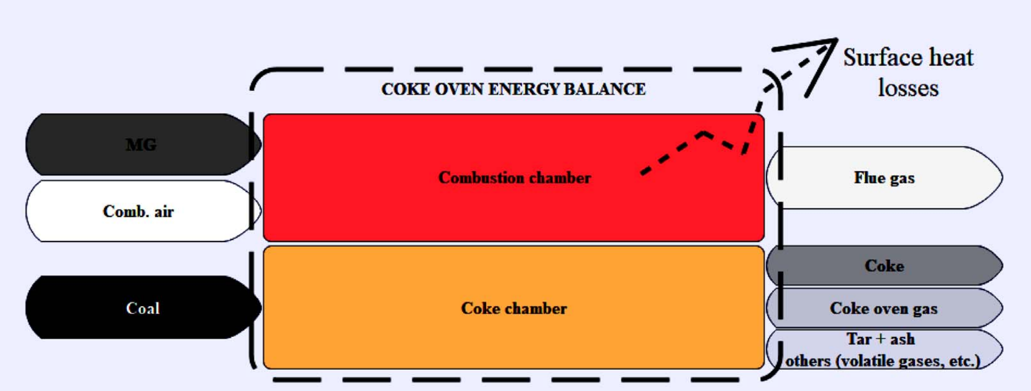
Figure 3. Oven surface temperature distribution captured by a thermal camera with estimated thermal losses.



Input	(kg/p)
MG	12,044
Combustion air	117,308
Coal	18,625
Total	**147,977**

Output	(kg/p)
Flue gas	129,352
Coke	11,994
Coke gas	2,720
Tar	1,415
Ash	1,490
Others (Volatile gases, etc.)	1,006
Total	**147,977**

Figure 4. Mass balance for the coke oven.



Input	(kJ/p)
Combustion heat of MG	38,080,500
Sensible heat of MG	886,899
Reaction energy	28,345,043
Total	**67,312,442**

Output	(kJ/p)
Sensible heat of flue gas	26,887,250
Sensible heat of coke	19,456,909
Sensible heat of coke gas	9,115,195
Sensible heat of tar	1,982,136
Ash	3,905,078
Others (Openness, leakages, etc.)	3,731,032
Surface heat losses	2,234,842
Total	**67,312,442**

Figure 5. Coke oven energy balance.

acquired. As shown in Figure 5, energy balance was attained for the coke oven.

According to the energy balance shown in Figure 5 for the coke oven, burning the MG in the combustion chamber produces approximately 38,080,500 kJ/p of combustion energy. With an ambient temperature of 20 °C as a reference, the MG fed to the oven has a temperature of 60 °C and delivers 886,899 kJ/p sensible heat to the combustion chamber. Being at the same temperature as the surrounding air, the combustion air that is fed into the oven is considered to have zero sensible energy. At high temperatures, the coal that is put into the oven transforms into coke, coke oven gas, tar, ash, and minute amounts of other volatiles. Coal reacts during the coking process, releasing some heat. The difference in the heating value of coal and the carbonaceous products that are produced during the process like coke, coke oven gas, and tar, is the amount of heat energy that is released during the reaction. The reaction energy was calculated to be 28,345,043 kJ/p. 56.57% of the energy entering the oven during the coking process comes from the mixed gas's combustion, 42.11% comes from the reaction, and 1.32% comes from the mixed gas's sensible energy. During the coking process, 34,459,318 kJ/p, or 51.2% of the energy entering the coke oven, is applied to the coal; however, 32,853,124 kJ/p, or 48.8% of the energy, escapes the oven as flue gas, surface heat losses, and other losses (openness, leakage, etc.). Figure 6 provides a visual summary of the mass and energy balance of the coke oven. Coal, coke, coke gas, and blast furnace gas heating values are shown in Figure 6 were supplied by the facility laboratories. Thermophysical characteristics of combustion air, tar, ash, and flue gas were calculated using relations and evaluations from papers written by Eisermann et al. [33], Eremin et al. [34], Fardhyanti and Damayanti [35], Ratnaningsih et al. [36], Lesniak et al. [37], Cengel and Boles [38].

Coke, tar, and ash exit the oven at 1100 °C, and coke oven gas exits the oven at 850 °C at the end of the coking process. As these products are taken out of the coke battery and allowed to cool to room temperature, the thermal energy that was gained during coking is lost to ambient. A proportional summary of the current oven's energy relationship can be found in Figure 7. Furthermore, a sizable amount of the energy input is lost to the environment due to the release of flue gas into the atmosphere, hot coke, and the cooling of the coke gas to ambient conditions. The estimates for the recoverability of these losses are also displayed in Figure 7. The energy lost during coking can be partially recovered with three distinct investments. The first option is to use a preheater to heat the combustion air using flue gas heat. The second approach involves recovering into use the thermal load of the hot coke by cooling it to the appropriate temperature inside the dry quenching unit that will be installed.

Lastly, an economizer can be used to recover a portion of the heat from the coke gas, which can then be used to heat areas, plant showers, or require hot water to process.

High-pressure water is sprayed to cool the hot coke. There is a loss of thermal energy due to the steam that is released into the atmosphere during cooling. According to a study by Takagi, 83% of the coke's sensible heat can be recovered by cooling the coke using the dry quenching method after the coking process is complete [39]. By implementing a dry quenching system in the current coke battery, it appears feasible to retrieve around 16,149,234 kJ/p of energy per oven. This amount is equivalent to about 24% of the energy input of the coke oven. Several studies reported

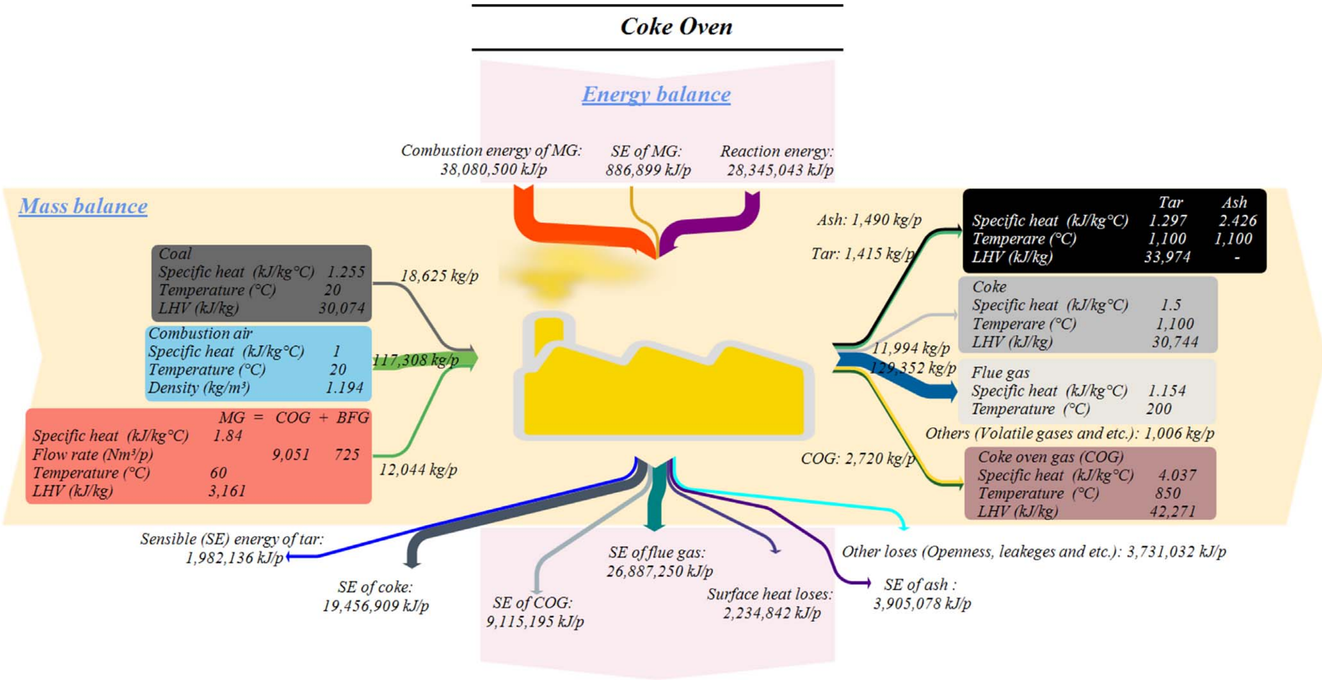


Figure 6. The coke oven's mass and energy balance.

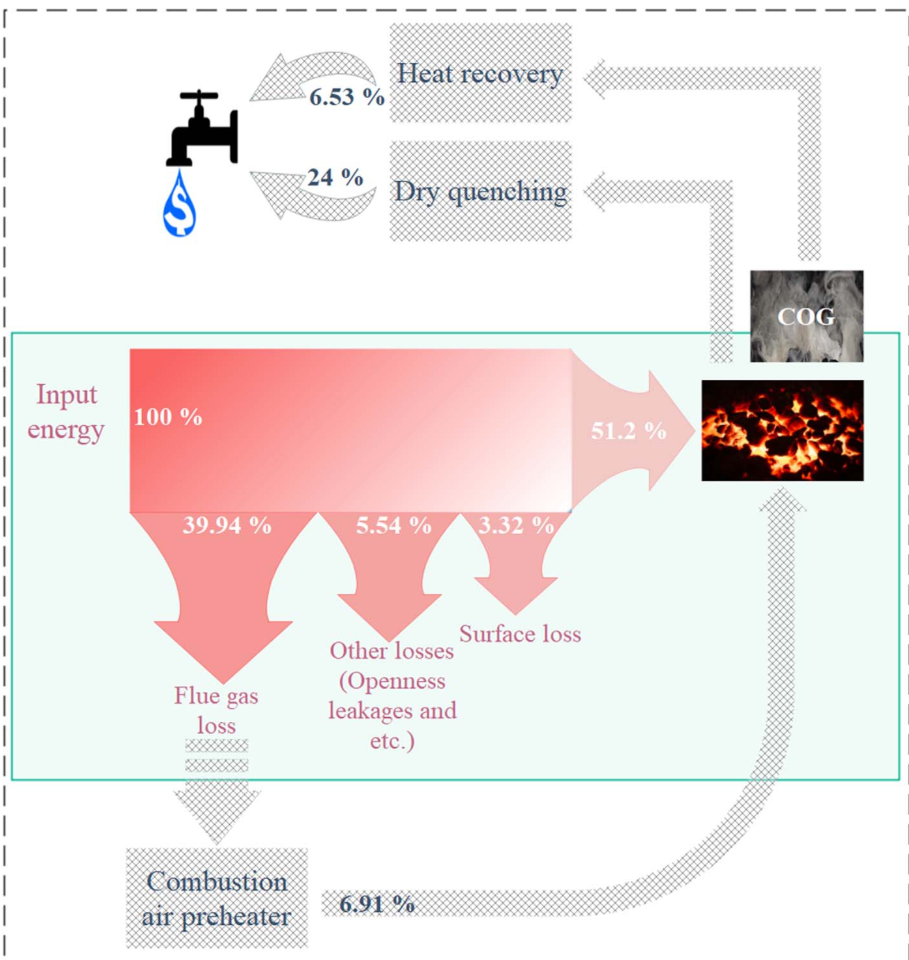


Figure 7. The proportional energy diagram of the coke oven.

in the literature claim that by recovering the sensible energy of coke oven gas into another fluid *via* a heat exchanger, it can be transformed into a form that can be used. Additionally, it states that lowering the temperature of the coke oven gas below 450 °C could result in tar condensation inside the heat exchanger and lower efficiency [40]. In a heat exchanger, approximately 4,392,256 kJ/p of heat recovery can be achieved by transferring the heat of the coke oven gas at 850 °C to another fluid until it cools to 450 °C. This amount is equivalent to 6.53% of the energy entering the coke oven and 48.19% of the sensible energy of the coke oven gas. About 200 °C is the temperature of flue gas, and before it is released into the atmosphere, some of its thermal energy can be recovered. Zhang and Chowdhury [41] and Zhang et al. [42] stated that by attaching a radial heat pipe heat exchanger to the coke oven flue gas line, hot water steam can be produced using the sensible heat of the flue gas. They claimed that in this manner, 17.31% of the sensible heat from the flue gas could be recovered [41, 42]. An energy recovery of 4,654,182 kJ/p can be achieved by using the flue gas heat from the coke oven with a heat exchanger to create steam or warm the combustion air. The combustion air was not preheated and had an average temperature of 20 °C during the study period. Recovering flue gas heat into the combustion air lowers the pressure on the environment from thermal pollution while increasing process energy efficiency. Achieving 58.11% input energy utilization can be possible through the recovery of flue gas heat into the combustion air. The recovery rate can be equal to 6.91% of the energy input. By substituting high-insulating alternative refractory materials for the precast and fireclay brick used in coke oven doors, walls, and roofs, heat loss from surfaces can be reduced. By recovery recommendations and minimizing heat loss for the coke oven under study, it is estimated that energy savings of more than 25,195,672 kJ/p can be realized. This approximate value represents 37.44% of the energy input for the coking process in the coke oven. The coke oven can save up to 8,818,485,200 kJ by performing 350 coking cycles on average per year. One kilogram of coal contains 70–80% carbon, and burning it releases 2.93 kg of CO_2, according to a study conducted by Jennifer *et al.* [43]. Turkey uses natural gas with a calorific value of 40,062 kJ/m^3, according to data from *BOTAŞ Petroleum Pipelines Co.* 2020 [44]. Natural gas is priced at \$4.1/m^3. For an oven, the potential economic size of recovery estimated amounts to \$902,496 annually. A reduction in carbon emissions of 859,153 kg per year could result from this saving, according to the evaluation. The savings' annual carbon trade can be equivalent price is roughly \$81,619. The 70 ovens in the coke battery could result in total annual savings of more than 617,294 GJ if the potential investment is made. For the coke battery, the economic value of the gain could be \$63,174,720 annually. The reduction of carbon emissions can be roughly 60.14 kt/year, and the gains in carbon trade value can be \$5,713,330/year for the coke battery.

8 Statement of significance

Based on the boundary conditions of a coke oven in the coke batteries of an integrated iron and steel plant, this study determined the mass and energy balance and identified savings potential. Due to its methodology and content, this study is an applied field study. Although raising the sector's awareness of potential savings is the study's primary goal, its broader impact is also can be assessed as providing a current resource for upcoming engineers and researchers in the field.

9 Conclusion

A single oven of a coke battery with 70 ovens is the subject of an energy analysis in this study. With the coke oven's operating conditions in mind, calculations and assessments were carried out. The study was carried out for a coking period of 18 h. The results showed that 51.2% of the input energy was found to be applied to the coal during the coking process, and 48.8% was lost because of flue gas, heat transfer from surfaces, and other ways like leaks and openness. As things stand, cooling at the end of coking process causes releasing the sensible energy of the final products into the atmosphere. An approximate recovery of 16,149,234 kJ/p sensible heat of coke per oven is anticipated with the installation of a dry coke quenching unit in the coking plant. This corresponds to 24% of the energy used for coking. It was found that by using a heat exchanger, 4,392,256 kJ/p or 6.53% of the energy supplied could be recovered from the sensible heat of the coke oven gas. By preheating the oven combustion air using flue gas heat, 4,654,182 kcal/p, or 6.91% of energy input, can be saved and the oven energy efficiency can reach 58.11%. By using refractory materials with high thermal insulation properties for walls, roofs, and coke oven doors, thermal insulation can be improved, and losses reduced. Achieving energy savings of 25.19 GJ is possible by recovering the heat from coke, coke oven gas, and flue gas for the per coking process. It was estimated that the furnace energy efficiency could increase to 82.11% with coke dry quenching and over 88.64% with coke gas heat recovery and insulation improvements. It is predicted that the coke battery could save more than 617,294 GJ/year. The projected recovery could result in an energy price equivalent of \$63,174,720, a \$5,713,330 carbon trading equivalent, and a 60.14 kt annual emissions reduction contribution.

Data availability statement

No data, models, or code were generated or used during the study.

Acknowledgments. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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