REDUCING ENERGY CONSUMPTION
AND REDUCING CO_2 EMISSIONS OF COKE PLANT

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Abstract. The efficient energy use of Coke Oven Plant is considered in this paper. The main objective is the reduction of energy consumption and reducing CO_2 emissions per production unit by use of waste heat for various needs of production site demands. The considered process consumes the external hot utilities 25.4 MW and cold utilities 24.9 MW. The use of waste heat for district heating and hot water supply allow reducing the external cold utilities by 23.5 MW. This heat can be used for heating of 1,869,825.6 m^3 in apartment buildings, municipal facilities, shopping malls and etc. The use of waste heat from flue gases for electricity production allows obtaining additionally about 7.5 MW of power that can be utilized for production needs and exported outside. The provided case studies show the pathway for an efficient retrofit of coke production and most profitable ways for investment.

Key words: Coke industry, waste heat, Total Site Integration, district heating, Energy efficiency in industry, CO_2 emissions.

1. Introduction

Due to the stable trend towards increasing the price on energy and high competition in energy-intensive industries, the problems of energy conservation in industry have become exclusively important. The most important point is the reduction of energy consumption in chemical and metallurgical industries, where the energy prices are the basic component of production cost. In recent years, Ukrainian enterprises have significantly reduced the steel production compared to 2011 by 17 % and cast iron by 15 % [1]. It is connected with a low energy efficiency of production but not only in metallurgical sector. The same situation is in the coke industry which is in production chain with metallurgy. In Ukraine, due to needs of extensive Metallurgical Industry 14 Coke-Oven factories have been set in operation. All of them were designed and built at the time of rather cheap energy resources and the design approaches did not pay attention to efficient energy use. Now all this factories, as a rule, are working far from optimum operation mode [2]. Reducing emissions is also an important challenge. For example, in 2011 Avdeevka Coke factory had 17759 tons of the harmful emission [3].

There are a lot of approaches in literature for utilization of waste heat of chemical processes that allow increasing the energy efficiency. Guang-yu M.A. et al have conducted analytical Research on utilization of waste heat of China and developed recommendations how to reduce the energy consumption for Iron & Steel Industry [4]. Shushuo Kang et al. in their work proposed a new utilization approach of the waste heat with mid-low temperature by integrating the CHP system and the ground source heat pump (GSHP) [5]. Gbemi Oluleye et al. present a ranking criterion for evaluating opportunities that utilize recovered energy from the available waste heat in process sites. Application of this methodology for petroleum refinery allowed to reduce the operating cost and CO_2 emissions by 26 % and 18 %

respectively when opportunities to use the recovered energy from waste heat within and outside the process site boundaries are explored [6].

Waste heat of the furnace, which is ejected from the flue gases can be used to generate electricity. Gabrielyan D.A. et al. have examined the potential use of magnetothermal power devices for recycling the waste heat from oil and gas companies and other waste heat sources [7]. Anton A. Kiss et al. proposed a novel selection scheme of energy efficient distillation technologies, with a special focus on heat pumps [8]. Hjaranson H. et al. described the application of the Rankine cycle to generate electricity at the ferrosilicon plant in Iceland [9].

There is high energy consumption for district heating needs in countries with a cold climate, such as Ukraine. Therefore, the potential of heat utilization for district heating must be considered. Fang Hao et al. have demonstrated potential for using low-grade industrial waste heat for district heating [10]. Jelena Ziemele et al multi-criteria model is developed to determine efficiency rating of the DH system [11]. Dario Brando et al considered the influence of the district heating temperature on the electric efficiency. . The results have highlighted that a decrease of the DH network temperature of 10 °C can improve the electric efficiency of the ORC generator of one percentage point [12].

Methods of increasing efficiency of Coke Plant by means of coke oven gas and coal gas using well described. For example Bermúdez et al. proposed a novel method of producing methanol from coke oven gas (COG), involving the CO_2 reforming of COG to obtain an appropriate syngas for the synthesis of methanol [13]. Lin et al. in the work offered a new polygeneration system with carbon capture is integrated, based on coal gas and coke oven gas inputs for methanol and power co-production. New system can achieve more than 5 % of primary energy saving ratio, and more than 50 % of exergy efficiency [14].

Formerly, Benzene Hydrocarbons Extraction and Coal Tar Distillation processes were examined by Tovazhnyansky et al during an inspection of Avdiivka Coke Plant [15]. With the help of stationary and portable devices, the measurements of process streams parameters were made. Next parameters were measured: streams temperatures, stream flow rates and compositions of the waste gases of the furnace. Cooling water stream flow rates and temperature of cooling water were measured as well as fuel consumption in the furnaces.

Partite integration of Coke Production processes were considered in the previous researches by Tovazhnyansky L et al that presented the research for reduction of energy consumption of Coal Tar distillation unit [15]. Later, Tovazhnyansky et al. presented the

research for reduction of energy consumption of separation of crude benzene at a one-column unit [16] and separation of crude benzene on a two-column unit [17] that has shown the reduction of energy consumption by 19 %. Ulyev et al. use the total temperature profiles of the production complex for estimation of the target energy values for several processes [18] and also to consider the possibility of integration for a heat pump within the overall production complex [19]. The use of Grand Composite curves and Total Site Profiles has demonstrated the possibility of heat pumps integration, which allows decreasing the external hot utilities usage by 27 % and cold utilities usage by 26.7 %, respectively [19]. However, there is still a considerable potential of utilization of waste heat of the considered processes. Mentioned processes consume the external hot utilities 25.4 MW and cold utilities 24.9 MW after heat integration of several production units [19]. The utilisation of waste heat for different needs considered in this paper.

There are some systematic approaches for the system design of chemical processes that allow to recycle waste heat.

The first is mathematical programmingthat is is divided into linear and nonlinear [20]. The task of linear programming is to find the minimum (or maximum) linear function with linear constraints. So, Yang Y. et al. used a linear programming for optimal design of district-scale distributed energy resource systems. The proposed distributed energy resource systems are found to reduce the total annual cost by 14.1 % [21]. However, in the most engineering problems of mathematical models cannot be reduced to a linear programming problem. Most mathematical programming tasks that occur in research projects and in designing tasks – a problem of nonlinear programming. Holtbruegge J. et al. provided a memetic optimization algorithm and verified its ability to handle such problems by optimizing a benchmark function. This study has shown that alternatives using reactive dividing wall columns can improve economics for industrial scale production of dimethyl carbonate and propylene glycol process up to 35 % over the base-case process [22]. However, in the design of heat exchange systems and heat recovery systems for industrial plants, there are too many variables, which greatly complicates the use of mathematical programming for this purpose.

The second direction that allows to consider the integration of the production complex is Total Site Analysis (TSA) [23]. Dhole and Linnhoff demonstrated the potential for expanding of the Heat Integration concept from individual process level to a Total Site (TS) level, which comprises of several production processes or industrial clusters. [23]. Fodor et al. modified Total Site Heat Integration (TSI) methodology

and shown the possibility of using the graphical methodologies and demonstrates using an industrial case study the implementation of a total site methodology using a stream specific ΔT_{cont} approach. The procedure allows making differences between heat transfer in the process streams inside the process and between process to utility and vise versa [24]. The paper Liew et al. demonstrated new method for calculating multiple utility levels in the Problem Table Algorithm. We further demonstrated that the Total Site Problem Table Algorithm yields more accurate results for Total Site Heat Integration analysis when compared with a graphical approach, which is prone to inaccuracies [25]. These methodologies are proposed for targeting of the minimum energy requirement of Total Site system. Velasco-Garcia et al. had put a lot of effort to show opportunities to optimize the utility system and cogeneration system in Total Site context [26]. Liew et al. [27] proposed the heat requirement targeting methodology for TSI considering the seasonal energy variation due to the integration of renewable energy and batch processes. Hackl R. et al. in [28, 29] analysed Sweden's largest chemical cluster with use of the TSA method. It shows that by site-wide collaboration it is possible to increase heat recovery and utilisation of excess heat in the chemical cluster. Proposed retrofit shown 50 % energy saving. Alaa Farhata et al. presented a new methodology that combines TSA and exergy analysis. The methodology allows for simultaneous use of both thermodynamic systems and heat exchangers networks. The combination of two types of utilities allows for better exploitation of the plants' energy profile [30]. Varbanov et al., considered advantages Total Site heat recovery targeting using multiple ΔT_{min} specifications for site processes [31]. Peng Yen Liew et al proposed methodology that able to design HEN with targeted energy requirement using Modified TS – Problem Table Algorithm and illustration on Modified TS Utility Distribution table [32]. Boldyryev et al in their work show a considerable potential for energy saving on Total Site level by heat recovery improvement by using intermediate utilities as well as capital cost reduction via minimum heat transfer area calculation [33]. Peng Yen Liew et al. in their work, an extended methodology is developed to target the minimum utility requirements in a steam system that considers the water sensible heat. The results demonstrate the significance of considering the sensible heat of water on the TS utility targets [34]. Kew Hong Chew et al. presented the research where showed extends the scope of the Pinch Analysis for process modifications of individual processes to total site heat integration [35, 36]. The Plus-Minus principle has been adapted to enable the beneficial process modification options to be selected in

order to maximise energy savings in total site heat integration. The illustrative case study shows that the Pluse-Minus principle application in the total site heat integration context can further improve heat recovery [35].

The industrial applications of TSA to existing plants has grown recently. Boldyryev et al. presented research where the energy efficiency of bromine production site is analysed. PA and TSA were used for estimation of energy saving potential and design of retrofit project. It is shown that the process with improved heat integration consumes 57 % of hot and 97 % of cold utilities required by existing production site [37]. Matsuda et al. by means of TSA for a large steel plant was able to identify large energy saving potential, especially in cooler side (power generation of 21.1 MW) [38]. Sahafzadeh et al. presented research where the energy efficiency of ammonia process site is analysed. Combined Pinch and Exergy Analysis is applied to identify how exergy loss is distributed throughout heat transfer process. The results show that 4 MW of electricity can be produced in exchange of adding 7,350 kW of high pressure steam. Total amount of exergy loss is reduced by 3,323 kW, which indicates 19 % reduction compared to the existing process [39].

The specified theoretical developments, as a rule, it isn't supplemented with the corresponding appendices of methodology. Providing the corresponding case studies is important for management of industrial sites for implementation of methodology potential and to use it for achievement of real economy in their plants.

Analysis of energy efficiency of coke oven site is considered in this work. The approach is based on TSA with heat pumps with utilisation of waste heat and detailed utility analysis. The use of the Total Site Profiles of the production complex allows to make the estimation of the target energy values for several processes. In this paper, Total Site Integration for utilization of waste heat of Coke Plant is carried out accounting the features of coke industry in order to get solution, which is close to optimal, and provide the pathway for efficient retrofit and manager decisions.

This methodology provides a link between the stage of the preliminary TSA and the implementation of the retrofit project of coke production. The objective is to reduce specific energy consumption of production complex after application of processes integration at the level of individual units and industrial complex.

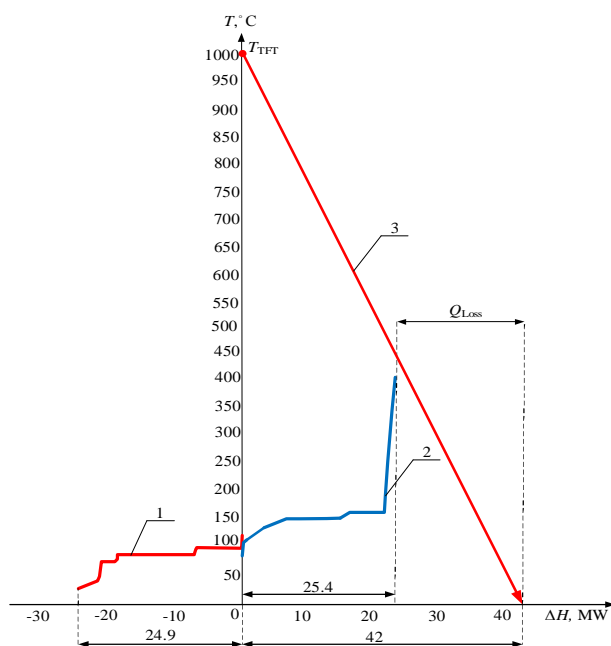## 2. Methodology

2.1. Total site analysis

Total site analysis gives the most effective way of highlighting the key points in these interactions. The use

of the total temperature profiles of the production complex has enabled the estimation of the target energy values for several processes. These profiles are constructed from the grand composite curves of individual processes that make up the production complex [40].

The use of the total temperature profiles of the production complex has enabled the estimation of the target energy values for several processes. The creation of a process profile is begun with the construction of individual Grand Composite Curves, which are further modified. The non monotonic parts of grand composite curves, i.e., so-called pockets, are isolated with vertical lines and cut off. After it is accomplished, the profiles of the source and sink of a Grand Composite Curve are shifted by ½ ΔT_{min}. In this case, the temperatures of the source profile elements are decreased by ½ ΔT_{min}, whereas the temperature of sink profile elements is increased by ½ ΔT_{min}. It is obvious that the temperature profiles are reduced to the real temperatures in each process using their own ΔT_{min} [40].

2.2. Total Site Profiles analysis

Total Site profiles of integrated process (Fig. 1) provide an opportunity to assess the potential of heat recovery inside the industrial complex, and the potential use of heat for different needs. As can been seen from the Total Site Profiles (Fig. 1), ΔT_{min} between hot and cold streams more than 50 ºC, it makes uneconomic use of the heat pump also excludes possibility of increase in a recuperation in industrial complex.

Fig. 1. Total Site Profiles of coke production^ 1 –Site Source Profile; 2 –Site Sink Profile, 3 – Profile of flue gas

2.2.1. Analysis of Site Source Profile

Site Source Profile (Fig. 1) has a 24.9 MW heat capacity. For achievement of target temperatures cold utilities (cooling water) are used. To reduce the specific energy consumption of the enterprise, it is proposed to consider the possibility of using heat capacity Site Source Profile for district heating system and hot water supply of the town Avdeevka.

When designing the district heating systems water is used as a heat carrier, the temperature of which are taking according to SNIP [41]. In district heating systems for residential and public buildings coolant temperature should not exceed 95 °C for two-pipe heating systems [41].

The schedule of the heat supply has to coincide with the schedule of internal heating, which has the temperature range 95–70 ºC. It means that at a minimum outside air temperature the heat carrier (water) flows directly into the heating devices with a temperature 95 ºC, and exits the building heating system with a temperature 70 ºC.

2.2.2. Analysis of Site Sink Profile

Site Sink Profile has a 25.4 MW heat capacity. In order to achieve the target streams temperature, streams heat up in a coke oven or using the steam generated by the CHP.

Capacity of Hot utility (Q_{Hmin}) shows the payload for furnaces. The projection of the flue gas temperature profile to the horizontal axis determines the capacity that is produced by burning fuel in furnaces. Flow rate of waste gases after the Total Site Integration is 40.77 kg/s.

The slope of the temperature profile of waste gases determines the amount of fuel entering the furnace [42].

These data can be used to calculate the heat exchangers and furnaces, as well as providing recommendations for reconstruction furnace due to declining capacity.

3. Case study

3.1. Process description

After the Total Site Integration the considered processes consumes 24.9 MW and 25.4 MW by the external cold hot utilities and 42 MW produced by the combustion of the coke ovens gas. The potential use of this power in the industrial complex is limited due to the large temperature difference

between the hot and cold streams (Fig. 1). However, this capacity can be used for the district heating needs, hot water supply system and the electricity production.

For use of waste heat for district heating needs and hot water supply, it is necessary to create new heat exchangers network. For this flow included in the source profile, recorded in stream data table 1.

Table. 1

Stream data for Site source profile

№	Stream	Type of stream	T_S, °C	T_T, °C	W, kg/s	r kJ/kg	C,kJ/ (kg·°C)	CP, kW/°C	ΔH, kW	α,kW/ (m²·°C)
1	Condensation of steam	Hot	100	100	5.55	1908	–	–	-8327,3	9
2.1	Condensation of steam	Hot	74	74	1.38	1816	–	–	-2298,3	8
2.2	Condensate from the column	Hot	74	30	1.38	–	3.23	4.45	-196	0.8
3	Refined absorption oil from the column	Hot	42	30	48.25	–	2.01	96.97	-1163,6	0.3
4	Refined absorption oil from the column	Hot	42	30	66.9	–	2.01	134.6	-1616	0.9
5.1	Condensation of steam	Hot	90	90	5.36	1908	–	–	-10227	9
5.2	Steam Cooling	Hot	90	30	5.36	–	3.23	17.32	-1039	0.56
6	Condensate of vaporizer water	Hot	90	50	0.160	–	4.19	0.670	28	0.8
7.1	Stream of light oil	Hot	135	100	0.043	–	2.03	0.087	3.04	0.5
7.2	Condensation of light oil stream	Hot	100	100	0.043	379	–	–	16.22	10
7.3	Condensate of light oil	Hot	100	45	0.043	–	2.03	0.087	4.77	0.5
8	Stripping fraction	Hot	100	80	0.642	–	1.567	1.006	20	0.3
9	Naphthalene fraction	Hot	100	95	0.428	–	1.785	0.764	4	0.3
10	Phenol fraction	Hot	100	50	0.171	–	1.823	0.312	16	0.3
11.1	Naphthalene in crystallizer	Hot	90	78	0.750	–	1.787	1.340	16.083	0.1
11.2	Crystallization of naphthalene	Hot	78	78	0.750	149.1	–	–	111.87	0.1
11.3	Naphthalene in crystallizer	Hot	78	60	0.750	–	1.787	1.340	24.125	0.1
12	District heating	Cold	70	95	173.5	–	4.38	760.4	19009	1
13	Water heating	Cold	10	65	12.79	–	4.32	83	3050	1
14	Water heating	Cold	10	65	6.31	–	4.32	83	1518	1

After analysing the data from Table 1, it can be concluded that not all streams may be used for district heating needs and hot water supply. Streams 7.3, 9 and 10 are very low heat load, which makes unprofitable inclusion of these streams in the heat exchange system. Heat capacity, which should be used is 23,552 kW.

Waste gases from the furnace consist mainly of air with small amounts of combustion products, therefore we stream heat capacity with high accuracy can be estimated by assuming that the stream consists only of air and assuming that the heat capacity air is equal to $C = 1.03$ kJ/(kg·K). Accordingly, the heat of flue gas generated by the combustion of fuel in furnaces, estimated from the equation (1):

$$Q_{\text{flue}} = G \cdot C \cdot \Delta T, \qquad (1)$$

where Q_{flue} – heat of flue gas, G – flow rate of waste gases = 43.9 kg/s, ΔT – the difference between the temperature of combustion and the temperature of ejection to the environment is 990 ºC.

Therefore, in furnaces by burning fuel is allocated 42 MW, equivalent to 4.89 tons of conventional combustion of fuel per hour.

3.2. District heating and water heating

In order to calculate the heat transfer equipment it is necessary to determine which streams can be used for district heating and which are for hot water supply system. It can be made by means

of the Grid Diagram for the considered streams. (Fig. 2). In the diagram grid applied a new heat transfer equipment, capacity and temperature were calculated.

Having constructed the chart, we determined that capacity, which can be used for district heating, is 18,984 kW (Fig. 2), and capacity that can be used for hot water supply is 4,568 kW (Fig. 2).
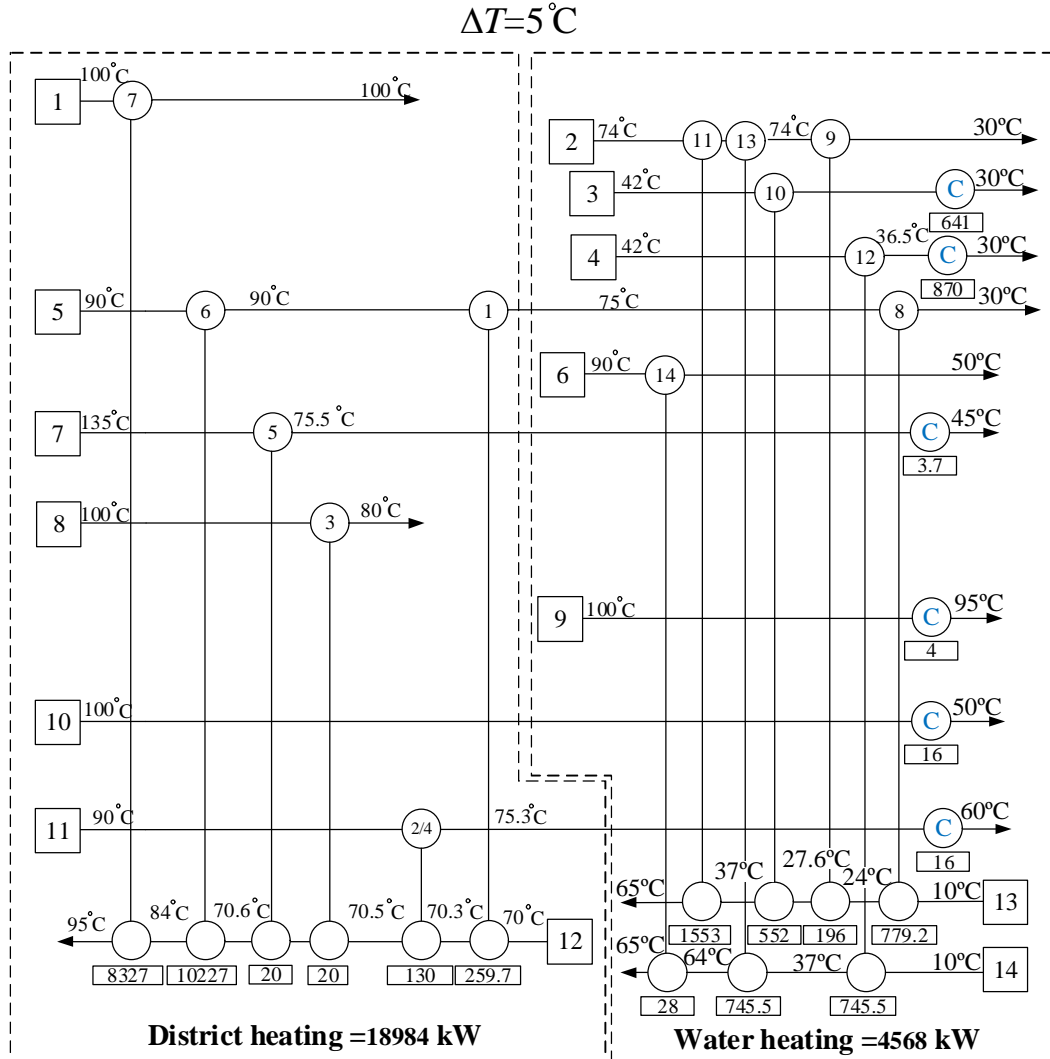

Fig. 2. Grid diagram of considered process

To calculate the mass flow rate of the water circulating in the district heating system, use the equation (2):

$$G_{\text{Water}} = \frac{Q_{\text{DH}}}{C_{\text{Water}} \cdot \Delta t}, \qquad (2)$$

where G_{Water} – the water mass flow, for district heating system; $Q_{\text{от}}$ – the maximum heat capacity of district heating system; C_{Water} – heat capacity for water; Δt_1 – the temperature difference between supply water and return water according to schedule, that is 25 °C.

The mass flow rate of the water circulating in the district heating system is 624.6 tons per hour.

Based on the temperature chart, the maximum load is 18,984 kW.

The potential use of heat from the Site source profile for the hot water system is 4,568 kW. Hot water temperature should be 65 °C [41]. The mass flow rate of water to the hot water system is 68.3 tons per hour.

The brief characteristics of the new heat exchangers are listed in Tables 2–3. New plate Compablock heat exchangers (Alpha Laval) were installed in streams with phase change. In cases where the flow does not change the phase state, gasketed plate heat exchangers installed [43].

Table 2

Heat exchangers for the district heating system
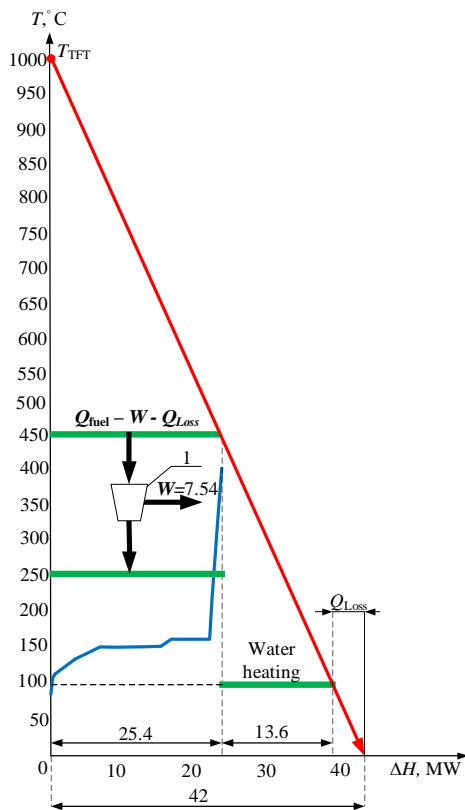
Heat exchanger	Load, kW	Hot flow					Cold flow					Surface area, m²
		stream no.	T_{init}, °C	T_{fin}, °C	Vapour fraction		stream no.	T_{init}, °C	T_{fin}, °C	Vapour fraction		
					init.	fin.				init	Fin	
T-1	259.5	5	90	75	0	0	12	70	70.34	0	0	28.82
T-2/T4	130	11	90	78	1	0	12	70.34	70.5	0	0	11.4
T-3	20.5	8	100	80	0	0	12	70.5	70.53	0	0	0.92
T-5	20	7	135	75.5	1	0	12	70.53	70.56	0	0	1
T-6	10227	5	90	90	1	0	12	70.56	84	0	0	166.1
T-7	8327	1	100	100	1	0	12	84	95	0	0	199.0
∑	18984	–	–	–	–	–	–	–	–	–	–	407.24

Having calculated parameters of heat exchangers, we can determine the potential volume of the heated buildings by a equation (3):

$$V = \frac{Q_{DH}}{a_{air} \cdot q_0 \cdot (t_{in} - t_{out})} \cdot L, \qquad (3)$$

where V – the volume of the heated buildings, Q_{DH} – the load on the heat exchange equipment, a_{air} – coefficient taking into account the change of the specific heat load, depending on climatic conditions = 1.06, t_{in} – the temperature inside the building = 18 °C, t_{out} – the outside temperature = -15 °C L – loss in the connecting pipes from the heat source (recuperative heat exchanger) to the building we accept 3 %.

Therefore, the volume of buildings that can be heated is 1,813,730.7 м³. Similarly, we count a heat exchanger surface area for hot water supply (table 3).

Having presented profiles of new district heating system, hot water supply and a source profiles in one Figure, it is possible to see that the recuperation of warmth will make 23.5 MW, and use external cold utilities will be reduced to 1.4 MW (Fig. 3).

Table 3

Water heating

Heat exchanger	Load, kW	Hot flow					Cold flow					Surface area, m²
		stream no.	T_{init}, °C	T_{fin}, °C	Vapour fraction		stream no.	T_{init}, °C	T_{fin}, °C	Vapour fraction		
					init.	fin.				init	fin	
T-8	779	5	75	30	0	0	13	10	24	0	0	10.34
T-9	196	2	74	30	0	0	13	24	27.6	0	0	5.94
T-10	522	3	42	36.6	0	0	13	27.6	36	0	0	123.3
T-11	1552.7	2	74	74	1	0.4	13	36	65	0	0	18.14
T-12	745.5	4	42	36.5	0	0	14	10	37	0	0	123.3
T-13	745.5	2	74	74	0.4	0	14	37	64	0	0	9.18
T-14	28	6	90	50	0	0	14	64	65	0	0	1
∑	4568	–	–	–	–	–	–	–	–	–	–	291.2

Fig. 3. Site source profile with new District heating and new water heating systems: *1* – Site source profile; *2* – District heating; *3* – Water heating

3.3. Use the energy of flue gases

After the TSI of during fuel combustion in furnaces produces 42 MW, while 16.6 MW are losses with the outgoing flue gases (Fig. 1). The use of waste heat for electricity production could significantly reduce the unit costs of the company. To assess the potential use of flue gases will consider Site sink profile (Fig. 4).

Fig. 4. Site sink profile with integrated turbine
1 – The turbine for electricity production

Let's define quantity of thermal energy which is supplied to the turbine [41]:

$$Q_{th} = Q_{fuel} - W - Q_{Loss}, \qquad (4)$$

where Q_{fuel} – heat of flue gas, W – the turbine operation, Q_{Loss} – heat losses.

The amount of heat that is supplied to the turbine will be 25.4 MW.

The quantity of electricity generated by the turbine can be estimated by following equation (5):

$$W = Q_{fuel} \cdot Ck \cdot (1-0.01), \qquad (5)$$

where W – the turbine operation; Q_{fuel} – heat of flue gas; Ck – conversion level of thermal energy in the electric power = 0.3 [44]. Thus it is necessary to consider that about 1 % of the developed electric power is spent for needs of the unit itself [44].

Thus, in the conversion of waste gases produced 7.54 megawatts of electricity. The utilization of 13.6 MW of heat flue gas by installing a heat exchanger (air-water) for heating water for the needs of hot water supply is also considered. Calculation of heat transfer surface is carried out using the following equation (6):

$$F = \frac{Q_{WH}}{K \cdot \Delta t_{mean}}, \qquad (6)$$

where Q_{WH} – the heat load on the hot water supply; K – heat transfer coefficient; Δt_{cp} – mean temperature difference. The heat transfer coefficient is calculated by the equation (7):

$$K = \cfrac{1}{\cfrac{1}{a_{WG}} + \cfrac{1}{a_{Water}} + \left(\cfrac{d}{l} + R\right)}, \qquad (7)$$

where α_{WG} и α_{W} – heat-transfer coefficient for the stream of waste gases = 50 W/m·K for the water stream = 700 W/m·K; δ – wall thickness; R – the thermal resistance of the wall material and pollution = 0.0001 m·K/W.

Surface area for new heat exchanger (air-water) is 5966 м².

4. Results and discussion

Using waste heat from coke plant for district heating and hot water supply, allows to reduce the consumption of external cold utilities by 23.5 kW at installation 698.4 m² heat exchange surface area. Must consider that the heating season lasts six months, and hot water supply for a year. Capacity which during the winter period is used for district heating needs, comes to the summer period on heating of water for hot water supply. The payback period is estimated by the equation (8):

$$P_1 = \frac{A_{ht} + B_{ht}\left(S\right)^c}{(Q_{Cold} - Q_{NEWCold}) \cdot S_{Cold} + (Q_{DH} \cdot S_{DH} + G_{WH1} \cdot S_{WH} \cdot 8000 + G_{WH2} \cdot S_{WH} \cdot 4000)} \, , \qquad (8)$$

where A_{ht} = 50,000 USD, B_{ht} = 500 USD for gasketed plate heat exchangers and 700 USD for Compablock heat exchangers, S is the heat exchange surface area, m², and, as a rule, c = 0.87 for plate heat exchangers [43], Q_{cold} – requirement for cold utility before integration, $Q_{NEWcold}$ – requirement for cold utility after integration S_{Cold} – the cost of cold utilities = 30 USD/(kW yr.), Q_{DH} – requirement for District heating system, G_{WH1} – hot water consumption = 68.4 m³/h, G_{WH1} – hot water consumption = 283.7 m³/h, S_{DH} – cost of 1 kW of heat energy for district heating system = =92.9 USD/(kW yr.) S_{WH} – the price for one cubic meter of hot water = 1.68 USD, 8000 and 4000 – is the amount working hours for the hot water system.

Capital costs is 899,853.9 USD. The annual profit from the implementation of the project is 3,532,386.9 USD, Payback period 3 months. Using the energy waste gases allows obtaining 7.54 MW of electricity.

The heat exchanger with surface area is 5,966 m² must be installed for use 13.6 MW heat capacity from the waste gases for hot water supply needs. Payback period estimated by the formula (9):

$$P_2 = \frac{A_{ht} + B_{ht}\left(S\right)^c}{G_{WH} \cdot S_{WH}} \qquad (9)$$

where A_{ht} = 50,000 USD, B_{ht} = 500 USD, S is the heat exchange surface area, m², and, as a rule, c = 0.87 for plate heat exchangers [43], G_{WH1} – hot water consumption= =203.6 m³/h, S_{DH} – cost of 1 kW of heat energy for district heating system = 92.9 USD/(kW yr.) S_{WH} – the price for one cubic meter of hot water = 1.68 USD.

Capital cost is 1,013,448 USD. The annual profit from the implementation of the project is 2,731,516.8 USD. Payback period of 0.37 years.

The results can be represented graphically on Total Site profiles (Fig. 5).

Numerical estimates of the energy consumption and recuperation in the existing and proposed projects are given in Table 3. The integration of individual processes and the integration of the TSA have been published previously.
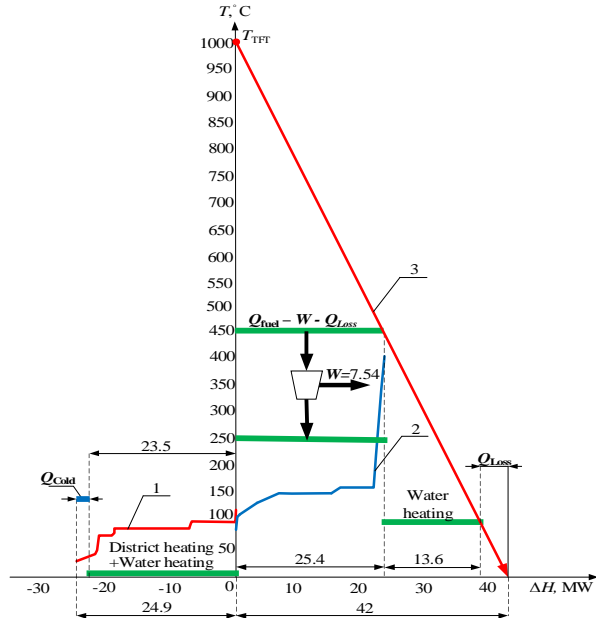

Fig. 5. Heat recovery potential on Total Site level: *1* – Site source profile; *2* – Site sink profile, *3* – Profile of flue gas

Table 3

Energy consumption and recuperation in the existing heat exchange system and the heat exchange system from the proposed project of reconstruction

Energy characteristic of the process	Process with existing heat exchange system	Integration individual processes	Total Site Integration	Integration after TSI
Power of hot outer energy carriers, MW	34.782	28.2389	25.3914	17.85
Power of cold outer energy carriers, MW	33.5091	26.9993	24.906	1.4
Heat recuperation power, MW	17.44	23.97	26.82	63.92

Despite the fact that this methodology has high efficiency, the project can face difficulties because of the imperfection of the legislative framework in the field of energy regulation.

5. Conclusion

The methodology to determine the potential use of waste heat after Total Site integration has been proposed. The use heat of Site source profile for new district heating system and water heating system allows reducing the external cold utilities usage by 23,522 kW. The heat transfer area and number of heat exchangers for a retrofitted heat exchanger network have been identified. The annual profit from the implementation of the project is 3,532,386.9 USD, and the payback period is three months.

The use of waste heat from flue gases for electricity production allows obtaining about 7.5 MW of power that can be utilized for production needs and exported outside. Harmful emissions in the atmosphere are reduced in proportion to reduction of hot utilities (furnace payload).

The ability to use the waste gases for heating the water has been considered and the parameters of the heat exchanger were calculated. The heat loss from the waste gases decreased from 16.6 MW to 3 MW. The annual profit from the implementation of the project is 2,731,516.8 USD, and the payback period is 0.37 year.

The provided case studies show the pathway for efficient retrofit of coke production and most profitable ways for investment. The results of this work can be used in coke and other industries for efficient energy use, CO2 mitigation and sustainability improvement of industrial regions.

Acknowledgments

Nomenclature

ΔH – change of enthalpy;
C – heat capacity;
CP – flowrate heat capacity;
Q_{Cmin} – requirement for cold utility;
T_S – supply temperature, °C;
T_T – target temperature, °C;
T_{TFT} combustion temperature of flue gas, °C;
α – heat transfer coefficient;
c – coefficient characterizing the linear dependence between the cost of a heat exchanger and its heat-exchange surface area;
W – flowrate;
r – heat of vaporization
P – payback period;
A_{HE} – cost of the installation of a heat exchanger;
B_T – rate equivalent to the cost of 1 m^2 surface area of heat transfer;
S_{cold} – cost of external utilities, USD;
W – turbine operation, kW.

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