

## An innovative method for waste heat recovery from flue gas treatment system through an additional economizer

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**Abstract** The usage of wet methods for flue gas dedusting from coal-fired boilers is associated with significant heat losses and water resources. Widespread emulsifiers of the first and second generation are satisfactory in terms of flue gas cleaning efficiency (up to 99.5%), but at the same time do not create conditions for deeper waste heat recovery, leading to lowering the temperature of gases. Therefore, in the paper, an innovative modernization, including installing an additional economizer in front of the scrubber (emulsifier) is proposed, as part of the flue gas passes through a parallel bag filter. At the outlet of the emulsifier and the bag filter, the gases are mixed in a suitable ratio, whereby the gas mixture entering the stack does not create conditions for condensation processes in the stack.

**Keywords:** Waste heat recovery; Flue gases; Feasibility study; Battery emulsifier second generation; Bag filters

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## Nomenclature

$\eta$	–	Einstein coefficient
$\dot{H}$	–	enthalpy rate, kJ/s
HHV	–	higher heating value, kJ/kg
$i$	–	specific enthalpy, kJ/kg
$\dot{m}$	–	mass flow rate, kg/s
$p$	–	pressure, bar
$T$	–	temperature, °C
$v$	–	velocity, m/s
$\dot{Q}$	–	heating rate, kW

## Subscripts and superscripts

<i>air</i>	–	air for heating flue gas in the mixing chamber
<i>be</i>	–	battery emulsifier
<i>ec</i>	–	economizer
<i>fg</i>	–	flue gas
<i>w</i>	–	water

## Abbreviations

AP	–	air preheater
CHP	–	combined heat and power
FWCRS	–	flue gas waste heat cascade recovery system
HPE	–	high-pressure economizer
IRR	–	internal rate of return
LPE	–	low-pressure economizer
LTE	–	low-temperature economizer
NPV	–	net present value
NPVQ	–	net present value coefficient
ORC	–	organic Rankine cycles
PB	–	simple payback period
SAH	–	steam-air heater
TPP	–	thermal power plant
WHR	–	waste heat recovery
WHRU	–	waste heat recovery unit

## 1 Introduction

It is well known that recovering waste heat from flue gas is beneficial for the improvement of the unit efficiency in power plants. However, less is known about the exergy destruction, the greenhouse effect, environmental pollution, economic features and other issues. Therefore, to reduce coal consumption and improve the efficiency of coal use in the existing coal-fired units there is a need to solve the full spectrum of waste heat recovery (WHR) problems. If in the coal-fired power plant units the exhaust flue gas

temperature can reach even more than 130°C, and about 50–85% of a boiler heat loss follows from the exhaust flue gas energy, it means that it accounts for 3–8% of the total energy input of the units [1]. Waste heat recovery leads to a reduction of the total losses of the steam generator and increases its thermodynamic efficiency [1]. Therefore, much research has been done on the feasibility of boiler flue gas waste heat recovery. One possibility is to use the low-temperature heat of the flue gases, together with the latent heat of contained water vapour, to preheat the low boiling point working fluid in the organic Rankine cycle (ORC) installations [2]. In order to accurately model this type of thermodynamic cycles, it is necessary to know both the outlet gas temperature [3] and the optimum boiling point of the low boiling point working fluids [4]. Sometimes, however, the possibilities for lowering the temperature of the exhaust gases are limited by the applied method of gas dedusting.

In some Asian countries, including Russia and Kazakhstan, wet gas dedusting methods became very popular [5]. The reason for this is the lack of policy for recovering the collected ash after the electrical precipitators and selling it as a building material. In the European Union, where gases are mainly cleaned by electrical precipitators, 80% of the waste ash is sold, which increases the economic feasibility of using this type of gas dedusting [6]. In recent years, second-generation battery emulsifiers have been widely used in many thermal power plants (TPPs) in Kazakhstan, firing mainly Ekibastuz/Karazhyra coal [7, 8].

The principle of operation of the second generation battery emulsifiers is a highly efficient heat and mass transfer between the ascending flow of flue gas swirled in the blades and the liquid supplied by the counter flow with the formation of a vortex emulsion layer in which effective gas cleaning takes place (the so-called phase inversion mode) [9]. Technical indicators of the second generation battery emulsifiers can be found in [10, 11]. A turbulent wet scrubber is described in [12].

Let us note that the benefits following the installation of wet scrubbers are: (i) low noise, stable operation, simple operation, and low investment costs, (ii) high dust efficiency, (iii) corrosion-resistant, anti-ageing, long service life, and can be customized according to requirements. These advantages, combined with the lack of a market for ash disposal and their relatively low cost, have made the use of these battery emulsifiers more acceptable compared to electrostatic precipitators [13, 14].

Let us recall that the flue gas waste heat is usually recovered by heat exchangers located at the flue tail of power plant boilers. For instance, Stevanovic *et al.* [15] studied the improvement of unit efficiency when a high-

pressure economizer (HPE) is used for recovering flue gas waste heat. This HPE was supplied cold or hot feed water on an old 620 MWe coal-fired unit, and the case of HPE fed with cold water proved to be competitive. To recover more waste heat effectively from flue gas, many flue gas waste heat depth use systems were put forward and analysed. The systems were more complex and can heat feed water and combustion air simultaneously. Wang *et al.* [16] assessed the coal-saving effect of a 600 MWe unit with a low-pressure economizer (LPE) installed in three cases, and 2–4 g/kWh standard coal was saved. In the papers, by Xu *et al.* [17, 18] it was proposed a novel flue gas waste heat recovery system (WHRS) in which a low-temperature economizer (LTE) is located between a high-temperature air preheater (AP) and a low-temperature AP, and 5.6 MW of exergy destruction is saved. Han *et al.* [19] proposed a new heat integration system based on the bypass WHRS. It consists of a steam-air heater (SAH) that is added between the air preheater (AP) and the pre-positioned AP. As a result, 4 g/kWh standard coal was saved in a 1000 MWe unit. Quite similarly, Yan *et al.* [20] optimized the bypass WHRS on a 1000 MWe unit by recovering the waste heat from the flue gas after the wet flue gas desulphurization. In this case, the net standard coal consumption was reduced to 5.38 g/kWh.

Fan *et al.* [21] developed a new system by combining flue gas WHR and the bleeding steam cascade energy utilization. The simulation result presents that the net heat rate of the novel cycle is improved by 104.8 kJ/kWh and the cycle net efficiency is increased by 0.61%. A feasibility study proves that it is possible to implement the novel cycle in a newly planned power plant. The total investment capital of the novel cycle was calculated at 7.44 million USD and the net annual revenue at 0.59 million USD compared with the reference cycle. A static capital investment payback period is expected within 15 years in a newly planned power plant.

Yang *et al.* [22] proposed a concept of WHRS on a 1000 MWe coal-fired unit, in which the AP was divided into the high-temperature AP, the main AP and the low-temperature AP, the waste heat from flue gas was used to heat condensed water by LTE and heat the combustion air by the APs, and 13.3 MWe additional net power output was generated.

Other possibilities are related to the application of organic Rankine cycles (ORC) – these possibilities follow the principal rules [23, 24]. In the paper of Huang *et al.* [25], three retrofit concepts were analysed and comprehensively compared in terms of thermodynamic and economic performance. The waste heat recovery via the ORC, an in-depth boiler-turbine integration, and coupling of both are proposed. The results show that the

in-depth boiler-turbine integration achieves better temperature matching of heat flows involved for different fluids and multi-stage air preheating, thus a significant improvement of power output which is much greater than that of an ORC-only system.

The goal of the paper is to present an economic analysis of an innovative flue gas dedusting method composed of a parallel battery emulsifier and bag filters. To achieve this, firstly, based on the in-house model of determining allowable flue gas temperature, the dew point of sulfuric acid vapour contained in the flue gases was calculated. This step is necessary to provide the proper thermodynamic parameters for modernization. Next, the analysed system before and after modernization is mathematically modelled and thermodynamically analysed for choosing the most efficient and optimal work parameters. Finally, the economic feasibility of the implementation of the proposed method is performed using data from several different thermal power plants.

To characterize the proposed novel concept in detail, this publication is divided into seven sections. The Introduction provides a detailed overview of the current state of relevant knowledge. In Section 2, the technical specifications on how to analytically determine the allowable flue gas temperature within the proposed system are presented. Innovative aspects of the solution (modernization) proposed are discussed in Section 3, which represents progress in the analysed field and at the same time significantly differ in favour of the developed system as compared to those currently operating on the market – we mean six Kazakh TPPs. Section 4, shows details of the mathematical model of the proposed system, its verification and a comparative analysis of six Kazakh heat-power plants. A brief Section 5 describes the results of the investment process of economizers for different steam boilers and conditions, and Section 6 contains conclusions regarding financial analysis of whole modernization, research and analysis of the developed system, as well as plans for its potential development, further research and testing. Finally, Section 7 looks specifically at the environmental and other benefits/impacts of the project.

## 2 Determination of the allowable temperature of exhaust gases after the economizer

The technical and economic analysis is made for waste heat recovery from different types of boilers using different types of coal (Table 1). There are two alternatives: (i) installation of an additional economizer or (ii) using

an air preheater before the existing battery emulsifier. However, which of the two possible options to choose should determine the allowable level of cooling of the exhaust gases in order to avoid low-temperature corrosion on the non-heated surfaces of the heat exchangers [13, 14]. In this paper, an additional economizer and a bag filter are considered.

The elementary composition and calorific value of the used coals are presented in Table 1. It should also be noted that the price of coal varies from region to region, which affects the payback period of WHR facilities.

Table 1: The elemental composition and calorific value of Ekibastuz and Karazhyra coal [5, 8].

Parameter	Units	Ekibastuz coal	Karazhyra coal
Carbon, $C^r$	%	46.03	50.65
Hydrogen, $H^r$	%	2.85	3.94
Nitrogen, $N^r$	%	0.86	0.97
Oxygen, $O^r$	%	6.56	13.41
Sulphur, $S^r$	%	0.70	0.28
Water, $W^r$	%	5.00	5.80
Ash, $A^r$	%	38.00	25.00
HHV	kJ/kg	16 493	18 828

Complete exclusion of low-temperature corrosion for economizers is provided if the temperature of the wall of the coldest section is higher than the dew point temperature by not less than 5 up to 10°C (minimum temperatures refer to minimum loads) [7].

An original method [1] was used to analytically determine the allowable flue gas temperature by calculating the dew point of sulfuric acid vapour contained in the flue gases. According to the methodology, the calculated allowable flue gas temperature is 94.5°C. In the present analysis, it is accepted that the temperature to which the gases in the utilization facility will be cooled down is 120 up to 125°C. At this temperature, the gases will enter the emulsifier or scrubber.

It should be noted that in emulsifiers, almost complete trapping of sulfuric anhydride occurs. This means that the dew point of sulfuric acid vapours  $t_{dp}^t$  contained in the flue gases after entering the emulsifiers approaches the dew point of water vapour itself. Therefore, it is not required to determine the stated temperature before the emulsifier stage.

### 3 The essence of the innovative method for waste heat recovery

#### 3.1 Baseline (current situation before modernization)

Most of the analysed TPPs are characterized by high exhaust gas temperatures ( $150\text{--}180^\circ\text{C}$ ), leading to large heat losses with the exhaust gases and respectively low efficiency of the steam generator. A characteristic feature of steam generators is that the process of cleaning the gases is accomplished by battery emulsifiers of the first or second-generation [26, 27] and they are used in almost all thermal power plants, except for those in which the first generation emulsifiers or even scrubbers are still in operation. To prevent corrosion of the gas path, the purified gases at the outlet are heated by adding hot air to them after the boiler air preheater. After heating in the mixing chamber, the purified gases are sent through the flue gas fan and then into the stack. The existing gas dedusting system not only does not allow the utilization of waste heat from the gases but leads to a further reduction in the efficiency of the steam generator by about 3 up to 4%. Figure 1 shows a schematic diagram of the gas path after the steam generator with a battery emulsifier.

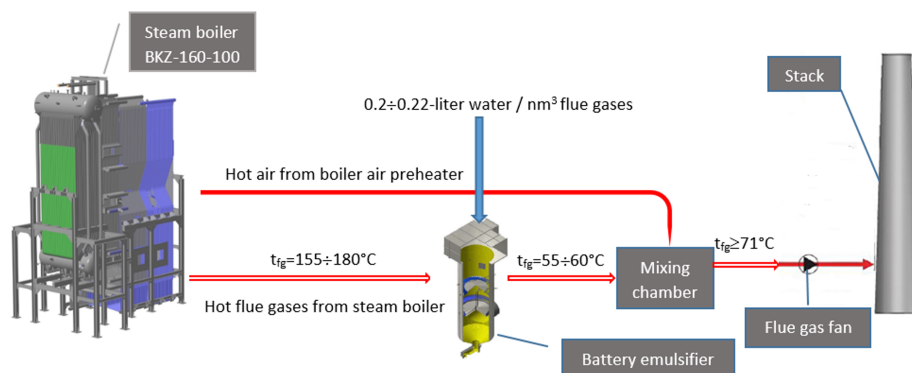


Figure 1: Schematic diagram of the gas path after the steam generator with a battery emulsifier.

#### 3.2 Description of the innovative method for heat waste recovery

Figure 2 shows two standard solutions for flue gas cleaning reactors. They are usually applied for the whole mass flux of flue gases.

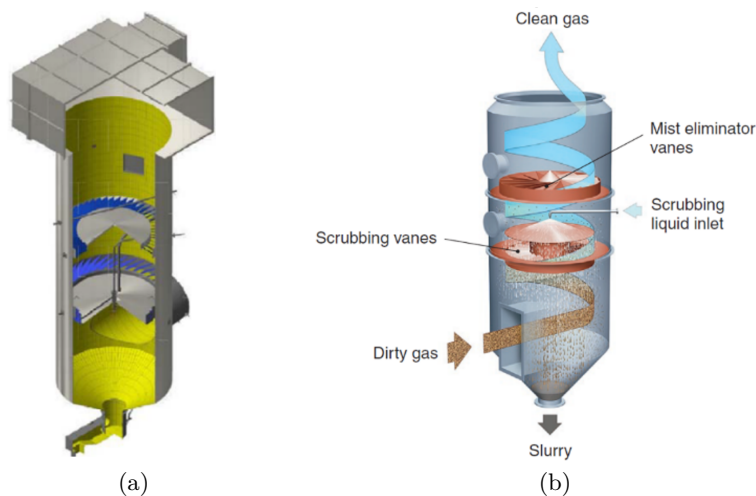


Figure 2: Flue gas cleaning plants: (a) battery emulsifier of a second-generation [9]; (b) wet scrubber (turbulent) [12].

The technical parameters of the turbulent wet scrubber include [12]:

- 100% efficiency with a particle diameter greater than 1  $\mu\text{m}$  (at the nominal flow rate),
- a maximum pressure drop of 217  $\text{mm}_{\text{H}_2\text{O}}$  for a liquid head of 0.36 m and a gas flow rate of 7  $\text{m}^3/\text{min}$ .

The method proposed to improve energy efficiency provides for more complete use of thermal energy of flue gases as well as the elimination of the need for additional preheating before entering the chimney. This can be achieved by directing a portion of the gas stream into a bag filter, which does not significantly reduce their temperature, and then mixing this portion with the mainstream in the existing mixing chamber to achieve the desired overall temperature. The bag filter pressure drop, which is connected in parallel with the emulsifier, (140 up to 170  $\text{mm}_{\text{H}_2\text{O}}$ ) does not differ from the resistance of the battery emulsifier, which will allow using the existing induced draft fan without changes. Moreover, such a scheme also allows deeper heat recovery from the main flue gas stream using an additional air preheater or economizer. Accordingly, two options for the implementation of this event are proposed:

1. Installation of a bag filter and economizer.
2. Installation of a bag filter and an air preheater.



Thus, several positive effects are simultaneously achieved:

- Energy consumption for heating flue gases with hot air is eliminated.
- Part of the thermal energy of flue gases is utilized.
- Deeper cleaning of gases from ash is carried out.
- Emulsifiers are unloaded and the volume of flush water directed to the ash dump is reduced, which reduces the load on the emulsifier and flush water pumps and theoretically makes it possible to reduce their power consumption (for example, by installing a frequency control when it is economically justified by the current prices and tariffs).
- If there is market demand and economically viable transportation opportunities, baghouse ash can be sold for use in construction, agriculture or other industries.

After installing the bag filter, as a result of eliminating the need for heating the exhaust gases with air and saving significant heat output, the annual coal consumption will decrease. At the same time, the level of cleaning of the total volume of gases from ash will be increased by about 15%.

The following option envisages improving energy efficiency with the installation of an additional economizer together with a bag filter. Only part of the gas flow (85%) should pass through the economizer and emulsifier, and the rest (about 15%) will enter the baghouse filter in parallel flow. A smaller part of the gases passing through the bag filter, after deeper cleaning, will be mixed with the rest of the gas volume. Even though after cleaning in the emulsifier, the relative humidity of the main gas stream will increase to 100%, and its temperature will drop to 50 up to 60°C, due to the rather high temperature of the gases after the bag filter, the mixed gases before entering the chimney reach the required 70 up to 72°C.

Figure 3 shows a diagram of the gas path after the installation of a bag filter and economizer.

In the economizer in front of the emulsifier, the exhaust gases will be cooled from the initial flue gas temperature down to 125°C, and the water flow from the return heating network entering the economizer will be heated from 55°C to a certain value depending on the water flow. The heat output of the economizer is calculated at an average boiler load. As a result of installing an economizer, the annual coal consumption will decrease by 1 800 up to 2 200 tons. Installing an economizer will lead to a slight increase in electricity consumption for water pumps. However, the total fuel savings

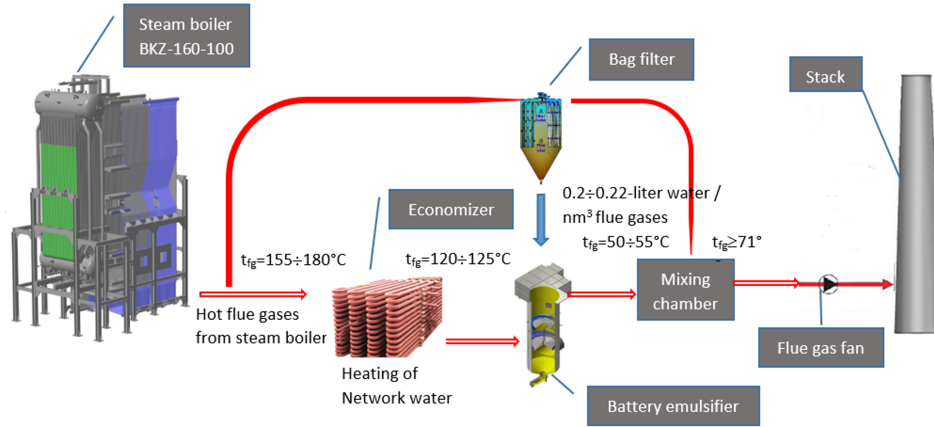


Figure 3: The system after modernization – the diagram of the gas path after installation of the bag filter and economizer.

due to energy-saving measures will amount to 2 800 up to 7 800 t/year, and the boiler efficiency will increase at the same 1.5 up to 3.7%.

#### 4 Comparison of the system before and after modernization

The comparison of the flue gas treatment system before and after the modernization is presented in the form of energy balances. According to the first law of thermodynamics, omitting heat and mass losses, the balance of enthalpy before modernization is as follows [28]:

$$\dot{m}'_{fg}i'_{fg} - \dot{m}''_{fg}i''_{fg} + \dot{m}'_{air}i'_{air} = \dot{m}'_{fg,be}i'_{fg,be} - \dot{m}''_{fg,be}i''_{fg,be} + \dot{m}''_w i''_w, \quad (1)$$

where  $\dot{m}$  is the mass flow rate,  $i$  is the specific enthalpy, and sub- and superscripts stand for: ' – inlet, '' – outlet,  $fg$  – flue gas,  $be$  – battery emulsifier,  $w$  – water,  $air$  – air for heating flue gas in the mixing chamber.

After the modification, the economizer is brought to the balance and air for heating the flue gas is no longer used. Moreover, part of the ash  $\dot{m}_{ash}$  is not mixed with battery emulsifier outlet water  $\dot{m}''_w$  but is collected. Therefore, the balance equation becomes as follows:

$$\begin{aligned} \dot{m}'_{fg}i'_{fg} - \dot{m}''_{fg}i''_{fg} + \dot{m}'_w i'_w = \dot{m}'_{fg,ec}i'_{fg,ec} - \dot{m}''_{fg,ec}i''_{fg,ec} + \dot{m}'_{fg,be}i'_{fg,be} \\ - \dot{m}''_{fg,be}i''_{fg,be} + \dot{m}''_w i''_w + \dot{m}_{ash}i_{ash}, \end{aligned} \quad (2)$$

where subscripts stand for: *ec* – economizer, *bf* – bag filter, *ash* – ash in the bag filters. For balance calculations, the next subsection presents the mass, momentum, and energy balance for the bag filter and battery emulsifier.

#### 4.1 Mathematical model of the battery emulsifier and the bag filter

The process scheme of the bag filter is presented in Fig. 4. The mass, momentum and energy conservation equations for the battery emulsifier are based on the nomenclature shown in Fig. 4:

$$\dot{m}'_{fg,bf} = \dot{m}''_{fg,bf} + \dot{m}_{ash}, \quad (3)$$

$$\Delta p_{bf} = \rho_{fg,mean} v_{fg,mean} \Delta v_{fg}, \quad (4)$$

$$\dot{H}'_{fg,bf} = \dot{H}''_{fg,bf} + \dot{H}_{ash}, \quad (5)$$

where  $\dot{m}$  is the mass flow rate,  $p$  – a pressure drop,  $\rho$  is the density,  $v$  is the velocity,  $\dot{H} = \dot{m}_i$  is the enthalpy rate,  $\Delta$  denotes the difference, and subscript *mean* represents the mean value for the inlet and outlet parameters.

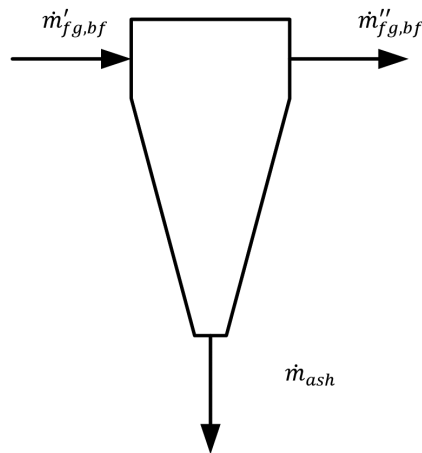


Figure 4: Process scheme of the bag filter.

The mass, momentum and energy conservation equations for the battery emulsifier are based on nomenclature from the process scheme presented in Fig. 5:

$$\dot{m}'_{fg,be} + \dot{m}'_w = \dot{m}''_{fg,be} + \dot{m}''_w, \quad (6)$$

$$\Delta p_{be} = \rho_{fg,be} v_{fg} \Delta v_{fg}, \quad (7)$$

$$\dot{H}'_{fg,be} + \dot{H}'_w = \dot{H}''_{fg,be} + \dot{H}''_w. \quad (8)$$

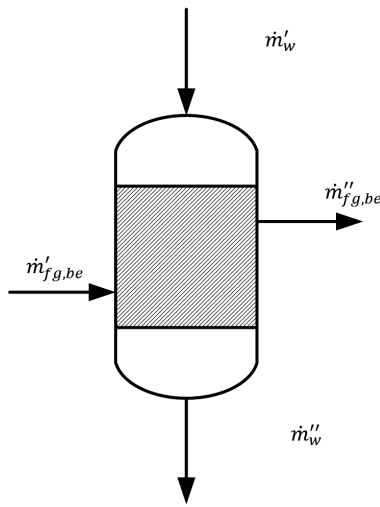


Figure 5: Process scheme of the battery emulsifier.

Flue gas at the inlet and water at the outlet contains ash. Moreover, the flue gas at the outlet of the battery emulsifier is saturated with water vapour. The amount of water contained in the exhaust gas is defined by Dalton's law of partial pressure:

$$p''_{fg,be} = p'_{fg,be} + p_{sat}(T''_{fg,be}) - \Delta p_{be}. \quad (9)$$

The  $p_{sat}(T''_{fg,be})$  is a saturation pressure for flue gas outlet temperature. This amount of water comes from the inlet water and reduces the amount of outlet water in the battery emulsifier mass balance. Assuming that the shares of the partial pressures are the same as the shares by volume to convert from partial pressures to mass, the molar mass of the gas mixtures concerned must be used.

## 4.2 Analysis of the optimal state of working parameters

The purpose of the modernization is to reduce the flue gas heat loss by replacing the additional hot air stream from the boiler with flue gases cleaned in the bag filter. Additionally, the flue gases at the inlet to the

battery emulsifier can be cooled to 120–125°C. This makes it possible to use an additional economizer to heat the water of the district heating. Due to process limitations, the remaining temperatures at the inlets and outlets of the devices and the inlet to the stack must remain unchanged. Therefore, to maximize heat recovery, it is necessary to maximize the heating rate of the economizer:

$$\dot{Q}_{ec} = \dot{m}'_{fg}i'_{fg} - \dot{m}''_{fg}i''_{fg} + \dot{m}'_w i'_w - \dot{m}''_w i''_w - \dot{m}_{ash} i_{ash} \rightarrow \max. \quad (10)$$

If the flue gas treatment system operates under steady conditions, the flue gas at the system inlet and water at the battery emulsifier inlet mass flow rates  $\dot{m}'_{fg}$ ,  $\dot{m}'_w$  and enthalpies  $i'_{fg}$ ,  $i'_w$  are constant. Enthalpy of ash from bag filters  $i_{ash}$  and water with ash from the battery emulsifier  $i''_w$  are also constant because both temperatures and composition do not change. On the other hand, the composition of flue gas at the outlet from the mixing chamber changes due to a change in flue gas moisture, which affects the flue gas outlet mass flow rate  $\dot{m}''_{fg}$ . The variable is also the amount of water to the battery emulsifier  $\dot{m}'_w$ , which is correlated with the flue gas to the battery emulsifier mass flow rate  $\dot{m}'_{fg,be}$ . The mass flow rate of flue gas to the bag filters equals  $\dot{m}'_{fg,bf} = \dot{m}'_{fg} - \dot{m}'_{fg,be}$  and it determines the mass flow rate of ash from bag filters  $\dot{m}_{ash}$  (Eq. (3)).

The graph in Fig. 6 presents the dependence of economizer heating rate  $\dot{Q}_{ec}$  and the flue gas temperature to the stack  $T''_{fg}$  as a function of the

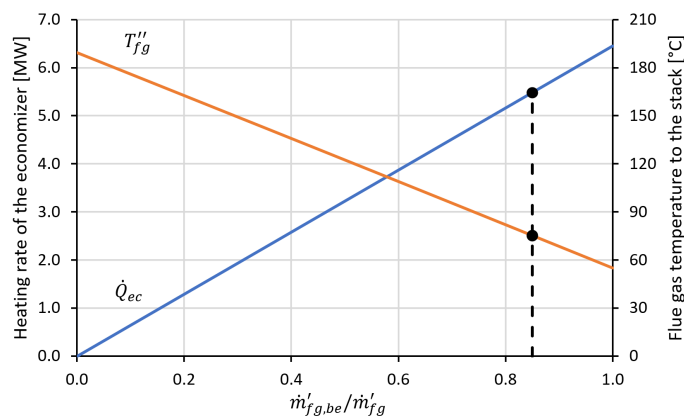


Figure 6: Heating rate of the economizer and flue gas temperature to the stack in the function of flue gas mass flow rate directed to battery emulsifier related to the total flue gas mass flow rate.

mass flow rate of flue gases directed to the battery emulsifier  $\dot{m}'_{fg,be}$  related to total flue gas mass flow rate  $\dot{m}'_{fg}$ . Calculations are based on the Stepnogorskaya BKZ-220-100F boilers parameters (Table 2) and employ open-source CoolProp thermodynamic libraries [29].

The heating rate of the economizer and the flue gas temperature to the stack are linear relationships. The vertical dashed line indicates the operating point of the flue gas treatment system for which the flue gas temperature to stack is 75°C.

### 4.3 Comparative analysis of six Kazakh thermal power plants

The comparative analysis was performed between several variants of waste heat recovery units (WHRUs) composed of economizer and bag filter. The WHRUs were integrated with several different power steam generators (BKZ 420-140; BKZ-220-100 F; BKZ 160-100), operating at different heat loads, with different temperatures of exhaust gases. The analysis also includes a hot water boiler type KTVK-100, located in Ekibastuzka TPP. In the present analysis, the case with the realization of an air preheater and a bag filter is not considered, but the results are similar to those with economizer and bag filters. In addition, the fuel used for boilers has extremely low prices, which implies low profitability of measures related to reducing fuel consumption. The calculations were performed for six Kazakh TPPs using first or second-generation emulsifiers for flue gas dedusting. Table 2 presents data on the technical parameters only for the bag filter and additional economizer option for different types of steam generators and hot water boilers in power plants and combined heat and power (CHP) plants.

The technical parameters are determined under real conditions, as the values are accepted as average for all boilers in 2020. The analysis was made for four different cities (Stepnogorsk, Almaty, Pavlodar, and Ekibastuz) with different climatic conditions. Coal prices and average operating hours also differ and this will have an impact on financial performance (payback period, net present value, internal rate of return). All boilers are equipped with a second-generation emulsifier system for wet flue gas dedusting. Normative (or measured) temperatures have been adopted in the evaluation of the amount of thermal energy for heating the gases after the emulsifier.

Table 2: Technical parameters of economizer with bag filter for different boilers.

Parameter/TPP	Stepnogorskaya BKZ-220-100F	Stepnogorskaya BKZ-190-100F	Almaty CHP-2 BKZ-420-140	Almaty CHP-3 BKZ-160-100F	Pavlodar CHP-2 BKZ-160-140	Ekibastuz CHP KVTK-100-150
Boiler steam generation rate, $D_{av}$ , t/h	205.8	136.3	380	160	137	1408
Average flue gas inlet temperature $t'_{fg}$ , °C	189.4	138.7	147	175	148	180
Flue gas outlet temperature $t''_{fg}$ , °C	125.0	125.0	120	120	120	120
Temperature of heated network water: inlet, $t'_w$ , °C outlet, $t''_w$ , °C	55.0 96.1	55.0 82.1	35.0 65.3	35.0 81.1	45.0 83.4	35.0 85.5
Network water flow, $\dot{m}$ m <sup>3</sup> /h	120	50	100	60	30	35
Estimated heating capacity of the economizer $\dot{Q}$ , kW	5 742	679	3 525	3 215	1 340	2 055
Recovered heat of gases $\dot{Q}_r$ , MWh/yr.	30 446	4 126	22 379	24 110	10 881	16 781
Heat loss with flue gases before units implementation $q'_2$ , %	9.39	5.66	6.02	7.13	6.89	8.55
Heat loss with flue gases after units implementation $q''_2$ , %	5.61	4.94	4.66	4.27	5.55	5.62
Increase in boiler efficiency, $\Delta\eta$ , %	4.31	0.89	1.49	3.17	1.52	3.38
Flue gas temperature after heat recovery and emulsifier $t_{em}$ , °C	55.0	55.0	60.8	53.2	52.5	53.1
Standard temperature of gases before entering the stack $t_{st}$ , °C	75.0	75.0	71.0	71.0	71.0	71.0
Required heat output for heating gases after the emulsifier $\dot{Q}_{em}$ , kW	1 824	1 147	905	1 015	878	589
Boiler operation time, hours/year	5 302	6 072	6 348	7 500	4 906	6 348

#### 4.4 Efficiency and economic analysis

Full thermal calculations of the WHRUs [30] (air preheater in combination with a bag filter) have been made, and the production, installation and commissioning costs have been estimated at European prices. The data

from the calculations are presented in Table 3. The ecological payments that can be avoided as a result of the realised savings from coal are also estimated.

Table 3: Investments and fuel savings for different boiler types.

Parameters/TPP	Stepnogorskaya CHP BKZ-220-100F	Stepnogorskaya CHP BKZ-190-100F	Almaty CHP-2 BKZ-420-140	Almaty CHP-3 BKZ-160-100F	Pavlodar CHP-2 BKZ 160-140	Ekibastuz CHP KVTK-100-150
Investment for the economizer, EUR	130 501	36 757	104 401	104 401	52 674	65 538
Investment for the bag filter, EUR	61 281	61 281	61 281	40 854	40 854	20 427
Total investment, EUR	191 783	98 038	165 682	145 255	93 528	85 966
Annual coal saving, t/year	10 459	3 105	7 055	8 034	2 867	4 323
Annual water savings, m <sup>3</sup> /year	33 889	45 470	52 475	31 949	25 023	14 854
Price of coal, EUR/t	7.35	7.35	10.11	10.11	6.37	4.10
Price of technical water, EUR/m <sup>3</sup>	0.1336	0.1336	0.1101	0.1101	0.04534	0.2154
Total savings, EUR/year	81 439	28 912	77 134	81 249	19 389	20 913
Savings due to harmful emissions reduction (based on the emission charge), EUR/year	7 628	2 282	5 206	5 937	2 121	3 205
Total cost savings and revenue, EUR/year	89 067	31 194	82 340	90 705	21 510	24 118
Specific savings, EUR/MWh	6.30	23.76	7.40	6.02	8.60	5.12

## 5 Comparative analysis of economizers for different steam boilers and conditions

The benchmarks for selection between different variants include:

- fuel savings,
- payback period (PB),
- net present value (NPV),
- internal rate of return (IRR),
- specific savings.



One of the most important criteria for evaluating the feasibility of the investment related to energy efficiency is the minimum investment per unit of energy saved  $(\text{EUR}/\text{MWh})_{\min}$ . This criterion is characterized by a high degree of objectivity, especially in countries where the price of fuels is many times lower than those on the world market. Figure 7 shows a graphical dependence on this criterion for all analysed objects.

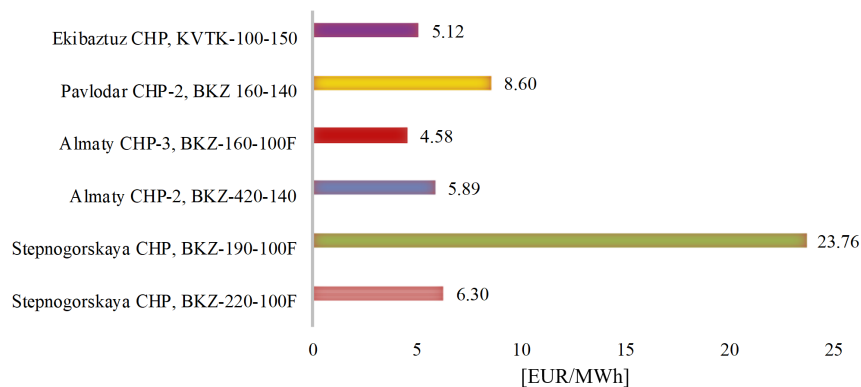


Figure 7: Specific savings for different boilers.

The analysis shows that the most economically feasible is the investment for boiler BKZ-160-100 F, in TPP-3 Almaty and shows that the investment for 1 MWh of saved energy is 4.58 EUR. This assessment is complex and includes a complex dependence on several criteria: fuel price, operating time of the steam generator, exhaust gas temperature, average boiler load, etc.

Undoubtedly, the price of coal has the greatest influence on the economic feasibility of the introduction of energy-saving equipment, because the assessment of savings is based on the most conservative method – the saved heat is estimated through the saved fuel. Since the introduction of a bag filter in the disposal system does not allow the entire gas flow to pass through the emulsifier, but only about 85%, which saves technical water, the price of water will therefore also have an impact on economic efficiency. An important advantage of the method is that the dry ash mass can be collected through the bag filter and even profits from its sale can be realized. In the present analysis, this advantage is not taken into account due to the lack of investor interest in the sale of ash in Kazakhstan.

In Europe and other countries such as the USA, Canada, and Japan, the ash trapped by dry filters is used as a building material – mainly for the construction of roads and highways [15].

## 6 Financial analysis

The results from the performed technical-economic analysis are used to prioritize the six options proposed in Table 4. This set of selected energy efficiency measures represents a CAPEX model, which can be successfully used by the company management for decision-making purposes [31].

Table 4: Estimated investments, savings, IRR, NPV, NPVQ and simple PB.

CHP/boiler type	Investment, EUR	Savings, EUR	IRR, %	NPV, EUR	NPVQ	PB, years
Almaty CHP-3, BKZ-160-100F	145 255	90 705	62.0	632 445	4.35	1.60
Almaty CHP-2, BKZ-420-140	165 682	82 340	48.8	540 297	3.26	2.01
Stepnogorskaya CHP, BKZ-220-100F	191 783	89 067	45.3	571 873	2.98	2.15
Stepnogorskaya CHP, BKZ-190-100F	98 038	31 194	29.4	169 418	1.73	3.14
Ekibastuz CHP, KVTK-100-150	85 966	24 118	25.1	120 820	1.41	3.56
Pavlodar CHP-2, BKZ 160-140	93 528	21 510	18.9	90 898	0.97	4.35

In Table 4 the proposed measures (options) are prioritized according to their IRR share. The following parameters are compared in the table:

- annual net savings for the entire operational life of the project,
- evaluation of the investment required for project implementation,
- IRR,
- NPV,
- net present value coefficient (NPVQ),
- PB.

The calculations have been obtained using the ENSI economy v6 [32] software product, with the results presented in Table 4. The proposed prioritization scheme is strictly informative offering decision-makers a possibility to compare and select the most attractive option. The aim of Figs. 8 and 9 is to compare the profitability of proposed measures in order to plan their sequence of implementation.

Figure 8 shows the IRRs against NPVs for all the projects, while Fig. 9 demonstrates the investment cost against the average annual savings over the project lifetime. In both cases, the size of the circle represents the (NPVQ). The larger the circle, the higher the benefit.

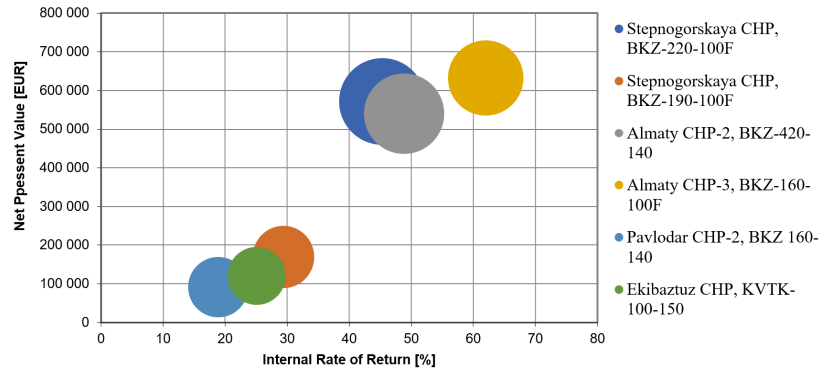


Figure 8: Relation of IRR in terms of NPV for all options; circle size corresponds to the NPV ratio.

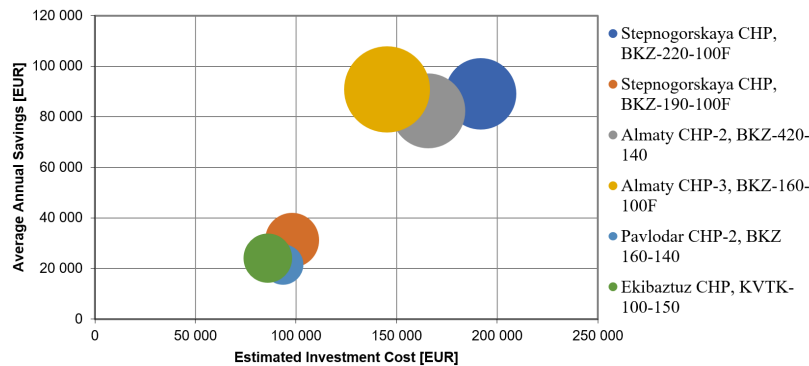


Figure 9: Investment costs for all options in terms of average annual savings during the operational life of the project; larger circles represent a higher net profit.

The results presented (Table 5, Figs. 8 and 9) show that the option of a WHRU with an air preheater and bag filter of Almaty CHP is more attractive. This is explained by the higher fuel prices in Almaty when compared to other regions.

## 7 Environmental and other project benefits/impacts

The main environmental effect resulting from the installation of WHRUs (economizers with bag filters) is a reduction of CO<sub>2</sub> and NO<sub>x</sub> emissions. The different boilers with included economizer and bag filter are estimated

to reduce coal consumption in the range of 2 867 to 10 459 tons/year, CO<sub>2</sub> emissions from 4 153 to 15 151 t CO<sub>2</sub>/year and NO<sub>x</sub> emissions from 18.4 to 67.2 t NO<sub>x</sub>/year, depending on the selected technology and equipment. The project's environmental impacts, for three investment options, are summarized in Table 5.

Table 5: Environmental impacts.

Option	Units	Stepno-gorskaya BKZ-220-100F	Stepno-gorskaya BKZ-190-100F	Almaty CHP-2 BKZ-420-140	Almaty CHP-3 BKZ-160-100F	Pavlodar CHP-2 BKZ-160-140	Ekibastuz CHP KVTK-100-150
Coal savings	t/year	10 459	3 105	7 055	8 034	2 867	4 323
Emission factor for coal	tCO <sub>2</sub> /t <sub>coal</sub>	1.4486	1.4486	1.4486	1.4486	1.4486	1.4486
Decrease of CO <sub>2</sub> from saved coal	tCO <sub>2</sub> /year	15 151	4 498	10 220	11 638	4 153	6 262
Decrease of SO <sub>2</sub> from saved coal	tSO <sub>2</sub> /year	65.6	19.5	47.4	54.0	19.3	29.0
Decrease of NO <sub>x</sub> from saved coal	tNO <sub>x</sub> /year	67.2	20.0	45.2	51.7	18.4	27.8

## 8 Conclusions

Using operational data and the thermodynamic in-house mathematical model, the complete analysis of variation rules of performance parameters of the flue gas waste heat cascade recovery system (FWCRS) such as main node temperatures, heat exchange quantities, as well as waste heat recovery efficiency, system exergy efficiency, and energy grade replacement coefficient of FWCRS was obtained. The conclusions are as below:

1. The suggested waste heat recovery technology includes both an additional air preheater equipped with a bag filter or additional economizer and a bag filter. Both technologies are applicable for steam generators and boilers that use “wet methods” technology for flue gas dedusting (i.e. scrubbers, emulsifiers first and the second generation). The suggested methodology makes possible a deeper temperature drop of the exhaust flue gases. A certain amount of the hot gases is cleaned with

a bag filter and then mixed with the wet gases after the emulsifier. Because of mixing, no additional thermal energy for heating the air from the boiler air preheater will be needed.

2. The performed technical analysis shows that the implementation of WHRU is financially viable, despite the very low price of fuel and feeding water, which further worsens the financial parameters of the project. Savings due to emissions reduction are also considered in the assessment of the financial indicators. This impact is considered to be insignificant, as the payback period is reduced by 0.3 years.
3. The implementation of WHRU for boiler BKZ-160-100F in Almaty CHP-3 has the most significant economic impact. The calculated IRR factor of 62.0% and the payback period of 1.6 years are very attractive. The remaining options including WHRU units have also a payback period (1.60–4.35 years) and can be classified as financially viable.
4. The implementation of the WHRUs has also a certain environmental impact. Reduction of coal consumption (from 2 867 to 10 459 tons/year) leads to CO<sub>2</sub> emission reduction from 4 153 to 15 151 t CO<sub>2</sub>/year and NO<sub>x</sub> emissions from 18.4 to 67.2 t NO<sub>x</sub>/year based on the boiler specifics.
5. The outputs from the study can be used as a decision-making matrix in the process of implementation of the respective technologies in TPP and CHP.

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## References

- [1] ILIEV I.: *Means and methods for waste heat recovery from low-grade gas-steam flows*. Monograph, University Publishing Center at the University of Ruse, Ruse 2013 (in Bulgarian).
- [2] KOWALCZYK T., ZIÓLKOWSKI P., BADUR J.: *Exergy analysis of the Szewalski cycle with a waste heat recovery system*. Arch. Thermodyn. **36**(2015), 3, 25–48.
- [3] RUTKOWSKI Ł., SZCZYGIEL I.: *Calculation Of the furnace exit gas temperature of Stoker fired boilers*. Arch. Thermodyn. **42**(2021), 3, 3–24.
- [4] MIKIELEWICZ J., MIKIELEWICZ D.: *Optimal boiling temperature for orc installation*. Arch. Thermodyn. **33**(2012), 3, 27–37.

- [5] ASKAROVA A.S., BOLEGENOVA S.A., GEORGIEV A., BOLEGENOVA S.A., MAXIMOV V.YU., MANATBAYEV R.K., YERGALIYEVA A.B., NUGYMANOVA A.O., BAIZHUMA ZH.T.: *The use of a new “clean” technology for burning low-grade coal in boilers of Kazakhstan TPPs*. Bulg. Chem. Commun. **50**(2018), Spec. Iss. G, 53–60.
- [6] NUNES L.J.R., GODINA R., MATIAS J.C.O.: *Characterization and possible use to fly ashes from anthracite combustion in a thermal power plant*. In: Proc. 2018 IEEE Int. Conf. on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe), Palermo, June 12–15, 2018, 1–4.
- [7] ZLATOV N., GLAZYRIN S., ZHUMAGULOV M., AIDYMBAYEVA Z.: *Wastewater treatment of the thermal power plants for desulfurization of flue gas*. J. Eng. Sci. Technol. Rev., Spec. Iss. (2020), 154–157.
- [8] DZHAKSYBAEV S.I., MURAVYEV I.YA.: *Big coal of Ekibastuz*. Nedra, Moscow 1990, ISBN 5-247-00833-2.
- [9] SHYOGOLEV V.A.: *Battery Emulsifier Swirler Unit with Replaceable Blade Machines*. Patent # RU129017U1, 2013-06-20, (2013).
- [10] BRICL M.: *Cleaning of flue gases in thermal power plants*. J. Energy Technol. **4**(2016), 45–56.
- [11] [https://www.mikropul.com/uploads/pdf/wet\\_scrubbers.pdf](https://www.mikropul.com/uploads/pdf/wet_scrubbers.pdf) (accessed 20 May 2022).
- [12] LEE B.K., MOHAN B.R., BYEON S.H., LIM K.S., HONG E.P.: *Evaluating the performance of a turbulent wet scrubber for scrubbing particulate matter*. J. Air Waste Manage. Assoc. **63**(2013), 499–506.
- [13] BUCHTA J., OZIEMSKI A.: *Flue gas heat recovery in high efficient coal-fired power plant*. In: Proc. 20th Int. Sci. Conf. on Electric Power Engineering (EPE), May 15–17, 2019, Kouty nad Desnou, 1–6.
- [14] SZULC P., TIETZE T.: *Recovery and energy use of flue gas from a coal power plant*. J. Power Technol. **97**(2017), 135–141.
- [15] STEVANOVIC V.D., PETROVIC M.M., WALA T., MILIVOJEVIC S., ILIC M., MUSZYNSKI S.: *Efficiency and power upgrade at the aged lignite-fired power plant by flue gas waste heat utilization: High pressure versus low pressure economizer installation*. Energy **187**(2019), 115980.
- [16] WANG C., HE B., SUN S., WU Y., YAN N., YAN L., PEI X.: *Application of a low pressure economizer for waste heat recovery from the exhaust flue gas in a 600 MW power plant*. Energy **48**(2012), 196–202.
- [17] XU C., XU G., ZHOU L., YANG Y., LI Y., DENG J.: *A novel flue gas heat recovery system integrated with air preheating in a utility boiler*. In: Proc. ASME Turbo Expo 2013, Power for Land, Sea, and Air, Vol. 2, Turbo Expo 2013, San Antonio, June 3–7, 2013. ASME Pap. GT2013–95185.
- [18] XU G., XU C., YANG Y., FANG Y., LI Y., SONG X.: *A novel flue gas waste heat recovery system for coal-fired ultra-supercritical power plants*. Appl. Therm. Eng. **67**(2014), 240–249.

- [19] HAN Y., XU G., ZHENG Q., XU C., HU Y., YANG Y., LEI J.: *New heat integration system with bypass flue based on the rational utilization of low-grade extraction steam in a coal-fired power plant*. Appl. Therm. Eng. **113**(2017), 460–471.
- [20] YAN M., ZHANG L., SHI Y., ZHANG L., LI Y., MA C.: *A novel boiler cold-end optimisation system based on bypass flue in coal-fired power plants, Heat recovery from wet flue gas*. Energy **152** (2018), 84–94.
- [21] FAN C., PEI D., WEI H.: *A novel cascade energy utilization to improve efficiency of double reheat cycle*. Energy Convers. Manage. **171**(2018), 1388–1396.
- [22] YANG Y., XU C., XU G., HAN Y., FANG Y., ZHANG D.: *A new conceptual cold-end design of boilers for coal fired power plants with waste heat recovery*. Energy Convers. Manage. **89**(2015), 137–146.
- [23] ZIÓŁKOWSKI P., HYRZYŃSKI R., LEMAŃSKI M., KRASZEWSKI B., BYKUĆ S., GŁUCH S., SOWIŹDŹAŁ A., PAJĄK L., WACHOWICZ-PYZIK A., BADUR J.: *Different design aspects of an organic Rankine cycle turbine for electricity production using a geothermal binary power plant*. Energy Convers. Manage. **246**(2021), 114672.
- [24] MIKIELEWICZ D., WAJS J., ZIÓŁKOWSKI P., MIKIELEWICZ J.: *Utilisation of waste heat from the power plant by use of the ORC aided with bleed steam and extra source of heat*. Energy **97**(2016), 11–19.
- [25] HUANG S., LI CH., TAN T., FU P., WANG L., YANG Y.: *Comparative evaluation of integrated waste heat utilization systems for coal-fired power plants based on in-depth boiler-turbine integration and organic rankine cycle*. Entropy **20**(2018), 2, 89.
- [26] ALEKHNOVICH A.N.: *Ash collection at homeland thermal power plants*. Private communication, (2020).
- [27] LEISTER N., KARBSTEIN H.P.: *Evaluating the stability of double emulsions. A review of the measurement techniques for the systematic investigation of instability mechanisms*. Colloids Interfaces **4**(2020), 1, 8.
- [28] SHAMSI S.S.M., NEGASH A.A., CHO G.B., KIM Y.M.: *Waste heat and water recovery system optimization for flue gas in thermal power plants*. Sustainability **11**(2019), 1881.
- [29] <http://www.coolprop.org> (accessed 20 May 2022).
- [30] NEMADE A.C., PONSANKAR S.: *Efficiency improvement in thermal power plants using waste heat recovery of flue gas-simulation study*. IOP Conf. Ser.: Mater. Sci. Eng. **912**(2020), 042015.
- [31] KOSTOV K., IVANOV I., ATANASOV K.: *Development and analysis of a new approach for simplified determination of the heating and the cooling loads of livestock buildings*. EUREKA: Phys. Eng. **2**(2021), 87–98.
- [32] <https://www.publnef-toolbox.eu/tools/ensi-eab-energy-auditing-buildings-bulgaria> (accessed 20 May 2022).