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DEVELOPMENT AND RESEARCH OF TECHNOLOGIES TO REDUCE THE HARMFUL ENVIRONMENTAL IMPACT OF COAL-FIRED CHP PLANTS

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ABSTRACT: The relevance of this work lies in the need to solve the problem of the negative impact of coal combustion processes on the environment and the development of measures to improve the environmental situation in the fuel and energy complex of Kazakhstan. Purpose of work – analysis of vectors of anthropogenic load on the environment from heat and power enterprises using coal fuel. Also, there is a need to explore possibilities of introduction and application of innovative technological solutions on reduction of quantitative indicators and component composition of pollutant emissions into the atmospheric air. In the process of research, modern technological developments and solutions for minimising the impact of thermal power plants on local environmental conditions and global processes in the atmosphere were analysed, the possibilities of their effective application at thermal power enterprises of Kazakhstan were explored, developed optimal and feasible measures to improve the environmental situation at the current stage of development of the country's fuel and energy sector.

Keywords: Air emissions, Ash collection, Combustion products, Modernisation, Environmental regulations.

1. INTRODUCTION

The tense global environmental situation has served as a compulsory impetus for the closure of coal-fired power plants in many developed countries. Despite this trend, conventional low-cost coal-fired power continues to perform well in developing countries. Therewith, using "green" coal technologies is considered a huge step forward toward a green economy. The global energy crisis, exacerbated by Russia's military aggression in Ukraine, has demonstrated that the developed world is not ready for a complete phase-out of fossil fuels, in particular, coal, whose use is increasing significantly. Therefore, while not excluding a steady decline in the share of coal-fired plants in the world in the long term, coal remains one of the main fuels used in thermal power today [1, 2]. In Kazakhstan, about 85% of electricity is generated in thermal power stations (TPS), with fossil solid fuels remaining the priority.

Coal is used without prior beneficiation [3]. As a result of conventional fuel extraction and treatment algorithms that focus on cheapness, the environment is under enormous anthropogenic pressure [4]. Therewith, the burning of fossil fuels – the electricity sector with its huge centralised power plants – is one of the mainstays of Kazakhstan's economy [3].

The energy sector, whose main fuel is coal, accounts for about 80% of total national greenhouse gas emissions [5]. According to the latest data, Kazakhstan emits 43.7% of pollutants into the atmospheric air of Central Asia, and carbon dioxide (CO_2) emissions have reached 12.8 tonnes per capita (Table 1) [6]. The problematic of adverse effects of pulverised coal combined heat and power (CHP) exploitation on the environment and finding solutions that would reduce the anthropogenic load from using fossil fuels, in particular – coal, is devoted to many scientific works, in particular to Malikova [7]. The adverse effects of flue gas emissions in the atmosphere are explored in the works of Utegulov and Utegulov [8].

Some researchers are convinced that efficient modernisation of operating thermal power plants with a priority on environmental friendliness, strict system of control and monitoring of environmental pollution parameters is realistic for the successful implementation of the "greening" method of thermal power production activity [9]. Man et al. emphasise opportunities that have been mastered and adapted to existing heat and power process technologies [10]. Researchers also focus on maximising the efficiency of combining technologies to reduce the adverse effects of coal-fired CHPs with energy efficiency programmes [11]. Aliyarov and Aliyarova explore in detail the application of technological innovations in the coal-fired thermal power industry [12]. The problematic

necessity of development, research and effective implementation of technologies for the reduction of adverse influence of thermal energy operating with coal fuel is an issue of acute topicality [2; 3].

Table 1 The carbon dioxide (CO2) emissions per capita for Central Asian countries [6]

Country	CO2 Emissions per Capita (tonnes)
Kazakhstan	12.8
Kyrgyzstan	1.3
Tajikistan	0.3
Turkmenistan	12.2
Uzbekistan	4.6

The purpose of the study is to explore the current state of development of innovative technologies to reduce anthropogenic pressures on the environment from pulverised coal CHP on the example of CHPs of JSC (joint-stock company) "Almaty Electric Stations" (CHP-2, CHP-3 of JSC "AlES"), feasibility study to optimise the interaction of resource and environmental components of production processes of pulverised coal energy.

2. RESEARCH SIGNIFICANCE

This article holds significant research value as it investigates the harmful environmental impact of coal-fired combined heat and power (CHP) plants and seeks innovative solutions to minimize their ecological footprint. The findings of this study have practical relevance for the development and modernization programs of thermal power enterprises in Kazakhstan that utilize coal as fuel. The research aligns with Kazakhstan's aspirations to adopt a European "green" economic course.

3. MATERIALS AND METHODS

Aspects of the environmental impact of pulverised coal CHP operation have been considered. Analytical work has been performed with volumes of information and scientific works in the field of the explored issues implemented to the specific features of the economic and ecological situation in Kazakhstan. Materials on the specific environmental impact of CHPs of JSC "AlES" have been explored. Using synthesis and evaluation methods, modern technological solutions for reducing the environmental impact of thermal power plants using solid fossil fuels (coal) are explored. The comparative-descriptive method and the method of analogy and association have been applied. Using them, the features of effective technological solutions to reduce the harmful effects of dust-coal TPS used in a world practice are identified, and the optimal technologies and concepts optimal for use in the heat and power system of Kazakhstan are highlighted.

A systems approach has been used to identify the effectiveness, features and benefits of specific technological solutions. When considering innovative technologies that will minimise the adverse environmental impact of CHP-2, CHP-3 of JSC "AlES" operations, it is assumed that these facilities are representative of the heat and power sector in Kazakhstan.

A comparative and descriptive analysis of existing and proposed mitigation methods has been performed, and the priority of specific solutions in terms of effectiveness and feasibility has been assessed. The possibility of combining the implementation of innovative technological solutions with the development of a system for monitoring environmental pollution parameters during the operation of the TPS is considered. The generalisation method was used to identify typical features and patterns in the problems explored, the possibilities for optimising the situation and finding the most beneficial solutions in economic and ecological terms. The main areas for optimising the synergy between the resource and environmental components of thermal energy production processes have been developed.

4. RESULTS

The projected increase in the price of primary fossil energy sources (oil, natural gas) makes it urgent to find alternative technologies for using coal. Kazakhstan is known to hold approximately 3.9% of the world's coal reserves [3]. Therewith, special attention should be focused on the necessity to reduce the anthropogenic burden on the natural environment. To achieve this purpose, the priority is to develop and implement a new area of industry policy development, which should ensure the transition to international standards, introduce modern technical regulations, and achieve significant reductions in environmental pollution.

Waste combustion products of fossil coal combusted in CHP contain fly ash, sulphur and sulphur dioxide, particles of unburned pulverised fuel, nitrogen oxides, sodium salts, vanadium compounds, soot particles, coke, gaseous products of incomplete combustion of fossil fuel (Table 2). All harm the environment and the human body, contribute to acid precipitation and the greenhouse effect, which has a global impact [5]. Fly ash often causes premature wear of chimneys and flues, and the sulphur dioxide causes severe corrosion on metal surfaces [4]. Special chimneys are constructed at the TPS, which allow the dispersion of exhaust combustion products, ash collectors are additionally installed to clean the flue gases more effectively from fly ash. Wet and dry inertia units and electrostatic precipitators, and in some cases combined ash collectors are used [8].

Table 2 Waste combustion products of fossil coal [12]

Waste Combustion Products	Description
Fly ash	Fine particles of ash and dust that are carried away with the exhaust gases
Sulphur	A yellow, non-metallic element that can be released during combustion
Sulphur dioxide	A colourless gas that is released when sulphur is burned
Particles of unburned pulverised fuel	Solid particles of coal that were not fully burned
Nitrogen oxides	A group of gases that are released during combustion, which can contribute to air pollution
Sodium salts	Compounds that contain sodium, which can be present in coal
Vanadium compounds	Compounds that contain vanadium, which can be present in coal
Soot particles	Fine black particles that are produced during incomplete combustion
Coke	A solid fuel that is produced during the process of coal combustion
Gaseous products of incomplete combustion of fossil fuel	A variety of gases that are produced when coal is burned incompletely, such as carbon monoxide, methane, and ethylene.

The efficiency of the operation of gas-cleaning systems is evaluated by the effectiveness of their product application and greatly depends on the physical and chemical properties of the captured particles and the parameters of dust and gas flow in general [10]. To achieve the necessary emission reductions from CHP-2, CHP-3 operations, JSC "AlES" needs to actively implement new and modernise existing emission reduction methods (Fig. 1). These gas emission units are very expensive, but very effective in reducing emissions [13]. A related challenge in realising these objectives can be the lack of sufficient capacity to accommodate cumbersome and expensive scrubbing plants, but these challenges are manageable. In a market economy, there has recently been variability in the choice of efficient fuels for power plants. For this purpose, the comparative efficiency of coal fuels with different properties and the economic viability of using certain types of coal at a particular TPS are evaluated [5].

Coal combustion products contain environmentally harmful constituents, some of which have toxic properties: fly ash, nitrogen and sulphur oxides [1; 7]. Flue gas cleaning systems are used for their timely removal. In most cases, they are gas-air auxiliary devices – smoke extractors and fans. These are used to supply the combustion air to the combustion chamber and to remove the combustion gases.

In addition, ash collectors are mandatory in the operation of a solid fuel power plant, in particular, coal-fired power plants. The simpler versions are mechanical dry or wet, with ash recovery rates of between 75% and 90%. Alternative electrostatic precipitators (Fig. 2) provide a high degree of gas purification (up to 99%) without first reducing the temperature of the flue gas or dampening it [5; 10; 12]. Dusty coal-fired power plants use ash and slag removal systems to arrange for off-site disposal of bottom ash and slag (Fig. 3). In addition, ash collectors are mandatory in the operation of a solid fuel power plant, in particular, coal-fired power plants. The simpler versions are mechanical dry or wet, with ash recovery rates of between 75% and 90%.

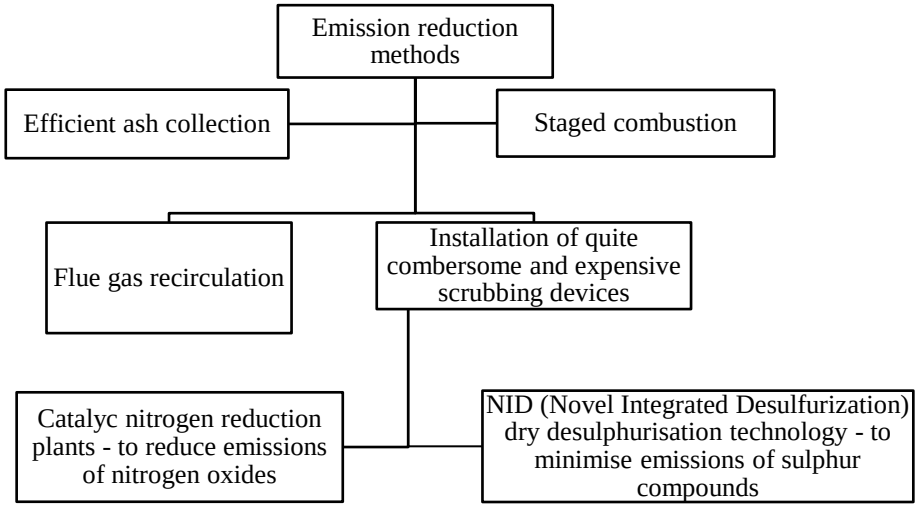

Fig.1 Emission reduction methods [11]

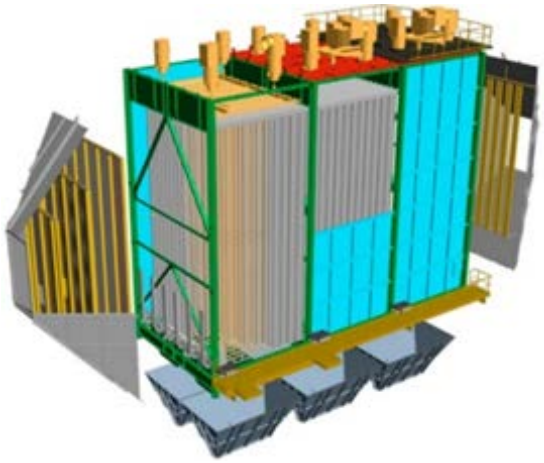

Fig.2 Electrostatic precipitator [5]

Alternative electrostatic precipitators (Fig. 2) provide a high degree of gas purification (up to 99%) without first reducing the temperature of the flue gas or dampening it [5; 10; 12]. Dusty coal-fired power plants use ash and slag removal systems to arrange for off-site disposal of bottom ash and slag (Fig. 3). The most common and frequently used method is the hydraulic method. To solve the problem of disposing of the slag and ash that are removed, ash ponds are used. The ash and slag mixture reaches the ash dump, where the solid slag and ash particles are separated from the liquid component, after which the clarified water, accumulated via receiving wells, is discharged into a designated water body or reused in production processes. The analysis of the current activities of CHP-2, CHP-3 of JSC "AlES" established that the main areas of impact during the operation of enterprises are emissions to the atmosphere, use of water resources for cooling and technological needs of TPS. These impacts are of a continuous, multi-year nature, with varying scales of impact [13; 6].

Every effort has been made to improve the efficiency and optimise the environmental parameters of pulverised coal CHP operation [9; 11; 14]. The current "green" course of industrial and economic development sought by the world community should be reflected in the modernisation of the heat and power sector in Kazakhstan. Analysing the data in Table 3, modern power units with single steam superheating are operating successfully in Europe and Southwest Asia. Hemweg's coal-fired TPS in the Netherlands is generally among the most environmentally friendly in the world while maintaining high-performance efficiency. Its distinguishing feature is the operation of the boiler in a specific supercritical pressure mode, resulting in low CO_2 emission [1]. Successful operation of power plants using new efficient technologies has demonstrated it is possible to achieve high levels of clean coal combustion that minimise emissions of pollutants into the atmosphere while guaranteeing high performance and operability of the TPS [14; 15].

Mechanical

- Conveyor belts augers

Pneumatic

- Using a strong air pressure in closed ducts

Hydraulic

- Flushing with water flow

Fig.3 Methods of ash removal [1]

Table 3 Examples of progressive power generation technologies [1]

Country	TPS	Unit capacity, MW	Steam pressure, MPa	Operating steam temperature, °C	Superheater steam temperature RH_1, °C	Superheater steam temperature RH_2, °C	Nominal efficiency, %
Denmark	Avedorevrket	390	30.0	580	600	-	48.3
Denmark	Nordjylland	411	28.5	580	580	580	47
Denmark	Skrbk	411	29.0	582	580	580	49
Netherlands	Hemweg	630	26.0	540	568	-	42
Finland	Meri Pori	550	24.4	540	560	-	45
Germany	Staudinger	509	26.2	545	562	-	43
Germany	Niederaussem	965	27.5	580	600	-	45.2
Japan	Tachibanawan	1050	25.0	600	610	-	43.5
China	Changshu	600	25.9	569	569	-	42
China	Wangqu	600	24.7	571	569	-	43
USA	Tanners Creek	580	24.1	538	552	566	39.8

The high level of efficiency in carbon dioxide, sulphur dioxide, nitrogen oxide, and dust emission reduction technologies is achieved through the active use of advanced electrostatic precipitators, maximum automation of production processes, using new construction materials and a strict control system [16; 17].

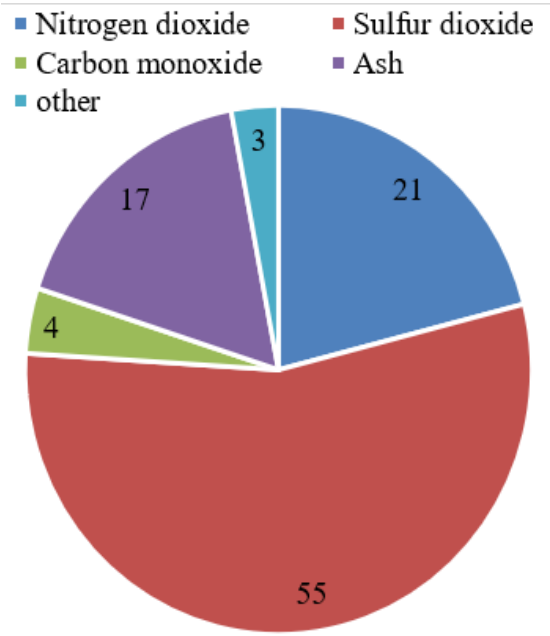

Fig.4 Structure of pulverised coal CHP emissions into the atmosphere using the example of CHP-2 of JSC "AlES" [13]

When analysing the specifics of the operation of heat and power facilities in Kazakhstan using the example of CHP-2, CHP-3 of JSC "AlES", attention should be paid to some of the features that directly or indirectly influence the adverse environmental load and the processes of selecting solutions to this problem. As the main fuel of CHP-2, CHP-3 of JSC "AlES" actively uses coal from Kazakhstani deposits with ash content of 37 to 41% on the working mass [3; 13; 18]. Flue gases, before being discharged into the ambient air, are always cleaned of ash. However, the main sources of environmental pollution are smokestacks [19; 20]. When burning coal fuel at CHP-2, CHP-3, large amounts of nitrogen oxide and dioxide, sulphur dioxide, carbon monoxide, coal ash, fuel oil ash, benz(a)pyrene are emitted into the air from the chimneys (Fig. 4).

The equipment installed at the plant has been in operation for more than 40-50 years [6; 21; 22]. The flaring technology of Ekibastuz coals, typical for all coal-fired CHPs in Kazakhstan, is accompanied by high combustion temperatures of pulverised coal, which causes the development of significant amounts of nitrogen oxides. The sulphur content of the coal results in sulphur oxide emissions [1]. The boilers are equipped with ash cleaning systems with an acceptable operating efficiency of about 96% [13; 23; 24]. Battery emulsifiers are used – the most common type of ash collector at CHP Kazakhstan.

5. DISCUSSION

The significant anthropogenic load on the environment from thermal power facilities using coal as fuel is multifactorial and is not limited to emissions of pollutants and toxic substances into the atmosphere. But the magnitude of the impact and the danger level of the adverse consequences draws the most attention to the atmospheric pollution vector from the combustion of pulverised coal TPS [1-3]. The problem of ash collection is becoming increasingly important in the first place. The researchers agreed on this point Askarova et al. [4], Kalmykov and Malikova [7].

An effective and efficient flue gas cleaning system reduces ash emissions into the atmosphere contributing to improving the reliability of the flue gas aspirators [6; 25]. Many scientists take standardised air pollutant emissions as basic information for further analysis and decision-making [5; 14; 22]. According to globally recognised air protection regulations, emissions from pulverised coal TPS are currently limited to four main indicators: sulphur oxides, nitrogen oxides, carbon oxides and fly ash (Table 4). Considering the current economic situation in the country, the implementation of environmental emission requirements for coal combustion in boilers of thermal power plants operating in developed countries would have as a primary consequence a significant increase in the cost of energy sold [15; 16].

Table 4 Current air pollutant emission standards in Kazakhstan compared to European Union standards for power plants, mg/m^3

Type of emissions	Kazakhstan	Intermediate standards	European Union
Solid particles (ash)	1200-1600	300-600	50-100
Sulphur dioxide	2000-3000	1000-1500	400
Nitrogen oxides	600	650	500

Source: completed by the authors based on [5].

The differences in emission standards between countries today are substantial, but they ensure that the transition to a green economy is adaptable. Many academics [9; 10; 12] have argued for this in their writings. Rossiter and Jones [19] are convinced that only management with an environmental focus can become an effective tool for improving the energy efficiency of enterprises.

A separate problem is a low rate of ash recycling (less than 8% in Kazakhstan compared to 90% in European Union countries) [1]. Nugymanova [5], and Walter and Epple [18] believe that the priority in the optimisation of the ash and slag management system should be a rational transition from the predominant use of ash dumps to efficient recycling processes. This fact is obvious and has been separately explored by many researchers. In industrialised countries, the dry ash removal method with subsequent utilisation of the ash as a binding material for road construction is a priority. In Germany, for example, 100% of the ash from coal-fired power plants is recycled in this way [8]. Numerous scientific studies have confirmed the necessity of introducing improved coal technologies at operating CHP.

Utegulov and Utegulov consider a combination of supercritical steam parameters and fuel combustion in a circulating fluidised bed to be effective [8]. Using modern steam turbines, they believe, can provide a significant increase in the thermal efficiency of CHP steam plants, and consequently reduce CO_2 emissions by up to 20% of the original levels [8; 15].

Methods of retrofitting operating equipment to reduce the number of nitrogen oxides in the emissions are proposed by scientists Jo et al. [9] and Man et al. [10]. Therewith, they are convinced that compliance with strict European Union regulations is becoming a reality. To reduce the concentration of harmful substances in flue gas emissions into the atmosphere, the oil-free firing method of a boiler unit is now common and quite adaptable, and plasma combustion technology is actively used [12; 13; 20]. Nugymanovaon examples of researches in real conditions of CHP-3 of JSC "AlES" operation, is convinced, that technology of plasma combustion of coal dust includes the use of microwave plasmons and positively influences on ecological indicators of CHP-3 operation [5]. The introduction and effective use of plasma fuel systems at thermal power plants allow a significant reduction of mechanical underburning, reducing the generation of nitrogen oxides by 50-60% [5; 15]. The absence of vanadium, tar, phenols and hydrocarbons in the emissions is a positive development [16].

In addition, emissions from boilers are nowadays monitored by instrumental methods [7; 13]. To minimise the influence of the human factor and to increase the efficiency of control over the parameters of gas flows, the introduction of a modern system for continuous environmental monitoring of emissions from chimneys is optimal [26]. These and other management measures have been explored and developed by contemporary scholars Rauner et al. [23]. They propose using effective management systems, strict controls and innovative technologies along with technological methods to optimise the heat sector. Thus, it can be argued that only in the close interaction of technological, economic and environmental components of the process of modernisation and optimisation of pulverised coal-fired power plants it is possible to achieve a real reduction of the adverse impact on the environment [24, 27].

First, the prerogative must remain to technologically modernise existing equipment and fuel combustion processes, considering current environmental regulations. Radical measures can carry an unsustainable burden from an economic standpoint [28]. The introduction of modern innovative technologies should be a priority in the development process of the heat and power sector in Kazakhstan. Secondly, among the technological solutions that deserve special attention are those that combine energy efficiency, increased productivity and minimised emissions of pollutants from coal combustion into the atmosphere.

Thirdly, the impact of good management practices cannot be excluded. Tighter control of air pollutant emissions and an effective environmental monitoring system can establish the most favourable conditions for the implementation of European green processes in the energy sector in Kazakhstan. The development of the energy sector of Kazakhstan's industrial and economic activities is inseparable from the global trends of the increasing importance of the environmental aspect in energy processes. Only a smooth, economically sound process of implementing the principles of the "green" economy and energy can establish a favourable balance without generating stressful adverse effects [29, 30]. Energy efficiency is inseparable from environmental safety, and this principle should be actively implemented in a phased manner in the thermal power sector in Kazakhstan.

6. CONCLUSION

The fundamental modernization of existing and the construction of new contemporary thermal energy facilities are required due to Kazakhstan's significant economic expansion and the greening of production energy processes. The use of gas instead of other fuels will lessen the negative effects on the environment. By burning gaseous fuels, pollution and hazardous emissions into the atmosphere are greatly reduced. Moreover, related issues such as

ash ponds, extended gas duct service life, and heat losses are also automatically resolved.

However, taking into account the current state of affairs in the context of a developing energy crisis, changing the primary fuel type continues to be a top priority in Kazakhstan's long-term energy sector development programs within the framework of the implementation of a green global economic course. And gradualness will be this process' primary hallmark. The urgent task for heat and power engineering in Kazakhstan, in particular CHP-2 and CHP-3 of JSC "AlES," is the introduction of energy-efficient, environmentally-oriented innovative technologies, through which it becomes possible to maximize control over processes of establishment of harmful substances and reduce the quantitative indicators of pollution.

The study managed to analyse the main aspects of anthropogenic load on the environment from thermal power plants using pulverised coal, on the example of CHP-2, CHP-3 of JSC "AlES", and to explore the possibilities of introducing and applying innovative technological solutions to reduce the quantitative indicators and component composition of pollutant emissions into the atmosphere from coal combustion processes. The main vectors of optimisation of the interaction between the resource and environmental components of the production processes of thermal power engineering, which uses coal as fuel, have been developed, considering the actual economic situation and the general area of "green" development in Kazakhstan.

The information obtained from the study can be used effectively for practical applications. Compliance with mandatory requirements in terms of maximum permissible concentrations of harmful substances in emissions of combustion products into the air, the gradual tightening of environmental load standards and bringing them to the standards of developed countries, application of modern innovative technological solutions in the coal-fired thermal power industry, minimisation of ash generation and addressing the issue of ash recycling will contribute, along with effective management measures and introduction of the environmental monitoring system, optimal modernisation of the existing pulverised coal TPS in Kazakhstan.

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