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Evaluation of the Economic Efficiency of Heat Recovery from Exhaust Gas of Diesel Power Plants in Kazakhstan

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ABSTRACT

In today's world, the issue of efficient energy consumption and reducing dependence on fossil energy resources is especially acute. Each extra kilowatt-hour of electricity is a significant burden on the expenses of any type of enterprise, leading to a decrease in its competitiveness. The first step in solving this problem should be a general reduction in energy consumption by increasing the energy efficiency of the equipment used, choosing the best solutions for engineering systems and implementing a range of energy-saving measures. This study presents an instrument for achieving energy efficiency by utilizing waste gas heat on the example of existing fixed assets of diesel power plants in Kazakhstan. Based on an analysis of the technical indicators of the equipment, an economic analysis of the feasibility of utilizing the internal combustion engine's (ICE) waste heat is carried out. With the help of the latter it is determined that in the conditions of market electricity tariffs in Kazakhstan, the indicated innovations can be implemented in 3-3.5 years.

Keywords: Energy Efficiency, Heat Recovery, Economic Efficiency, Secondary Energy Management

JEL Classifications: Q40, Q42, Q47

1. INTRODUCTION

Given the exhaustibility of minerals that de facto form the energy sector in many countries, there is a need for direct diversification of the economy from its dependence on the direct consumption of such resources. It is the current situation that has become the basis for the ideas of countries' transition to the so-called "green economy," which has been mentioned for about two decades in the programs of various governments and international organizations. However, the direct incentives for the transition are primarily compliance with the Paris Agreement, as well as climate change, which become factors of influence on the ecosystem of a particular country and, accordingly, the impact on the life of society of this country and the economic system (Piacentino et al., 2019).

The economy of Kazakhstan is deeply dependent on the resource component, since, in addition to dependence on international

energy markets (like any transition economy), Kazakhstan is also dependent on water resources, 45% of which are purchased, which once again emphasizes the economic and environmental context of energy efficiency (Shadrina, 2019). It must be understood that the introduction of energy efficiency tools is due to the experience of turbulence in the commercial segments of national economies and the need to reduce the risks of volatility in energy markets (Bhardwaj et al., 2019). Disregarding the interests of commercial companies, ignoring the state of their needs lead to problems of the national economic system and the destruction of social institutions (Fedorova and Mushketova, 2019).

One of the key tasks of achieving economic efficiency in the modern energy sector is to increase the production of electricity at thermal power plants through the use of non-traditional energy sources (Bhowmik et al., 2018; Akhmetshin et al., 2019; Kozhakhmetova et al., 2019). Combined technologies using waste heat of exhaust gases have great potential in the reconstruction

of old and the design of new diesel and gas turbine power plants (Robb, 2011; Morgan et al., 2016).

The relevance of the study of economic efficiency in this context is due to the number of diesel generators operating in the world (World Electric Power Plants Database, 2018): Asia - 59,000; Europe - 65,000; North America - 45,000; in other countries - 47,000. Until 2025, it is planned to commission additionally about 26,000 diesel generators around the world. According to Kazakhstan market estimates, over the past 25 years, TSS alone supplied the country with 3500 diesel generators (Group of Companies TSS, 2019) with a capacity of 30 to 1000 kW. Such a volume is primarily due to the sharply continental arid climate. That is, in the economic system of Kazakhstan there is a steady demand for energy from power plants.

The energy efficiency of manufacturing enterprises is primarily interesting from the point of view of economic efficiency, since the cost of production, a significant part of which is the energy component, significantly affects the commercial success of the company and the financial stability of all operating activities (Iazzolino et al., 2019). On the other hand, less dependence on global energy markets allows producers of goods (especially FMCG niches) to keep the price level in the zone of accessibility for consumers (Katopodis and Sfetsos, 2019). Optimization of the energy component of company's operating cycle allows this company to adapt most optimally to the market and organize its activities more flexibly, which enhances the competitiveness of both a single business unit and the economic system as a whole, facilitating its transition to the principles of sustainable development (Leal-Arcas et al., 2019). This reveals the need to implement energy optimization programs supported by the goals of the transition to green energy until 2050 (WGI Project, 2014), and to conduct, as one of the steps of diversification processes, an economic analysis of the feasibility of utilizing ICE waste heat in Kazakhstan.

2. METHODOLOGY

Modernization of existing diesel generators in Kazakhstan is justified only when it provides the economic effect of reducing

operating costs. Therefore, the basis of the methodology for evaluating the effectiveness of the introduction of innovations in this study is an analysis of the technical characteristics of equipment before and after modernization.

In accordance with the methodology (Gransberg and O'Connor, 2015), the economic feasibility of introducing equipment for waste heat from internal combustion engines is assessed on the basis of an analysis of the dependences on the ambient temperature:

- ICE efficiency
- Specific amount of water vapor generated due to the waste heat of the ICE
- Specific amount of electricity generated through the use of generated water vapor.

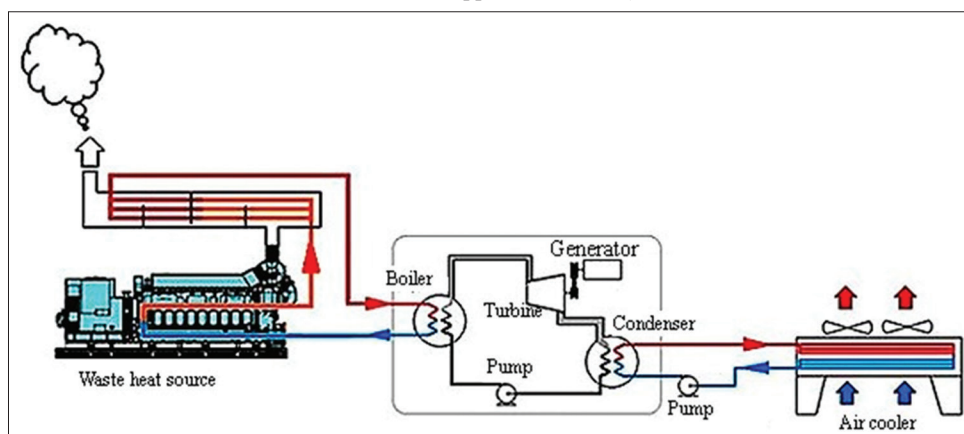
3. RESULTS AND DISCUSSION

The search for optimal technical solutions for the utilization of waste heat is based on minimizing emissions of pollutants from the exhaust gases of internal combustion engines operating on heavy fuels (Nazemi et al., 2016). This is mainly accomplished by utilizing steam-generating circuits. Water (Rankine cycle) and organic liquids (Organic Rankine Cycle - ORC) are used as a working fluid in these utilization circuits (Yfantis et al., 2015). It is proposed to use toluene, heptane, pentane, isobutane, and freons as working fluids in ORC (R123, R134a, R245ca, R245fa) and other organic substances.

If one uses Freon R245fa (Quoilin, 2007), then the efficiency of the recycling plant may be 13...14%. Quoilin (2007) suggests that the use of Freon R245fa or another working fluid, for example, TFE, in ORC leads to a deeper use of the potential of the exhaust gases from the internal combustion engine. This can lead to a total reduction in fuel consumption for a diesel power plant to 9.1%. The technological scheme of the integrated utilization of waste heat from an internal combustion engine is shown in Figure 1.

Utilizing heat from the ICE cylinder water cooling circuit, exhaust gas, or combining exhaust gas heat with cooling water heat are simple options for converting waste heat from ICEs to electricity.

Figure 1: The technological scheme of the integrated utilization of waste heat of an internal combustion engine (on the basis of source Power + Generator Application [2019])



The waste heat from the water in the engine cover can be combined with the waste heat coming out of the exhaust pipe. Initially, heat from cooling water is understood as the intermediate heat-transfer agent. The intermediate heat carrier is then heated to the desired temperature by the heat of the exhaust gases. Such a scheme works well enough at low ambient temperatures. However, in hot climates, problems arise associated with the temperature level in the condensation circuit of the intermediate heat-transfer agent. In addition, when using organic substances as a working fluid, it is difficult to fulfill the following requirements:

- It should not be toxic and fire hazard. It should also be environmentally friendly
- It should be inexpensive and easily accessible.

In connection with the foregoing, it is advisable to consider the utilization of waste heat in diesel generators in the Rankine cycle using fresh water as a working fluid. Prospects for the utilization of heat from the exhaust gases of diesel power plants in Kazakhstan are based on an analysis of climatic conditions in the country. The results of the analysis of climatic conditions make it possible to form an optimal technological scheme for utilizing the waste heat of a diesel generator. The change in the average monthly air temperature during the year is shown in Figure 2.

The absolute maximum air temperature in the southern regions of Kazakhstan can reach 44...45°C, the absolute minimum temperature in the northern regions of Kazakhstan can reach -45...-48°C (Construction Climatology, 2017). Such a large difference in air temperatures in summer and winter requires an assessment of the efficiency of the internal combustion engine depending on the outside temperature. In addition, a sufficiently large cold period in some cases requires an analysis of the possibility of using the waste heat of an ICE for heating rooms. Therefore, it is advisable to consider the technological scheme (Figure 3), which provides for both obtaining additional electricity and heat for heating the premises due to the waste heat of the ICE.

The waste heat of the ICE enters the steam generator 1, where dry superheated water vapor is generated. In the summer time, all the generated steam enters the steam turbine 3, which is connected with the electric energy generator 4. After expansion in the steam turbine 3, the waste steam enters the condenser 5. The condensate from the condenser 5 is pumped again by pump 6 to the steam generator 1. In the winter period, part of the steam enters the water heater 2, through which the coolant of the room heating system circulates. The amount of steam entering the water heater 2 is selected so that it is completely condensed in this heat exchanger. In the cold period of time, the steam turbine 3 operates at variable loads.

Using the data of thermodynamic analysis of an ICE cycle (Goodenough and Baker, 2007), the authors obtain a simple relationship between the efficiency of an ICE with a turbocharger η and specific fuel consumption $g(ta)$ $\eta = f[g(ta)]$. Then data processing (Saber et al., 2013) gives the following dependence of engine efficiency on outdoor temperature:

$$ta := -45, -44 \dots 45 \quad (1)$$

Figure 2: The average monthly temperature in the regions of Kazakhstan: T1(x), To1 – North-Kazakhstan region; T3(x), To3 – South-Kazakhstan region; N, x – month of the year

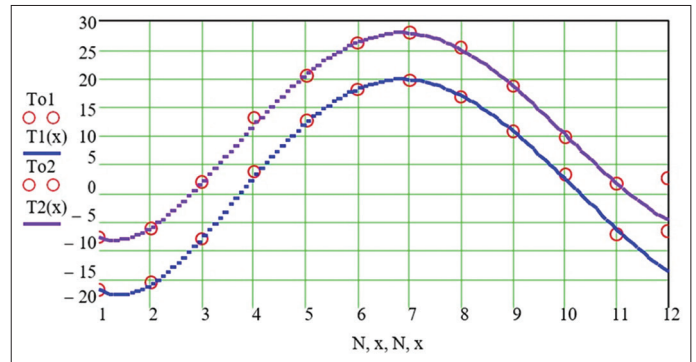
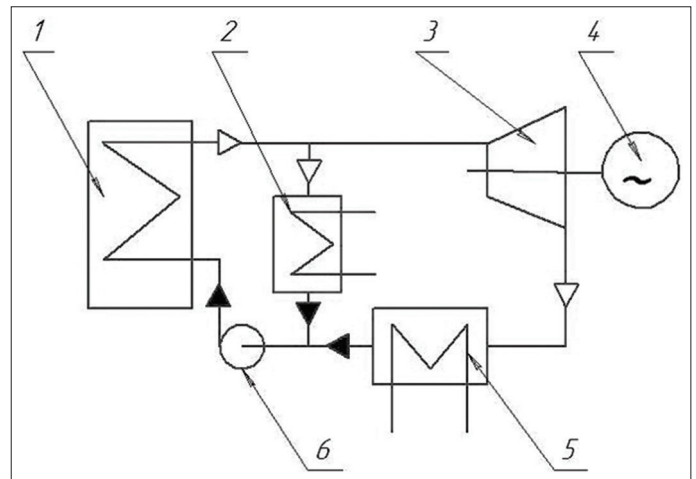


Figure 3: Schematic diagram of the utilization of waste heat of an ICE: 1 – steam generator; 2 – water heater; 3 – steam turbine; 4 – electric power generator; 5 – capacitor; 6 – pump



$$P := 1000 \dots 3000 \quad (2)$$

$$\eta(ta, P) := \frac{0.12}{kg(ta, P)} \quad (3)$$

$$kg(ta, P) := (0.3 + 4.362 \times 10^{-4} \cdot ta + -2.946 \times 10^{-6} \cdot ta^2) \cdot (1.11 - 0.1 \cdot \frac{P}{2000}) \quad (4)$$

A graphical interpretation of this equation is shown in Figure 4.

An increase in the ambient temperature from -45°C to +45°C (Figure 4) leads to a decrease in ICE efficiency by 11.4%.

Another important factor in assessing the prospects for using the ICE waste heat is the determination of the possible amount of water vapor generated from the heat of the exhaust gases. Using the methods of calculating the utilization generator (Topolski, 1998; Zweers and Kok, 1999; Ahmed et al., 2018; Tian et al., 2017), the authors performed a computer simulation of the technological process of generating superheated steam due to the heat of the exhaust gases.

The amount of heat received by the equipment of the recovery steam generator, according to the equation, can be determined as follows:

$$Gt \cdot (I_{g_1} - I_{g_2}) = Gp \cdot (iw_2 - iw_1) + Gp \cdot [(iw_0 - iw_2) + r] + Gp \cdot (h_1 - h_0) + Q_{in} \quad (5)$$

Where $Gt \cdot (I_{g_1} - I_{g_2})$ – the amount of heat given off by the exhaust gases, kJ/h; $Gp \cdot (iw_2 - iw_1)$ – the amount of heat received by water in the economizer, kJ/h; $Gp \cdot [(iw_0 - iw_2) + r]$ – the amount of heat spent on the evaporation of water in the evaporator, kJ/h; $Gp \cdot (h_1 - h_0)$ – the amount of heat spent on steam overheating, kJ/h; Gt – the amount of fuel consumed by the ICE, kg/h; I_{g_1} and I_{g_2} flue gas enthalpy at the inlet and outlet of the recovery steam generator, respectively, kJ/kg; iw_1 and iw_2 – enthalpy of water at the inlet and outlet of the economizer, respectively, kJ/kg; r – the heat of vaporization of water, kJ/kg; h_0 and h_1 – enthalpy of steam at the inlet and outlet of the superheater, respectively, kJ/h; Gp – the amount of generated steam in the recovery steam generator, kg/h; Q_{in} – the amount of heat loss to the environment, kJ/h.

The results of computer simulation are presented in Figure 5 in the form of the dependence of the specific amount of generated superheated steam on the ambient temperature.

The data in Figure 5 are obtained at: the temperature of the ICE exhaust gases – 400...420°C, superheated steam temperature – 380...390°C, specific fuel consumption in ICE – 0.220...0.240 kg/kWh. Computer simulation shows that for modern ICEs, up to 0.557 kg of superheated steam can be obtained from each kW of engine power. A decrease in the amount of generated steam with a decrease in ambient air temperature is associated with an increase in heat loss to the environment from equipment and gas flues.

The data in Figure 5 are well described by the following regression dependence in the range of outdoor temperatures from -45 to +45°C:

$$Gp(ta) = 0.536 + 4.831 \times 10^{-4} \cdot ta, \text{ kg/kW} \quad (6)$$

Based on the data in Figure 5, it is possible to determine the steam flow rate to the turbine depending on the ambient temperature. Assuming that the internal relative efficiency of a steam turbine in a first approach $\eta_{int} = 0.3$ and total efficiency of the reduction gear and generator of electric power $\eta_g = 0.95$, then the approximate value of the power of the electric energy generator depending on the ambient temperature according to the procedure (Steam Turbine Generator, 2019) can be represented in the following form (Figure 6).

An analysis of the data in Figure 5 shows that when utilizing the waste heat of an ICE, it is possible to obtain up to 0.04 kW of additional electricity from each kW of engine power of the main generator. The data in Figure 6 can be described by the following regression dependence in the range of outdoor temperatures from -45 to +45°C

$$N(ta) = 0.037 + 8.857 \times 10^{-5} \cdot ta, \text{ kW/h} \quad (7)$$

Figure 4: The dependence of internal combustion engine's efficiency η from outside temperature ta and crankshaft speed P

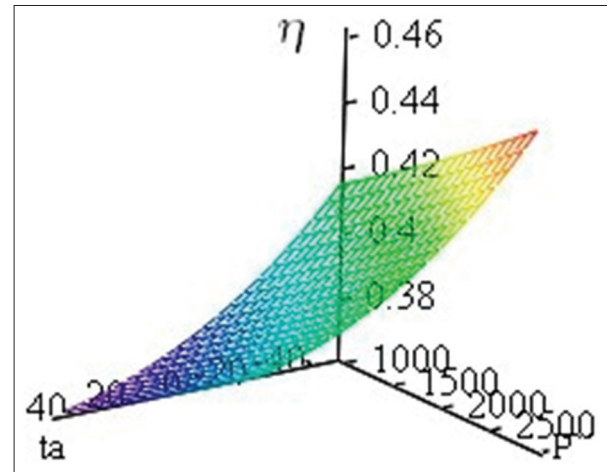


Figure 5: Dependences of the specific amount of generated superheated steam ($Gp(ta)$, kg/kW) on ambient temperature ta , °C

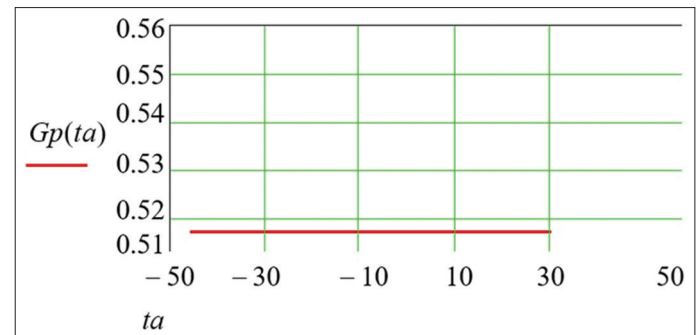
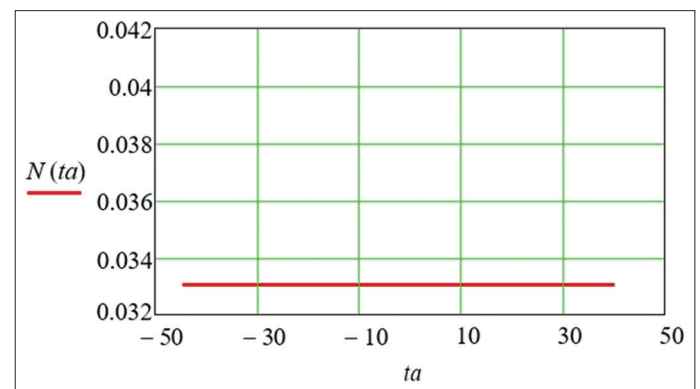


Figure 6: The dependence of the specific power of an additional electric generator ($N(ta)$, kW/h) from ambient temperature ta , °C



The results are obtained on the possible amount of additional electricity that allow the authors to make a preliminary assessment of the efficiency of utilizing the waste heat of ICEs. An assessment is performed using a diesel generator 150C-T400-1PM5 (engine power 180 kW; turbocharging).

The amount of additional electricity that can be obtained through the utilization of waste heat is approximately $0.04 \times 180 = 7.2$ kW h. The annual amount of electricity for 11 months will be 57888 kW h.

The cost of electricity in Kazakhstan for legal entities in 2019 ranges from 16.53 tenge per 1 kW • h with VAT up to 26.71 tenge per 1 kW • h with VAT, which is 0.043-0.069 USD/kW (Inform Bureau, 2019). It should be noted that the cost of 1 kW of electricity 0.08674 USD/kW was obtained as optimal when introducing the technology for the utilization of waste heat of ICEs in Colombia (Zarante et al., 2018). The indicated cost of 1 kW of energy includes profitability of 18%. The payback period for innovation is 7 years. With electricity prices in Kazakhstan in 2019, a consumer can save about 3000 USD/year from additional electricity by upgrading a diesel generator 150C-T400-1PM5.

While estimating the total cost of equipment similar to that proposed in the technological scheme (Figure 2), the authors conclude that the modernization of existing diesel generators can pay off in 3.0-3.5 years. With a service life of modified diesel generators 150C-T400-1PM510 - 12 years, taking into account the cost of maintenance it can bring up to 20,000 USD to the owner.

Considering diesel generators that are common in Kazakhstan, it can be noted that supercharged diesel engines have an efficiency ranging from 0.41 to 0.44. In this case, heat loss with exhaust gases and cooling water can be from 50% to 55% of the energy expended in the ICE (Jawad and Ayyash, 2020). Such significant energy losses determine the feasibility of modernizing diesel generators by retrofitting them with waste heat recovery circuits.

Such modernization in the sharply continental climate of Kazakhstan increases the production of electricity on existing machines by an average of 10-12% without additional fuel consumption, that is, it creates a significant saving effect. Moreover, there are a number of problematic aspects for implementing waste energy utilization programs: technical, economic, and managerial in nature. In the market conditions in Kazakhstan, there are difficulties with the selection of steam turbines for diesel generators with a capacity of less than 1000 kW, which generally slows down the modernization of fixed assets of enterprises. However, it is important to understand that the effectiveness of managing the company's secondary energy resources depends on the effectiveness of overall corporate governance. Point optimization will only create a temporary positive economic effect. At the same time, an improvement in the macroeconomic background (such as, for example, planned liberalization of electricity prices (Paryono et al., 2020) can serve as a powerful incentive to reduce the payback period of investments in targeted heat recovery projects (Cooremans and Eco'Diagnostic, 2012).

The exhaustibility of natural resources, existing global climate problems, as well as the direct positive social effect of the implementation of environmental initiatives, sooner or later will lead to the fact that global society will be forced to live on the principles of a "green economy." However, the latter requires a significant technological breakthrough, which allows reducing the adaptation period of the existing rules of the world economy to new standards. To date, the most optimal way for implementation is precisely the efficient use of already created energy. The latter allows not to consume even more resources, and also not to create a negative impact from unused energy (after all, it does not create new products, but leaves a "carbon footprint"), thereby

the efficiency and relevance of the disposal of waste energy is not in doubt.

4. CONCLUSIONS

The transition of countries to the principles of green energy can be partially achieved through the introduction of diesel generators' waste heat recovery technology. In Kazakhstan, such a transition is economically viable and is planned until 2050. With the existing level of waste heat recovery equipment, it is possible to increase the electricity generated by diesel generators by 10-12%, that is, create an equivalent saving effect in the enterprise budget. At the same time, with an improvement in the macroeconomic background, the created positive economic effect will grow due to market conditions and access to technologies (more modern equipment).

The introduction of secondary energy processing at an individual enterprise creates a corporate precedent for innovative implementation. Thereby triggering a chain reaction of technology introduction by other companies (associated with the first vertically or horizontally), which generally increases the level of competitiveness in the industry and the national economy.

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