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A System of Improving Energy and Ecological Efficiency, Using the Example of Fuel Oil Combustion in Power Plant Boilers

Wilhelm Jan Tic and Joanna Guziałowska-Tic *

Department of Process and Environmental Engineering, Opole University of Technology, 45-758 Opole, Poland
* Correspondence: j.guzialowska-tic@po.edu.pl; Tel.: +48-77-449-8111

Abstract: Most climatic changes are not just the result of human activity, but also of business models that harm the environment. An attempt to attain an ecological balance is an answer to the challenge posed by this situation. The combustion of liquid fuels results in the atmospheric emissions of pollutants, such as nitrogen oxides (NOx), sulfur dioxide and hydrocarbons. To reduce emissions of these pollutants and at the same time attain an ecological balance, specific modifiers are applied. This paper presents an analysis of the energy efficiency and ecological efficiency of fuel oil combustion in power plant boilers based on the results of tests carried out by the present authors, in which a Fe/Mg/Ce modifier was used. The tests were carried out for system capacities ranging from 1 to 5 MW. It was found that savings on fuel, which resulted from the implementation of a system for the control and supervision of power plant operation, were in the range of 4 to 6%, and those resulting from the use of the combustion modifier were from 2 to 4%. Moreover, it was found that the system designed to improve efficiency also provided the extra result of reducing CO_2 emission and equivalent emission (SO_2, NO_2, and particulate matter).

Keywords: fuel oil combustion; modifier; energy efficiency; ecological efficiency; power plant boiler; environmental sustainability

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1. Introduction

As global petroleum resources are being depleted, heavy fuel oils are growing in importance [1,2]. In recent years, the qualitative and quantitative requirements regarding high-quality, low-sulfur and low-aromatic diesel oils and fuel oils have become more stringent worldwide. At the same time, the quality of available petroleum resources has been deteriorating [3]. Heavy fuel oil combustion processes are known to generate harmful atmospheric emissions. Kim and Jeong calculated that the combustion of 1 TCE (ton of standard carbon equivalent) of heavy fuel oil generates 3115.6 kg CO_2, 0.42 kg CO and 0.025 kg N_2O [4].

The attainment of an ecological balance has developed into a global initiative in recent years. Many highly industrialized countries which emit high quantities of CO_2 are seeking various energy solutions to attain balanced development. In his paper, Bekun examined the effect of renewable and non-renewable energy, economic growth and investments in the energy sector on CO_2 emissions in India during the period 1990–2016 [5]. For this purpose, canonic co-integration regression (CCR), a fully modified method of ordinary least squares (FMOLS) and dynamic ordinary lowest squares (DOLS) were applied. The results of the above regression showed that renewable energy reduced CO_2 emissions by 1.24%, 1.15% and 1.25%, respectively, while the consumption of non-renewable energy increased emissions by 0.71%, 1.08% and 0.84%, respectively [5].

In 2021, the production volume of liquid fuels in Poland was 27.2 mln m^3, to which heavy fuels contributed a total of 5%. As markets emerged from the pandemic-induced weakening in 2020, higher volumes of major grades of medium distillates were produced in 2021 and 3% more liquid fuels were produced in Poland [6]. It has been forecast that the production volume of liquid fuels in Poland in 2030 will reach 36.5 mln m^3 according to a base scenario, and as much as 39 mln m^3 in an optimistic scenario. These forecasts take into account the latest changes to the economy imposed by the ongoing energy transformations and the new reality brought by the European Green Deal [7].

Poland's current energy policy until the year 2040 comprises three of the most important pillars. The first pillar of the project, fair transformation, calls for EUR 12.75 billion of EU funds over the next 10 years for areas where the economy is dependent on fossil fuels. The second pillar calls for the creation of a zero-emission energy system parallel to the existing one over the next 20 years. This task is to be based on two strategic components–nuclear energy and maritime wind energy [8]. The third pillar of energy policy concerns the good quality of air. The project calls for abandoning coal as a heat source in private households; by 2030 in towns and by 2040 in the countryside [9]. Fossil fuels will gradually be replaced with other heat sources, such as heat pumps. The number of households connected to urban heating networks is to increase to 1.5 million by 2030.

A key challenge for energy transformation in Poland is to create an energy system that satisfies not only society's energy requirements, but also the need for environmental protection, where local initiatives will play a major role. Drożdż and others performed a survey among local government authorities to gauge social acceptance of energy policy. The survey suggests that in order to boost the awareness of respondents, the Polish government should prepare a publicity campaign on energy policy [10].

As requirements regarding the use of fuels are becoming increasingly stringent, it is vital to use modifiers and reduce the atmospheric emissions of pollutants. The use of modifiers in fuel combustion processes has been described in numerous reports. Most of them relate to motor fuels [11–13], and information on light or heavy fuel oils is rather limited

The literature survey was carried out using the Scopus platform–one of the largest multidisciplinary databases. [14,15]. Published reports were searched from the citation "fuel oil combustion modifier". Figure 1 shows the number of papers published in the years 1965–2022. Since 1965, only a few more papers on fuel oil combustion modifiers have been published every year, resulting in a total of 63 papers to date. Figure 2 shows the subjects of the papers: 41% of the papers relate to Engineering, 20% to Environmental Science, and 9% to Energy and Materials Science. The category named Other includes papers related to physics and astronomy, business and management, earth sciences and biochemistry.

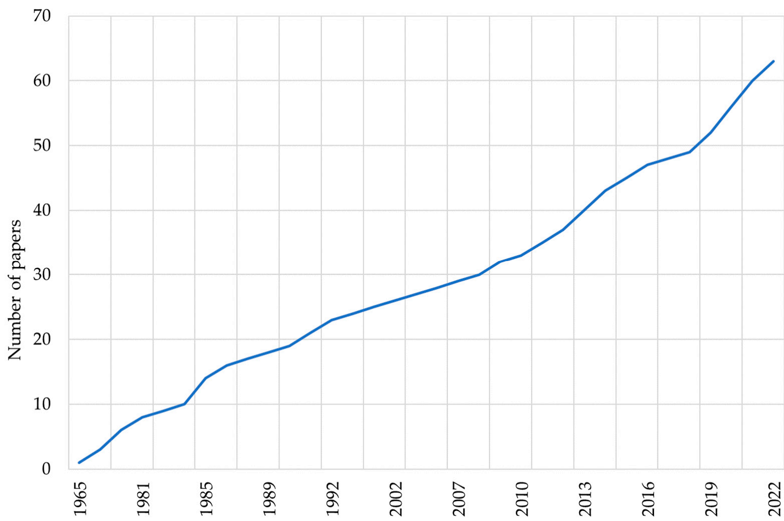

Figure 1. The number of papers published in the years 1965–2022 for the key words "fuel oil combustion modifier", authors' report based on https://www.elsevier.com/pl-pl/solutions/scopus (accessed on 27 October 2022).

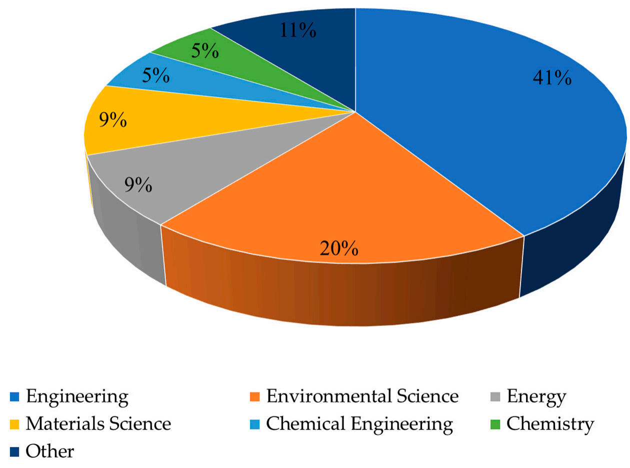

Figure 2. The subjects of the papers published in the years 1965–2021 for the key words "fuel oil combustion modifier", authors' report based on https://www.elsevier.com/pl-pl/solutions/scopus (accessed on 27 October 2022).

An important question in the use of additives in the combustion of heavy fuel oils in power plant boilers is to improve their ecological and energy efficiency. The characteristics of the modifiers used with heavy fuel oils, including their composition, method of addition, advantages and disadvantages, are described in Table 1.

Table 1. Additives used with fuel oil (own analysis based on the literature).

Composition of Catalyst	Methods of Introduction	Advantages and Disadvantages	Literature Source
Organometallic compounds of iron and calcium	The organometallic compounds are dissolved in oil at concentrations of 1/4000 and 1/6000	The addition of calcium to heavy fuel oil was associated with lower consumption of fuel and with a higher reduction of NO_x and emissions of particulate matter than it was observed for the iron-based modifier	[16]
Iron chloride(III), hydrated magnesium chloride, copper chloride(II)	Dissolved in petroleum	Surface reactions tended to prevail and the catalyst had no significant impact on the reactions when lower amounts of metallic additives were added	[17]
Sodium hydroxide, sodium chloride, sodium carbonate and potassium carbonate, potassium hydroxide, potassium chloride, potassium carbonate	Dissolved in petroleum	The introduction of these compounds into oil poses serious problems and the resulting suspensions tend to be unstable	[18]
Nickel ions	Dissolved in heavy fuel oil	The use of nickel ions resulted in lower concentrations of compounds, and higher concentrations of CO_2 and water in the gas emissions; SO_2 concentration was also lower	[19]
Copper nanoparticles	Nanoparticles at a concentration of 1000 ppm, dissolved in the aqueous phase	Nanoparticles affect the properties of the oil produced and lead to the formation of less water in the process	[20]
Fatty-acid organic iron salts	Concentration of the iron-based catalyst in mazout—60 ppm	Heat recovery was 8% higher, NO_x emission was 9% lower	[21]
Organometallic additives based on iron, calcium, manganese and magnesium, dissolved in naphthalene	- conc. Fe—12%, - conc. Mn—6–10%, - conc. Mg—3.5–8%, - conc. Ca—4%.	Reduction of particulate matter from 50–80% for the various additives	[22]
Magnesium oxide	- 500 g suspension/ton of mazout, - 200 g suspension/ton of mazout	21% higher process efficiency, 67% lower emissions of SO_2, 40% lower emissions of NO_x	[23]

Table 1. *Cont.*

Composition of Catalyst	Methods of Introduction	Advantages and Disadvantages	Literature Source
Organometallic salts of rare-earth metals, mainly Ce, Pr, Nd	The modifiers were added into the liquid fuel in amounts ranging from 20 to 200 ppm, in terms of the metal	The modifier was adsorbed on the fuel surface, enabling its complete oxidation	[24]
Hydrocarbon solution of cyclic and aliphatic amino compounds	- 10–30% cyclic amino compounds - 5–10% aliphatic diamines - 0.1–1% of naphthalene was added to fuel oil with a very low sulfur content, at a volume ratio of 0.0005%.	Higher combustion efficiency, 6.5% lower emissions of CO, 60% lower emissions of hydrocarbons, 38% lower emissions of particulate matter, A basic analysis indicated such elements as C, O, Na, Mg, Al, Si, S, K, Ca, Ti, V, Zn and Fe, of which Ca, Fe and N came mainly from the fuel additive.	[25]
50% active polymer dispersed in metoxypropylene acetate with barium	22.70 wt% Ba	A 36% reduction in volatile organic compounds After applying the modifier, the concentration of soluble ions (Cl^-, Na^+, K^+, Ca^{2+}) and elements (Fe, Mn, S, Ca, Ba) in particulate matter increased. The tendency of an increased barium concentration in particulate matter corresponded to a similar tendency of reduced smoke emissions.	[26]

Information on this subject in the literature is scarce. Santos et al. investigated the ecological efficiency of a combined-cycle power plant capacity of 500 MW. They found that ecological efficiency for natural gas varied between 91.6% and 95.4%, and the performance of engines fueled with diesel oil ranged from 89.4% to 94.1% [27]. Korczewski et al. carried out a real-life study of the energy and ecological effects of the use of modified marine fuel oils. They built a laboratory stand to study the newly obtained fuel oil and assessed their impact on flue gas emissions and on atmospheric pollution with harmful chemicals, as well as the deteriorating effect of such fuels on engine components [28].

The new environmental goals set by the European Green Deal and the aim towards ecological balance have led to a search for innovative and ecological energy solutions. Therefore, this paper aims to examine the possibilities of saving energy and reducing the environmental impact of emissions by applying solutions that improve combustion efficiency. This paper presents an analysis of the efficiency of a system designed to improve fuel combustion. The system comprises a control and monitoring component, which enables the precise control of the boiler parameters, and a modifier, which improves the effect of fuel oil combustion. The energy and ecological efficiency analyses of fuel oil combustion were based on the results of tests the authors had performed using a Fe/Mg/Ce modifier. The modifier was a mixture of fatty acid metal salts and metal hydroxides, dispersed in an organic solvent. The modifiers were synthesized as described by the authors in an earlier paper [21]. The results of its physico-chemical, toxicological and ecotoxicological properties indicate that the modifier is safe for human health [29] and the environment [30]. One more important aspect of research on the modifier was the method of its introduction into the fuel oil flux just before combustion. The authors used a dedicated applicator, which enabled the precise dosage of the modifier into the fuel oil flux fed into the test boiler. The applicator was described in detail by the authors in [31].

2. Materials and Methods

The authors used a system for improving the energy efficiency and ecological efficiency of fuel oil combustion, which was developed by them. The system enables the precise control of boiler parameters, leading to the reliable assessment of savings in fuel consumption [32]. The system requires the use of precise measuring instruments that enable round-the-clock measurement of fuel consumption, analysis of flue gas and control of chimney losses with a view to optimizing the combustion process parameters.

The solution enables the optimization of fuel oil combustion parameters and leads to the assessment of its benefits; namely, the amount of extra energy generated and reduction of harmful emissions arising in the combustion process. An analysis of the energy efficiency and ecological efficiency of fuel oil combustion was performed based on the results of tests the authors had carried using a Fe/Mg/Ce modifier. The modifier was a mixture of fatty acid metal salts with metal hydroxides, dispersed in an organic solvent.

In the fuel oil combustion process, the modifier was used at a concentration of 50 ppm in terms of the combined sum of the metals used, and it remained the same for the various system capacities. The subject of the study was a medium fuel oil named "Ekoterm", which satisfied the requirements of the Polish Standard: Petroleum products–fuel oils PN-C-96024:2020-12 [33] and of the Regulation of the Minister of Economy concerning the qualitative requirements on the fuel oil sulfur content, and on the types of facilities and conditions of the use of heavy fuel oils [34]. The physico-chemical properties of the medium fuel oil used in combustion tests are shown in Table 2.

Table 2. Physico-chemical properties of the medium fuel oil.

Parameter	Unit	Value
Calorific value	MJ/kg	43.0
Carbon	%	88.0
Hydrogen	%	10.0
Sulfur	%	1.0
Moisture content	%	0.50
Ash	%	0.1
Others	%	0.4

The oil combustion tests were carried out using a Logano 30 kW three-draft water boiler from Buderus (Warsaw, Poland). The boiler was equipped with a blow-in multi-fuel burner, type ABC UNI 65, rated thermal input 25–60 kW, from ABC-Eko, capable of handling light oils and medium range oils.

To assess the impact of modifiers and the refurbishment of the fuel oil combustion process, the amount of heat generated by burning the investigated fuel sample was calculated, the heat balance was determined and the efficiency of the boiler was established. A comparison of the efficiency of the boiler determined in the fuel oil combustion tests allows us to determine the extra amount of generated energy gained from using the modifier and from refurbishing the system. The uncertainty of establishing the boiler's efficiency, at a certainty level of 95%, is 0.5%. The authors describe the results of tests in this regard in the paper [31,32].

The extra generated amount of energy was calculated as the difference between the amount of energy obtained from the same amount of oil in combustion with the use of the modifier and/or system refurbishment, and in combustion without the modifier or system refurbishment.

The extra amount of energy resulting from the use of the modifier was calculated from Formula (1):

$$\Delta E_k = PG \times (1 + E_k) - PG \tag{1}$$

where:

ΔE_k—annual savings on the consumption of energy with the use of the catalyst [MWh];

E_k—effect of using the modifier [%];

PG—production of energy [GJ].

Extra energy generated due to refurbishment was calculated using Formula (2):

$$\Delta E_m = PG \times (1 + E_m) - PG \tag{2}$$

where:

ΔE_m—annual savings on the consumption of energy using the refurbishment [MWh];

E_m—the effect of using the refurbishment [%].

The combined extra energy generated is the sum of extra energy generated using both the modifier and the boiler refurbishment (3):

$$\Delta E_i = \Delta E_k + \Delta E_m \tag{3}$$

where:

ΔE_i—annual savings on the consumption of final energy [MWh].

The ecological effect is understood as a reduction of the amount of pollutants being introduced into the environment, which is attributed to the implementation of the system for improving the energy efficiency and ecological efficiency of fuel oil combustion.

It is not feasible to prepare an environmental impact report for every envisaged investment project because, in addition to the analysis of potential environmental risks, such a report is supposed to comprise a complete analysis of ecological effects. Therefore, an assessment of the environmental impact caused by emissions attributed to investment works or refurbishment is usually omitted from such reports. It is assumed that the ecological effect assessment will be applicable to the operation phase. Such an assessment has been reduced to the calculation of the avoided emission, expressed as two separate values: for greenhouse gasses (CO_2) and for other pollutants (SO_2, NO_x and particulate matter), referred to as the equivalent emission.

For projects associated with energy savings, the ecological effect as a reduction of emission was calculated from the energy saved ΔEi and the related emission values, using the relationship (4):

$$e = \Sigma\Delta Ei \times we,i \tag{4}$$

where:

e—ecological effect [kg].

Calculations were separately carried out for equivalent emission (particulate matter, SO_2 and NO_2) and additionally for CO_2. These calculations were carried out using Formulas (5) and (6):

$$e_{CO2} = \Sigma\Delta Ei \times we, CO_2 \tag{5}$$

$$er = \Sigma\Delta Ei \times we, r \tag{6}$$

where:

e_{CO2}—reduction of emission CO_2 [kg];

e_r—reduction of equivalent emission [kg];

ΔEi—annual savings on the consumption of final energy [MWh];

we, CO_2—CO_2 emission [kg/MWh];

we, r—equivalent emission for other pollutants (particulate matter, SO_2, NO_2) [kg/MWh].

The calculations were based on the following values of CO_2 emission and equivalent emission for fuel oil [35]:

- ✔ CO_2 emission = 270 kg/MWh;
- ✔ Equivalent emission = 3.26 kg/MWh.

Energy in GJ was converted into MWh using the relationship (7):

$$1 \text{ MWh} = 3.6 \text{ GJ} \tag{7}$$

3. Results

The authors developed and used a system for improving the energy efficiency and ecological efficiency of fuel oil combustion. The system enables the reliable assessment of savings in fuel consumption [31]. It requires the use of precise measuring instruments that enable round-the-clock measurement of fuel consumption, analysis of flue gas and control of chimney losses with a view to optimizing the combustion process parameters. The solution enables the calculation of the ecological and energy effects of the use of the modifier, and the boiler control and monitoring system.

The results of earlier tests, as described in [31,36], indicated that the use of a system designed to improve the energy efficiency of boiler systems is only cost effective for boiler capacities from 1 to 5 MW.

The system for improving the energy efficiency and ecological efficiency of fuel oil combustion comprises a modifier and a solution enabling the control and supervision of the boiler operation parameters. The system is designed to improve the efficiency of energy generation and distribution, resulting in reduced environmental emissions of harmful combustion products. Both the extra energy generated and the reduced emission of harmful compounds are the effects of the use of the modifier and of the fuel oil combustion system refurbishment, shown in [31,32,36].

On the basis of the analysis of the test results described by the authors, it is assumed that savings resulting from the use of the modifier are approximately 2–6% (depending on system capacity), and those resulting from the system refurbishment are approximately 4–6%. Both the value of the extra energy resulting from the use of the modifier and that resulting from the boiler control and monitoring system have been assessed by experts in the implementing company [31,32].

The calculation of ecological and energy efficiency of the fuel oil combustion process is based on the comparison of generated energy and reduced environmental emissions of harmful products in the phase of fuel oil combustion where the system for improving efficiency was or was not used.

The proposed system takes into account improvements in efficiency based on the results of fuel oil combustion tests not only with the use of the modifier, but also with the use of the control and monitoring. The latter has the main advantage of being able to improve energy generation and distribution, and also to reduce harmful environmental emissions.

3.1. Energy and Ecological Effect of Applying the Modifier

The generated extra amount of energy resulting from the use of the modifier was calculated as the difference between the amount of energy obtained from the same amount of oil by combustion with/without the use of the modifier (Table 3).

Table 3. Extra energy generated with the modifier for system capacities from 1 MW to 5 MW.

Average System Capacity, MW	GJ of Energy per 1 MW Capacity, GJ/MW	Production in GJ	Effect of the Modifier, %	Extra Energy Generated, GJ
MW	EM	PG	Ek	ΔEk
1	8000	8000	4.0	320.0
2.5	10,000	25,000	3.0	750.0
5	10,000	50,000	2.0	1000.0

In order to calculate how much energy is generated per year (PG) in medium-capacity systems, it was assumed that, for low-capacity systems to reach 1 MW, it takes 8000 GJ of energy and this is the lowest value. Higher-capacity systems are characterized by better performance, so, for system capacities of 2.5 and 5 MW, the figure is 10,000 GJ/MW. Multiplying the system capacity by the assumed number of GJ per 1 MW, we obtain the value of energy generated per year (“Production in GJ”); Formula (1).

The extra energy generated depends on the modifier and on the installed system for improving efficiency; the higher it is, the higher the system capacity. The highest value of 1000 GJ/year was obtained for the 5 MW system. In the 1 MW system, the extra energy generated was only 320 GJ/year.

The combustion of fuel oil in power plant boilers inescapably involves the emission of gasses which are harmful to the environment. Modification of the fuel combustion method by using a solution that improves the energy efficiency system, namely, the modifier and the boiler system refurbishment, leads to the reduction of such emissions.

The ecological effect of the use in the fuel oil combustion process of the solution designed to improve the energy and ecological efficiency is understood as the reduction of the volume of pollutants being released into the environment.

The system for improving the energy and ecological efficiency of fuel oil combustion streamlines the process of energy generation and its distribution. The solution enables fuel oil combustion to be carried out so that it has less environmental impact. The environmental advantages of introduction of the modifier and the boiler control and monitoring system into the fuel oil combustion process were assessed, taking into account the value of reduction of the emissions of CO_2, SO_2, NO_2 and particulate matter. The favorable effect of an organometallic modifier based on Fe and Mg, which improved combustion and reduction of the flue-gas concentrations of sulfur oxides and reduction of the emission of solid particles in oil combustion, was also described by Paullikkas in [37]. Similarly, the addition of magnesium oxides into the oil results in the complete combustion of the fuel, the generation of extra energy, and reduced emissions of SO_2 and NO_x [23].

It was assumed that evaluation of the ecological effect will only concern the phase of operation. The ecological effect was evaluated by separately calculating the avoided emission in the combustion of fuel oil for CO_2 and for the other pollutants (equivalent emission of SO_2, NO_2 and particulate matter).

The ecological effect was assessed by comparing the values of CO_2 emission and equivalent emission before and after installing the system for improving the energy and ecological efficiency of fuel oil combustion. When the system is used, an extra amount of energy is generated, which means that less fuel oil is used to reach the required system capacity. The combustion of less fuel oil means that less harmful compounds are emitted into the environment. The ecological effect is the value of avoided emission.

The ecological effect was separately calculated for the case when the modifier was used and for the case when the boiler control and supervision system was used. The value of CO_2 emission was calculated by multiplying the system capacity in MWh and the CO_2 emission factor for fuel combustion, which is 270 kg/MWh of energy. Similarly, the value of equivalent emission was calculated by multiplying the system capacity in MWh and the equivalent emission factor for fuel combustion, which is assumed to be 3.6 kg/MWh.

Table 4 shows the ecological effect, expressed as a reduction of CO_2 emission and equivalent emission, associated with the improvement in the combustion efficiency and attributed to the use of the modifier.

Table 4. The ecological effect as a reduction of CO_2 emission and equivalent emission due to the modifier.

Average System Capacity, MW	Extra Energy Generated, GJ	Annual Savings on the Consumption of Final Energy, MWh	Reduction of CO_2 Emission, kg and kg/MWh		Reduction of Equivalent Emission, kg and kg/MWh	
MW	DWE_k	ΔEi_k	e_{CO2}, kg	e_{CO2}, kg/MWh	e_r, kg	e_r, kg/MWh
1.0	320.0	88.9	24,003.0	24,003.0	289.8	289.8
2.5	750.0	208.3	56,241.0	224,964.5	679.1	271.6
5	1000.0	277.8	75,006.0	15,001.2	905.6	181.1

The extra amount of energy generated was calculated, in GJ/MWh, assuming that 1 MWh corresponds to 3.6 GJ. The values of reduction in CO_2 emission and equivalent emission were calculated from Formulas (5) and (6).

Combustion with the use of the modifier leads to the generation of an extra amount of energy. This means that less fuel needs to be consumed to reach the assumed capacity, so the emission of harmful pollutants is reduced. In a 1 MW system, the use of the modifier leads to the reduction of CO_2 emissions of approximately 24,000 kg/year and the reduction of equivalent emission of approximately 290 kg/year. For increasing system capacities, the value of reduction of the emission of pollutants will be increasingly higher: for a 5 MW system, reduction of CO_2 emission is approximately 75,000 kg/year, and equivalent emission is approximately 906 kg/year.

The value of a reduction in CO_2 emissions and equivalent emissions per 1 MWh is lowest for a system with a capacity of 5 MW, and, in this case, amounts to 15,001.2 kg/MWh and 181.1 kg/MWh, respectively, for CO_2 emissions and equivalent emissions. If the system capacity is reduced to 2.5 MW, CO_2 emissions and equivalent emissions per 1 MWh rise to 22,496.4 kg/MWh and 271.6 kg/MWh, respectively. A further reduction in system capacity to 1 MW has a lower impact on restricting CO_2 and equivalent emissions. In this case, the amount of CO_2 emissions was 24,003.0 kg/MWh and that of equivalent emissions was 289.8 kg/MW.

3.2. Energy and Ecological Effect of Refurbishment

The extra energy generated due to the use of the control and monitoring system for the fuel oil combustion process (effect of refurbishment) is shown in Table 5.

Table 5. Extra energy generated with refurbishment for system capacities from 1 MW to 5 MW.

Average System Capacity, MW	GJ of Energy per 1 MW Capacity, GJ/MW	Production in GJ	Effect of Refurbishment, %	Extra Energy Generated, GJ
MW	EM	PG	E_m	ΔE_m
1	8000	8000	6.0	480.0
2.5	10,000	25,000	5.0	1250.0
5	10,000	50,000	4.0	2000.0

The value of extra energy generated depends on the average system capacity and on the efficiency of the boiler operation control and supervision system. For a system capacity of 5 MW, the extra energy generated is 2000 GJ/year. Lower capacity systems will generate less extra energy, respectively. This results from the fact that lower capacity systems have worse performance, which will grow higher with higher capacities. As in the case when the catalyst was used, the lowest amount of energy was generated for a system capacity of 1 MW; the value was 480.0 GJ/year.

The value of a reduction in CO_2 emissions and equivalent emissions resulting from the use of the boiler control and monitoring system is shown in Table 6.

Table 6. The ecological effect as a reduction of the emission of CO_2 and equivalent emission due to the refurbishment.

Average System Capacity, MW	Extra Energy Generated, GJ	Annual Savings on Consumption of Final Energy, MWh	Reduction of CO_2 Emission, kg and kg/MWh		Reduction of Equivalent Emission, kg and kg/MWh	
MW	DWE_m	ΔEi_m	e_{CO2}, kg	e_{CO2}, kg/MWh	e_r, kg	e_r, kg/MWh
1.0	480.0	133.3	35,991.0	35,991.1	434.6	434.6
2.5	1250.0	347.2	93,744.0	37,497.6	1131.9	452.8
5	2000.0	555.6	150,012.0	30,002.4	1811.3	362.3

The boiler control and monitoring system enables the combustion of fuel oil in optimum operating conditions for the boiler. The solution also contributes to the reduction of the environmental emission of harmful products of combustion. The value of reduction of such emissions depends on the installed system capacity and is higher for higher system capacities. For a system capacity of 1 MW, the use of the boiler control and monitoring system results in the reduction of CO_2 emission by approximately 36,000 kg/year and equivalent emission (SO_2, NO_2 and particulate matter) by some 435 kg/year. For the system capacity of 2.5 MW, the reduction of CO_2 emission and equivalent emission is approximately 93,750 kg/year and approximately 1132 kg/year, respectively. The highest reduction of CO_2 emission and equivalent emission, approximately 150,000 kg/year and approximately 1800 kg/year, is reached in a 5 MW system.

The value of a reduction in CO_2 and equivalent emissions resulting from a refurbishment of the fuel oil combustion process per 1 MWh depends on the capacity of the system installed. The reduction in emissions, taken to be the amount of saved emissions, is least with a 5 MW system, and amounts to 30,002.4 kg/MWh with regard to CO_2 emissions and 362.3 kg/MWh with regard to balanced emissions. With a system of 2.5 MW, the reduction of saved emissions is greatest and amounts to 37,497.6 kg/MW and 452.8 kg/MW with regard to CO_2 and balanced emissions, respectively. With a system of 1.0 MW capacity, the value of reduced CO_2 emissions is 35,991.1 kg/MW and that of equivalent emissions is 434.6 kg/MW.

3.3. Summary of the Energy and Ecological Effect of Applying a System for Improving Energy and Ecological Efficiency

A comparison of the extra energy effect resulting from the use in the fuel oil combustion of a solution for improving the ecological and energy efficiency, composed of a modifier and a control and supervision system, is shown in Figure 3.

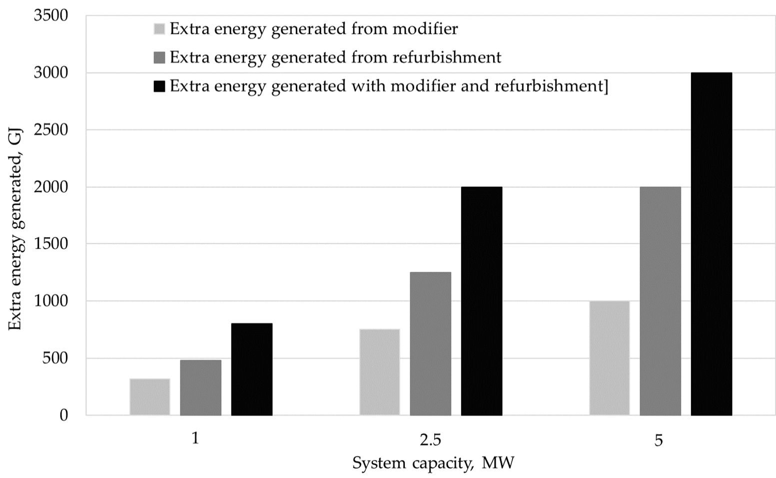

Figure 3. The extra energy effect of using the modifier and refurbishment for system capacities from 1 MW to 5 MW.

Both the extra energy generated, which is attributed to the use of the modifier in the combustion process, and the boiler control and supervision system depend on the installed system capacity; the higher they are, the higher the system capacity. The highest combined extra energy generated (3000 GJ/year) was reached for the highest capacity system of 5 MW. For the 1 MW system, the extra energy generated was 800 GJ/year. An increase in extra energy in comparison with energy production capacity, expressed in %, is the highest in low-capacity systems and it decreases with system capacity.

The extra increase in energy, which is attributed to the use of the modifier and of the boiler control and supervision system, is 10.0% for a system capacity of 1 MW and 6.0% for a 5 MW system. The result is directly related to the assumed values of the effect of the use of the modifier and of the refurbishment; the lower the value, the higher the system capacity.

The combined ecological effect, comprising the reduction of CO_2 emission and equivalent emission as the result of implementation of the complete system for improving the energy and ecological efficiency, is illustrated in Figure 4.

The values of CO_2 emission and equivalent emission for the combustion of fuel oil in a process with the modifier and with the boiler control and supervision system were calculated as the difference between emission figures for capacities ranging from 1 MW to 5 MW, without the system for improving the energy efficiency and ecological efficiency of fuel oil combustion minus the emission figures obtained when the system was used. The difference is the avoided emission.

The highest value of the avoided emission, obtained for a system capacity of 5 MW, is approximately 225,000 kg/year for CO_2 emission and approximately 2700 kg/year of equivalent emission. For lower system capacities, the avoided emission is also lower for a

2.5 MW system, CO_2 emission and equivalent emission are approximately 150,000 kg/year and approximately 1800 kg/year, respectively. For a system capacity of 1 MW, the values of avoided emission of CO_2 and equivalent emission are approximately 60,000 kg/year and approximately 725 kg/year, respectively.

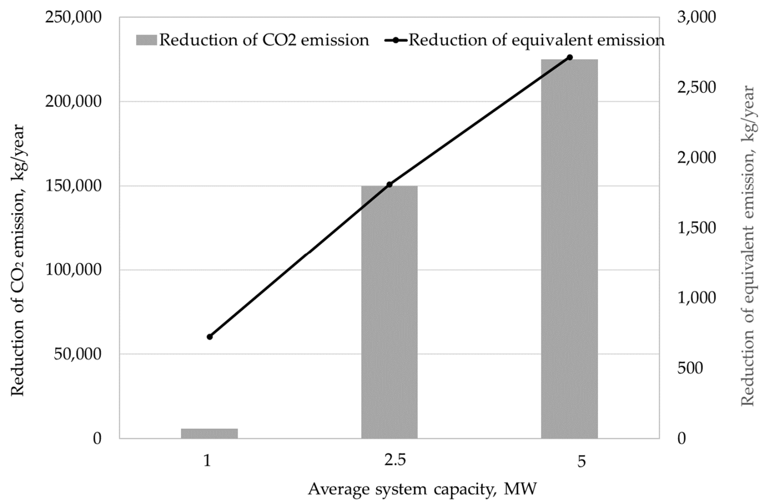

Figure 4. The combined ecological effect as a reduction of the emission of CO_2 and of equivalent emission as the result of implementation of the complete system for improving the energy and ecological efficiency of fuel oil combustion.

To show the effectiveness of the system for improving energy and ecological efficiency, the reduction of emissions per 1 MW of capacity for a system of varied capacities was compared; Figure 5. In this case, the least effectiveness was attained for a system of 5.0 MW capacity. The values of reduced emissions were 45,000 kg/year in the case of CO_2 emissions and 540 kg/year in the case of equivalent emissions. In the case of systems with a capacity of 2.5 MW and 1.0 MW, the amount of reduced CO_2 and equivalent emissions assumes comparable values, and is about 30% higher compared to a system with a capacity of 5.0 MW.

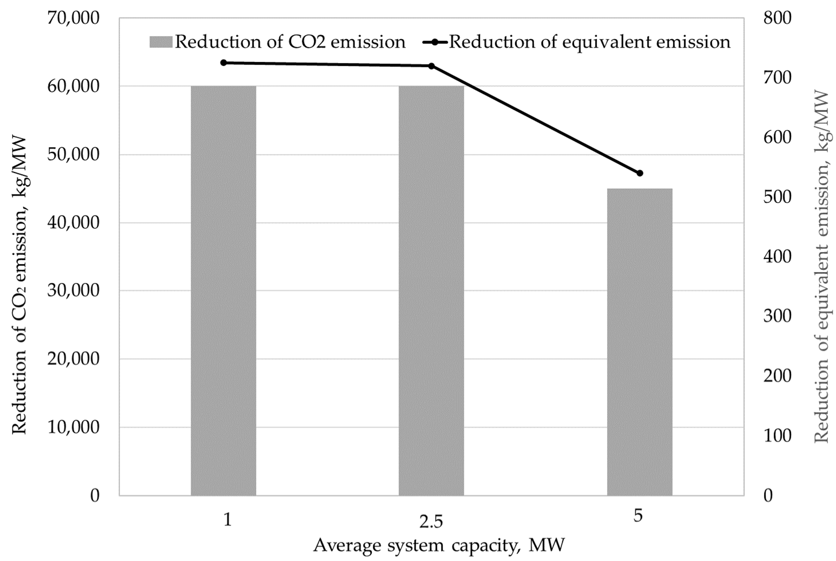

Figure 5. The size of emission reductions per 1 MW of capacity for the system for improving energy and ecological efficiency.

The combined CO_2 emission in the combustion of fuel oil in systems ranging from 1 MW to 5 MW, using the modifier, the boiler control and supervision system and the complete system for improving combustion efficiency is illustrated in Figure 6 in contrast to the process without modification.

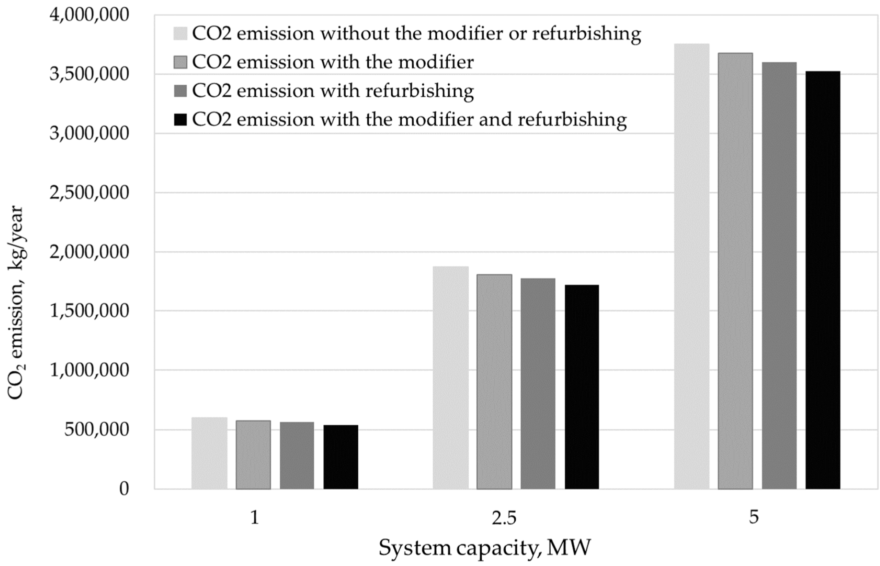

Figure 6. CO_2 emission in fuel oil combustion for system capacities from 1 MW to 5 MW.

For all of the system capacities of interest, the highest CO_2 emissions were observed in fuel oil combustion in which the system for improving the energy and ecological efficiency was not used. CO_2 emission depends on the installed system capacity and its value is the highest—375,000 kg/year—for the highest system capacity of 5 MW. For systems with lower capacities—1 MW and 2.5 MW—CO_2 emission is 600,000 kg/year and 1875 kg/year, respectively. The use of the modifier in the combustion of fuel oil results in the reduction of combined emission of CO_2 as follows: to 575,000 kg/year, 1,800,000 kg/year and 3,675,000 kg/year for the system capacity of 1 MW, 2.5 MW and 5 MW, respectively. Slightly lower values of CO_2 emission in comparison with the oil combustion process with the modifier were obtained in the case of boiler refurbishment. In the fuel oil combustion process in which the authors used the complete system for improving the energy and ecological efficiency, that is, both the modifier and the boiler refurbishment, the value of CO_2 emissions were 540,000 kg/year, 1,725,000 kg/year and 3,525,000 kg/year for system capacities of 1 MW, 2.5 MW and 5 MW, respectively.

As in the case of CO_2 emission, the value of equivalent emission depends on the installed system capacity, as well as on the use of the modifier and boiler refurbishment. Equivalent emissions for system capacities ranging from 1 MW to 5 MW with the modifier, with the boiler control and supervision system, or with the complete system for improving the energy and ecological efficiency in comparison with combustion without modification, are illustrated in Figure 7.

The highest equivalent emissions were observed in the combustion of fuel oil without modification. These values vary with system capacity as follows: for system capacities of 1 MW, 2.5 MW and 5 MW, they are 7245 kg/year, 22,640 kg/year and 45,280 kg/year, respectively. In the process of oil combustion in the presence of a modifier, equivalent emission can be limited to the value of 6955 kg/year, 21,960 kg/year and 44,370 kg/year depending on system capacity. As for CO_2 emission, refurbishment of the boiler system results in slightly lower equivalent emissions in comparison with a combustion process based on the use of a modifier. In systems where both the modifier and the boiler refurbishment were used, the values of equivalent emissions were the lowest, depending on the system capacity as follows: for 1 MW, 2.5 MW and 5 MW, the equivalent emissions were 6520 kg/year, 20,830 kg/year and 42,560 kg/year, respectively.

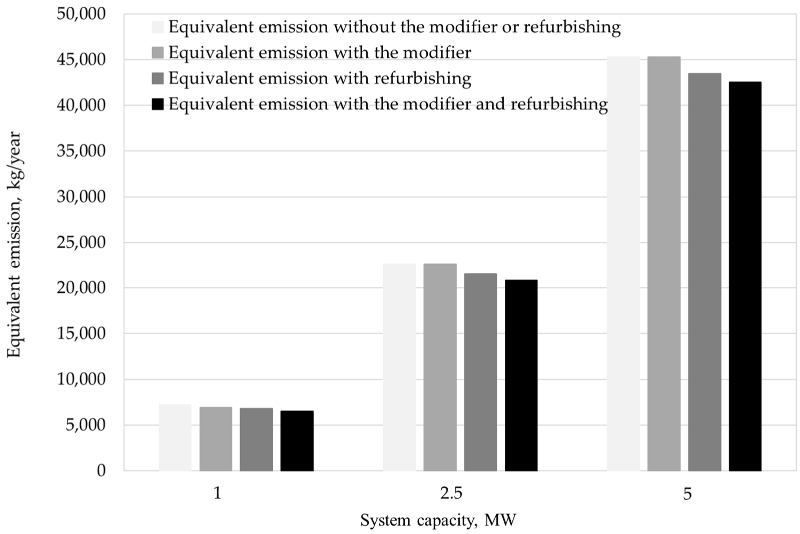

Figure 7. Equivalent emission (SO_2, NO_2 and particulate matter) in fuel oil combustion for system capacities from 1 MW to 5 MW.

4. Conclusions

The use of a system for improving the energy and ecological efficiency of fuel oil combustion in power plant boilers results in major energy savings and in reduced emissions of harmful components of flue gas. The system comprises a modifier which improves the effect of combustion and a solution enabling the precise control of boiler parameters along with a reliable assessment of savings in fuel. The tests were carried out for system capacities from 1 MW to 5 MW. It was found that savings in energy, which resulted from the application of a system enabling the control and supervision of the boiler room operation, varied between 4 and 6 depending on the system capacity. Savings attributable to the use of modifiers were in a range of 2 to 4%.

The amount of reduction of CO_2 and equivalent emissions resulting from a refurbishment of the fuel oil combustion process depends on the capacity of the system installed. In this case, the most effective system is one with a capacity of 1 MW and 2.5 MW, for which the amount of reduction in CO_2 and equivalent emissions is at a similar level and amounts to ca. 60,000 kg/MWh and ca. 720 kg/MWh, respectively. For a system of 5.0 MW capacity, the reduction in both CO_2 and equivalent emissions is about 30% higher.

Poland's energy policy is largely based on conventional fuels. It calls for the abolition of coal as a source of heat in private households by the year 2040. However, the present political situation and the turmoil on the energy market could cause this deadline to be extended. Therefore, the correct course of action is to seek innovative methods of producing energy from conventional fuels, such as the system of improving energy and ecological efficiency proposed in this paper.

A key challenge for energy transformation in Poland is to create an energy system that corresponds to social requirements not only with regard to energy demand, but also environmental protection. Therefore, it is important to prepare a publicity campaign on energy policy in order to show society the opportunities and risks of introducing the European Green Deal.

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