energies

Review

The Cost-Efficiency Analysis of a System for Improving Fine-Coal Combustion Efficiency of Power Plant Boilers

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Abstract: Hard coal is widely used as a source of energy, and a number of catalysts have been developed to minimize the noxious impact of this fuel on combustion. This paper presents the cost-efficiency analysis of a system for improving the combustion of solid fuels, especially fine coal, in power boilers. The system is provided with a control and supervision device. It has been designed for better accuracy in controlling the boiler operating parameters, with a view to improving combustion efficiency due to the use of catalysts. The tests were carried out for system capacities ranging from 3 to 100 MW. It was found that, depending on the size of the system in the range of 3–100 MW, savings in the fuel consumption ranged from 2% to 8% due to the implementation of novel solutions in the boiler plant operation and from 2 to 6% due to the use of the combustion catalysts. Apart from boosting energy efficiency, the use of catalysts and the efficiency-boosting system resulted in the costs of overhauls being cut by about 20%. The payback time depends on system capacities, and it is between 6.75 and 1.74 years for capacities ranging from 3 to 75 MW and 2.0 years for a 100 MW plant.

Keywords: fine coal; combustion; market analysis; Desk Research; efficiency; refurbishment; catalysts; payback time

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1. Introduction

During the last few decades, the consumption of energy has increased, specifically owing to the development of new technology, based predominantly on a limited and unsafe energy structure, composed of such fossil fuels such as hard coal, petroleum and gas [1]. More than 38% of electric energy globally is generated from hard coal [2]. For emerging markets such as India or China, hard coal is an attractive source of energy because of its high resources and low cost of mining [3].

Figure 1 shows total hard coal output in Poland and in the European Union (EU) in the years 1990–2019. The diagram shows that the value has been going down almost incessantly since 1990. In the year 2019, the hard coal production volume for the European Union was 65 10^6 t, which is 77% lower than the value of 277 10^6 t in the year 1990. In 1990, hard coal was produced by 13 member states of the present European Union, compared with only two states (Poland and the Czech Republic) in 2019 [4,5]. Poland produced 61.6 10^6 t of hard coal, which was 95% of total hard coal production volume in the European Union, whereas the Czech Republic did 3.4 10^6 t (5%) [6]. In comparison with 123 10^6 t in the year 2012, when the last peak in the hard coal production volume was observed in the European Union, Poland cut its production volume by 22%, and the Czech Republic did by 70%. All the other former hard coal-producing states had ceased their production by that time.

In the year 2019, 47% of hard coal was used for power generation. Since 2013, hard coal supplies for power generation have clearly been decreasing. This is due to the fact that hard coal tends to be replaced with natural gas and renewable sources of energy [4].

As regards the consumption of hard coal in 2019, the value for the European Union was 176 10^6 t, of which more than 60% falls to Poland (39%) and Germany (23%), followed by France and the Netherlands (6% each). The decreasing trend in hard coal consumption in the EU is confirmed by the fact that only 37% of hard coal consumption was satisfied from production in the year 2019, compared with 71% in 1990 [4].

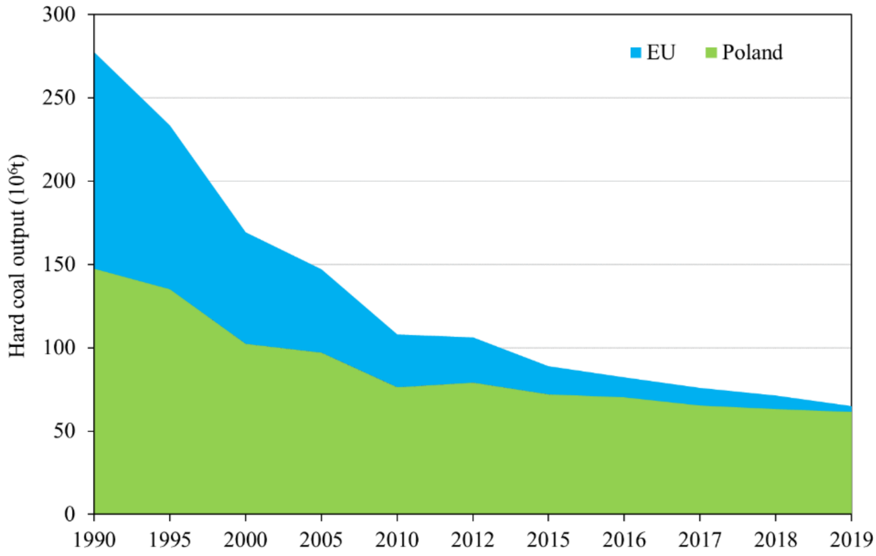

Figure 1. Hard coal output in Poland and the European Union in the years 1990–2019 according to [4,7].

In 2019, the European Commission declared that greenhouse gas emissions in Europe would have been cut down by 50–55% by the year 2030 (in comparison with 1990) and that complete carbon neutrality would have been achieved by the year 2050 [8]. According to the Polish hard coal industry program, the domestic demand for hard coal by the year 2030 will be running according to one of the three possible scenarios, none of them forecasting a rapid decline in hard coal production (Figure 2) [9].

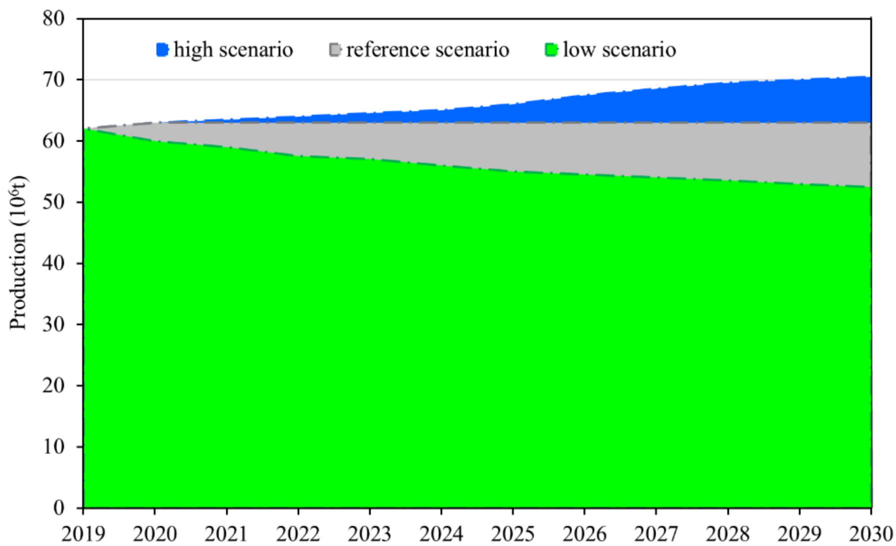

Figure 2. The forecast of hard coal production in Poland, 2019–2030 according to [9].

The low scenario is based on the assumption that the total consumption of hard coal in the domestic economy will have been cut down by 15% by the year 2030 in comparison with 2019. This scenario is based on the lowest costs: although it leaves to the market forces the problem of solving any issues arising in connection with investments in the public power sector, it also is a source of problems for the hard coal mining industry, which will have lost much of its market share for its product by the year 2030. On the other hand, according to the reference scenario, the present level of demand for hard coal is not going to change, even though some changes will be taking place in the consumption structure, namely, growth in the public power sector and a decrease in households. The structure of fuel consumption can also be affected if locally available resources, such as gas and municipal waste, are used or if the share of renewable energy sources for generating heat increases.

The high scenario is based on the assumption that the market for power coal in Poland will develop. According to this variant, the total demand for hard coal will be more than 15% higher than in the year 2019. It also permits a higher demand for hard coal in the public power sector and in new hard coal markets. The implementation of this scenario will involve high expenditure to finalize any ongoing or planned investment projects concerning new hard coal-based power plants in the public sector. In other market segments, departing from hard coal at a slower rate may arouse opposition from local communities. Facing an inevitable decrease in power hard coal consumption in market segments other than the public power sector, domestic demand for hard coal will be affected by developments in the public power sector and by the process of its consolidation [9].

Using a novel approach, based on the time series prediction method, Li et al. predicted the consumption of hard coal in Poland by the year 2030. Based on that method, they found that hard coal consumption would be decreasing gradually until the year 2027 and will then stabilize, reaching a 20% lower level in 2030 than in 2019 [10].

The use of fossil fuels (hard coal, gas, petroleum) for the production of energy generates significant emissions of CO_2, NO_x, SO_2 and particulate matter, contributing to the death of thousands of people [11]. Coal, sulfur, oxygen, hydrogen, small amounts of nitrogen and traces of heavy metals are the main components of hard coal. Its combustion generates toxic gases, such as carbon dioxide (CO_2) and carbon monoxide (CO), sulfur dioxide (SO_2) and sulfur trioxide (SO_3), as well as nitrogen dioxide (NO_2) and nitrogen monoxide (NO), which cause health effects and environmental problems [12]. These gas emissions may cause various diseases which attack the skin, cardiovascular system, brain, blood and lungs, and may lead to various kinds of cancer [13].

The combustion of hard coal generates the highest amount of CO_2 among all the fossil fuels. Hard coal generates 58% more CO_2 than does petroleum and twice as much as natural gas on combustion [14]. The use of hard coal as an energy carrier causes phenomena such as smog, acid rain and the emission of particulate matter. High environmental pollution caused by boilers and thermal plants based on the combustion of hard coal is regarded internationally as the main subject of ongoing international research studies, focused on how to reduce emissions generated by the combustion of hard coal as fuel [13].

Since hard coal and fine coal are widely used as energy sources in Poland, catalysts are required to enable the reduction of the noxiousness of these fuels on combustion.

A number of catalysts have been described in the literature, which are used with hard coal or fine coal for reducing atmospheric emissions. Their reducing effect on emissions was reported in [15,16] for CO and NO_x and in [17,18] for SO_2. On the other hand, Yu et al. and Doggali et al. described the inhibitory effect of the catalysts on the combustion of hard coal [19,20].

In their earlier paper [21], the present authors studied the effect of polymetallic catalysts comprising a mixture of metal compounds at concentrations of 100, 200, 250 and 350 ppm on atmospheric emissions in the combustion of type IIA fine coal, which is intended for use in heating boilers. Based on these studies, it was found that the optimum additive is composed of Cu, Na, Mg, NH_4^+, Ca urea, and is used at the level of 350 ppm [22].

There is not much information in the literature on the economic effects of the use of catalysts for solid fuels. Therefore, the present authors chose to perform economic analysis for the system, which improves the fine-coal combustion efficiency of power boilers based on a preselected catalyst. The market of the potential users of the system is also characterized.

2. Materials and Methods

Information on savings in energy during the hard coal combustion process in which the system for improving energy efficiency had been implemented was analyzed based on data collected in the project [23]. The system comprises an additive that improves combustion and a control and supervision system that enables an optimum operation of the boiler.

The existing metering infrastructure and provisional instruments, installed by a company that offers the system for the tests [22], are used for the settlement of the economic and ecological effects resulting from the use of the catalysts. Computer-based remote control handling the catalyst dosage system, boiler operating parameters and long-term archiving of measurement data is also available [24]. The company that offers implementation of the system guarantees boiler servicing as well. The company that offers the implementation of the system to improve the solid-fuel combustion energy efficiency is competitive also as regards the innovative method of settling accounts with customers, based on the ESCO concept (Energy Saving Company): a remuneration for using the system is covered from savings in the cost of energy [25,26]. The total savings comprise the following components: improved energy efficiency, lower costs of overhaul and lower environmental costs.

The system comprises an additive that improves combustion and a control and supervision system that enables an optimum operation of the boiler. The necessary data required for assessing hard coal consumption for energy production in the Polish market in the year 2019 were obtained using Desk Research [27]. The method is based on the analysis of records in available data sources, comprising specifically their compilation, mutual verification and processing. Desk Research helps arrive at conclusions about the problem of interest [27]. There are a number of papers in the literature in which research methodology is based on that type of analysis [28,29].

The analysis was based on the following data sources:

- hard coal output and consumption in Poland, based on statistical data;
- the National Bank of Poland's website (www.nbp.pl, accessed on 20 February 2021)—PLN/USD conversion based on the exchange rate of 24 February 2021 (USD 1 = PLN 3.69);
- generally available lists of companies where combustion systems are used (e.g., www.enpol.pl, www.agroenergetyka.pl, www.polskiasfalt.pl, etc. accessed on 20 February 2021);
- websites that provide solutions to problems with fuel combustion.

The diagram in Figure 3 shows the respective steps of data acquisition for a Desk Research analysis.

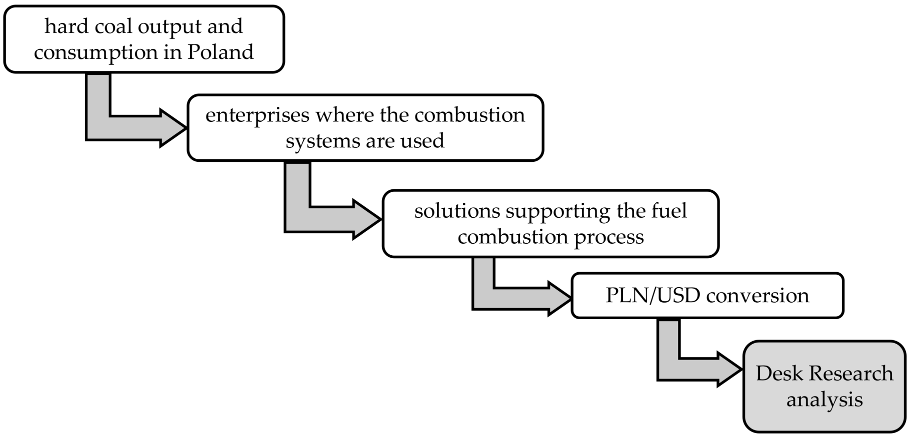

Figure 3. Stepwise acquisition of data for a Desk Research analysis.

The next step was to carry out an analysis of the final users' preferences and expectations using CATI (computer-assisted telephone interview). The method provided some reliable and valuable information on the chances of implementing a system to improve energy efficiency in the Polish market. CATI is used for gathering information in quantitative market research and public opinion polls by means of computer-assisted telephone interviews [30]. This method also helps find many research papers in which methodology was based on CATI [31,32].

To have a preliminary view of the scale of interest the energy-efficiency system may arouse, the study was carried out among its potential users. To begin with, the highest prospects were identified based on interviews with experts. As the result of such consultations, it was found that the prospects are: "combined heat-and-power plants (CHPs) and power plants," "auto-producing thermal plants" and "agriculture." Moreover, such a group includes some of the companies in the category "construction and other industries," namely, cement plants.

Next, the authors attempted to contact 221 entities representing the above groups. The respondents were those responsible for the combustion process in such entities (chief power engineers, boiler room managers, thermal plant foremen, boiler operation coordinators, maintenance managers and employees of the environmental protection department). The purpose of such conversations was to initiate contact with those responsible for making decisions on issues connected with the combustion system and to present essential information on the offered solution. An attempt was made to obtain the person's declaration concerning their willingness to cooperate or to be provided with more detail. Definitely more often than not, those responsible for the above matters provided a positive response to the information they had been offered, were willing to have a look at the materials provided to them, and, in some cases, a preliminary declaration to cooperate was obtained from them.

In the case of CATI, there exist non-random errors resulting from failures to perform part of the sample. Such errors are found also in other research methods, and they may result from a refusal to take part in the survey, indecision, or from other circumstances. CATI is a very attractive technique from the researcher's point of view because it takes much less time to collect data compared with direct interview techniques. On the other hand, it has the drawback that the sample performance percentage is usually much lower than in direct interviews. It is estimated that, on average, only 1/3 of the pre-selected phone numbers called the result in a conversation [33].

The statistical sampling error is an unavoidable component of any survey. It exists simply because, in an induction survey, conclusions regarding a whole population are drawn based on a sample. Such inference is, per se, exposed to error, but the magnitude of such statistical error can be determined from the assumed confidence level [34]. In the survey performed by the present authors for 221 companies, the statistical error for the assumed confidence level of 0.95 was 6.4%.

In the case of CATI surveys, the survey group is usually 1000–2000 respondents [31,32]. If the respondents are a specialized group, the number is definitely lower than that, depending on the size of the target group in the territory covered by the survey.

The number of interviews is much lower in a survey involving a specialized respondent group compared with that obtained in a social survey. Mays et al. used an online survey questionnaire concerning the advantages and barriers found in QSAR methods for REACH [35]. Having sent 280 questionnaires with 8 questions addressed to potential respondents, the authors obtained only 33 completed questionnaires. The group was then extended, and a questionnaire with only 3 questions was used to obtain 29 completed questionnaires. Unfortunately, the survey took 8 months. The authors concluded that the total sample was too small to represent a whole population and that the trends shown by the results enabled its correct interpretation.

The study has resulted in 41 complete CATI interviews with information that is useful for the subject matter of the study.

The interviews indicate that the highest prospects among the potential customers are (in decreasing order):

1. thermal plants, CHPs and district heating companies/enterprises;
2. housing co-operatives and cement plants;
3. horticultural production (market gardens producing fruit and vegetables, other agricultural farms using large-scale greenhouses).

It was also found that the manufacturers of bituminous mixes are not to be regarded as prospective customers simply because they typically operate gas-fueled production plants.

The other entities, contacted by the authors, have failed to respond, either because they were not interested or because they are not to be regarded as prospective customers because (starting from the most frequently stated reasons in decreasing order):

1. they were too busy or unwilling to talk on the phone, even after being contacted again at the appointed time, suggested by them (in most cases, the person seemed to believe they were being contacted about an acquisition, which had an adverse effect);
2. the person contacted believes their system does not need any improvement (harmful emissions within the standard range, advanced high-efficiency systems);
3. the entity operates a gas-fueled system;
4. there are ongoing refurbishment works, an overhaul of the combustion system, maintenance or other works aimed to improve the system.

The nature of the reasons stated above indicates that some of the respondents could definitely be encouraged after the system has been implemented in several sites. This would provide references and information on the specific sites where the system is working (case-study descriptions), and it would create foundations on which to build the system's market position, resulting in stronger interest among potential customers. Just as important is a suitable marketing campaign aimed at providing potential customers with information on the specific profits they may have after installing the solid-fuel combustion energy-efficiency system.

The main objective of the CATI study was to obtain information on the following:

- the most frequent problems in boiler operation;
- the respondents' awareness of the profits the implementation of catalysts for their combustion system will bring;
- the degree of the respondents' willingness to implement a system that improves energy efficiency and solves other issues related to operation in their company;
- determinants of their decision concerning the implementation of catalysts for their combustion system.

For the purpose of the introduction of the new system improving fuel-combustion efficiency, the authors carried out an economic analysis by assessing savings in the fuel and the extra amount of energy.

The economic assessment was carried out for the company that is responsible for marketing the system on the one side and for the company that has chosen to implement the system in its operation. Both the revenue side and the cost side were taken into account. Calculations were made using the equations shown in Supplementary Materials.

3. Results

3.1. Market Analysis of Potential Users

To begin with, the authors carried out a market analysis of the potential users of the system for improving the fuel-combustion energy efficiency. According to the results of the market analysis, most of the respondents (thermal plants, CHPs, cement plants, horticultural production establishments) use a solid fuel in the form of hard coal or fine coal with calorific values of more than 23 GJ/t and sulfur content of less than 0.8%. Currently, the market price of fine coal varies between USD 135–175/t (PLN converted into USD). The consumption of hard coal in 2019 by the various consumer groups is shown in Table 1.

Table 1. Hard coal consumption in Poland in 2019 according to [36].

Consumption	Percentage, %	Amount, 10^3 t
Power plants and CHPs	53.59	36,605
Heating boilers in the public power sector	1.73	1182
Auto-producing thermal plants	0.20	139
Public thermal plants	4.54	3100
Construction and other industries	24.64	16,826
Transport	0.02	15
Small consumers, including:	15.28	10,436

Hard coal consumption by the target group of interest in 2019 was 38 810 thousand tons. After excluding power plants, which are classified in statistical sources in the same group as CHPs, and including cement plants, in which the combustion of hard coal in 2019 was ab. 5% of its total consumption by the “construction and other industries,” hard coal consumption is assessed at approx. 25 10^6 t.

3.1.1. The Fuel Type Used

At the beginning of the interview, the respondents were asked about the fuel type they used (Figure 4). The question was intended to limit the study only to those entities operating solid-fuel fired systems.

The diagram above shows the structure of the respondents in terms of fuel type (Figure 4). Most of the respondents (ab. 73.6%) use hard coal or fine coal, which shows how popular these two fuel types are.

3.1.2. Awareness of the Solutions for the Combustion Process

The respondents’ awareness of innovative techniques to improve fuel-combustion efficiency was then tested. The respondents were asked whether they had heard of any catalysts that improve the fuel-combustion energy efficiency or reduce the emissions of harmful substances/gases. The distribution of the answers to that question is shown in the diagram below (Figure 5).

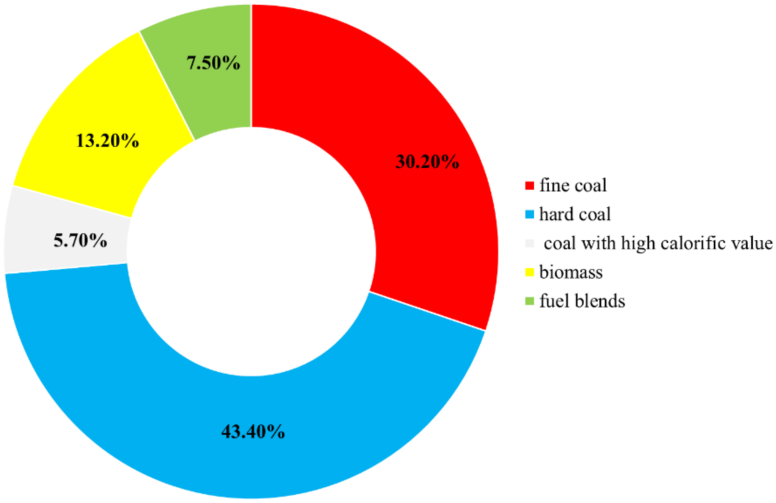

Figure 4. Distributions of answers to the question: "What type of fuel is used in your enterprise?".

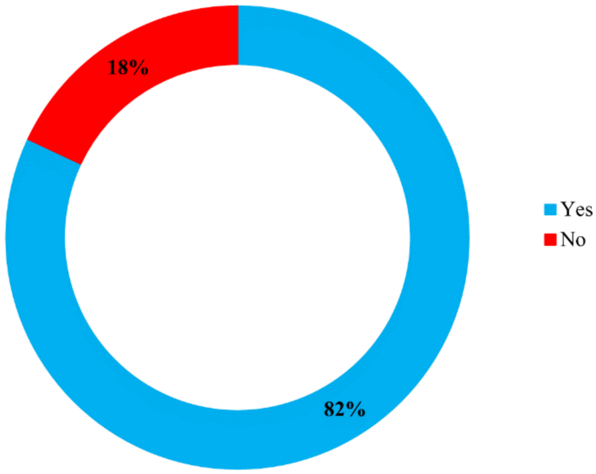

Figure 5. Distributions of answers to the question: "Have you ever heard of any combustion catalysts which improve energy efficiency or reduce the emissions of harmful substances and gases?".

In total, 82% of the respondents have, indeed, heard that catalysts existed that improve energy efficiency and help reduce environmental emissions. This indicates high awareness among the respondents of the feasibility of the implementation of systems designed to improve energy efficiency. The observation confirms high chances for the effective promotion of the innovative catalyst among the responding enterprises. Some of the respondents, being aware of the efficiency of such solutions, were willing to know the details of their implementation.

3.1.3. The Present Scale of Use

The next step was to ask the respondents if they were using any catalysts designed to improve hard coal-combustion efficiency and to reduce the formation of carbon or other deposits and harmful emissions. The question was intended to provide knowledge of the types of additives that are actually used in the combustion process (Figure 6).

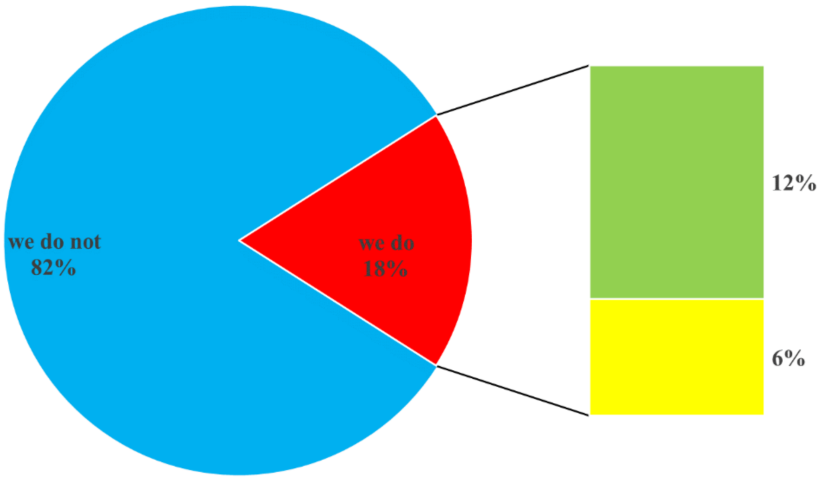

Figure 6. The scale of use of catalysts for fuels and the solutions for improving combustion among the respondents, as indicated by answers to the question: "Do you use any catalysts for fuel combustion? If you do, what is the purpose of its use?".

The use of catalysts in order to improve hard coal combustion efficiency, reduce carbon and other deposits, as well as harmful emissions, is rather unpopular at present. Taking into account the number of individuals who have ever heard of the solution, these facts do not seem to be helping with implementing the system. Part of the reason why is the fact that the benefits of the use of such catalysts have not been understood properly, a testing period analysis was not carried out correctly, and that the catalysts offered or those available on the market were of low quality.

Those respondents who declared that they were not using any catalysts were asked why. The most frequent explanation was that they did not need such a product—this answer was provided most frequently by the operators of heating systems that had been in use for only a few years. Another frequent answer was that they comply with the harmful emission standards. Part of the respondents emphasized that they feel they were using is low-sulfur hard coal that, combined with an advanced electrofilter system installed only 5 years before, results in no fear of emission limits being exceeded before the year 2050, and the filters were operating at some 30% of their capacity. Remarks were also heard that the catalysts were inefficient, and this was substantiated with a bad experience in using similar solutions encountered during the many years the respondents had been working in the industry.

According to some of the respondents, their partic1ular furnace type does not permit the inclusion of a catalyst application system; they emphasized that the boiler is a complex mechanism with a high regime of parameters, and the inclusion of any catalyst will disturb the whole process taking place in it. Some of the respondents made remarks indicating they were not aware that a catalyst might have a beneficial effect on the combustion process.

The respondents' reluctance to use this type of solution seemed to be caused by economic factors. Financing new projects is prevented by low costs of energy on the market. In a private, profit-oriented company, no person is willing to spend money on some dispensable gadgets. Some of the respondents feared high costs of investment combined with a rather low return.

The catalyst application system offered by the present authors is able to oppose effectively the opinions declared by the respondents. The control and supervision system, as developed by these authors, enables the calculation of the exact savings to be generated by the installed system. According to documented studies, the assessed minimum level of savings due to the use of the catalyst in systems based on solid fuels is, on average, 4% (or even 5%) for systems long past their last refurbishment. The catalyst is applied using a dedicated device that has been designed for boilers, so its manual application is not required. The system enabling the catalyst to be added into the hard coal fuel was described in detail by the present authors in their previous paper [21].

3.1.4. Major Problems with Boiler Operation

The respondents were then requested to indicate what kind of problems they have with their boiler operation. The purpose of the question was to verify whether the catalyst would be able to reduce or eliminate such complications. The respondents indicated a number of areas in which they were not satisfied with how their boiler was working (Figure 7).

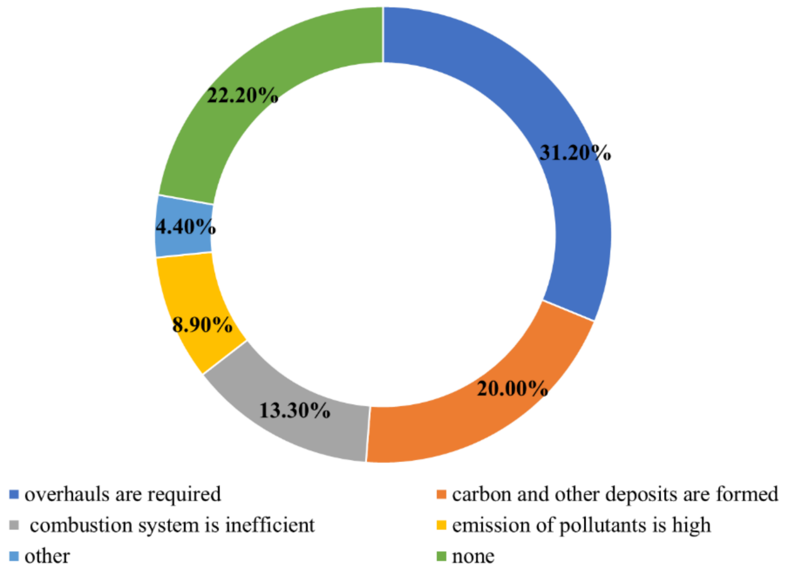

Figure 7. The most frequent problems in boiler operations.

Frequent failures, resulting in the requirement of overhaul, were the most frequently reported issue. The compulsory, frequent replacement of parts, mainly pressure control valves, is also a significant problem. Part of the users provides regular maintenance of their boilers, ensuring their overhaul at regular intervals, thus limiting expected failures. Ignition arches are the most problematic parts of the boilers, which require an overhaul once a year. The presence of scale in water boilers is also a problem, which affects their operation: it has to be removed from the grates quite frequently.

One of the major problems taking place during the boilers' operation is a large amount of carbon and other deposits. The respondents emphasized that this depends on the quality of hard coal. Cleaning the boiler in an emergency will not solve the very problem; only an overhaul will improve its efficiency and will reduce harmful emissions, but the deposits will continue to be formed even then. The respondents are of the opinion that the reason why the carbon and other deposits are formed is the low quality of the fuel.

In addition to the above-mentioned complications, the respondents have indicated other problems such as glowing grates and leaking boilers.

Some of the respondents denied any major issues in boiler operation, explaining that they just cared and provided proper maintenance to their equipment.

The system which improves coal-combustion efficiency would solve most of the problems reported by the respondents. Having to carry out an overhaul is usually caused by improper operation or the wear and tear of boiler parts taking place too fast. The use of a catalyst and optimization of its work will slow down the boiler parts' wear and tear and will help eliminate most of the carbon and other deposits—this is the response to the second major problem reported by the respondents. As regards the combustion system, the catalyst will much improve its efficiency [21]. Many (more than 20%) of the respondents denied there were any problems with their boilers at all. Part of the reason why could be that the respondents were simply not aware of how they could boost boiler efficiency. With all probability, the use of a catalyst would reduce the formation of carbon and other deposits and would improve the combustion system efficiency. This leads one to the conclusion that it will suffice to create in some of the potential customers the need to use such catalyst.

3.1.5. Willingness of the Respondents to Implement the System

On a scale of 1–10, the respondents assessed their willingness to implement a solution that improves energy efficiency and helps solve problems with system operation (Figure 8).

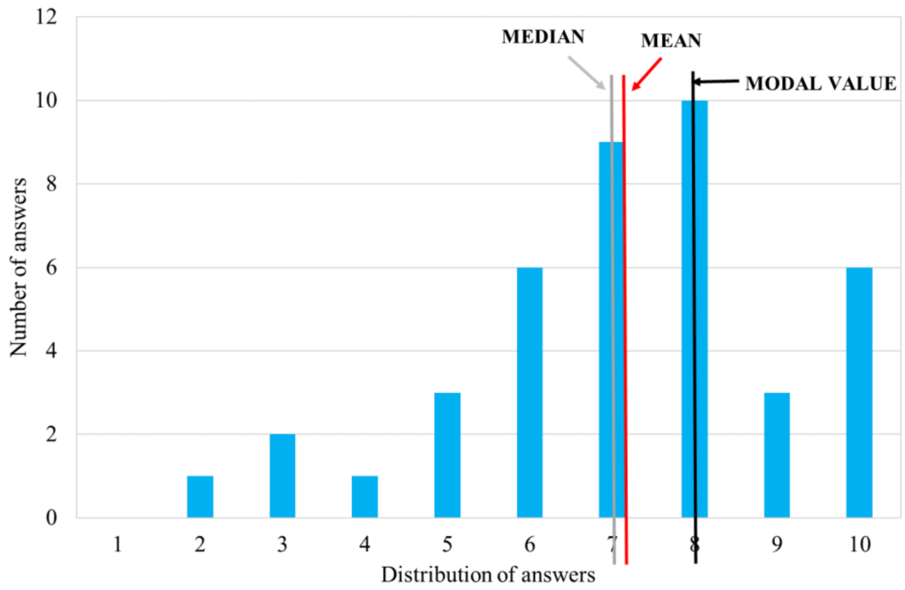

Figure 8. The distribution of the frequency of answers to the question: "On a scale of 1–10, assess your willingness to implement in this company a system which improves energy efficiency and helps solve problems with system operation?".

The respondents assessed their willingness to implement such a system at, on average, 7.15. The most frequent answer (the modal value) was 8. The median in the set of answers was 7.

3.1.6. Factors Affecting Decisions to Implement the System

In the next part of the study, the respondents were requested to indicate the factors affecting their decision to implement a fuel-combustion energy efficiency system or a solution for reducing harmful emissions and pollution. The purpose of the question was to know what the potential users of the system are guided by in their decision making (Figure 9).

For the largest group of potential users, the essential aspect determining their decision concerning the implementation of a system to improve boiler efficiency is the economic side, specifically, the costs of its implementation and the payback time.

The respondents were of the opinion that it is rather hard to decide on the implementation of the system in this rather early stage of its development (absence of reference solutions). They also emphasized the importance of the catalyst-testing period. Testing the catalyst and seeing how it works in other sites is very good to begin with, though ultimately, financing the project is the essential aspect, anyway.

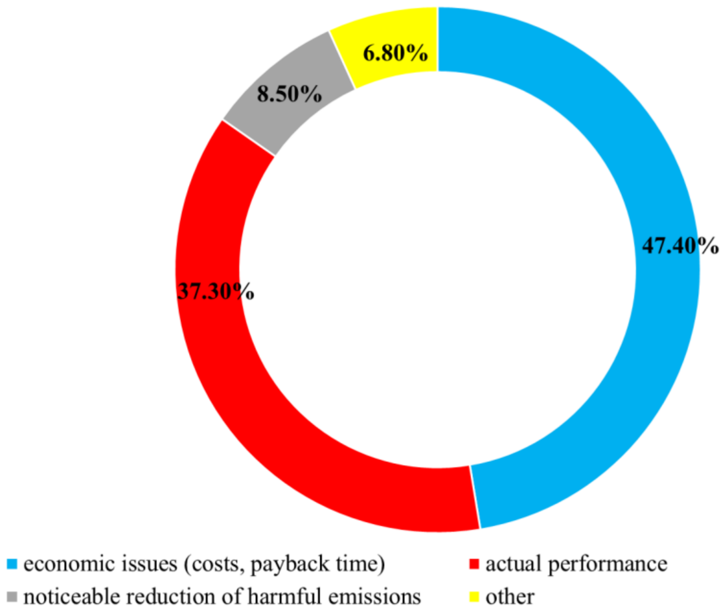

Figure 9. The factors affecting a decision concerning the system implementation.

The decision on choosing a good solution to improve boiler efficiency will also depend on its actual performance. The respondents indicated that performance would have to be confirmed by a history of adequate results or else appropriate tests would have to be carried out on the boilers operated by potential users in their specific sites. They also indicated that the new system would noticeably have to reduce harmful emissions.

Summing up, the choice of catalyst largely depends on how much the project costs and whether it is cost effective. This is very good news for a company that intends to offer a very advantageous system of settling accounts (absence of preliminary costs). It may encourage potential customers who are not sure if they do want to use catalysts because of the financial aspects.

Nearly as important for potential customers are the actual, measurable economic and ecological effects of using the catalyst. The company has an advantage also in this regard, having carried out complex studies on the problem.

3.2. Economic Analysis

The control and supervision system enables the boiler's operating parameters to be controlled with great accuracy, leading to very reliable measurements of savings in fuel consumption [23]. The system supports an effective use of the catalysts that improve fuel combustion, enable accurate measurements of the boiler's control parameters that help obtain accurate fuel consumption data, performance of flue gas analyses and control of chimney losses for optimized combustion process parameters. The solution provides information enabling the calculation of the economic effects of refurbishment and the use of the catalyst.

The economic effect was calculated from the results of own studies. Savings are the consequence of the boiler's extra efficiency, resulting from the use of the catalyst and the optimization of its operating conditions. The reported studies were carried out by the authors as part of the project described in [23] and in paper [21].

The authors of the papers mentioned above found out that the highest efficiency was achieved for the catalyst comprising the salts of metals, such as Na, Cu, Mg, and the ammonium cation being introduced into the hard coal fuel in the amount of 350 ppm, in terms of the metals and the ammonium cation [22]. Savings on the fuel were calculated based on fuel combustion tests in a laboratory boiler with or without the catalyst and then in commercial tests. The tests showed that savings resulting from the use of the catalyst varied between 2% and 6% depending on the system capacity. The tests also covered optimization of the boiler operation parameters to improve its performance. It was found that savings due to the system modernization would be 2% to 8%, depending on the system capacity. In either case, the highest savings were achieved for the 3 MW systems.

Based on the answers to the questionnaire from the users of power boilers and our own studies, the application of the system that improves solid fuel-combustion efficiency is only cost-effective in the case of thermal plants and CHPs with capacities above 2 MW. Below that value, the costs of implementation are too high, and the investment is not cost effective. Power plants and CHPs with capacities above 100 MW use advanced high-efficiency boilers, of which the refurbishment would cost too much, and implementation could be a challenge.

An economic analysis of the use of a system that improves coal-combustion efficiency was performed separately for the company, which offers implementation of the system and for the implementing user company, with a break-down to the revenue side and the cost side.

3.2.1. Revenue Side

The figures showing annual energy production volume and hard coal consumption in systems with capacities ranging from 3 MW to 100 MW are shown in Table 2.

Table 2. The annual energy production volume and hard coal consumption for systems with a capacity ranging from 3 MW to 100 MW.

Mean System Capacity, MW	Energy-Per-Power Indicator, GJ/MW	Production Volume, GJ	Boiler Efficiency, %	Calorific Value of Hard Coal, GJ/t	Annual Consumption of Hard Coal, t
MW	EM	PG	S	K	IW
3	8000	24,000	70	24	1428.57
10	7500	75,000	75	23	4347.83
30	7000	210,000	82	22	11,640.80
70	7000	490,000	85	22	26,203.20
100	7000	700,000	88	22	36,157.00

To calculate the annual consumption of hard coal in medium-capacity systems, it was assumed that low-capacity energy sources (3 MW) have the lowest efficiency, that is 70%. For systems with higher capacities, the efficiency is higher—88% for a 100 MW system [23]. Likewise, for systems with 3 MW capacity, to generate 1 MW, it takes 8000 GJ—this is the highest value. For higher-capacity systems, the indicator is lower, e.g., 7000 GJ/MW for a 100 MW system. In these calculations, it is assumed that the calorific value of hard coal ranges from 22 GJ/t to 24 GJ/t, the lowest-capacity system working on hard coal with the highest calorific value.

Multiplying the system capacity by the assumed indicator of GJ per 1 MW capacity, we obtain the annual volume of production of energy ("Production in GJ"), Equation (1). To find the annual consumption of hard coal for a given type of system, "Production in GJ" is first divided by the calorific value of hard coal and is then divided the obtained value in GJ/MW by the efficiency of the source (this value indicates the efficiency of the system), Equation (2).

The annual consumption of hard coal grows with the installed system capacity and is 1 428.57 t/year for a 3 MW system. For a 100 MW system, the annual consumption of hard coal is 36,157.00 t. The specific number of t of hard coal saved as the result of the application of the system that improves fuel-combustion efficiency in system capacities ranging from 3 MW to 100 MW was calculated from Equation (3), Table 3.

Table 3. Savings in the fuel due to the use of the system that improves fuel-combustion efficiency.

Mean System Capacity, MW	Annual Consumption of Hard Coal, t	Savings in the Fuel Due to the Catalyst, %	Savings in the Fuel Due to the Catalyst, t	Savings in the Fuel Due to the Refurbishment, %	Savings in the Fuel Due to the Refurbishment, t	Total Savings in the Fuel, t
MS	IW	K	OK	M	MM	OP
3	1428.57	6.00	85.71	8.00	114.29	200.00
10	4347.83	5.00	217.39	6.00	260.87	347.26
30	11,640.80	4.00	465.63	4.00	465.63	931.26
70	26,203.21	3.00	786.10	3.00	786.10	1,572.20
100	36,157.02	2.00	723.14	2.00	723.14	1,446.28

In addition to the catalyst, the solution for improving coal-combustion energy efficiency comprises a boiler control and supervision system. It was designed to improve the efficiency of energy generation and distribution ("Savings in the fuel due to the refurbishment"). It is assumed that savings in the fuel due to the use of the catalyst will be ab. 2–6% (depending on system capacity), and savings due to the refurbishment, ab. 2–8%.

Both values have been assessed based on the results of own studies and by experts from the company, which is responsible for marketing the system [21,23].

Both the savings in hard coal due to the use of the combustion catalyst and savings due to the refurbishment of the combustion process vary with the installed system capacity. For system capacities ranging from 3 MW to 70 MW, these savings grow with the system capacity. The highest combined savings in the fuel, namely 1572.20 t/year, were achieved for a 70 MW system capacity. For 100 MW, savings in fuel were 1 446.28 t/year.

Taking into consideration total savings in the fuel per 1 MW of the installed system capacity, the highest savings in hard coal were 66.67 t and were obtained for a 3 MW system. For a 100 MW system, saving in the hard coal fuel per 1 MW of the installed capacity is 14.46 t.

The economic effect of the use of the catalyst and of the control and supervision system was calculated from Equations (5) and (6), Table 4. The total effect was calculated from Equation (7).

Table 4. The economic effect of the use of the system which improves fuel-combustion efficiency.

Mean System Capacity, MW	Annual Consumption of Hard Coal, t	Mean Price of 1 t of Hard Coal, USD	Annual Cost of Fuel, USD	Savings in the Fuel Due to the Catalyst, USD	Savings in the Fuel Due to theRefurbishment, USD	Total Economic Effect, USD
MS	IW	CW	KP	EK	ES	EE
3	1428.57	175	249,999.75	14,999.25	20,000.75	35,000.00
10	4347.83	165	717,391.95	35,869.35	43,043.55	78,912.90
30	11,640.80	140	1,629,712.00	65,188.20	65,188.20	130,376.40
70	26,203.21	140	3,668,449.40	110,054.00	110,054.00	220,108.00
100	36,157.02	135	4,881,197.70	97,623.90	97,623.70	195,247.80

The assumed average price of hard coal varies between USD 135 and 175 per t, depending on its annual consumption. The annual cost of fuel consumption was calculated by multiplying the estimated average price of 1 t of hard coal by the required number of t of the fuel, depending on the average system capacity. In order to define the economic effect of using the system for improving energy efficiency, one has to take into account the annual cost of fuel, savings due to the catalyst ("Savings in the fuel due to the catalyst") and due to the refurbishment.

The obtained economic effect that results from the saved amount of hard coal depends on the system capacity. The highest effect was obtained for low-capacity systems. This is the consequence of low boiler efficiency, leading to higher efficiency in the use of the catalyst and of the entire system for improving energy efficiency.

In addition to improving energy efficiency, the use of the catalyst and of the system for improving energy efficiency leads to the costs of the overhaul being reduced by some 20%. This is connected, among other things, with a reduced tendency to form deposits and with the system being kept in a generally better condition. This issue was studied for 3 months as the boiler was operated using the system. Details of the calculations of the economic effect due to the implementation of the system for improving energy efficiency are shown in Table 5.

Table 5. The economic effect of the use of the catalyst and reduction of the costs of overhaul.

Mean System Capacity, MW	Annual Costs of Overhaul, USD	Reduction in the Costs of Overhauls, USD	Economic Effect of the Refurbishment, USD	Total Economic Effect (of the Refurbishment and of Reduction in the Costs of Overhauls), USD
MS	KR	OR	EE	EEK
3	6500	1300	35,000.00	29,800.00
10	15,040	3010	78,912.90	66,882.90
30	35,570	7115	130,376.40	101,921.40
70	60,705	12,140	220,108.00	171,543.00
100	60,975	12,195	195,247.80	146,467.80

The annual costs of overhauls were found based on expert opinions and discussions with the users of coal-fired power boilers. The total economic effect, resulting from using a system that improves coal-combustion energy efficiency and, from reducing the costs of overhauls, was calculated as the difference between the economic effect according to the data in Table 4 and the costs of overhauls before and after the refurbishment.

The split between the vendor of the energy-efficiency system and the implementing user is shown in Table 6.

Table 6. The economic effect, as split between the system vendor and the system user.

Mean System Capacity, MW	Total Economic Effect, USD	Economic Effect per 1 MW of System Capacity, USD	System Vendor's Revenue (30%), USD	Customer's Savings (70%), USD
MS	EEK	EE1	PD	O
3	29,800.00	9933.33	8940.00	20,860.00
10	66,882.90	6688.29	20,064.87	46,818.03
30	101,921.40	3397.38	30,576.42	71,344.98
70	171,543.00	2450.61	51,462.90	120,080.10
100	146,467.80	1464.68	43,940.34	102,527.46

The total economic effect connected with savings in the cost of fuel as the result of using the system for improving energy efficiency depends on the system capacity. Its highest value, of approx. USD 171,543.00, was obtained for a 70 MW system. For a system with 100 MW capacity, the calculated economic effect was lower because the system is based on high-performance equipment. Per 1 MW of the system capacity, the highest economic effect (USD 9933.33) was obtained for the minimum capacity, i.e., the 3 MW system. With growing average system capacities, the economic effect per 1 MW decreases and is USD 1464.68 for a 100 MW system.

It was assumed that the vendor of the complete energy-efficiency system receives a remuneration equal to 30% of the economic effect of using the system. The other 70% of such economic effect is on the side of the implementing user. Both the system vendor's revenue and the customer's savings depend on the system capacity, and they increase for increasing system capacities, except that the revenue for a 70 MW system is higher than that for a 100 MW system.

3.2.2. Cost Side—System Vendor

When analyzing the cost side of the project, one must take into account the cost of catalyst production (which is incurred by the system vendor) and the cost of all the other components of the system.

The costs of the vendor of the energy-efficiency system, including the catalyst cost and the servicing cost, are shown in Table 7.

Table 7. The costs of the vendor of the components of the system that improves coal-combustion energy efficiency.

Mean System Capacity, MW	Annual Consumption of Hard Coal, t	Cost of Catalyst Per 1 t of Hard Coal, USD	Annual Cost of Catalyst Supplies, USD	Servicing Costs, % of the Cost of Catalyst Supplies	Servicing Costs, USD	System Vendor's Costs, USD
MS	IW	KK	KKR	KS	SR	SK
3	1428.57	0.81	1157.14	80	925.71	2082.85
10	4347.83	0.81	3521.74	70	2465.22	5986.96
30	11,640.80	0.80	9312.64	60	5587.58	14,900.22
70	26,203.20	0.75	19,652.40	40	7860.96	27,513.36
100	36,157.00	0.70	25,309.90	20	5061.98	30,371.88

It was assumed that some 0.5 kg of the catalyst is used per 1 ton of hard coal [23]. The cost of production of 0.5 kg catalyst varies between USD 0.70 and 0.81, depending on production capacity. Other costs on the vendor's side are the boiler servicing costs. It was assumed that the provision of servicing for the whole system is on the vendor's side. In the calculations, it was assumed that the cost of servicing is 80% to 20% of the cost of production and provision of catalysts, depending on system capacity. The cost of the system vendor is directly proportional to the installed capacity and, at USD 2 082.85, it is the lowest for a 3 MW plant; for a 100 MW capacity plant, the cost is USD 30 371.88.

The system vendor's profit has been calculated as the difference between the revenue from the system implementation in the user's plant and the costs incurred (Table 8). The scale of the profit is proportional to the plant capacity ranging from 3 MW to 70 MW and is the highest for 70 MW plants. For a 100 MW plant, the profit at USD 13 568.46 per year is much lower. A reverse relationship was obtained by recalculating the profit of the implementing user per 1 MW capacity: the highest profit of USD 2 285.72 per 1 MW of installed capacity was obtained for a 3 MW system and the lowest, at USD 135.69 per 1 MW of installed capacity—for a 100 MW system.

Table 8. The system vendor's profit after subtracting all costs.

Mean System Capacity, MW	System Vendor's Revenue, USD	System Vendor's Costs, USD	System Vendor's Profit (Revenue Minus Costs), USD	Profit per 1 MW of System Capacity, USD
MS	PD	SK	ZS	ZS1
3	8940.00	2082.85	6857.15	2285.72
10	20,064.87	5986.96	14,077.91	1407.79
30	30,576,42	14,900.22	15,676.20	522.54
70	51,462.90	27,513.36	23,949.54	342.14
100	43,940.34	30,371.88	13,568.46	135.69

3.2.3. Cost Side—System User

It is assumed that the final user incurs other costs of implementation and refurbishment of the system. The costs on the system user's side are covered from part of the savings (part of the amount referred to as "Customer's savings (70%)" in Table 6).

The user's costs are connected with the cost of purchase of the system that improves fuel-combustion energy efficiency and has been offered by the system vendor. It is assumed that the cost of implementation of the system in the user's plant is twice as high as that of the cost of purchase. Shown in Table 9 are the system user's costs and the payback time.

Table 9. Calculation of the system user's costs.

Mean System Capacity, MW	Cost of System Purchase and Implementation, USD	Customer's Total Savings, USD/Year	Cost of Applicators (Purchase and Implementation), USD	Annual Cost of Employing System Operators, USD/Year	Payback Time, Years
MS	PT	O	KI	KE	T
3	17,880.00	20,860.00	67,750	8130.00	6.72
10	40,129.74	46,818.03	70,000	11,382.11	3.11
30	61,152.84	71,344.98	75,000	13,008.13	2.33
70	102,925.80	120,080.10	80,000	14,634.15	1.74
100	87,880.68	102,527.46	85,000	16,260.16	2.00

In addition to the costs of implementation of the system for improving energy efficiency, the system user incurs the cost of employing extra personnel to operate the system and the cost of purchase and implementation of the applicator with which the catalyst is introduced into the fuel. The applicator is designed so as to introduce the catalyst into the time-varying fuel flux in a continuous manner before feeding it into the boiler [21,24].

According to estimates, the cost of purchase and implementation of the applicator, which is required for introducing the catalyst into the fuel, ranges from USD 67 750 to 85,000 for various system capacities. Additionally, the cost of employing the system operators depends on the system capacity, and it varies between USD 8130.00 and 16,260.16 per year. The payback time, calculated from Equation (9), depends on the system capacity as well. It was assumed in the calculations that the catalyst concentration is constant at 350 ppm, and the cost of overhaul is 20% lower. Other assumptions will result in a different payback time. The investment brings the lowest profit for low-capacity systems, e.g., for a 3 MW system, the payback time is 6.72 years. The payback time is shorter for higher-capacity boilers, and the highest profits are obtained for 70 MW systems, with a payback time of 1.74 years.

4. Conclusions

The combustion of coal-based fuels is the source of environmental pollution. These emissions can be reduced with the help of catalysts being introduced straight into the fuel. This paper presents the cost-efficiency analysis of a system that improves solid-fuel combustion in power boilers.

In a market study, it was found that the target user group (thermal plants, CHPs, cement plants, horticultural production) uses mainly hard coal or fine coal as solid fuels. Their combustion efficiency can be improved by using a dedicated device comprising a control and supervision system for better accuracy in controlling the boiler operating parameters and in improving combustion efficiency due to the use of catalysts, addressing specifically the issue of fine-coal combustion.

Economic benefits from the use of the system are achieved both by the vendor and by the user. The study was carried out for system capacities ranging from 3 to 100 MW. It was found that, depending on the size of the system ranging from 3 MW to 100 MW, fuel savings were from 2% to 8% due to the refurbishment improving the boiler plant operation and from 2% to 6% due to the use of the combustion catalysts. Apart from boosting energy efficiency, the use of the catalyst and the efficiency-boosting system resulted in the costs of overhaul being cut by about 20%.

It was assumed that the economic effect of the system implementation was shared between the vendor and the user in the ratio of 30%/70%. The vendor's profit was calculated by subtracting the costs involved in the system implementation from the vendor's revenue obtained from the user. The system user's costs are the cost of purchase and implementation of the system plus the cost of purchase and implementation of the catalyst applicators plus the costs of employing system operators. The payback time for the user depends on system capacities: it varies between 6.75 and 1.74 years for capacities ranging from 3 to 75 MW and is 2.0 years for a 100 MW plant.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/en14144295/s1, Equation S1: the annual volume of generated Energy, Equation S2: the number of tons of hard coal combusted with the use of the catalyst, Equation S3: total savings in the fuel due to the use of the catalyst and due to the boiler refurbishment, Equation S4: the cost of the hard coal combusted in the system, Equation S5: savings in the fuel due to the catalyst, Equation S6: savings in the cost of fuel due to the refurbishment, Equation S7: total savings in the cost of fuel due to the system for improving fuel-combustion energy efficiency, Equation S8: the economic effect on the user side, Equation S9: the payback time for the costs incurred by the user of the system.

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References

1. Nyashina, G.S.; Strizhak, P.A. The influence of liquid plant additives on the anthropogenic gas emissions from the combustion of coal-water slurries. *Environ. Pollut.* **2018**, *242*, 31–41. [CrossRef]
2. Zhao, C.; Zhang, W.; Wang, Y.; Liu, Q.; Guo, J.; Xiong, M.; Yuan, J. The economics of coal power generation in China. *Energy Policy* **2017**, *105*, 1–9. [CrossRef]
3. Wang, Q.; Song, X. Why do China and India burn 60% of the world's coal? A decomposition analysis from a global perspective. *Energy* **2021**, *227*, 120389. [CrossRef]
4. Coal Production and Consumption Statistics. Available online: https://ec.europa.eu/eurostat/statistics-explained (accessed on 2 May 2021).
5. Sivek, M.; Jirásek, J.; Kavina, P.; Vojnarová, M.; Kurková, T.; Bašov, A. Divorce after hundreds of years of marriage: Prospects for coal mining in the Czech Republic with regard to the European Union. *Energy Policy* **2020**, *142*, 111524. [CrossRef]
6. Manowska, A.; Tobór-Osadnik, K.; Wyganowska, M. Economic and social aspects of restructuring Polish coal mining: Focusing on Poland and the EU. *Resour. Policy* **2017**, *52*, 192–200. [CrossRef]
7. Polish Coal Market. Available online: https://polskirynekwegla.pl (accessed on 2 May 2021).
8. Brauers, H.; Oei, P.-Y. The political economy of coal in Poland: Drivers and barriers for a shift away from fossil fuels. *Energy Policy* **2020**, *144*, 111621. [CrossRef]
9. Program for the Hard Coal Mining Sector in Poland, Poland's Ministry of Energy. 2019. Available online: https://www.gov.pl (accessed on 2 May 2021).
10. Li, Y.; Zhang, H.; Kang, Y. Will Poland fulfill its coal commitment by 2030? An answer based on a novel time series prediction method. *Energy Rep.* **2020**, *6*, 1760–1767. [CrossRef]
11. Paraschiv, S.; Paraschiv, L.S. Analysis of traffic and industrial source contributions to ambient air pollution with nitrogen dioxide in two urban areas in Romania. *Energy Procedia* **2019**, *157*, 1553–1560. [CrossRef]
12. Munawer, M.E. Human health and environmental impacts of coal combustion and post-combustion wastes. *J. Sustain. Min.* **2018**, *17*, 87–96. [CrossRef]

13. Bascom, R.; Bromberg, P.A.; Costa, D.L.; Devlin, R.; Dockery, D.W.; Frampton, M.W. Health effects of outdoor air pollution. *Am. J. Respir. Crit.* **1996**, *153*, 477–498.
14. Paraschiv, S.; Paraschiv, L.S. Trends of carbon dioxide (CO_2) emissions from fossil fuels combustion (coal, gas and oil) in the EU member states from 1960 to 2018. *Energy Rep.* **2020**, *6*, 237–242. [CrossRef]
15. Prelec, Z.; Mrakovcić, T.; Dragicević, V. Performance study of fuel oil additives in real power plant operating conditions. *Fuel Process. Technol.* **2013**, *110*, 176–183. [CrossRef]
16. Sui, Z.; Zhang, Y.; Yao, J.; Norris, P.; Cao, Y.; Pan, W.-P. The influence of NaCl and Na_2CO_3 on fine particulate emission and size distribution during coal combustion. *Fuel* **2016**, *184*, 718–724. [CrossRef]
17. Wang, Z.; Wang, S.; Zhang, Q.; Fang, Q.; Chen, W. Influence of environmentally friendly and high-efficiency composite additives on pulverized coal combustion in cement industry. *J. Combust.* **2016**, *2016*, 8205945. [CrossRef]
18. Liu, Y.; Che, D.; Xu, T. Catalytic reduction of SO_2 during combustion of typical Chinese coals. *Fuel Process. Technol.* **2002**, *79*, 157–169. [CrossRef]
19. Yu, S.; Xie, F.; Jia, B.; Zhang, P. Influence Study of Organic and Inorganic Additive to Coal Combustion Characteristic. *Procedia Environ. Sci.* **2012**, *12*, 459–467.
20. Doggali, P.; Kusaba, H.; Einaga, H.; Bensaid, S.; Rayalu, S.; Teraoka, Y.; Labhsetwar, N. Low-cost catalysts for the control of indoor CO and PM emissions from solid fuel combustion. *J. Hazard. Mater.* **2011**, *186*, 796–804. [CrossRef]
21. Tic, W.J.; Guziałowska-Tic, J. The effect of modifiers and method of application on fine-coal combustion. *Energies* **2019**, *12*, 4572. [CrossRef]
22. Tic, W.J.; Zadorożny, A. Catalyst for the Combustion of Solid Fuels, Especially Coal Fuel in the Form of Fines. PL Patent Application No. 236091, 30 November 2020.
23. Project, 2015. Research on the system of energy and ecological efficiency of combustion of liquid and solid fuels. Innovative Economy Operational Program 2007-13 (No. POIG.01.04.00-16-159/12).
24. Tic, W.J.; Zadorożny, A. Solid fuel catalyst dosing system. Industrial design W.130088, Date of submission of the application 31 May 2021.
25. Bednarowska, Z. Desk research—Exploiting the potential of secondary data in market and social research. *Mark. Rynek* **2015**, *7*, 18–26.
26. Brown, P.; Von Daniels, C.; Bocken, N.M.P.; Balkenende, A.R. A process model for collaboration in circular oriented innovation. *J. Clean. Prod.* **2021**, *286*, 125499. [CrossRef]
27. Schmieder, L.; Scheer, D.; Iurato, C. Streams Analysis for Better Air Quality: The German Lead City Program Assessed by the Policy Package Approach and the Multiple Streams Framework. *Energies* **2021**, *14*, 596. [CrossRef]
28. Adamska, M. Motivation factors for sales personnel in small and medium-sized enterprises. *Polityki Eur. Finans. Mark.* **2018**, *20*, 7–19.
29. Park, J.; Kim, S.D.; Choi, S.O. Demonstrating the effects of behavioral control beliefs on the actual WEEE discharge routes: A case study in South Korea. *Resour. Conserv. Recy.* **2020**, *163*, 105088. [CrossRef]
30. Lecube, A.; Sánchez, E.; Monereo, S.; Medina-Gómez, G.; Bellido, D.; García-Almeida, J.M.; Martínez de Icaya, P.; Malagón, M.; Goday, A.; Tinahones, F.J. Factors Accounting for Obesity and Its Perception among the Adult Spanish Population: Data from 1,000 Computer-Assisted Telephone Interviews. *Obes. Facts* **2020**, *13*, 322–332. [CrossRef] [PubMed]
31. The Consumption of Fuels and Energy Carriers in 2019, Statistics Poland. Available online: https://stat.gov.pl (accessed on 2 May 2021).
32. Zheng, S.; Lam, C.-M.; Hsu, S.-C.; Ren, J. Evaluating efficiency of energy conservation measures in energy service companies in China. *Energy Policy* **2018**, *122*, 580–591. [CrossRef]
33. Jabkowski, P. The impact of not carrying out some part of interviews on the validity of statistical inference in social research. Telephone interviews and CATI in view of systematic errors. *ASK* **2007**, *16*, 67–86.
34. Zhang, X.; Kuchinke, L.; Woud, M.L.; Velten, J.; Margraf, J. Survey method matters: Online/offline questionnaires and face-to-face or telephone interviews differ. *Comput. Hum. Behav.* **2017**, *71*, 172–180. [CrossRef]
35. Mays, C.; Benfenati, E.; Pardoe, S. Use and perceived benefits and barriers of QSAR models for REACH: Findings from a questionnaire to stakeholders. *Chem. Cent. J.* **2012**, *6*, 159. [CrossRef]
36. Simsek, Y.; Urmee, T. Opportunities and challenges of energy service companies to promote energy efficiency programs in Indonesia. *Energy* **2020**, *205*, 117603. [CrossRef]