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Testing the Bioeconomic Options of Transitioning to Solid Recovered Fuel: A Case Study of a Thermal Power Plant in Slovakia

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Abstract: This paper deals with the state and perspectives of bioenergy development in the context of exploiting the potential of available natural resources. We analyse the economic benefits of transitioning to alternative biofuel within the research task in cooperation with the Vojany black coal power plant. Within the applied methodology, a non-parametric data envelopment analysis method was used to confirm the most economically efficient types of fuels used in the combustion process. The assumption of fuel efficiency was confirmed by testing fuel combustion combinations directly in the power plant. The transition to 100% combustion of solid recovered fuel creates the potential for sustainable production of the analysed power plant and compliance with the current emission values of basic pollutants and new stricter limits, which will be binding in the EU from August 2021. The proposed solutions were analysed by Monte Carlo simulation. An estimate of the economic results achieved by the power plant was simulated, assuming a complete transition to solid recovered fuel. The results of the study support the feasibility of creating a circular waste management market, with the Vojany black coal power plant as the largest user of solid recovered fuel in Slovakia and abroad.

Keywords: solid recovered fuel; alternative biofuels; combustion; pellets; biomass; bioeconomics

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1. Introduction

The current world economy is highly dependent on the supply of natural resources, which we use to produce fuel and electricity and meet other needs. The very high consumption of fossil fuels has caused high levels of pollutants in the atmosphere, with the worst cases in urban areas [1]. There are deposits of many raw energy materials in Slovakia (for example, anthracite, uranium, oil, natural gas, coal, gasoline, lignite and others), and four raw materials are used in industry in the country: oil, natural gas, brown coal and lignite. When evaluating the potential of a synthetic fuel, it is necessary to take into account its physico-chemical properties (moisture content, carbon content, calorific value, density), which determine its use with certain types of biomass [2,3]. For the correct use of different types of biomass, it is also necessary to take into account their calorific value and density per occupied volume. These are the characteristics of biomass that are reflected in economic results.

Unlike fossil fuels (coal, oil and natural gas), the combustion of fresh (non-fossil) biomass is almost neutral in terms of carbon dioxide (the main greenhouse gas) emissions in a changing climate. The amount of carbon in the form of carbon dioxide, which is produced by burning non-fossil biomass, is equal to the amount of carbon that plants "withdraw" from the atmosphere during their lifetime through photosynthesis. Combustion of fossil fuels, on the other hand, is a crucial anthropogenic factor contributing to climate change, as it releases carbon into the atmosphere in the form of carbon dioxide. It was in the earth's crust for millions of years [3].

Many countries around the world are focusing on renewable energy sources due to depleted oil reserves. The trend is also expanding to transport fuel. Most environmentally friendly countries around the world are considering biomass for economic use and have focused on national policies to meet future energy requirements and carbon reduction targets. In the context of following the Kyoto Protocol, these countries are primarily focused on reducing emissions and complying with energy requirements [4].

In Slovakia, too, biomass is a stable long-term energy source with less dependence on short-term weather fluctuations and seasonal climate variability. At the same time, its use requires relatively low investment cost. However, biomass is also the only type of renewable energy that depends on the sufficiency of raw materials for fuel production and a stable and reliable supply and is subject to rising prices depending on rising demand for fuel and transportation costs [5]. On the one hand, biomass has significant potential in the development of regional and local economies and provides an opportunity to revive agricultural activity in rural areas. On the other hand, large centralized biomass-based energy projects can pose a huge risk to rural areas, especially in terms of environmental degradation (e.g., by senselessly increasing logging in forests or "cleaning" forests from wood residues after logging), but also due to biomass exports as an important energy source outside the region. The basic types include solid biomass (wood fuel: briquettes, pellets), straw, wet biomass and other crops. In our paper, as will be further specified, we focus on the pellet form of biomass, a solid recovered fuel, the processing of which we see for the future in Slovakia.

The main goal of this paper is to design an efficient solution for combustion at a specific thermal power plant in a sustainable and economically advantageous way through the testing of solid recovered fuel. The implementation of this study, thus, focuses on confirming that the Vojany black coal power plant needs to transition to the combustion of 100% solid recovered fuel.

In the following sections, we provide a state of art that we have transformed into a methodological process. The analysed power plant shows long-term unprofitable results due to a long-term decline in electricity prices, high prices of CO_2 emission quotas and high costs of transporting hard coal. We solved the identified problem by applying subsequent analysis. In terms of achieving the aim of the paper, we discuss the results of the study in comparison with relevant sources and subsequently propose solutions in connection with future research.

2. Using Synthetic Fuels as a Substitute for Hard Coal

In the global energy mix, as already mentioned, coal is still the main fuel, although the demand for coal energy is declining in terms of the global elimination of its use. Achieving the EU's binding target of reducing carbon emissions by 2030 requires a shift to low-carbon energy forms and innovative technologies, such as carbon capture and storage [3]. In 2018, the total emissions of European coal-fired power plants amounted to 625 million tonnes of CO_2, which represents almost 15% of the EU's total greenhouse gas emissions. Although the transition to a low-carbon economy expands the possibilities, the economic and social impacts in many coal regions, such as the use of the capital assets of a coal-fired power plant, should not be neglected. In this case, biomass could play an important role as an unconventional fuel, which would keep the power plant infrastructure in operation [1]. Biomass combustion is one possibility in a multi-stage process that is economically important because it leads to energy production. According to global, national and regional information, biomass energy production has recently become increasingly common. This is due to a large amount of agricultural, forestry and waste biomass available for use in energy production at existing solid fuel plants. Combustion of biomass with coal is most common, but more and more countries are aware of the environmental concerns that arise with the combustion of biomass, which generates large amounts of gases, dust and ash [6].

A large amount of information can be found in the world literature on gas and dust emissions from the combustion of solid fuels and biomass. However, there are not many studies on the effects of compact biomass combustion [7,8]. An example is Poland, which uses biomass on a large scale to produce energy. Pellets are especially popular, because they are easy for customers to handle, have a high calorific value and produce a small amount of ash [9]. In terms of energy production, pellets are much better than raw biomass, because higher biomass density reduces transport costs and improves combustion parameters. Compared to raw biomass, the combustion of pellets leads to a reduction in particulate emissions into the atmosphere. During the production of pellets, their composition can be controlled [10,11].

Available sources also contain descriptions of problems that are encountered with the use of biomass-heating furnaces. There are mainly failures in the use of furnaces due to the corrosion of machinery, the formation of difficult-to-remove slag or combustion control disorders [12–14]. One reason for these problems is the presence of aggressive chemical compounds that form during the combustion of biomass and other fuels that are not environmentally neutral [15]. Particular attention is paid to gaseous acid anhydrides, non-metallic oxides and halogens, as well as potassium salts and other solid combustion products present in ash. Previous studies have shown that biomass combustion produces high emissions of free chlorine and hydrogen chloride (especially in the case of straw), which poses a high risk of corrosion of heating equipment [16–18].

Burning wood biomass from plants also produces relatively fewer chemicals that cause mechanical corrosion and damage. Therefore, the most appropriate way to minimize the above problems appears to be to choose the correct biomass mixture at the pellet production stage [19].

Commonly used additives that reduce emissions of acid anhydrides into the atmosphere are lime, limestone, dolomite and aluminosilicates (especially kaolinite and bentonite) [20]. Additives that increase the melting point of ash are aluminosilicates, sulphur and lime. Monedero et al. described the process of adding Ca/Mg-lignosulfonate to wood pellets, which resulted in lower CO and NO_x emissions. Wang et al. described the neutralization of Cl_2 and HCl with sorbents based on $CaCO_3$, CaO, $Ca(OH)_2$, Na_2CO_3 and $BaCO_3$ introduced into the furnace. At the same time, they stated that $BaCl_2$ (formed by the reaction of $BaCO_3$ + 2HCl) was more stable than $CaCl_2$ at high temperatures (above 700 °C). All sorbents were analysed at temperatures of 500–600 °C [21,22].

Another study confirmed that biomass pellets depend mainly on three factors: temperature, residence time and volatile matter content. Heat loss from unburned carbon was not significant in that study. Low NO_x emissions were observed at low excess air levels, as NO_x can be reduced by CO and carbon, which are commonly used in reducing the NO_x reaction. SO_2 emissions were higher from coal combustion than from coal co-combustion with biomass pellets due to the high sulphur content of the coal. Increasing the biomass content would dilute the sulphur in the blended fuel content, thus reducing SO_2 emissions [23,24].

The European Commission recommends avoiding barriers to the use of fuels made from waste products that do not cause higher levels of environmental pollution. The big challenge faced by countries on all continents is to move waste-to-energy processes to the level of material recovery. Taking on this challenge would address the energy balance in countries with large population growth and those dependent on imports of basic resources, such as the countries of Central Europe. A balance between material and energy recovery of waste is a unique chance to use waste efficiently and meets the requirements in order to gain a certain degree of independence from non-renewable energy sources [25].

2.1. Use of Pellets on the World Market

In Europe, North America and Asia (China, Japan and South Korea), wood pellets are mostly used for co-firing in coal-fired power plants [26–28].

In 2017, the demand for European pellets grew by 2.5 million tonnes, while production rose to 1.4 million tonnes. In 2018, 20.1 million tonnes of pellets were produced. Europe and

China are the world's leading producers of pellets. For several years now, the sector has been booming, and pellet production has spread across the EU, enabling rural development. The annual market and trade data report of the United States Department of Agriculture's Foreign Agricultural Service confirms that the EU wood pellet market was not affected by the COVID-19 pandemic but warns of further market expansion that could be limited by member states' sustainability requirements [29–33].

After 2020, according to the EU report and the information we obtained, it is expected that the demand for wood pellets will increase to 30.8 million metric tonnes. The expectation for EU producers is to produce 18.5 million metric tonnes of wood pellets this year, up from 17.7 million last year [29]. The United Kingdom is the largest consumer of pellets, followed by Italy and Denmark. Germany is the main pellet-producing country in the EU, followed by Sweden and Latvia.

In terms of sustainability, the report states that European traders and end users of industrial wood pellets demand clear, consistent, harmonized, long-term government regulations. Several member states have developed their own sustainability rules, including Belgium, Denmark and The Netherlands [34]. The Renewable Energy Directive II report states that the sustainability of biomass production will be assessed at the level of resource extraction, not forestry, as was originally proposed. The EU member states will also be able to impose additional sustainability requirements for biomass fuels. By the end of 2026, the European Commission will assess the impact that these additional requirements may have on the internal market to ensure the harmonization of sustainability criteria for biomass fuels [35].

In India, the State Regulatory Commission is required to identify and implement renewable purchasing obligations. To achieve the goal set out in India's National Action Plan on Climate Change, the government has introduced a Renewable Energy Certificate mechanism [36]. As presented at the 21st Conference of the United Nations Framework Convention on Climate Change, it is envisaged that India's national contribution of installed biomass capacity will increase from the current capacity of 4.4 to 10 GW by 2022 as part of an overall goal to increase electricity generation from fossil fuels to 40% by 2030 [37].

Studies report that electricity generation with biomass pellets and/or co-incineration of biomass pellets and a coal substitute can help meet targets in countries with low solar/wind resources (and limited availability of waste) and extensive agricultural and forestry residues, as these countries can attract investment through the mechanism of energy management and renewable energy sources [38,39].

Other available sources indicate that the following countries have significant potential to change to alternative fuels: Slovenia, Slovakia, Latvia, Estonia, Ireland, Sweden, Luxembourg, Romania, Portugal, France, Bulgaria, Finland, Lithuania, Czech Republic, Poland, Germany and Austria [40].

2.2. Cost Optimization of Biomass in the World

Various studies have examined the cost of delivering wood pellets under different scenarios or conditions. For example, in their research, Obernberger and Thek analysed in detail the costs of supply chain components and the total cost of pellet production in Austria [5]. A similarly oriented study was published by Ehrig et al., who analysed the differences in the costs of the pellet supply chain [41].

Purohit and Chaturvedi determined the cost of producing electricity from biomass-based pellets and identified whether its technical potential in India would be exploited [36]. Additionally, based on detailed assumptions regarding input costs and technical factors, the authors estimated that the cost of biomass pellets could be EUR 64 per tonne, with an offset electricity cost of EUR 0.12 per kWh (more than the cost of imported electricity from coal). Similar conclusions were reached in a study dealing with techno-economic modelling of the use of biomass pellets [36–41].

In another study, a team of authors investigated whether wood pellets for heating buildings in China are more sustainable than coal by comparing the energy, environmental and economic aspects of the two energy sources. They modelled pellet and coal heating systems using an approach based on the gradual modelling of the life cycle of energy reserves and the consumption and emission of air pollutants in GJ [42]. They also analysed the cost of wood pellets and their competitiveness in the market of heating alternatives. The results showed that the energy-saving potential when using pellets instead of coal was 1382 MJ for every one GJ of heat produced. Greenhouse gas emissions from pellets amounted to 11.76 kg CO_2 eq. GJ^{-1}, which was approximately 94% less than emissions from coal-fired heating systems. The use of wood pellets also reduced SO_2 and NO_x emissions. In China, the price of pellets is significantly higher than the price of coal, which is a major obstacle to the transition from coal to pellets. Multiple consumption of wood residues, unstable heat values of pellets, limited supplies and a lack of standards and heating equipment are also problems in the transition from coal to pellets [22].

Another study examined greenhouse gas and air pollutant emissions; the financial implications of electricity production from steam-treated pellets, including fuel cycle activities (biomass supply, pellet production and combustion); infrastructure equipment that allows 100% combustion of pellets at a production station in Ontario, Canada, that previously used coal. Pellets can reduce air pollutant emissions in the fuel cycle by 30% for NO_x, 97% for SO_x and 75% for particulate matter (PM_{10}) compared to coal. Less stringent retrofitting requirements for steam-treated pellets compensate for slightly higher pellet production costs, leading to lower electricity generation costs compared to conventional pellets (USD 0.14/kWh vs. USD 0.16/kWh) [43].

Results from Georgia suggest that co-firing wood pellets with coal is generally not a commercially viable option. However, incinerating a smaller proportion (<15% wood pellets) may have been possible in the initial period (2009–2011), when the price of wood pellets fell. Sensitivity analysis shows that the conclusions are robust, and the most important factors are the relative prices of coal and blended fuel. Therefore, the authors reject the null hypothesis that co-incineration is economically possible and suggest the use of policy instruments to stimulate the bioenergy market in the form of subsidies or tax adjustments [44].

A study of the economic feasibility of wood pellet production in Iran was performed by calculating economic indices and analysing their sensitivity using the Computer Model for Feasibility Analysis and Reporting (COMFAR III) software developed by the United Nations Industrial Development Organization (UNIDO) for three scenarios with annual capacity of 48,000, 75,000 and 120,000 tonnes. The cost of wood pellet production for the plans was 104.29, 107.63 and 106.92 EUR/Mt. Acceptable internal rate of return (45–124%) and net present value (EUR 7–14 million) support the feasibility of wood pellet production in Iran. The results show that energy production costs are higher for wood pellets (43.5 EUR/MWh) due to the high initial investment in wood pellet boilers compared to established fossil fuels and low oil and gas prices in Iran [45].

Boukherroub et al. calculated the return on investment for scenarios involving the production and transport of pellets with different operating rates, the level of state aid, the cost of collection and the selling price of pellets. Significant findings on specific case studies of supply chains, as well as differences in the results of certain cost components, were demonstrated by existing studies. For example, the cost of biomass for the production of pellets, such as palletization costs, varies in some studies in the literature, including capital and operating expenses. These large cost ranges lead to uncertainty that prevents these studies from being used to evaluate strategies for optimizing the cost of wood pellets. The question arises as to whether we can explain these cost differences by differences in supply chain design, type of raw material used or geographic chain. In-depth analyses are required to answer this [14].

Although there are contradictory views on the co-firing of biomass in the form of different forms of pellets as a coal substitute, authors agree on the need to create sustainable technology to reduce the use of fossil fuels for energy production and, thus, participate and help to reduce greenhouse gas emissions, which is also the subject of this research. Co-

combustion of coal and biomass has the advantages of relatively simple implementation and effective reduction in emissions of CO_2 and other pollutants (SO_x, NO_x) into the atmosphere [46]. Co-combustion of biomass with coal does not have to incur any losses in the overall efficiency of the boiler after adjusting the combustion output for the new fuel mixture. However, guaranteeing a stable and cheap supply of biomass together with an optimal supply system is a key aspect of successful co-combustion of biomass [47].

Studies of this type involving a specific organization in Slovak conditions are in the development phase and are being conducted in cooperation with academia. We are already considering the use of solid recovered fuel in Slovakia, which, unlike solid alternative fuel, is perceived as a certified biomass-based fuel. Current analyses are focused primarily on environmental characteristics, but the economic evaluation of the use of solid recovered fuels is absent.

3. Materials and Methods

This paper describes the procedures and methods used in solving research questions concerning the current knowledge and requirements of the Vojany black coal power plant. We formulated the following hypotheses for this study:

1. Combustion of solid recovered fuel at the Vojany black coal power plant is more cost-effective than combustion of black coal.
2. There is potential to produce synthetic fuel from pellets and biomass at the Vojany black coal power plant.

The methodological procedure for the case study of the Vojany black coal power plant is presented in Figure 1.

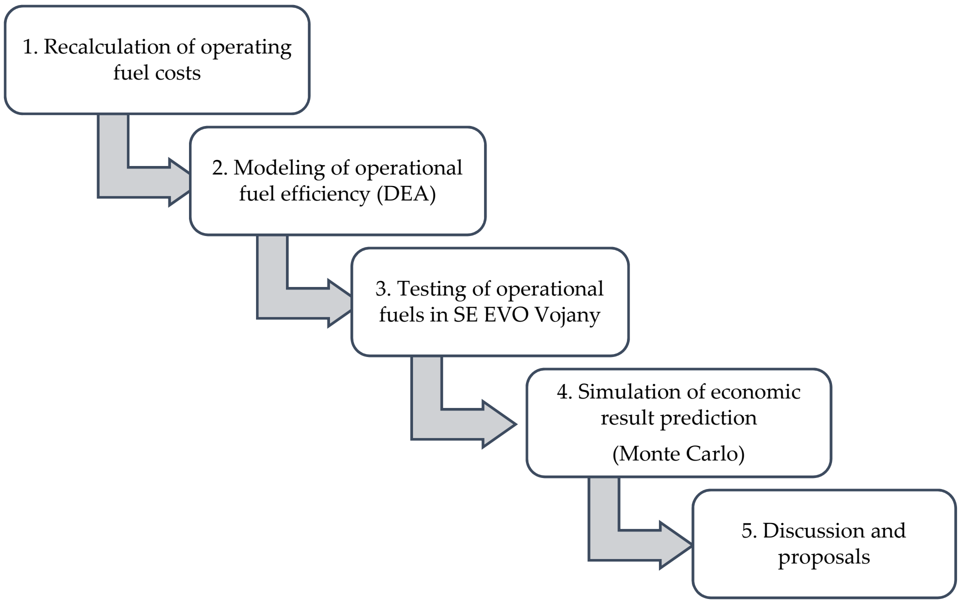

Figure 1. Methodology of case study in five steps. Source: Own processing.

First step of the methodology

As a part of the analysis of the profitability of co-incineration of 100% solid recovered fuel, we assessed the economic possibilities of fuels in the boilers and the CO_2 emissions at the Vojany black coal power plant (Table 1).

Table 1. Input data for cost calculation.

Fuel Type (2019)	Heat Value (GJ)	Fuel Price EUR/t with Transport	Fuel Price EUR/GJ with Transport
Wood chips	9.5	43.83	4.61
Solid recovered fuel free	23	15.00	0.65
Solid recovered fuel pellets	26	39	1.50
Black energy coal	25.23	98.45	3.90
Heat rate	12.17	-	-

Source: Own processing.

We also relied on other input data, such as the average sales price of electric power for 2019–2020 (EUR 50.40/MWh). This electricity was produced from black coal and wood chips. The price for processing stored ash in stabilizer landfills was in the range of EUR 3.71 per tonne. This price consists of two parts, 0.66 EUR/t for landfilling and 3.05 EUR/t for processing and storage of stabilizer by an external company.

At present, in addition to charges imposed by Act 401/1998 Coll. for air pollution, as amended, businesses that produce air pollution must also pay for actual CO_2 emissions. The European Union Emission Trading Scheme is a cornerstone of the EU's climate change strategy. It applies not only to the 28 EU member states, but also the three member states of the European Economic Area, which are Norway, Iceland and Liechtenstein. The trading period of 2013–2020 was characterized by the fact that, in addition to sectors receiving a free allocation of emission allowances from the state, electricity producers were obliged to purchase all emission allowances. Table 2 presents the average historical prices of emissions per 1 tonne of CO_2 emitted into the atmosphere and the price of allowances of the last contract in 2020.

Table 2. Development emission allowances price per 1 tonne of CO_2.

Period	Average Price of Emissions in EUR per 1 t/CO_2
Contract to 20.05.2020	20.3
2019	24.72
2018	15.56
2017	5.80
2016	5.23

Source: Own processing by European Energy Exchange AG.

The price per 1 tonne of CO_2 emissions increased significantly during the period, rising from an average of EUR 5.23/t in 2016 to EUR 24.72/t in 2019. This was related to the EU's policy on reducing greenhouse gas emissions by at least 40% by 2030 (compared to 1990 levels). To accomplish this, the sectors covered by the EU Emissions Trading System need to reduce their emissions by 43% compared to 2005. This means that the total number of allowances will decrease faster than before starting in 2021, from 1.74 to 2.2% per year. The annual reduction in emission allowances results puts the market in a deficit, which puts upward pressure on prices. According to analysts, the current decline in emission allowance prices is the result of the coronavirus crisis, as well as low oil prices. The current fall in the price of emission allowances will most likely not be a long-term trend, and the price will return to its original level with the prospect of further growth after the crisis.

Therefore, a further increase in the price per tonne of CO_2 emissions is expected in the future; it should increase to EUR 20 per tonne of CO_2 in 2050.

Taking into account the current prices and fees for CO_2 produced on the market of operational fuels, we calculated the price of the cost per 1 MWh of a specific fuel. We calculated the price for produced CO_2 only in the case of fuels for which fees are not forgiven by the state and the legislation of the Slovak Republic. For this calculation, we had to identify the price per tonne of CO_2 with the number of tonnes of CO_2 per 1 MWh that Vojany black coal power plant would produce if it replaced biomass with coal.

Second step of the methodology

To confirm the combustion efficiency of individual types of fuels, we used data envelopment analysis (DEA) [48]. DEA is a widely used non-parametrical and linear programming technique for evaluating the relative efficiency of DMU's [49]. Since DEA can handle multiple inputs and outputs, it is an appropriate method. DEA applications in this area can be found in, Liu et al., Longo et al., Peng and Cui, Racz and Vestergaard and Wang and Sueyoshi [50–54]. This analytical method is also suitable for measuring the effectiveness of various environmental and economic processes. Most DEA models help evaluate the operational performance of incinerators. The DEA technique also measures the efficiency of incinerators based on inputs and outputs through benchmarking [55]. Chen et al. proposes a model of the DEA network to measure the efficiency of incinerators from waste treatment to electricity generation [56]. We used an input-oriented model, which operates in such a way that it tries to achieve the required efficiency of inefficient units by reducing the input values, which is also the desired goal of the Vojany black coal power plant. We choose this model based on rising costs caused by the rising price of transporting black coal from the Russian Federation, increasing emission quotas and the falling price of electricity. The model is compiled in accordance with the production characteristics of the Vojany black coal power plant, which we used to select the input and output variables. The input variables represented the number of employees, the operating costs of fuels (water, additives, etc.), the costs of CO_2 emissions and the purchase price of fuels with transport. The monitored outputs were the amount of electricity produced, total sales (including revenues from support services and regulated electricity) and the amount of fuel produced per year. The dataset of this study is available from the corresponding author on request.

Our research is focused on tracking costs from a comprehensive centralized perspective with an emphasis on reducing transportation costs, as well as research by Petridis et al. [57].

Based on the identified position, it was possible to recalculate different development scenarios. Thus, a choice can be made as to whether the Vojany black coal power plant will continue working on the most effective reduction in emissions by burning wood chips, which will result in slower economic growth. Another alternative is to reduce emissions by operating with 100% solid recovered fuel. In this context, we expressed the weights of inputs and outputs, limiting conditions and defined parameters, and determined the degree of efficiency of the investigated operating fuels (black coal, wood chips, solid recovered fuel pellets and solid recovered fuel free). Subsequently, we identified the most efficient types of fuels. Based on that, we also performed the appropriate laboratory tests.

Third step of the methodology

Combustion tests of the research material were performed in a trial period from 10–11 March 2020. The test was based on the decision of Slovak Environmental Inspectorate in Kosice to verify the impact of co-incineration of 50% solid recovered fuel on emissions, i.e., to determine the volume of emissions from co-incineration of 50% solid recovered fuel as an alternative to black coal. Table 3 describes the sample of alternative fuel delivered to the Vojany black coal power plant on 28 January 2020.

Table 3. Solid recovered fuel test results, supplied by RAMEKO, Ltd.

Parameter	Unit	Sample Number 371/2020 Value	Uncertainty U	Procedure
Total water in alternative fuel (humidity)	%	5.55	3.0%	IPP 152 (STN P CEN/TS 1541)
Combustion heat in anhydrous sample	MJ/kg	24.92	0.8 MJ/kg	IPP 154 (STN EN 15400)
Calorific value in anhydrous sample	MJ/kg	23.34	0.8 MJ/kg	IPP 154 (STN EN 15400)
H in anhydrous ample	%	7.69	15	IPP 153 (STN EN 15407)

Source: Own processing by Vojany black coal power plant (2020).

In the test of co-combustion of coal and 50% solid recovered fuel with the biomass of the Vojany power plant, three suppliers of solid recovered fuel cooperated to ensure sufficient volume for this test and to predict the supply of a sufficient amount of solid recovered fuel for subsequent tests (Figure 2).

Figure 2. Solid recovered fuel deliveries. Source: Own processing by Vojany black coal power plant (2020).

On the first day, the dosing of solid recovered fuel from the Vojany power plant warehouse into the storage tank proceeded without any problems (Figure 3), and the regulation of the amount of solid recovered fuel and biomass with the mentioned caloric content of 50% of alternative fuel worked.

Figure 3. Dosing of solid recovered fuel into tank from landfill of Vojany black coal power plant. Source: Own processing by Vojany black coal power plant (2020).

On the second day of the test, a smaller problem arose when backfilling the original black coal belts and the solid recovered fuel storage tank, making it necessary to reduce the dosage of solid recovered fuel and biomass by 7%. Based on these combustion tests, it was necessary to solve the problem with the original dosage of solid recovered fuel and biomass of 50% caloric composition, so that the backfilling of overflow would not repeat. At the same time, it was necessary to design the right way to clean the original tank (milling cutter, cleaning platform, etc.) to avoid unnecessary costs for the power plant by purchasing new conveyor belts and a tank for the solid recovered fuel, as well as costs related to downtime during alternative fuel combustion.

The tests were performed with specified ratios of black coal, solid recovered fuel and wood chips (Table 4). Using the original information system, the regulation of the boiler output was tested.

Table 4. Quantities and proportions of fuels during the test.

	Black Coal		**Solid Recovered Fuel**		**Wood Chips**	
	Heat Value GJ/t	**24.5**	**Heat Value GJ/t**	**23.5**	**Heat Value GJ/t**	**9.5**
	(t)	**% (Caloric Ratio)**	**(t)**	**% (Caloric Ratio)**	**(t)**	**% (Caloric Ratio)**
10 March 2020	272	49.5	242	42.2	118	8.3
11 March 2020	331	57.0	218	36.0	106	7.1

Source: Own processing.

During the test on 10 and 11 March 2020, the fluidized bed boiler in block B15 had a standard output of 61 MW. The measured values of TZL, SO_2, NO_x and CO were within limits during the test according to the laws of the Slovak Republic.

The solid recovered fuel dosing condition was set at 17.3 t/h. At a boiler temperature of 836 °C, the pressure was 10.4 KPa, and at a temperature of 864 °C, the pressure reached 1.6 KPa, with a total overflow of 4.4 KPa.

During the combustion trial, we measured all flue gases and exhaust gases according to the Decision of the Slovak Environmental Inspectorate (no. 9676/57/2019-46967/2019/571020106/Z32), which imposes consequences for non-compliance with measured values of TZL, SO_2, NO_X, etc.

Subsequently, we performed a technical evaluation of the tests. We present the exact volumes of combustion on individual days from 10 to 20 March 2020, as well as the energy calorific value in GJ, based on which we developed economic and environmental proposals and recommendations for further analysis of the use of synthetic fuels not only at the Vojany black coal power plant, but in the energy industry in general.

Fourth and fifth steps of the methodology

Based on a study by Pradhan et al., who predicted the economic recovery of fuel pellets using Monte Carlo simulation, a similar model of the conditions of the Vojany black coal power plant confirmed that the proposed framework generally reduces excessive dependence on fossil resources and facilitates bioenergy support with its competitive price [58]. These results were also supported by other proposals based on prediction using Monte Carlo simulation and evaluation of price competitiveness of possible scenarios testing the Vojany power plant and the possibility of its sustainable development. The results of the study are discussed, which, in addition to simulating economic results, also confirms similar results obtained in other studies, and suggestions for future research are provided.

4. Results

Slovakia is highly dependent on energy imports, importing more than 90% of total energy sources. This amount represents about 20% of the country's total imports. Reducing the country's dependence on imports of energy sources may be achieved by greater use of renewable energy sources, which at the same time would reduce the production of greenhouse gases and the burden on the environment. According to predictions, it is possible that in the next half-century, oil resources will be depleted (the impact of this assumption can be seen in the current rising oil prices in world markets), and the lifespan of other fossil fuels is estimated at 100 to 200 years (natural gas, 85 years; black coal, 200 years).

These crucial factors confirm the need to identify new renewable energy sources that can reliably cover Slovakia's energy needs. The current use of renewable energy sources is estimated to be around 4%. As a sharp rise in the price of fossil fuels can be expected and their extraction will become more financially demanding, it is appropriate to assume that renewable energy will soon be the most important domestic energy source. The Vojany black coal power plant has great potential for the use of renewable energy sources, which can be used at the regional, local and individual level.

4.1. Calculation of Electricity Generation Costs According to Alternative Combustion

The following calculations were determined by the heat rate (HR) indicator amount of GJ bound in the fuel required for the production of 1 MWh using the technology at units 5 and 6 of the Vojany black coal power plant (Table 5).

Table 5. Conversion of operating fuel costs.

Type of Operational Fuels	Total Costs of Operational Fuels
Black coal	68.86 €/MWh
Wood chips	56.15 €/MWh
Solid recovered fuel pellets + biomass combustion	30.64 €/MWh
Solid recovered fuel free + biomass combustion (84%:16%)	21.94 €/MWh

Source: Own processing.

A total of 0.482 tonnes of black coal is needed to produce one MWh of electricity (at a given calorific value of black coal). We added the emission factor to the costs because it is the production of CO_2 by burning fossil fuels. There are no fees for this. To produce 1 MWh of electricity (at a given calorific value of wood chips), 1.281 tonnes of wood chips are needed. The amount of saved CO_2 emissions, the so-called CO_2 free, is due to the waived fees for burning wood chips. It is like the closed cycle of CO_2 circulation captured by the photosynthesis of plants. This is so-called zero circulation. Therefore, we do not add their value to the total cost of producing 1 MWh of electricity from wood chips. For the production of 1 MWh of electricity (at a given calorific value of pellets with solid recovered fuel + biomass), 0.468 tonnes of pellets are needed. The amount of CO_2 emissions saved is based on the low emission quotas for this type of fuel. On the same principle, we calculated the amount of free pellets + biomass for the production of 1 MWh of electricity (at a given calorific value), and 0.47 tonnes of free pellets are needed. Emissions charges, as in the previous case of pellets, are low compared to black coal. Therefore, this charge does not increase the cost of using this fuel. If an agreement is reached under which the Vojany black coal power plant will pay for imported solid recovered fuels, the last two alternatives will arise. The price already includes transport costs.

In 2019–2020, the revenues from the combustion of black coal and wood chips and support services at the Vojany black coal power plant totalled EUR 24,337,889.89. The costs amounted to EUR 33,278,469.50. In total, the power plant had a loss.

In these calculations, we only counted the main fuels for the production of electricity at the Vojany power plant, or those which, with their legislative advantages, could help to achieve better economic results. We also did not include the costs of storing ash and limestone, which are used in the boiler to capture hazardous substances from fuel combustion.

4.2. Measuring the Economic Efficiency of Operational Fuels

Solid recovered fuel brings an opportunity for the Vojany black coal power plant, which has produced electricity from black coal for many years and, since 2009, also from biomass. Due to the high proportion of CO_2 in black coal, a possible alternative is solid recovered fuel with an admixture of biomass and ash from the plant sludge, needed to maintain the stability of the fluidized bed (heat carrier).

Tests with solid recovered fuels began at the end of 2019 and continued at the plant in 2020 with the co-combustion of solid recovered fuel and biomass. At the same time, the ecological burden from the volume of the sludge pond was reduced. We performed the tests during normal operation according to the approved schedule. The intention was to analyse the potential use of these mixtures in the production of electricity, with solid recovered fuel, biomass and ash from the sludge added to the black coal to maintain the stability of the fluidized bed.

The results obtained based on the DEA model with input characteristics are shown in Table 6. The characteristics of the input-oriented model were similar. The main factors for the energy security of the Slovak Republic are rationalizing energy consumption and optimizing the mix of energy sources.

Table 6. Solution of non-parametric data envelopment analysis (DEA) method of measuring eco-efficiency. DMU, decision-making unit.

DMU	Weight λ	Efficiency
1	0.158425621	1.23228500190572
2	0.959805092	
3	0.994280774	
4	0.998348568	

Source: Own processing.

The combustion of combined fuels that took place in 2019–2020 shows an overall inefficiency in measurement. For example, decision-making unit (DMU) 1, black coal, which in the case of input orientation has efficiency of 0.158425621, shows inefficiency. To be effective, the Vojany black coal power plant must take certain measures. It can reduce inputs (by reducing operating costs related to expensive transport) or try to increase outputs (by increasing the amount of energy produced, which would require further investment). However, with the current global challenges involved in cleaner production, this solution is environmentally inefficient. To determine the economic and environmental efficiency and profitability of heat production from biomass, it is necessary to analyse cost items and revenues and compare them among potential alternatives. Several external factors enter into this complex process, such as development, current situation and market trends for fossil fuels and alternative energy carriers, their availability, prices and environmental impact, development of biomass processing and combustion technologies, energy policy, state support for renewable energy and increasing the country's energy independence.

It is clear from the results that solid recovered fuel pellets and free pellets had the highest combustion efficiency in 2019–2020 in combination with wood chips; therefore, field testing was carrying out at the Vojany black coal power plant. After evaluating the costs and economic efficiency of producing and processing solid recovered fuels, in the following sections, we deal with the research of the experimental ratio of desirable and efficient fuels.

4.2.1. Tests of Combustion of Black Coal, Solid Recovered Fuel and Wood Chips at the Vojany Black Coal Power Plant

We calculated using values from 10 March 2020, when a 24 h test was performed with a caloric content of 50% solid recovered fuel and biomass (Table 7).

Table 7. Final combustion tests of black coal, solid recovered fuel and wood chips.

Date	Black Coal	GJ	%	Wood Chips	GJ	%	Solid Recovered Fuel	GJ	%	Total in %
10 March 2020	272	6746	50	118	1121	8	242	5687	42	100
11 March 2020	331	8209	57	106	1007	7	218	5123	36	100
12 March 2020	435	10,788	81	99	941	7	66	1551	12	100
13 March 2020	489	12,127	81	106	1007	7	82	1927	13	100
14 March 2020	410	10,168	73	157	1492	11	99	2327	17	100
15 March 2020	190	12,152	75	169	1606	10	100	2350	15	100
16 March 2020	405	10,044	74	369	3506	26	0	0	0	100
17 March 2020	421	10,441	77	146	1387	10	70	1645	12	100
18 March 2020	435	10,788	73	147	1397	10	107	2515	17	100
19 March 2020	564	13,987	73	190	1805	9	145	3408	18	100

Source: Own processing by Vojany black coal power plant.

In the recalculations, we can see that on 10 March 2020, 100% of the total volume was burned, and the black coal at a volume of 50% showed values of 272 t and 6746 GJ. Adding the volumes of solid recovered fuel and wood chips on that day, it showed better values of 360 t and 6898 GJ. Converting solid recovered fuel and wood chips from that day to 100% volume, the values are 720 t and 13,796 GJ. With a volume of 100% black coal, the values are 544 t and 13,492 GJ (Table 8).

Table 8. Statistical conversion to 100% calorific value of solid recovered fuel and wood chips in recovered fuel.

24 h	Percentage (%)	t	GJ	Effectiveness (coeff.)	MWt	MWh
Wood chips	8	118	1211	0.2938	336.39	98.83
Solid recovered fuel	42	242	5687	0.2938	1579.72	464.12
Black coal	50	272	6746	0.2938	1873.89	550.55
Total solid recovered fuel pellets + wood chips	8 + 42	360	6898	0.2938	1916.11	562.95
Total solid recovered fuel free + wood chips	2 × (8 + 42)	720	13,796	0.2938	3832.22	1125.91
Black coal	2 × 50	544	13,492	0.2938	3747.78	1101.10

Source: Own processing.

A very important component of the statistical conversion to 100% of the caloric content of solid recovered fuel and wood chips as a substitute for hard coal was the test operation of the combustion of 50% of the calorific content of the three fuels together on 10 March 2020 (24 h co-incineration test). According to the output data of this test, we mathematically statistically calculated the value of 100% from the 50% caloric share of the fuel and calculated the positive final values.

According to these calculations, there was a higher energy calorific value for 100% solid recovered fuel with wood chips, by 304 GJ, compared to black coal. In terms of MWh produced, the value was higher by 24.81 MWh compared to black coal. We recommend that the caloric content should be in a ratio of 84% solid recovered fuel to 16% wood chips (Table 9).

Table 9. Monthly recalculation of operation for solid recovered fuel and wood chips at a ratio of 84%:16%.

30 Days	Percentage (%)	t	GJ	MWt	Efficiency (Coeff.)	MWh
Wood chips	16	7080	72,660	20,183.33	0.2938	5929.86
Solid recovered fuel free	84	14,520	341,220	94,783.33	0.2938	27,847.34
Total	100%	21,600	413,880	114,966.67	0.2938	33,777.21

Source: Own processing.

In the monthly recalculation according to the mathematical statistical method applied above, we can say with certainty that when comparing the volumes of solid recovered fuel and wood chips, wood chips with a third of the total volume burned, producing only 5929.86 MWh, while solid recovered fuel reached 27,847.34 MWh.

4.2.2. Economic Evaluation of Solid Recovered Fuel Combustion

Instead of black coal, we propose the use of 100% solid recovered fuel combined with wood chips for combustion. The input cost per 1 energy unit is lower than per 1 energy unit of black coal burned so far. Table 10 shows the calculation for annual conversion to 100% solid recovered fuel and wood chips.

Table 10. Annual conversion of combustion of solid recovered fuel and wood chips in the ratio of 84%:16%.

2020/2021	Percentage (%)	t	GJ	MWt	Amount of Electricity Produced in MWh	Cost per 1 MWh	Planned Revenues in €	Total Cost in €	Profit/Loss
Wood chips	0.16	28,592	271,627	75,452	21,881.07	21.94	21,430,045.52	18,583,207.73	2,846,837.80
Solid recovered fuel free	0.84	150,110	3,452,523	959,034	278,119.88				
Total	100%	178,702	3,724,150	1,034,486	300,000.95				

Source: Own processing.

When calculating the turning point for the Vojany black coal power plant, we can identify the impact of changes in sales and fixed and variable costs on business profitability, which is one of the key elements of the economic management and planning of the plant. The amount of electricity it has to sell to cover fixed costs is 228,668.28 MWh.

Subsequently, we derived three possible scenarios from the tested processes to determine the probability of the economic plan of the Vojany power plant reflected in economically and technically sustainable solutions, which will be the subject of further scientific research.

5. Discussion

Until 2019, the Vojany black coal power plant produced energy mainly from the combustion of black coal with an admixture of wasted wood chips. The plant has technology capable of co-burning fuels made from solid recovered fuel. We can consider this fuel a step towards a cleaner future. Today, in particular, it is required that waste not be landfilled, but also that it be recovered in one of the ways described above. The Vojany power plant produces energy from the fuel, which produces a lot of CO_2 that is discharged into the air. On the other hand, some solid recovered fuels have a partially closed cycle, which means that the release of CO_2 into the air from combustion is somewhat less than for black coal. All of the features of solid recovered fuel are closely linked to concepts such as sustainable development, circular management and waste management programs. The Vojany power plant has been aiming for the greening of electricity production. This is evidenced by the replacement of low-emission burners on EVO II and units B1 and B2 of EVO I, as well as the use of wood chips in the production of electricity units B5 and B6 currently in operation.

From the results of the analysis of the Vojany black coal power plant, we can confirm that the costs of electricity production are similar to those reported by Purohit and Chaturvedi (2018). However, the cost depends on the ratio and structure of the pellets in combination with wood chips [42].

The results of the Monte Carlo simulation (Figure 4) confirm the positive economic results achieved from the combustion of solid recovered fuel at the Vojany power plant. The x-axis contains simulated values of the economic result in EUR with the probability of achieving it in % (y-axis). When estimating the economic results of the power plant, a certain probability of the development of the price and the produced amount of electricity was considered. This represents the economic and environmental sustainability of the power plant in the transition to combustion of 100% solid recovered fuel [58].

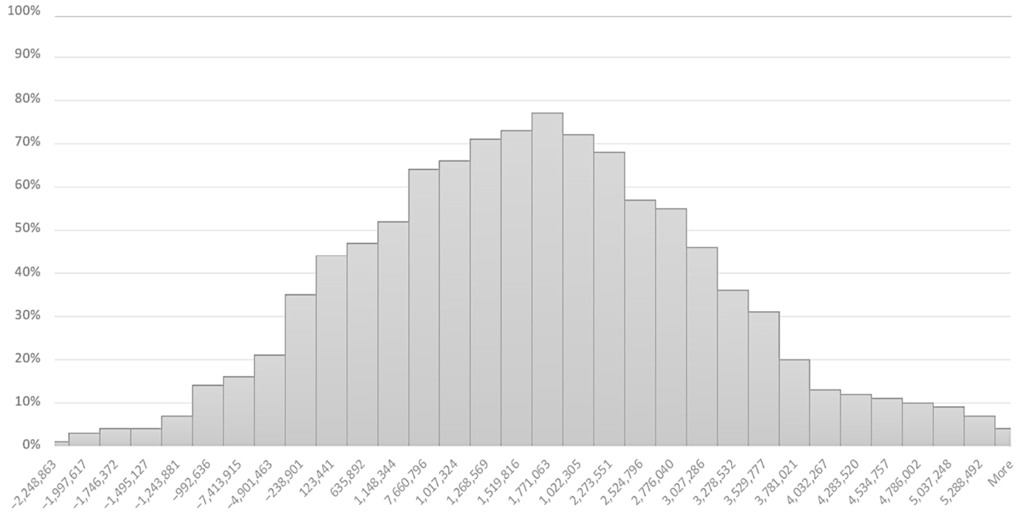

Figure 4. Histogram of profit (EUR) at Vojany black coal power plant. Source: Own processing.

The results of our study confirm the hypothesis regarding more cost-effective combustion of solid recovered fuel at the Vojany black coal power plant compared to black coal. With this solution, the thermal power plant can achieve sustainable environmental and economic results.

We can confirm the hypothesis that the power plant has the potential to produce synthetic fuel from pellets and biomass. This is evidenced by the experience of foreign studies and by the Slovak Republic moving in a sustainable direction in this area.

In this context, we propose the following measures:

- Expand production capacity by purchasing machinery for the production of solid recovered fuel in the future.
- Start lobbying for approval of price regulation in the industry from the production of electricity by co-incineration of solid recovered fuel, with a higher installed capacity than currently by Decree No. 18/2017.
- Present the production of solid recovered fuel near the plant as a good business opportunity.
- Achieve the best possible conditions from the suppliers of these fuels and strive to obtain the lowest possible price for solid recovered fuel.
- Publicize the environmental aspects of using these fuels and their positive impact on the environment.

If it is decided in the future that the Vojany black coal power plant will fully implement solid recovered fuel for electricity generation, fuel supplies must be at a constant level. If the power plant invests in the reconstruction needed for efficient waste incineration, it will certainly need long-term and reliable suppliers. It will, therefore, also be in the interest of the plant for cities and municipalities to expand the construction of sewers, wastewater treatment plants and waste collection and sorting facilities as much as possible. All of these activities will not only help the Vojany power plant to provide enough recovered fuel, it will also have a positive effect on the environment. The reason is the replacement of black coal by biofuels. This solution (Figure 5) would bring much-needed new jobs to the Zemplín region. Therefore, it is necessary to decide on suppliers who can deliver the necessary quantities. The possible future use of solid recovered fuel at the Vojany black coal power plant also brings suitable business opportunities, because waste is produced throughout Slovakia.

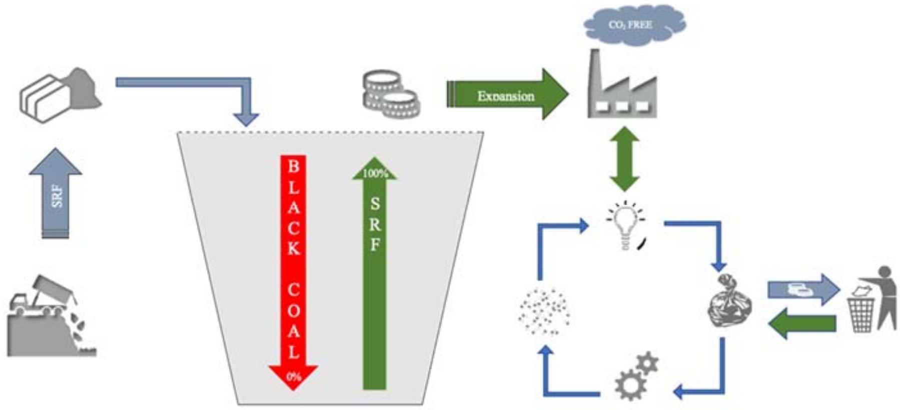

Figure 5. Proposed solution for Vojany black coal power plant based on study results. Source: Own processing.

Our proposals are closely related to the objectives of the Waste Management Policy of the Slovak Republic, a strategic document dealing with the problem. They are also linked to sustainable development, which aims, among other things, to reduce the extraction of fossil fuels and, thus, save them for future generations. This fulfils the objectives of the circular economy. Therefore, it is necessary to address the optimal conditions of co-combustion. Incentives and favourable regulatory and environmental policies will be the main factors supporting the development of co-combustion technology.

The primary purpose of biomass processing is to equip it with characteristics that will ensure a simple environmental–technological conversion to useful energy. Solid recovered fuels are characterized by a typical energy content that makes them attractive for many industrial processes [59].

Research by other authors has shown that the optimal size of solid recovered fuel supply depends on transport and location [48].

With a typical energy-based biogenic content of about 50–65%, solid recovered fuel is an attractive carbon-neutral fuel. For this reason, it qualifies for subsidies such as emissions trading certificates (e.g., EU Emissions Trading Scheme). We also see potential for the conditions of the Vojany black coal power plant.

Even in a circular system, where the physical and technical properties of materials, components and products are maintained in the economy for a longer time, at the highest possible value, the production and use of solid recovered fuel can be a complement to material recycling. This is particularly the case when the technical value, represented by the calorific value or biogenic content of materials, clearly outweighs other technical, environmental and economic value related to their return (e.g., materials that cannot be sustainably or even practically recycled due to low quality). The recent EU strategy for energy waste promotes the increased use of solid recovered fuel as part of the transition process, with the EU's waste hierarchy used as a guiding principle. The intention is to implement prevention at a higher level, prevent reuse and recycling, and at the same time contribute to DE carbonization in line with the Energy Union Strategy and the Paris Agreement [60].

The use and production of waste are potentially integral parts of a solid waste recovery system, especially where there is an opportunity to use it as a substitute fuel in existing fully fossil fuel (coal or heavy oil) plants.

A study carried out by Bildirici and Özaksoy [61] showed evidence of a one-way causal dependence of economic growth on biomass energy consumption in the Slovak Republic. Their findings support the hypothesis that energy consumption from biomass is controlled by the country's economic growth. Based on this, the authors recommended that the Slovak Republic support the consumption of energy from biomass in order to achieve sustainable economic growth.

At present, more and more companies in Slovakia, similar to abroad [62,63], have started to produce pellets and briquettes from waste material in various ecological projects and are even beginning to develop technology for their processing and use. This also sets up the conditions for the creation of new jobs in the development of the region. At the same time, this presents an opportunity for Slovakia to create a market for the sorting of waste destined for resale.

The idea of using this solution is also the result of long-term intensive cooperation between Slovak power plants and the Faculty of Business Economics at the University of Economics in Bratislava with seat in Košice and proves the usefulness of connecting academia with business.

After obtaining the necessary permits, it is expected that Slovak power plants will start operating with the co-combustion of black coal and new fuel at the beginning of 2021. The Vojany black coal power plant, thus, aims to reduce its dependence on imported primary energy sources and support the circular economy in the region. The perspective of this development has been confirmed by research since 2018.

6. Conclusions

The use of synthetic fuels is increasingly important for the production of clean energy from renewable sources. An important aspect is the need to increase the production of several forms of wood waste, because growing industries in Europe, Canada and the United States are capable of producing about 10 million tonnes of biomass pellets per year. One of the main problems of the pellet industry is that the vast majority of pellets are made from wood waste, which will result in a shortage, as the industry cannot produce enough waste to meet the global demand for biomass pellets. Therefore, new possibilities for the use of various types of biomass are being sought, which will be of particular importance soon.

Each specific stage of the combustion process is very important in the development of overall process models due to the large number of variables involved. An assessment of economic and environmental impacts in the use of combined biomass has not yet been conducted in Slovakia; therefore, there are still areas that require further research and analysis. To ensure a continued supply of alternative fuels for the Vojany black coal power plant boiler, an investment in machinery is required. It will be necessary to invest in order to build an unloading station, which consists of crushers, transport fans, cyclone, press, sorter, trolley, loader and other components, which are further specified according to the specific type.

When developing proposals to increase the economic and environmental efficiency of operating units, we expressed operating costs, which include material and energy costs. As part of the research, we propose to focus on reducing the costs associated with emission quotas and transport in the distribution of alternative fuels. Based on the above findings and critical research, we can say that co-incineration of solid recovered fuel in the production of electricity is possible from a technical, legislative and economic point of view.

Based on the obtained results, we can grasp the topic as an interdisciplinary problem, within which it will be possible to obtain new information about known facts due to a new interpretation of the environmental–economic problem of more advantageous use of pellets or currently tested wood briquettes. In the next stages of research, it will be possible to set up a concept that takes into account aspects of the dimensions of sustainable development and determines an acceptable way to implement new technologies at the Vojany black coal power plant.

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