Alternative Sources for Sustainable Development of Thermal Power Plants: Case Study of Slovak Republic as a significant potential for transformation

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Abstract: This research paper deals with the possibility of using alternative types of fuels for electricity production. Power plant Vojany (PPV) is a thermal power plant in eastern Slovakia, which is part of the company Slovenské elektrárne, a. s. (SE). For many years, it mainly used imported (Russian Federation) black coal for electricity production. PPV decided on co-combustion of biomass and Refuse-Derived Fuel (RDF), which brought much better economic conditions due to their price and economic efficiency, while partially closing the CO_2 cycle. The authors work with a hypothesis of the production of energy in the cleanest possible way and with the least possible damage to the environment, thus becoming an inspiration for similar transformation of other power plants in the V4 region. The results point to the fact that potential RDF resources in the V4 region are not sufficient for the transition of several coal-fired power plants to burning RDF also due to the already existing and newly completed capacities for energy recovery of waste.

Keywords: economic efficiency, 2030 Agenda, black coal, transformation, multi-fuel mix, thermal power plant

1 Introduction

The impact of power plants on the environment is currently a worldwide problem. The largest producer of electricity in Slovakia is SE with a market share of 66 %, producing a total of 21.66 gigawatt hours of electricity in 2023. The net electricity supply of SE reached 19.57 GWh. Thanks to nuclear and hydropower, up to 96.5% of electricity delivered to the network is without CO_2 emissions from the production of nuclear, hydro, photovoltaic power plants and biomass co-combustion. SE operates two nuclear power plants (Mochovce, Jaslovské Bohunice), one PPV, 31 hydroelectric power plants (mainly on the Váh and Hron rivers) and two solar power plants (Mochovce, Vojany).

Electricity generation in thermal power plants is traditionally based on the combustion of coal, gas, or fuel oil. Thermal power plant Nováky, located in Zemianske Kostoľany (Prievidza district), ceased electricity and heat production from lignite on 20 December 2023 and is entering a new phase of transformation. Its existing infrastructure offers potential for renewable energy deployment as well as alternative industrial uses. PPV, situated in eastern Slovakia in the Michalovce district, benefits from its proximity to the Ukrainian border, which historically enabled the import of semi-anthracite coal from the Donbass-Kuzbass mining region. Since 2009, biomass in the form of wood chips has been co-fired at the plant, increasing from 7% (80-90 tons per day) to up to 22% (approximately 400 tons per day). Between 2009 and 2015, this transition reduced CO_2 emissions by more than 220,000 tons, while the plant continues to explore pathways towards alternative energy sources.

2 Literature Review

All activities undertaken have some impact on the environmental elements [1]. Countries are forced to seek new stable renewable energy sources [2]. EU has set an ambitious goal of achieving net zero CO_2 emissions soon [3] as industry, production, logistics, a multitude of businesses all have a significant environmental footprint [4]. This requires rapid increase of RES share in the energy mix, as stated in all 2050 EU energy mix decarbonization scenarios of the European Commission [5, 6]. It is very important that various educational institutions and NGOs increase knowledge on environmental protection and environmental elements to spread the importance of sustainability [7].

In accordance with the EU's target of eliminating energy production from black coal and considering that generating power from black coal is becoming economically unfeasible, these power plants have several options [8]: gradual shutdown, replacement with more efficient power sources using cleaner fuels, or reconstruction and repowering to enhance energy efficiency and extend their operation before eventual shutdown. A viable alternative for carbon footprint reduction of power production is represented by large power plants refit to co-firing various biomass and waste materials or even to full fuel switch from black coal to other environmentally more friendly fuels [9, 10].

In today's rapidly changing and unpredictable economic, political, and natural environments and long-term corporate planning is often unfeasible. Integrated operations-focused management system promotes the achievement of business objectives and enables efficient utilization of organizational resources [11]. While the obtained gases and liquids might serve to produce materials rather than energy or biofuels in the transportation sector [12, 13], their low-cost and energy-efficient cleaning still poses a challenge [14].

The greatest challenge the world is facing is climate change, and every country has the duty and ability to invest in renewable energy to reduce greenhouse gas emissions [15]. Analysis of electricity production costs provides basic information on the economic viability of individual power production technologies [16, 17]. Using techno-economic models, Agbor et al. [18] analyzed 60 scenarios of various biomass-based materials (wood chips, straw, biomass residues) co-combustion with powder coal in a 500 MWth boiler to estimate its technical potential, costs, and environmental benefits. Abdelhady et al. [19] used the model Levelised Cost of Electricity (LCOE) to estimate techno-economic feasibility of power production from rice straw in Egypt. Simulation results indicate average nominal and average real LCOE for proposed power plants of 105.5 and 63.3 €/MWh, which are very competitive values in comparison with LCOE of other renewable power sources in Egypt. Further results indicate significant sensitivity of LCOE to feedstock costs and discount rate. In their newer work, location of five biomass power plants in Egypt is proposed using available agricultural biomass to cover over 5% of country´s power consumption [20]. Cuong et al. [21] identified biomass as an "intermediate" power source with higher related LCOE than other Renewable Energy Sources (RES) - or natural gas - based power sources, but still lower than nuclear power plants or coal power plants with carbon capture and storage.

Carbon tax as well as environmental fees have an increasingly significant impact on electricity production costs. Considering solely the contribution of CO_2 costs of power generated from black coal, an increase from around 5 €/MWh in 2011 up to 30 €/MWh at the beginning of 2021 was observed and the costs are still rising [22]. CO_2 costs exceeded 80 €/t at the end of 2021, their development was volatile and at the beginning of 2023 they even reached a peak of more than 100 €/t for a moment, this increasingly burdens power generation from coal and other fossil fuels and provides strong incentive for projects leading to the reduction in net emissions [23].

Another fact supporting such projects is related to public health and environmental impact of power generation and the associated costs that are not internalized (not part of electricity market price). Such costs, termed externalities, can amount to tens of €/MWh [24]. A study by Rabl and Spadaro [25] quantified the power production externalities in Europe to 10 €/MWh for natural gas power plants and up to 50 €/MWh for coal power plants. Similarly, Streimikiene [26] estimated the average 2010-2020 externalities of power production for individual fuel types for the

Central-European region at 20 to 22 €/MWh for natural gas and 43 to 47 €/MWh for black coal.

The core concept of industrial transformation is to enhance competitiveness of businesses by improving resource efficiency and productivity [27]. Based on the available and analyzed literature sources, the assumption of V4 countries' potential for alternative feedstock production allowing transformation of several coal power plants in the region to multi-fuel power sources can be drawn.

3 Research Methods

A combination of non-parametric efficiency assessment using the Data Envelopment Analysis (DEA) and sensitivity analysis assessing the stability of economic results when changing key input parameters and verifying the research hypothesis was applied. The chosen methodological framework was designed to compare alternative fuel scenarios in PPV while maintaining the same technological and performance constraints, thus eliminating distortions resulting from different production scales.

Economic parameters of the most favorable alternative were used to predict future operation of the power plant using sensitivity analysis to identify the most important factors affecting the economics of power plant operation.

3.1 Input Data for Calculations and Power Production Alternatives

Input data for the applied analyses come from four main sources: official statistical databases of the European Commission: Eurostat, EU Emissions Trading System (EU ETS), and Ember, documentation and public materials of the Ministry of Environment of the Slovak Republic, internal technical and economic documents of the analyzed company (PPV), and publicly available market price indicators of fuels and electricity.

Input data required to assess the actual PPV operation, propose three operation alternatives, and to evaluate the feasibility of RDF and biomass use in power production in PPV are presented in Table 1. Average values of biomass: Lower Heating Value (LHV) of 11.5 $GJ.t^{-1}$, black coal CO_2 emission factor of 2.12 $t.t^{-1}$, RDF CO_2 emission factor of 1.30 $t.t^{-1}$, and CO_2 released from biomass combustion of 1.36 $t.t^{-1}$ were considered.

Table 1

Input data and parameters of fuels combusted in 2022

Parameter	Year		
	2021	**2022**	**2023**
Black coal price (€.t^{-1})	102.65	261.98	230
RDF price (€.t^{-1})	13.82	12	37
Biomass price (€.t^{-1})	48.56	62.91	120
Assumed yearly average electricity price (€.MWh^{-1})	61.37	144.17	195
CO_2 allowances cost (€.t^{-1})	42.57	66.63	88.23
Net heat rate of PPV (GJ.MWh^{-1})	12.30	13.34	12.80
Average black coal LHV (GJ.t^{-1})	24.84	23.40	24.60
Average RDF LHV (GJ.t^{-1})	22.45	17.20	21

PPV can operate with a fuel mix – a fact confirmed by PPV steam boiler vendor, reflected in the definition of operation alternatives.

CO_2 emission factors and LHV are based on standardized Intergovernmental Panel on Climate Change (IPCC) values and technical specifications of fuel suppliers. CO_2 emissions from biomass are climate-neutral in terms of allowance accounting according to the EU ETS methodology. However, the physical amount of CO_2 released is explicitly stated in Table 1 for the sake of completeness of the environmental balance. Fuel prices (black coal, RDF, biomass) shown in Table 1 represent real historical market prices. Black coal prices in €.t^{-1} for 2019-2023 and the development of electricity prices are shown in Figure 1. Electricity prices were taken from Eurostat databases and from publicly available market indicators of wholesale electricity prices in EU.

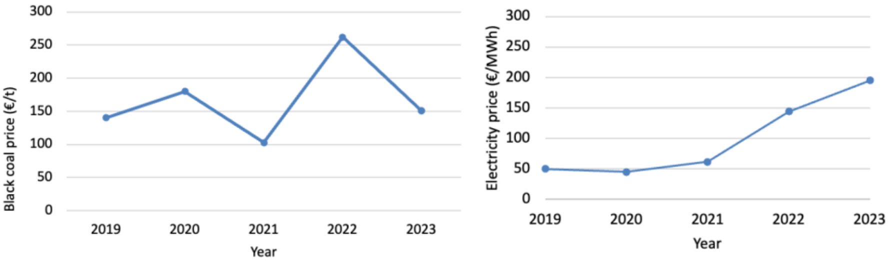

Figure 1

Black coal prices and electricity prices in 2019 – 2023 [28]

Several additives are consumed in the power production process: limestone ($CaCO_3$) and calcium hydroxide ($Ca(OH)_2$) for flue gas desulphurization and dechlorination during black coal and RDF combustion, and calcium oxide (CaO) for ash stabilization. Dosing of additives, their purchase price, and their contribution to power production costs are provided in Table 2.

Table 2
Dosing of additives and associated costs of power production of 55 MW

Additive	**Cost ($€.t^{-1}$)**	**Additive consumed ($t.h^{-1}$)**			**Additive costs ($€.MWh^{-1}$)**		
		A_1	**A_2**	**A_3**	**A_1**	**A_2**	**A_3**
$CaCO_3$*	50	2	0.50	1	1.81	0.45	0.91
$Ca(OH)_2$**	164	-	0.50	1	-	1.49	2.98
CaO	163	-	-	-	0.25	0.10	0.02
Total costs of additives dosed ($€.MWh^{-1}$)	-	-	-	-	2.06	2.04	3.91

*- relates to power produced from black coal and RDF
**- relates to power produced from RDF only

The costs of additives ($CaCO_3$, $Ca(OH)_2$, CaO) shown in Table 2 are based on real operating data of PPV for 2022. Consumption of additives was modelled linearly depending on the energy share of individual fuels. Uncertainties associated with the dosage and prices of additives are included in the total variable costs, which form the input of the DEA model.

PPV fuel mix alternatives considered in calculations are as follows:

Alternative 1 – Combination of black coal and biomass in fuel energy input ratio of 90:10 (PPV operation before 2019 as part of test operation).

Alternative 2 – PPV has been allowed by the Slovak Environmental Inspectorate (SIE) to use RDF in power production in August 2020 by a decree issued by the Ministry of the Environment of the Slovak Republic, following successful RDF co-combustion tests in 2019. This is reflected in the actual PPV operation, employing fuel mix of black coal, RDF, and biomass. Fuel energy input is divided between black coal (50%), RDF (33%), and biomass (17%).

Alternative 3 – Expected PPV operation with total black coal phase-out from fuel mix and RDF and biomass co-combustion in the fuel energy input ratio of 2:1, currently a theoretical alternative.

Data presented in Tables 1 and 2 were compiled based on corporate documents relating to PPV, fuel purchases, and technological parameters of the facility, with these values serving as basic input for economic and technical comparison of individual fuel scenarios and the subsequent assessment of their efficiency using DEA and sensitivity analysis.

3.2 Efficiency Evaluation and Sensitivity Analysis

Efficiency of the combustion process alternatives was assessed using the non-parametric DEA method, which allows comparing the relative efficiency of multiple Decision-Making Units (DMUs) while simultaneously considering multiple inputs and outputs. In this study, DMUs do not represent separate enterprises, but technological scenarios for the operation of a single production facility with a different fuel mix.

Three alternatives (DMUs) were considered in the analysis. Alternative 1 (DMU1) represents the historical operation of the power plant with a dominant share of black coal. Alternative 2 (DMU2) corresponds to real operation after co-firing of RDF and biomass is permitted. Alternative 3 (DMU3) represents a theoretical scenario of complete phasing out of black coal and its replacement with a combination of RDF and biomass.

An input-oriented CCR DEA model assuming constant returns to scale was applied as all alternatives use the same technology with comparable capacity and differ only in fuel structure. Input orientation reflects managerial control over fuel and operating costs, while electricity output is technologically constrained. Similar DEA-based approaches have been used to assess thermal power plant efficiency under environmental regulation in China [29] and within advanced two-stage DEA frameworks in Tunisia [30], highlighting the importance of efficiency improvements for sustainable and resilient energy systems.

The DEA model was solved using the optimization tool AtoZmath in the R program, which uses linear programming to calculate relative efficiency of individual DMUs. The model considered one aggregate input - total annual operating costs - and two outputs, which are annual electricity production and annual Cash Flow (CF).

Formally, the DEA model [31] is defined by an input and output matrix.

Input matrix, equation (1),

$$X = \left[x_{ij}\right], i = 1, \dots, m \;\; j = 1, \dots, n \tag{1}$$

contains individual inputs in rows (in this case, one aggregated input) and individual DMUs in columns.

Output matrix, equation (2),

$$Y = \left[y_{ij}\right], i = 1, \dots, s \;\; j = 1, \dots, n \tag{2}$$

contains individual outputs in rows and individual DMUs in columns. Each column of either matrices therefore represents one alternative of PPV.

Relative efficiency of the evaluated unit (DMUq) is determined by maximizing the objective function (f(x)), defined as the ratio of the weighted sum of outputs to the weighted sum of inputs:

$$\max f(x) = \frac{\sum_{i=1}^{s} u_i y_{iq}}{\sum_{j=1}^{m} v_j x_{jq}} \tag{3}$$

Function f(x) in equation (3) represents the objective function of the DEA model, the maximization of which determines the relative efficiency of the evaluated decision making unit with respect to other DMUs in the analyzed set.

Under these conditions, equations (4-6) are written as:

$$\frac{\sum_{i=1}^{s} u_i y_{ik}}{\sum_{j=1}^{m} v_j x_{jk}} \leq 1,\ \ k = 1, \ldots, n, \tag{4}$$

$$u_i \geq 0,\ \ i = 1, \ldots, s, \tag{5}$$

$$v_j \geq 0,\ \ j = 1, \ldots m. \tag{6}$$

Weights u_i and v_j are endogenously determined by the optimization solver to maximize the relative efficiency of the evaluated unit while maintaining the condition that the efficiency of DMUs in the set is below 1. Such formulated problem represents a linear programming optimisation problem, which can be converted into matrix form and solved using standard optimisation methods.

Figure 2 shows an illustrative example of the DEA efficient frontier for an input-oriented model.

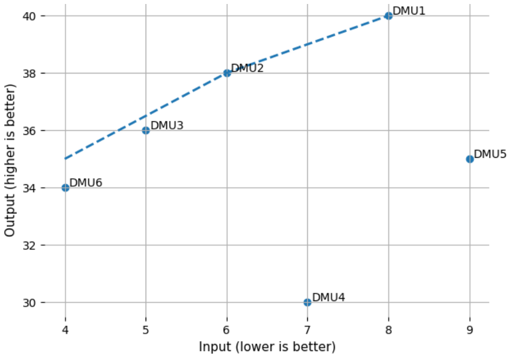

Figure 2
DEA efficient frontier example

The horizontal axis represents the level of input, with lower values indicating better performance, while the vertical axis represents the level of output, with higher values indicating higher performance. Individual points represent DMUs. The dashed efficient frontier represents the optimal value of the DEA objective function f(x), defined in equation (3), and is formed by the most efficient DMUs for which the value of this function reaches f(x)=1; maximization of the objective function f(x) thus determines the relative efficiency of individual units evaluated. DMU1 and DMU2 are located on the efficient frontier and are, therefore, considered efficient, while DMU3, DMU4, DMU5, and DMU6 lie below this frontier, indicating their relative inefficiency and the potential to reduce inputs while maintaining the level of outputs. Figure 3 provides a geometric interpretation of the optimisation problem defined by equation (3).

To complement the DEA efficiency assessment, a sensitivity analysis was conducted to evaluate the effect of changes in key economic inputs on the PPV CF. Using a deterministic one-at-a-time approach, individual variables were varied independently while other parameters remained constant, allowing clear identification of their partial effects. The analysis focused on electricity prices, variable operating costs, investment costs, and tax burden, each adjusted within a ±10 % range to reflect realistic short-term fluctuations and ensure comparability of impacts. The effect of changes in input parameters was evaluated through the relative change in CF, which represents the output variable of the sensitivity analysis. Graphical representation of the results was used to compare the significance of individual factors, while the direction and steepness of the curves express the nature and intensity of their impact on the economic results of the model.

Figure 3 schematically illustrates the conceptual framework of the sensitivity analysis applied in this study.

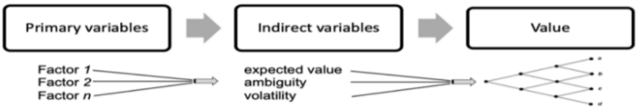

Figure 3

Sensitivity analysis method

In the first phase, key input variables are defined including the main economic and operational factors of the model, such as electricity price, variable operating costs, investment costs, and tax burden. These variables represent the primary sources of uncertainty in evaluating the economic performance of the PPV.

In the second phase, the input variables are transformed into indirect variables that reflect their expected values and variability. This step incorporates input uncertainty into the economic model without explicitly defining probability distribution.

In the final phase, these transformations lead to the resulting economic indicator, namely CF. Branches shown in Figure 5 illustrate alternative scenarios of CF development based on different combinations of changes in the input variables. The figure thus provides clear visual explanation of the effect of changes in key input parameters on the resulting economic outcome.

Sensitivity analysis was further used to verify the robustness of the chosen economic model and the stability of the obtained DEA results. Identification of parameters with dominant influence on CF provides a basis for assessing the risks associated with the power plant operation and for defining the conditions under which it may be necessary to adjust the operating mode or fuel mix.

To expand the analytical framework, deterministic CF scenario prediction based on a linear regression model estimated by the Ordinary Least Squares (OLS) method was applied. The regression model expresses the relationship between CF and selected economic variables, namely the Price of Electricity (P), Variable Costs (VC), and the quantum of electricity generated (Q).

Based on the estimated regression relationship, three development scenarios were defined – optimistic, reference and pessimistic – which differ in the assumed dynamics of key input parameters. The prediction was implemented in the form of gradual extrapolation of input variables in the period of 2024 – 2030 and the subsequent calculation of the expected CF value.

The linear regression model was defined in the form (equation (7)):

$$CF = \alpha + \beta_1 P + \beta_2 VC + \beta_3 Q + \varepsilon \tag{7}$$

The aim of the scenario prediction is not an accurate point forecast but an assessment of the direction and relative stability of the economic performance of the PPV under different market and operating conditions.

To illustrate possible future development of the economic performance of the PPV, a CF prediction was prepared for the optimistic, reference, and pessimistic scenarios based on the regression model and scenario assumptions.

4 Results

Energy efficiency evaluation in Sustainable Development (SD) increases and the DEA method has become an important and commonly used analytical tool to evaluate overall efficiency of used and analyzed factors. Here, DEA and sensitivity analysis are applied in the assessment of energy efficiency and identification of factors at the enterprise level.

4.1 Effectiveness of Combustion Process Management

An effective process (Table 3) with focus on sustainable performance was identified. This means that there is a set of options for biofuel combustion to select the most suitable alternatives according to the regional context.

Table 3

Efficiency of combustion process alternatives

No.	Score	Rank	Slack v1	Slack u1	Slack u2
DMU1	0.3049	3	0	0	48680392.1663
DMU2	0.4721	2	0	0	3073727.8593
DMU3	1	1	0	0	0

Slack v and u represent the potential improvement in input and output parameters for inefficient units compared to their comparably efficient final reference goals. DMU1 cannot reach the efficiency limit (efficient aim), gaps are given on Slack u2 to shift DMU to the efficient limit (aim), the same is true for DMU2. The most efficient model is DMU3 with the highest efficiency score based on RDF. Of the remaining carbon sources, the results match the recent trend of promoting the use of cellulosic materials. In terms of fuel type, our results suggest that widespread adoption of renewable biomass sources should be prioritized over traditional black coal combustion.

These analyses also provide targets for the improvement of inefficient biofuels, which mainly affect the process outputs in the form of profit (Slack u2). Thus, it is necessary to focus on the possibilities of acquiring these resources while preserving the principle of sustainability, even though resource acquisition is considered a key in the calculation of operating costs depending on the type of biomass and region. For combustion efficiency in PPV, transport of RDF over long distances must be considered.

4.2 Sensitivity Analysis

Subsequently, sensitivity analysis of CF to the change in electricity prices was performed (Figure 4) to provide guidance for further data collection and modelling. The required investment and feedstock purchase and processing costs are crucial factors determining the feasibility of power production from renewable sources.

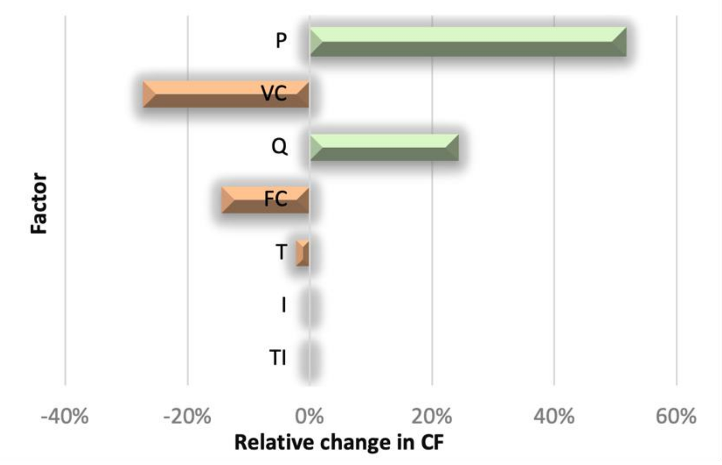

Figure 4
Influence of factors on CF

Then, a sensitivity analysis of the impact of changes in selected economic factors on the CF value of the PPV power plant was performed (Figure 4). The analysis provides a basis for identification of crucial input parameters with the greatest effect on the economic performance and sustainability of the operation.

The most significant factor is P, with a 10% increase leading to an increase of approximately 52% in CF. The second most significant factor is VC, with a 10% increase leading to a decrease of approximately 27% in CF. Parameter Q, which represents the quantum of electricity produced and delivered, also has a significant impact. A change in this parameter by 10% leads to a change of approximately 25%` in CF, which reflects the sensitivity of the economic result to changes in production caused by operational or market constraints. Parameter Q was,therefore, included in the sensitivity analysis and subsequently used in further assessment to link the technical and economic aspects of the PPV operation.

Conversely, factors such as Tax (T), Investments (I), and Time (TI) show only a marginal impact on the CF value. Their relatively low sensitivity suggests that an inaccuracy in their estimate has only limited effect on the overall economic evaluation of the operation.

The rising straight line reveals the factor causing an increase in CF (P, Q). The decreasing straight line (VC) means that an increase in the factor causes a decrease in the CF value. The steeper the slope of the line, the more significant the factor (Figure 5).

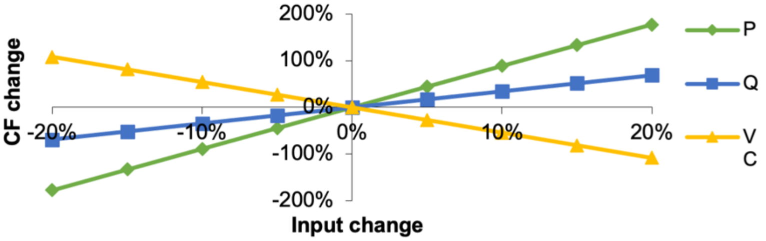

Figure 5

Influence of relative change of the most significant input parameters on CF

Supporting policies, including taxation reduction and investment stimulation schemes, contribute to the development of renewable power production infrastructure and the related supply chains [32]. Feedstock availability, its variability, and power plant location should be considered, among other factors, in the determination of the most feasible project eligible for subsidy. Uncertainties related to the feedstock supply chain should be assessed in a related feasibility study [33].

The estimated CF of PPV is based on the amount of electricity consumption in the Slovak Republic, economic prediction of energy intensity development, and the use of primary energy sources in compliance with the decarbonization goals according to the Integrated National Energy and Climate Plan (INECP) of the Slovak

Republic. This change in CF due to electricity price change over time is shown in Figure 6.

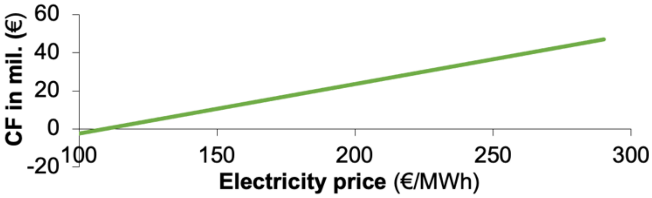

Figure 6
Associated change in CF due to electricity price change over time

However, considering future operating costs, profitability will be significantly reduced, and highly negative CF is to be expected in the last years of the power plant's life. From the point of view of PPV, ensuring stable income and transferring a part of the risk arising from the electricity price volatility and uncertain prices of emission allowances in the future must be considered.

5 Discussion

A hypothesis was formulated: *There is an assumption that V4 potential for alternative feedstock production allows transformation of several coal power plants in the region to multi-fuel power sources.* Its confirmation or rejection is based on the current knowledge and legislation of the V4 countries and their capacities for Municipal Waste (MW) energy recovery.

Slovakia will not avoid higher rate of energy recovery of waste, also in connection with the legislation. The Ministry of Environment of the Slovak Republic has adopted the obligation to landfill only the output from the treatment of mixed MW and bulky waste if its calorific value in dry matter does not exceed the value of 6.5 MJ/kg from January 1st, 2027 [34].

Table 4
Energy recovery and combustion of MW in V4 countries in t [35]

Country	**Existing capacities for energy recovery of waste**	**Prepared capacities for energy recovery of waste**
Slovak Republic	635,000	530,000
Czech Republic	1,165,000	941,000
Hungary	2,190,000	0
Poland	2,974,000	1,015,000
Total V4	**6,964,000**	**2,486,000**

With the current capacities of waste-to-energy facilities, a significant part of waste is imported to Slovakia for the purpose of its recovery using various methods, including energy recovery. More than 702 thousand t of waste were imported to Slovakia in 2020 mainly from Austria, Italy, and Germany. At the same time, projects for energy recovery from waste are prepared in the region. Their capacity of 2.5 million tons (Table 4) is comparable to the possible increase in RDF production (almost 2.1 million t) [35].

It is likely that these facilities, once completed, will represent significant competition to the use of RDF by co-firing in existing coal-fired power plants in the region. However, Hungary is not preparing new capacities as it plans to use its existing capacities or to prioritize its own sources of waste within the framework of Circular Economy (CE), and thus minimize waste import. Circular systems inherently depend on the collaborative efforts of all parties involved in products' life cycle, including businesses, consumers, and governments [36, 37].

Implemented scenario prediction of CF development is shown in Figure 7.

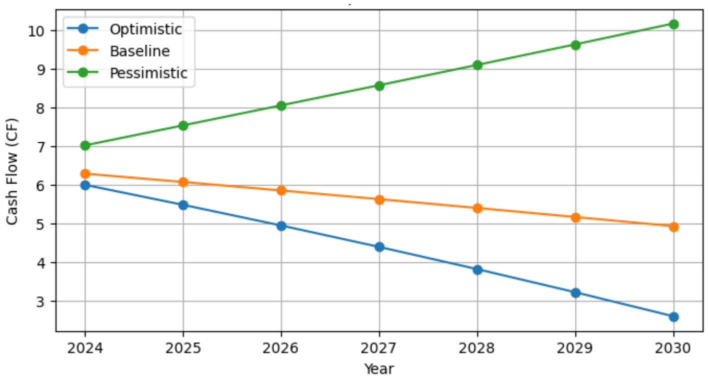

Figure 7

Scenario-based prediction of CF in mil. €/year

Conclusion: The hypothesis was not confirmed, and its rejection can be stated. The identified possibility of increasing RDF production in the V4 region at the level of over 2 million tons (35 to 44 mil. GJ/year) can replace black coal for one medium 250 to 300 MW power plant unit with 30 to 35% net electric efficiency (corresponding to fuel energy consumption of around 30 mil. GJ/year), or partially replace black coal for several power units in the co-combustion mode. This represents only a fraction of the installed capacity of coal-fired power plants in the V4 countries. Existing and planned capacities for energy recovery of waste will compete with such RDF use.

Scenario analysis has confirmed that CF is highly sensitive to P and VC. Scenario comparison shows that long-term economic performance is driven mainly by external price signals and fuel mix structure rather than short-term operational adjustments. The reference scenario indicates gradual decline in economic performance, reflecting rising environmental costs and limited flexibility of carbon-based operations, which is consistent with the DEA results. In contrast, the favorable scenario with higher share of RDF and more stable electricity prices provided positive medium-term results, highlighting the economic resilience of low-carbon and waste-based fuels. The negative scenario demonstrates the vulnerability of carbon-intensive models under adverse price and emission cost developments, which explains why DEA favors alternatives with lower emission intensity under regulatory pressure (EU ETS).

From the perspective of policy-making and strategic management of energy companies, Figure 8 clearly demonstrates that the transition to a diversified fuel mix is not just a reaction to regulatory requirements, but a rational response to changing economic conditions. The scenario prediction thus provides an argumentative bridge between the quantitative DEA results and the broader context of energy transformation, strengthening the interpretative and applied value of the work.

Considering regional context of the V4 countries, the results indicate that the identified potential for RDF production and waste-to-energy recovery creates the prerequisites for partial transformation of existing coal capacities. Although this potential does not enable a blanket replacement of coal in all power plants, it provides sufficient basis for the conversion of selected facilities to a multi-fuel regime, especially in countries with lower rate of waste-to-energy use. The methods used thus jointly support the hypothesis that the potential of the V4 region allows for the transformation of a part of coal-fired power plants into flexible multi-fuel energy sources, while the extent of this transformation is conditioned by regional differences.

This development is consistent with the results of the sensitivity analysis and supports the conclusions of the DEA model, which favors fuel alternatives with lower cost and emission burdens.

Conclusions

The results show that combining DEA, sensitivity, and scenario analysis enables robust assessment of the transformation potential of coal-fired power plants in the V4 countries. The analysis confirms that economic viability is increasingly shifting toward fuel mixes with lower carbon intensity and higher share of alternative fuels.

Multi-fuel configurations based on RDF and biomass achieve more efficient cost-to-output conversion and demonstrate higher resilience to the volatility of electricity price and increasing emission costs than the coal-based alternatives. DEA results indicate that the inefficiency of coal-oriented options stems mainly from their limited ability to generate CF, rather than from excessive inputs, highlighting a structural disadvantage of carbon-intensive fuel mixes.

The EU ETS significantly reinforces this disadvantage by increasing VC and reducing CF, a finding consistent with sensitivity and scenario analyses which identify electricity prices and emission costs as dominant long-term drivers of economic performance. While reference and pessimistic scenarios signal declining sustainability of coal-based operations, optimistic scenarios with higher RDF shares remain economically viable in the medium term.

For V4 countries, the results suggest that the transformation potential of coal-fired power plants is not primarily constrained by technical limitations but rather by the availability of alternative fuels, regional waste management capacities, and differences in regulatory and market conditions. Although the findings are based on a single case study, the analyzed power plant is technologically representative of coal-based facilities operating under similar market and policy frameworks across the V4 region. The results therefore provide transferable insights into how fuel diversification, electricity price signals, and emission pricing jointly shape the economic feasibility of transition to multi-fuel and low-carbon configurations.

If 4,220,000 tons of MW (16.73%) were energetically processed within V4 in 2020, there were 4,220,000 tons of MW (16.73%), this amount should increase by another 2,087 thousand tons in future, which represents a replacement of more than 1 mil. ton of black coal and reduction of CO_2 production from burning black coal by more than 2.2 million tons producing approximately 2 mil. MWh of electricity. Among the V4 countries, Slovakia has the greatest potential, as only 7.95% of MW was processed to energy in 2020 [38].

Since 2019, the PPV has been using a combination of three fuels, including hard coal, biomass, and RDF. In the next period, gradual reduction of hard coal and a larger share of RDF and waste biomass are considered, which also requires technological adjustments. This fuel change had a positive economic impact on the PPV in the form of purchasing cheaper fuels and savings on CO_2 charges.

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