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Carbon Capture and Storage (CCS) Implementation as a Method of Reducing Emissions from Coal Thermal Power Plants in Poland

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Abstract: The Polish economy, and especially the energy sector, is facing an energy transformation. For decades, most electricity in Poland has been generated from hard coal, but in recent years, renewable energy sources have been gaining an increasing share of the market. The aim of the energy transformation is to reduce the carbon footprint in electricity production, which translates into the decarbonization of the economy, including manufactured products. Currently (2024), increasing the share of renewable energy sources raises major challenges in terms of energy storage or other activities and forces cooperation with flexible sources of electricity generation. One of the challenges is to determine what a decarbonized energy mix in Poland could look like in 2050, in which there would be sources (with a smaller share of coal sources in the mix than currently) of electricity generation based on hard coal with CCS technology. In order to do this in an economically efficient manner, there are aspects related to the location of power plants that would remain in operation or repower current generating units. The added value of the study is the simulation approach to the analysis of the problem of assessing the effectiveness of CCS technology implementation together with the transport and storage infrastructure, as well as the multi-aspect scenario analysis, which can determine the limits of CCS technology effectiveness for a given power unit. Positive simulation results (NPV amounted to 147 million Euro) and the knowledge obtained in the scope of the correlated and simultaneous impact of many important cost factors and prices of CO_2 emission allowances make this analysis and its results close to reality. Examples of analyses of the effectiveness of CCS system implementations known from the literature are most often limited to determining linear relationships of single explanatory variables with a specific forecasted variable, even if these are multifactor mathematical models.

Keywords: CO_2 reduction emission; CCS; CCUS; coal thermal power plant; optimization; Poland

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1. Introduction

1.1. Energy Transformation

The current energy mix in Poland is dominated by the volume of hard coal and brown coal power plants. The increase in the share of renewable energy sources is related to issues regarding the significant increase in energy production from stable sources (water, biogas, biomass) and weather-dependent fuel-saver sources (photovoltaic and wind energy) [1]. Plans for the energy mix are evolving in Poland, with new updates increasing the future share of low-emission sources [2,3]. In this respect, Wojtaszek et al. [4] conducted a comparative analysis of Poland and Germany for challenges (resignation from electricity generation from coal-fired power plants) and changes in energy policy with particular emphasis on the perspective of 2050. Wierzbowski et al. [5] also analyzed the Polish energy policy from the same time perspective, in which coal-fired power plants currently play the main role. There are plans for the development of small and large nuclear power as well as storage of electrical energy within the framework of the policies [6]; the former is relatively expensive considering the investment outlays, and the latter is not economically viable for now [7], and we are extracting less and less coal and at higher operating costs [8]. Currently (2024), there are plans to eliminate or significantly reduce hard coal production in Poland [9]. Some researchers see a partial analogy to the energy problems (present and past) of Finland, which already has a nuclear power plant [10].

Nyga-Łukaszewska et al. [11] analyzed the cointegration of the hard coal and natural gas markets in the period from 2011 to early 2019. The main conclusion from the analyses was that the Polish power industry is more closely linked to the international coal market than to the natural gas market, while for heating the relationships are reversed. Lorenc et al. [12] used a research method based on statistical analysis, including mainly the analysis of the correlation between the prices of shares of the dominant company (from the coal mining and other areas) and the prices of shares, e.g., a company separated from existing structures. The above aspects are related to new challenges faced by energy companies, such as sustainable development and circular economy.

Pluta et al. [13] analyzed various scenarios of changes in the energy mix from the perspective of 2050, with particular emphasis on the possibility of achieving a 95% reduction in CO_2 emissions while maintaining energy security (mainly as certainty of energy supply). The subject of energy security and its impact on the shaping of generation capacity in Poland was also discussed in the following works [14,15].

Progress in the field of CO_2 capture and utilization methods has been noticeable for many years [16]. Its main barrier to development in the EU was the high level of investment outlays and operating costs compared to the level of CO_2 emission fees, the so-called ETS, or compared to alternative investments in sources with lower emission coefficients calculated per unit of generated electricity [17–21]. Economic barriers are not the only type of factors influencing this technology; issues related to legal requirements for countries and life cycle assessment (LCA) analyses of electricity production are of great importance [22]. Moreover, there are still issues of infrastructure, investment, and the use of electricity in other areas as well [23]. Additionally, some countries see sources of competitive advantages in the economic field in decarbonization issues.

Bui et al. analyzed various industries, particularly in the context of the development of renewable energy technologies. They also examined different CO_2 capture and storage methods [24]. Wang et al. investigated the use of Convolutional Neural Networks to evaluate combustion technologies, including their efficiency [25].

The main novelty lies in the methodology for selecting existing power plants suitable for adding carbon capture and storage (CCS) technology. This approach considers multiple parameters, including Monte Carlo simulations, to assess potential sites. For traditional thermal power plants, key factors include proximity to thermal coal supplies (i.e., transportation distance) and access to the electricity grid. However, in the context of CCS, additional considerations, such as the distance for CO_2 transport and the associated costs, are also crucial.

1.2. Energy Mix in Poland Currently and in 2050

In the coming years, the departure from coal in Poland will involve repowering or new locations for coal thermal power plants. In the context of capacity market requirements, carbon production footprints, and fees for CO_2 emissions into the atmosphere, companies whose operations are associated with a high level of carbon footprint are facing new challenges.

An analysis of the impact of potential changes in the price ratio of domestic and imported coal and their impact on the volume of coal imports to Poland was carried out by Kamiński et al. [26]. In contrast, a mathematical model using thirteen scenarios of the price ratio was developed by [27].

Repowering old coal units to gas or nuclear, but also CCS, provides the possibility of expanding the range of possibilities for coal thermal power plants. In each of these possibilities, due to, among others, the uneven demand for energy in the system (taking into account energy production from renewable energy sources, the so-called Duck curve), a thermal energy storage installation with a capacity of 200–1200 MWh was analyzed by Bartela et al. [28]. Hard coal mining in Poland is not only about economics, business, and energy but also government, climate, and social policy, including adapting to plans [29]. On the other hand, the development of nuclear energy and hydrogen is planned. The idea of switching new electricity generation units to natural gas is questionable due to prices, availability, and issues related to energy security. One solution is to introduce a mixture of natural gas and hydrogen into the gas network, which, thanks to zero-emission hydrogen production, reduces the total carbon footprint [30].

One of the methods of CO_2 management is the production of synthetic methane from CO_2 obtained from exhaust gases using amine scrubbing and hydrogen from renewable sources. This was conducted, among others, in an experimental installation in a power plant located in Łaziska Górne [31]. However, since 2013, experiments were carried out in this area in which the achieved efficiency of CO_2 separation was above 85%, and energy demand was 4.8–7.5 MJ/kg CO_2 [32].

The share of electricity production from hard coal is decreasing year by year (Figure 1). Additionally, the plans for changes in the production structure in the energy sector, as well as in the mining sector, are important because they indicate the disappearance of the share of the above-mentioned carrier in the future energy mix in Poland. The location of the main coal thermal power plant unit in Poland is presented in Figure 2.

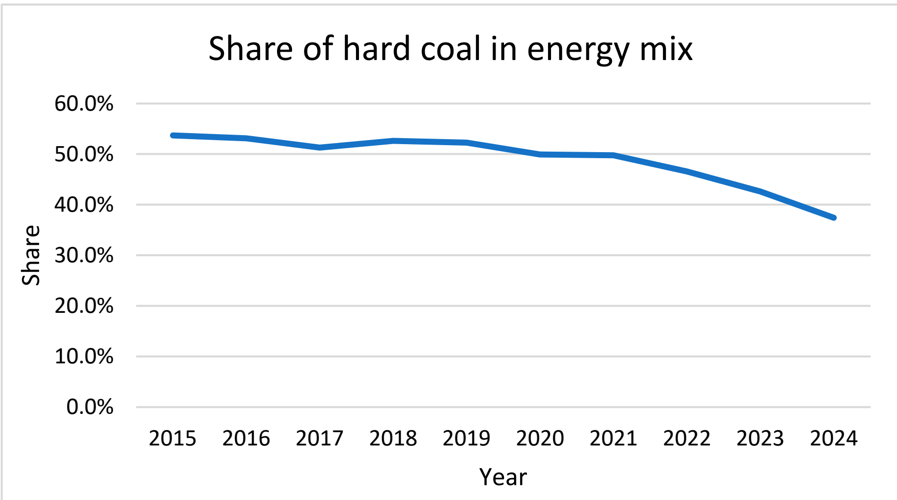


Figure 1. Share of energy from coal thermal power plants in the energy mix in Poland from 2015 to June 2024. Source: own study based on [33].

The scientific value of the publication is the simulation approach to the analysis of the problem of assessing the effectiveness of CCS technology implementation together with the transport and storage infrastructure and the multi-aspect scenario analysis, which determines the limits of CCS technology efficiency for a given power unit capacity. Positive simulation results and the knowledge obtained in the field of correlated and simultaneous impact of many important cost factors and CO_2 emission allowance prices make this analysis valuable and its results reliable. Examples of analyses of the effectiveness of CCS implementations known from the literature are most often limited to determining linear relationships between single decision variables and a specific forecasted output, even if these are multifactorial mathematical models.

Figure 2. Location of coal thermal power plants (only power plants with a capacity higher than 900 MW) in Poland. Source: own study based on [33–35].

2. Calculation Methods

A proprietary methodology for the effectiveness of CCS technology implementation for coal-fired power units was developed. The CCS system assumes the construction of a carbon dioxide capture installation, the transport and storage of CO_2, and the monitoring of the facility for the next 30 years after the end of storage. In order to apply it, the data necessary for the analyses were selected.

2.1. Data for Calculations

Over the past dozen or so years, the prices of hard coal for energy have been lower than the prices of natural gas per 1 MWh of energy. Exceptionally, there were short periods when the prices of hard coal for energy were higher than the prices of natural gas: at the beginning of 2020 and 2023. The detailed price profile is marked in Figure 3a for 2023, and half of 2024 is shown in Figure 3b.

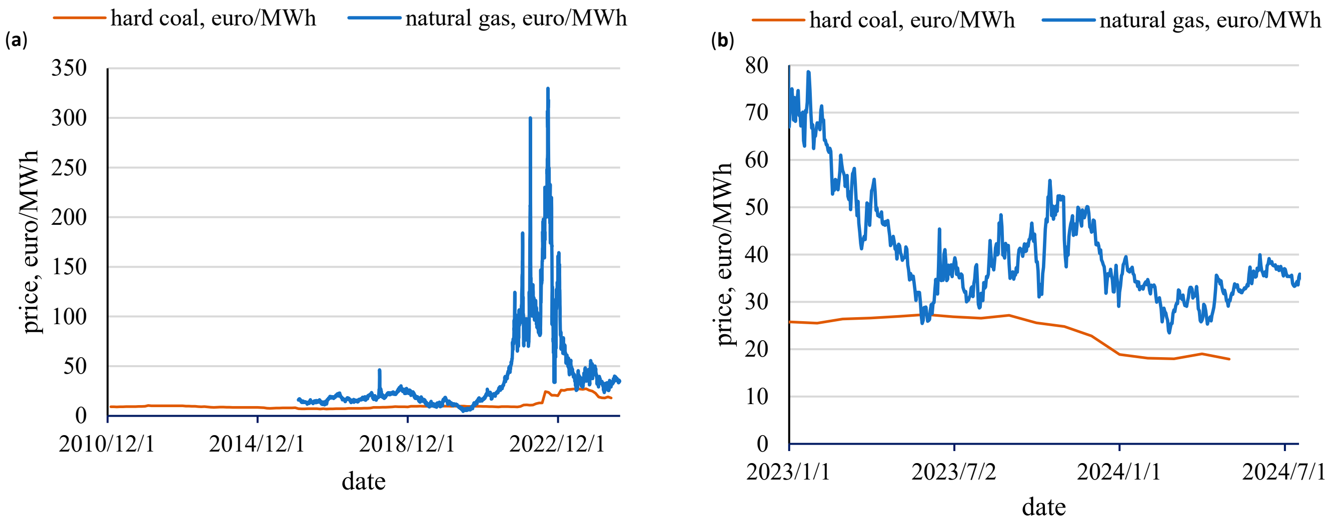


Figure 3. (**a**) Hard coal (2010–2024) and natural gas (2015–2024) prices per 1 MWh. (**b**) Hard coal and natural gas prices per 1 MWh. Values from (**a**) reduced to a range of 2023–2024. Source: own study based on [36].

Historic record prices of natural gas occurred in 2022 (330 Euro/MWh), contributing to the increase in electricity prices and inflation in many economies, including Poland. The increase in electricity prices was caused, among other things, by the fact that gas power plants operated as one of the peak sources (merit order principle [37]) for electricity production. Additionally, much higher price fluctuations are noticeable for natural gas (on world exchanges) than for hard coal. Prices of hard coal also achieved records in 2022.

Since the beginning of 2023, the price of natural gas has been on a downward trend (from 72 to 35 Euro/MWh), except for the period from August to October 2023. The prices of thermal hard coal have also shown a downward trend from around 27 to 19 Euro/MWh. The prices of thermal hard coal against the background of the prices of CO_2 emission allowances are presented in Figure 4.

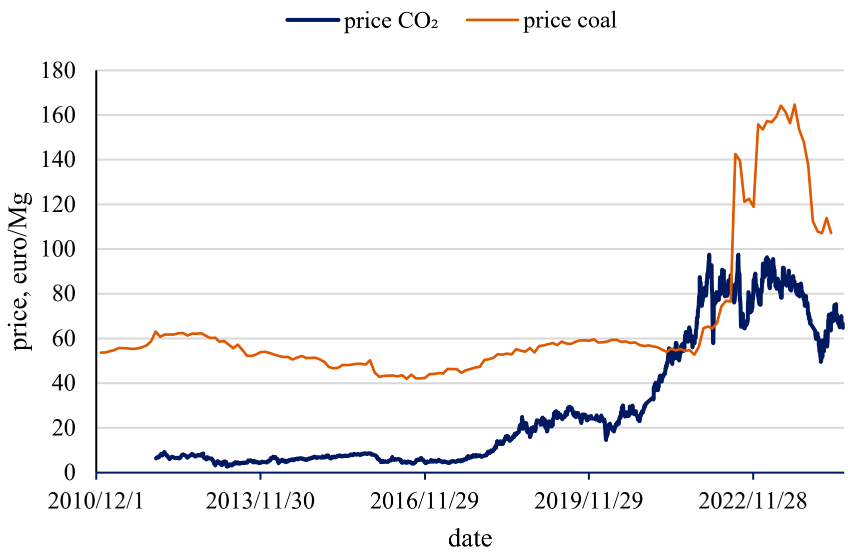


Figure 4. Hard coal and CO_2 emission prices per 1 Mg. Data for the period: 2010–2024. Source: own study based on [38–40].

Electricity prices are presented in Figure 5.

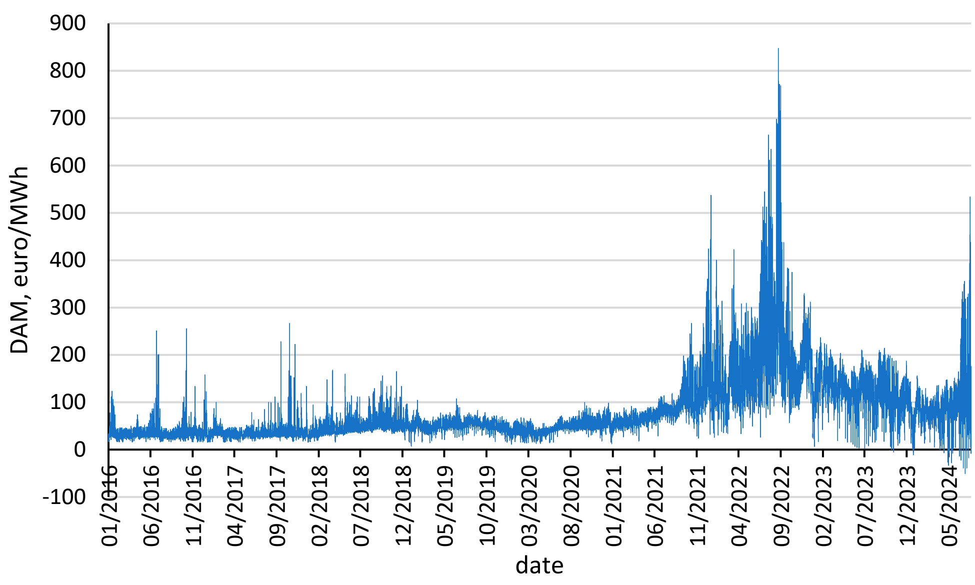


Figure 5. Day-Ahead Market (DAM) electricity price in Poland from 2016–June 2024. Source: own study based on TGE data [41].

In a study prepared by the IISD organization [42,43], the costs for carbon dioxide capture and storage in Canadian conditions were indicated, depending on the concentration of CO_2 in the stream from which capture is to take place. These values range from 27 to over 150 CAD per ton of CO_2 (Figure 6). Additionally, considering the learning curve [44] in this technology, the decreases in cost over the years do not change significantly without clear support; e.g., with subsidies, it is difficult to obtain profitability at least at a minimal level [43].

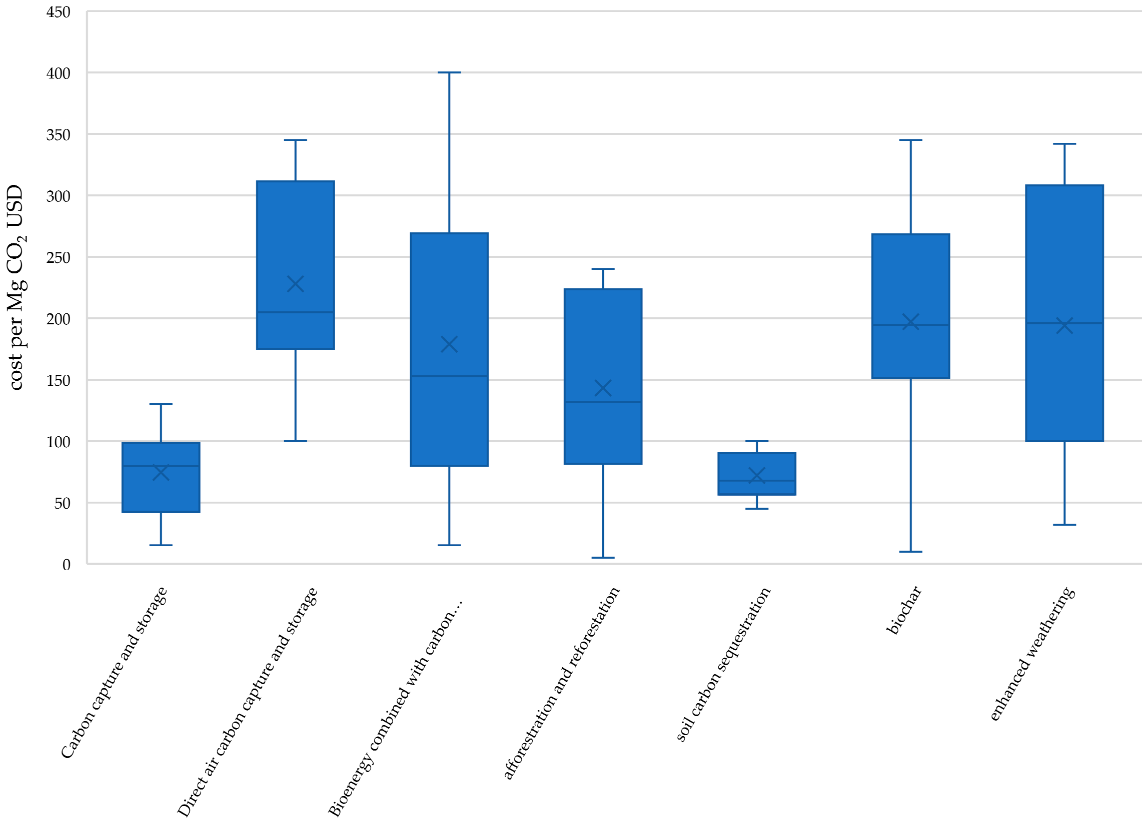


Figure 6. Unit cost values for CO_2 technology components. Source: own study based on [42].

2.2. Methodology

2.2.1. Research (Decision) Problem

The key research problem concerns the resolution of the prospects for the operation of coal-fired power units (plants) in Poland by selecting the optimal strategy for further operation. This strategy assumes an assessment of the justification for the following:

- operation in the current technological and business model, i.e., burning coal until the technical capacity of the units and paying for CO_2 emissions according to market prices, and
- expansion of existing power units with CCS systems.

2.2.2. Approach to Analysis

The research was conducted using a scenario approach.

The adopted decisive criterion is the difference between the differential financial flows for both scenarios of the operation of a model power unit (power plant) with a nominal capacity of approximately 200 MW of electric power. The expansion scenario of the power unit assumes the following:

- the addition of a carbon dioxide capture system,
- transport infrastructure for compressed CO_2,

- construction of an installation for injecting CO_2 into the rock mass (saline structures), and subsequent monitoring during the period of operation and 30 years after the mine is liquidated.

2.2.3. Simulation Model

In the analysis, we assume that all calculations will be performed using an original model of economic efficiency assessment based on Monte Carlo simulation techniques. The model allows for estimating total net cash effects measured as differences in cash flows of Scenario 2 and Scenario 1 in a differential approach regarding variations in production scale and availability of CCS. In particular, the cash flow structure includes costs/expenses related to the following:

- coal transport,
- construction of a CO_2 capture installation (CCS unit) at the power plant,
- processes of carbon dioxide capture, transport, and storage,
- distance for coal deliveries and carbon dioxide injection,
- construction of infrastructure for carbon dioxide transport (pipelines) and injection in salt caverns, and
- cavern decommissioning and storage site monitoring for the next 30 years.
- The idea of the analysis is presented in Figure 7.

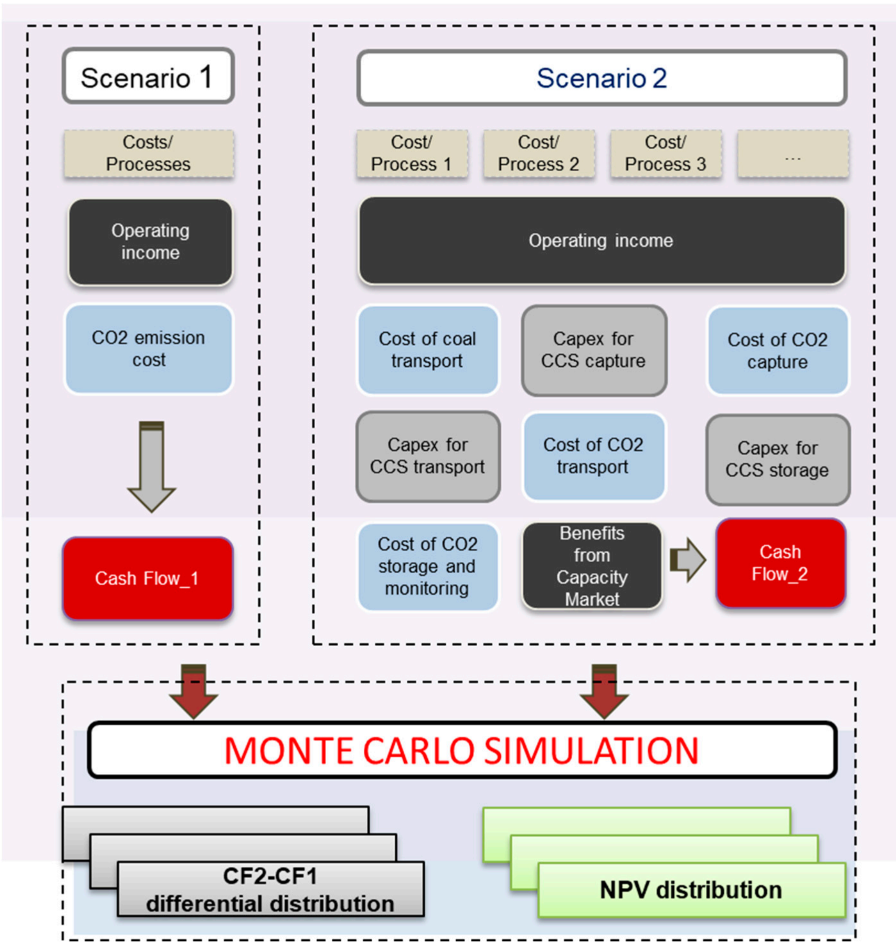


Figure 7. Income and cost components for the analyzed scenarios in the simulation model. Source: own study.

The key performance measures were as follows:

- averaged (annualized) difference in the cash flow of both scenarios: CF_1 and CF_2 for 25 consecutive periods, and
- the net present value (NPV), understood as the sum of 25 annual differences in the cash flow of individual scenarios: $\sum_{ij=0}^{25}(CF1\_i; CF2\_j)$.

These variables were marked as forecasted (outputs) in the developed simulation model. The principle of interpretation of the results was as follows:

- if the average updated difference was positive, the NPV was also positive, and
- an NPV greater than 0 indicated the advantage (higher value) of Scenario 2, i.e., the model of the power plant with a CCS unit and transport infrastructure and storage.

As you can see in the attached diagram (Figure 7), we did not analyze the variables that cancel each other out in both scenarios. As an example, we can give the price of coal and the amount of coal purchased to be burned, or the costs associated with the construction of a power unit. In turn, the key uncertain decision variables in the simulation model were as follows:

- productivity of the power unit with and without CCS infrastructure (P),
- unit cost of coal transport (uCCT),
- unit cost of carbon dioxide capture (uCC_CO2)
- length of the pipeline transporting CO_2 (dP),
- unit cost of electricity (Ep),
- unit cost of CO_2 transport (uCT_CO2),
- market prices of CO_2 emission allowances (Mp_CO2),
- unit costs of CO_2 storage and monitoring (uCS_CO2).

For all the above variables, individual distributions were established as follows:

- P: triangular distribution (min: 2500; mean: 6000; max: 7800) [h/year],
- uCCT: triangular distribution (min: 0.2; mean: 0.3; max: 0.4) [Euro/Mg],
- uCC_CO2: triangular distribution (min: 1; mean: 1.2; max: 2) [Euro/Mg CO_2],
- dP: triangular distribution (min: 50; mean: 250; max: 400) [km],
- Ep: Pearson5 distribution ((α = 6.39; β = 688.8) [Euro/MWh],
- uCT_CO2: triangular distribution (min: 0.05; mean: 0.07; max: 0.08) [Euro/Mg CO_2],
- Mp_CO2: GLlogistic distribution: (α = 90; β = 9; γ = 0.85) [Euro/Mg CO_2],
- uCS_CO2: triangular distribution (min: 6; average: 8; max: 10) [Euro/Mg CO_2].

The selection of triangular distributions was motivated by the literature [45–47]. In particular, when constructing the productivity distribution (P), it was assumed that the power plant with a CCS system would operate with the expected productivity of around 6000 h/y (currently, some coal-fired blocks previously reported to the Capacity Market operate at 25–35% of their nominal power). The availability of a CCS system will enable such an installation to be reported to the auction system in the future (currently, high-emission coal-fired units can no longer be reported to the Capacity Market auctions). We also assumed that the CO_2 pipeline system would be carried out over a maximum distance of 350 km, and electricity needed for CO_2 capture, transport, and storage processes would come from the installation's own production, resulting in reduced sales on the market.

The distribution of market prices of CO_2 emission allowances was considered to be crucial, with a strong impact on the results of the analysis. The following steps were taken in its construction:

- historical prices since 2012 were analyzed,
- a representative period was selected, and
- for CO_2 emission prices above 40 Euro/Mg, the parameters of the best-fit distribution were estimated based on empirical data, then the GLlogistic distribution was selected (Figure 8a) and modified for expected values in the future (Figure 8b).

The idea of the modification was to correct the probability density function of the distribution to achieve the expected (average) value close to 90 Euro/Mg and to have most of the sampled values in the range of 40–130 Euro/Mg, with a probability close to 1. We believed that there is a relatively small probability that CO_2 allowance prices would fall below 40 Euro/Mg or exceed 120 Euro/Mg—the functionality of the ETS system at these price levels seems to meet its objectives.

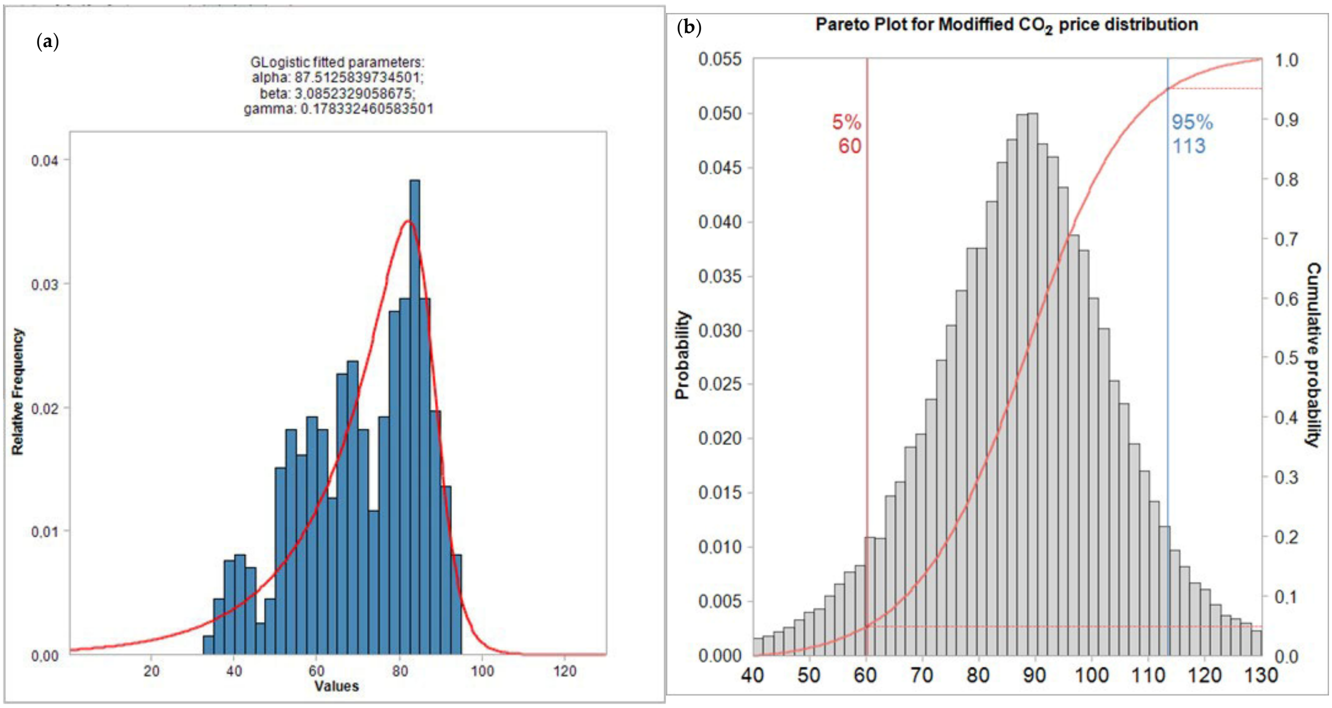


Figure 8. (**a**) Original distribution for the price of CO_2 allowances [Euro/Mg]. (**b**) Modified distribution [Euro/Mg]. Source: own study.

To reflect the differences in energy consumption for a CCS unit, based on [47], we assumed that electricity for self-consumption for a CCS unit would reduce 29% of the total electricity production of the power block. The amount of operating income was a product of market electricity prices and electricity output (production). For modeling electricity prices, we analyzed historical data of electricity from Towarowa Giełda Energii (TGE) in the same period as for CO_2 allowances (2001–July 2024), and then we chose the Pearson5 distribution as the best fit (Figure 9a). We decided not to correct this distribution, allowing for price shocks in the future. The average difference between power units without and with a CCS unit equals 240 MEuro per year with respect to selected electricity distribution.

In order to obtain a relatively correct picture of reality and the relationships between uncertain variables included in the distributions, the following rules were introduced to the sampling procedures:

- with high productivity, the investor will be more willing to pay higher fees for CO_2 transport over longer distances (high probability, strength: 0.5–0.7),
- higher prices of CO_2 emission allowances will result in higher electricity prices (high probability, strength: 0.55),
- higher productivity of the power unit and CCS installation will positively influence the costs of carbon dioxide capture (high probability, strength: 0.7),
- a larger tonnage of delivered coal and received CO_2 will cause the pressure to reduce unit prices in transport (medium and high probability, strength: 0.7–0.8), and
- high prices of CO_2 emission allowances may lead to potentially higher profits from CCS, and thus an increase in pressure on the prices of materials and components, services, and remuneration in this process (low and medium probability, strength: 0.3–0.5).

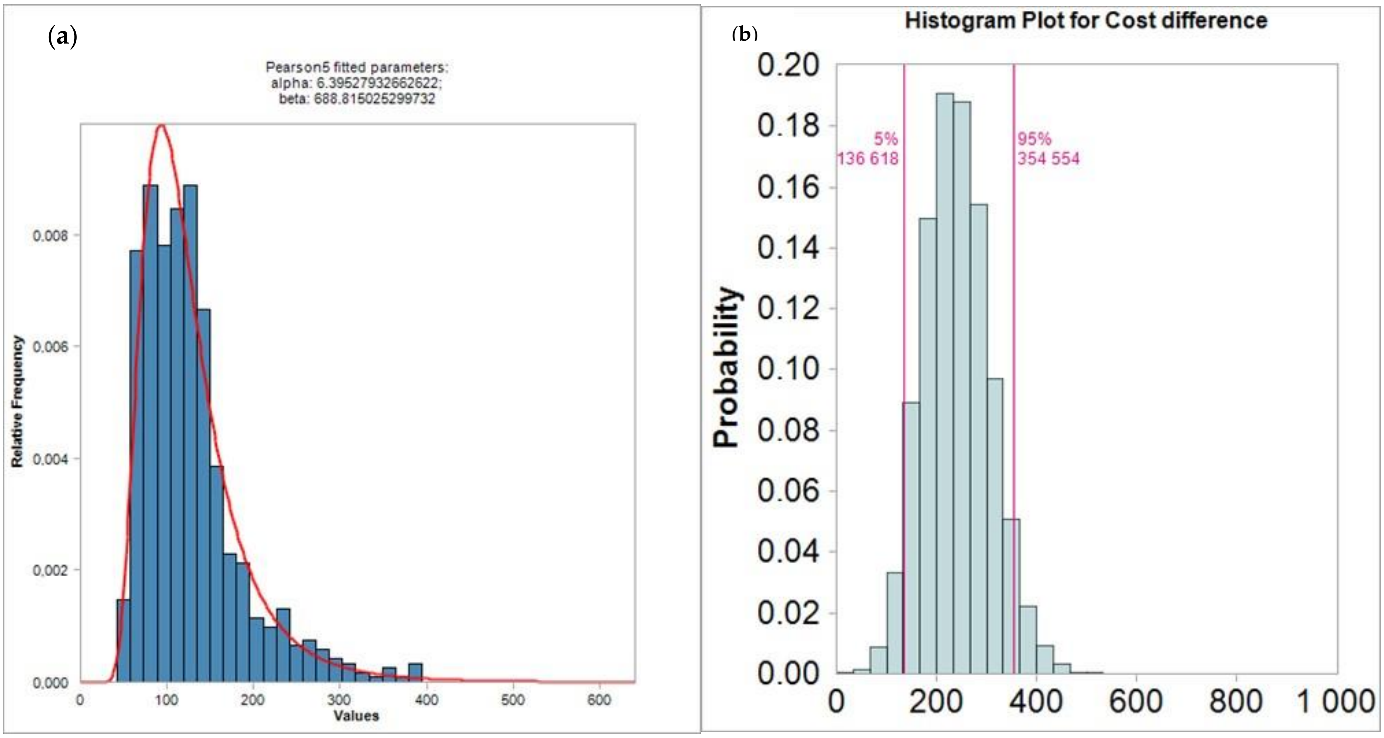


Figure 9. (**a**) Best-fit distribution of electricity price [Euro/MWh]. (**b**) The distribution of income differences between power units without and with a CCS unit [MEuro/year]. Red line in the left chart–fitted distribution curve (Pearson5). Source: own study.

These dependencies in the form of a correlation matrix were entered into the simulation model. The model was recalculated for 10,000 iterations, and then the distributions of the forecasted (output) variables and their descriptive statistics were generated. The calculation model, with the most important items, is presented in Table 1. The values presented in the individual cells are randomly selected in the Monte Carlo simulation.

Table 1. Visualization of the calculation model (spreadsheet)—exemplary numbers. Source: own study.

Years of Analysis	Unit	Sum of 1–25	0	1	2	3	…	23	24	25
Coal consumption	mln Mg/y		1.7	1.7	1.7	1.7	…	1.7	1.7	1.7
Coal LHV (coal calorific value) [48]	MJ/kg		21.0	21.0	21.0	21.0	…	21.0	21.0	21.0
Nominal power	MW		600.0	600.0	600.0	600.0	…	600.0	600.0	600.0
Efficiency	%		40%	40%	40%	40%	…	40%	40%	40%
Productivity	h/y		4381.2	4381.2	4381.2	4381.2	…	4381.2	4381.2	4381.2
Productivity (incl. CCS consumption)	h/y		3285.9	3285.9	3285.9	3285.9	…	3285.9	3285.9	3285.9
Coal transportation distance	km		0.0	0.0	0.0	0.0	…	0.0	0.0	0.0
Unit cost of coal transport [11,40]	Euro/Mg/km		0.3	0.3	0.3	0.3	…	0.3	0.3	0.3
Cost of coal transport	mln Euro		0.0	0.0	0.0	0.0	…	0.0	0.0	0.0
Unit CO_2 emission [33,49]	Mg CO_2/MWh		0.99	0.99	0.99	0.99	…	0.99	0.99	0.99
CO_2 uptake efficiency	%		0.9	0.9	0.9	0.9	…	0.9	0.9	0.9
CO_2 total emission	mln Mg/y	99.9	3.8	3.8	3.8	3.8	…	3.8	3.8	3.8
CO_2 emission without CCS	mln Mg/y	99.9	3.8	3.8	3.8	3.8	…	3.8	3.8	3.8
CO_2 emission with CCS	mln Mg/y	10.0	0.4	0.4	0.4	0.4	…	0.4	0.4	0.4
Unit price of CO_2 [50]	Euro/Mg CO_2	94.7	94.7	94.7	94.7	94.7	…	94.7	94.7	94.7
Cost of CO_2 emission with CCS	mln Euro	966.4	37.2	37.2	37.2	37.2	…	37.2	37.2	37.2
Cost of CO_2 emission without CCS	mln Euro	9663.6	371.7	371.7	371.7	371.7	…	371.7	371.7	371.7
Capex for CCS unit [24,43]	mln Euro	300.0	300.0							
Unit cost of CO_2 capture (without electricity)	Euro/Mg		6.1	6.1	6.1	6.1	…	6.1	6.1	6.1
Cost of CO_2 capture	mln Euro/y	569.3	21.9	21.9	21.9	21.9	…	21.9	21.9	21.9
CO_2 transportation distance	km		0.0	0.0	0.0	0.0	…	0.0	0.0	0.0
Unit cost of CO_2 transport	Euro/Mg/km		0.07	0.07	0.07	0.07	…	0.07	0.07	0.07
Cost of CO_2 transport	mln Euro/y	0.0	0.0	0.0	0.0	0.0	…	0.0	0.0	0.0
Capex for CO_2 storage&monit.	mln Euro	100.0	100.0							
Capex for CO_2 transport pipelines	mln Euro	0.0	0.0							
Unit cost of CO_2 storage&monit.	Euro/Mg		7.1	7.1	7.1	7.1	…	7.1	7.1	7.1
Cost of CO_2 storage&monit.	mln Euro/y	696.9	26.8	26.8	26.8	26.8	…	26.8	26.8	26.8
Unit income from the Power Market	Euro/kW		90.2	90.2	90.2	90.2	…	90.2	90.2	90.2

Table 1. *Cont.*

Years of Analysis	Unit	Sum of 1–25	0	1	2	3	...	23	24	25
Total income from the Power Market	mln Euro/y	1407.5	54.1	54.1	54.1	54.1	...	54.1	54.1	54.1
Cost discount of CO_2 avoidance	mln Euro	0.0	297.8	0.0	0.0	0.0	...	0.0	0.0	0.0
Electricity price	Euro/MWh	127.7	127.7	127.7	127.7	127.7	...	127.7	127.7	127.7
Total operation income with CCS	mln Euro/y	20,269.2	779.6	779.6	779.6	779.6	...	779.6	779.6	779.6
Total operation income without CCS	mln Euro/y	27,025.6	1039.4	1039.4	1039.4	1039.4	...	1039.4	1039.4	1039.4
Income difference	mln Euro/y	6756.4	259.9	259.9	259.9	259.9	...	259.9	259.9	259.9
Total operation cost of DO with CCS	mln Euro/year	1812.3	505.3	52.3	52.3	52.3	...	52.3	52.3	52.3
Total operation cost of DO without CCS	mln Euro/year	9663.6	371.7	371.7	371.7	371.7	...	371.7	371.7	371.7
Cost difference	mln Euro/year	7851.3	−133.6	319.4	319.4	319.4	...	319.4	319.4	319.4
Annual cost difference	mln Euro		38.0				...			
CF (diff.)	mln Euro		−393.5	59.5	59.5	59.5	...	59.5	59.5	59.5
Discount rate	%		10%	10%	10%	10%	...	10%	10%	10%
Discount factor			1.00	0.91	0.83	0.75	...	0.11	0.10	0.09
DCF	mln Euro		−393.5	54.1	49.2	44.7	...	6.6	6.0	5.5
NPV	mln Euro		146.9							

To assess the cash flow and the NPV, the following formulas and conversions are used:

Energy production per year:

$$EPr = CPP * CFPP \tag{1}$$

where:

EPr—energy production, MWh/y;
CPP—power unit, MW;
CFPP—capacity factor of the power plant, h.

Mass of coal consumption (*MC*):

$$MC = \frac{EPr}{nel} \times \frac{3.6}{LHV} \tag{2}$$

where:

LHV—calorific value, which reaches 21 MJ/kg [11,40,48];
nel—efficiency of the coal power plant.

Mass of CO_2 production in the power plant:

$$MCO2 = EPr * CO2f \tag{3}$$

where:

CO2f—emission CO_2 factor, Mg/MWh.

Cost of coal transport (*TCC*):

$$TCC = MC \times uCCT \times CTD \tag{4}$$

where:

uCCT—unit cost of coal transport, euro/km/Mg;
CTD—coal transport distance, km.

Cost of CO_2 transport (*TCCO2*):

$$TCCO2 = MCO2 \times uCT\_CO2 \times dP \tag{5}$$

where:

dP—length of the pipeline transporting CO_2, km;
uCT_CO2—unit cost of CO_2 transport, euro/km/Mg.

Utilization costs of CO_2 storage and monitoring (*UCCO2*):

$$UCCO2 = MCO2C \times uCS\_CO2 \tag{6}$$

where:

MCO2C—mass of CO_2 capture, Mg;
uCS_CO2—unit costs of CO_2 storage and monitoring, euro/Mg CO_2

Emission costs of CO_2 (*ECCO2*):

$$ECCO2 = (MCO2 - MCO2C) \times \text{Mp\_CO2} \tag{7}$$

where:

MCO2—mass of CO_2 produced, Mg;
MCO2C—mass of CO_2 capture, Mg;
Mp_CO2—market prices of CO_2 emission allowances, euro/Mg.

2.3. Power Unit and Supercritical Coal Combustion Process

A unit with a nominal capacity of 600 MW is analyzed. It is powered by crushed and ground coal, which is sent to a boiler, where it is burned with air. Solid waste—ash and slag resulting from coal combustion—is removed from the boiler and then sent to a landfill. The calorific value, *LHV*, of coal reaches 21 MJ/kg. The generated steam at a pressure of about 24 MPa and a temperature of 600 °C is directed through a turbine blade system to a steam turbine coupled to an electricity generator. The working medium then goes to the condenser and then to the boiler. The exhaust gases are dedusted and cleaned, after which they go to the chimney. In the CCS system, after dedusting and cleaning the sulfur, mercury, and nitrogen oxide compounds, exhaust gases are cooled and sent to the CO_2 separation installation, where in the last stage, they are compressed and injected into the pipeline under high pressure. Then, they go to the injection installation and are introduced into the deposit through deep holes. The analyzed system, together with CCS, uses almost 35 MW for its own needs [24].

2.4. Investment Outlays for the CCS Installation

Based on [45–47], it was assumed that the investment outlays for the CO_2 separation system would amount to approximately PLN 450 million (Euro 100 million) for the assumed scale of production (200 MW.

In turn, the investment outlays related to the pipeline construction, in connection with the purchase of land, preparation of technical documentation, exclusions from use, permits, compensations, and permanent infrastructure for a distance of 250 km, were determined at PLN 600 million (approximately Euro 133 million). For the analyzed smaller and larger CO_2 storage distances, these costs were scaled proportionally. This is an acceptable simplification for the purposes of this analysis.

For the purposes of building a salt cavern and injecting and monitoring CO_2, costs of around PLN 300 million (Euro 67 million) were assumed.

3. Results

The results of the analyses were presented for the following values of key technical parameters of the power unit, CCS installation, cost assumptions, and prices of CO_2 emission allowances. Some of these numbers are based on the authors' own data; others are determined based on [47].

- The nominal power of the power plant: 600 MW el.,
- the power plant efficiency: 0.40,
- CO_2 emission factor (CO2f): approx. 1 ton CO_2/MWh,
- the coal calorific value (LHV): 21 MJ/kg,
- detailed forecast period: 25 years,
- installation monitoring period after injection completion: 30 years,
- base values of decision (explanatory) variables, i.e., unit costs of CO_2 management at the level of average values in triangular distributions,

- with a probability of 90%, the value of the CO_2 allowances price is in the range of 60–115 Euro/Mg, with an average of 87 Euro/Mg,
- with a probability of 90%, the value of the electricity price is in the range of 61–240 Euro/Mg, with an average of 130 Euro/Mg,
- the investment outlays for CO_2 capture installation: 300 million Euro; for pipeline construction: 53 million Euro; and for salt cavern and storage installation: 100 million Euro, and
- the reference distance for CO_2 transport: 100 km.

The results of the analyses are illustrated in Figure 10.

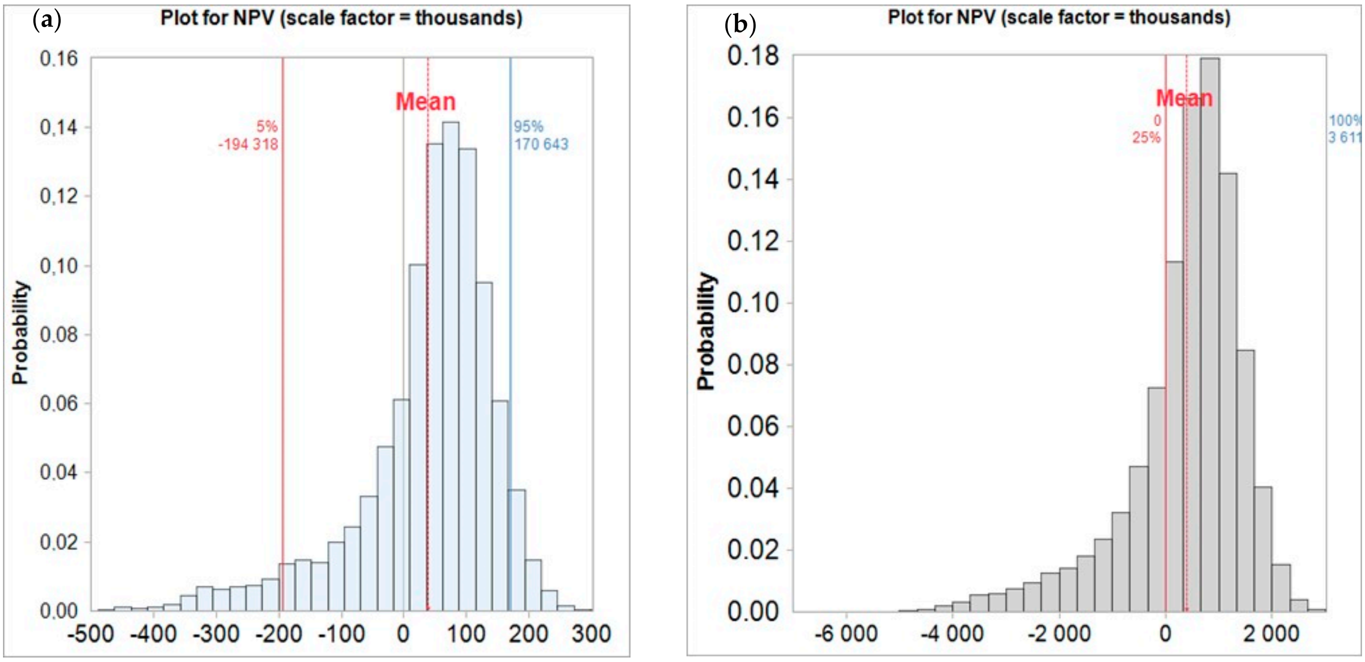


Figure 10. (**a**) Distribution for CF differences between Scenarios 1 and 2. (**b**) Distribution for NPV of Scenarios 1 and 2.

Analyzing Figure 10a,b and Table 2, it can be seen that the expected value of the average annualized cash flow difference (CF_2—CF_1) is approximately 38 million Euro; the annual cash effect of the scenario with CO_2 sequestration is positive and significant. Consequently, the expected value of NPV for the 25-year analysis period amounted to 147 million Euro. It follows that at emission allowance prices of 90 Euro/Mg CO_2 and assumed total outlays of 220 million Euro with respect to coal and CO_2 transport distances, it is economically viable to develop a CO_2 capture unit and transport and storage system. In addition, Table 1 shows that 90% of annualized differential cash flow observations fall within the range of −194 to 170 million Euro. The distributions of the NPV are left-skewed and centrally concentrated. In this case, the probability of receiving an NPV greater than 0 is 75% (Figure 10b) (Table 2).

The tornado plot for annualized cash flow differences (CF2-CF1) attached to the analysis indicates a list of parameters with a distinctive impact on the conditional mean value of CF2-CF1 and their variability. The dominant role is played by the volatility of market prices of CO_2 emission allowances and the productivity of the power unit. The next places are occupied by the unit cost of CO_2 transport, electricity prices, and carbon dioxide capture costs. The influence of the remaining uncertain (explanatory) parameters plays a significantly smaller role in determining the conditional mean of the CF2-CF1 annualized differences (Figure 11).

Table 2. Basic statistics for analyzed distributions in thousands of euros.

Variable Name	CF_2-CF_1 Distribution	NPV Distribution
	Location statistics	
Mean	38,002	147,319
Minimum	−488,156	−5,154,794
Maximum	297,753	2,764,841
	Spread statistics	
St. dev.	109,249	1,100,910
Variance	1×10^{10}	1×10^{12}
Risk ratio	4.29	7.05
CofV	2.87	7.47
	Shape statistics	
Skewness	−1.41	−1.41
Kurtosis	5.53	5.53
	Percentiles	
5%	−194,318	−2,193,777
95%	170,643	1,483,953

Source: own study.

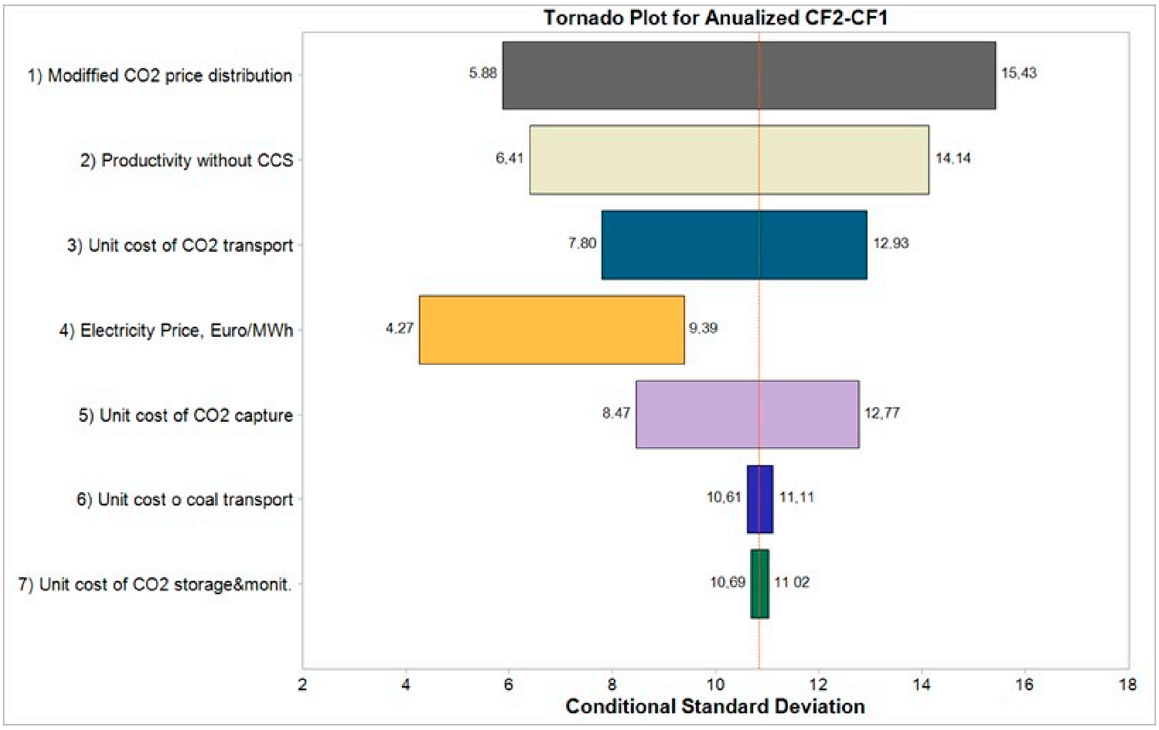


Figure 11. Sensitivity analysis/tornado plot for CF2-CF1 annualized differences under conditional standard deviation. Source: own study.

4. Discussion

In order to deepen the analysis, a scenario analysis was performed. In each scenario, the distances of carbon dioxide storage and the length of coal transport routes to the power plant were changed stepwise. The results are presented in Table 3. Each cell in the table presents the expected NPV value for the established transport distances of coal and CO_2. In total, the table includes 26 different combinations (scenarios) for the length of the coal and carbon dioxide transport distance. The range from 0 to 350 km corresponds to the realities of Polish coal-fired power plants and covers salt structure locations available in the country, where carbon dioxide can be stored.

Table 3. NPV average (expected) values as a function of the coal distance to the power station and storage unit.

		NPV Average Values [mln Euro]					
	Difference of Transport Distance [km]	**CO_2 to Cavern, Distance**					
		0	**50**	**100**	**170**	**250**	**350**
Coal to Power Unit	0	388	268	147	−6	−232	−447
	50	164	85	−62		−400	−672
	100	−27	−118	−269		−673	−885
	250	−660	−768	−947		−1242	−1543
	350	−1100	−1202	−1306		−1663	−1941

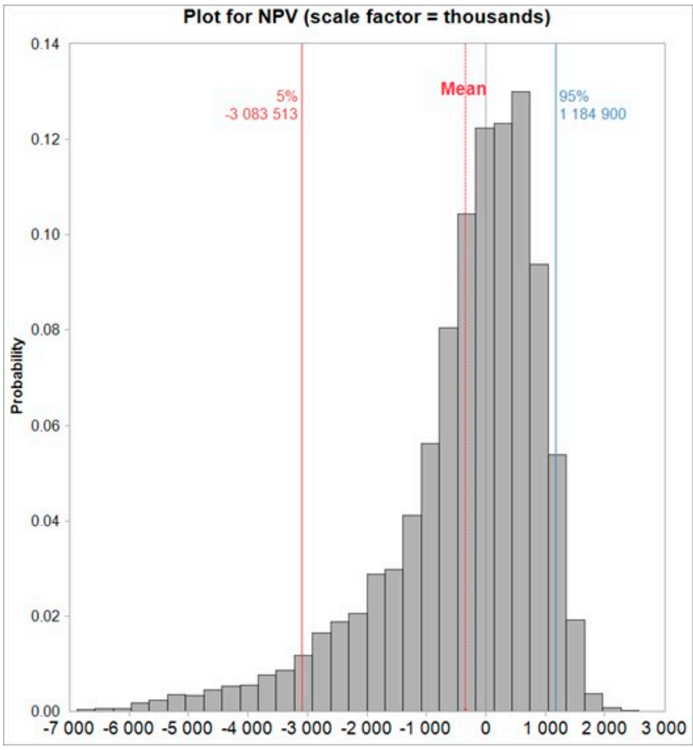
Source: own study.

Based on the attached table, it can be seen that for the maximum assumed distance in the transport of coal and CO_2, the expected (average) NPV value decreases significantly. At a distance of around 170 km from the storage site, the NPV becomes negative. Simultaneously, a coal transport distance over 100 km causes the NPV to drop below 0. There are only five scenarios (approx. 20% of all analyzed) with a positive NPV. In the developed simulation model, it was assumed that the entire capital expenditures are financed with equity. The decrease in the NPV value is mainly the result of a strong increase in investment outlays on the CO_2 transport pipelines. However, it should be emphasized that these are results obtained with the assumed relatively high price of CO_2 emission allowances.

The importance of the CO_2 emission allowance price model seems to be crucial. Figure 12 presents the simulation results—the distribution of the NPV, defined as highly probable for the range of historical CO_2 allowances price in the period of 2021 (January) to 2024 (August). Based on these data, the average price of CO_2 emission allowances is 70 Euro/Mg, with 90% of all prices falling within the range of 34–91 Euro/Mg CO_2. Based on this distribution, the average value of the differential NPV equals −350 million Euro. A total of 90% of all realizations of the expected results are in the range of −3.083 to 1.184 million Euro. Therefore, with the difference in CO_2 emission allowance prices of around 20 Euro/Mg (other explanatory variables are unchanged), the NPV value is lower by almost 500 million Euro, with a distance for CO_2 injection of 100 km.

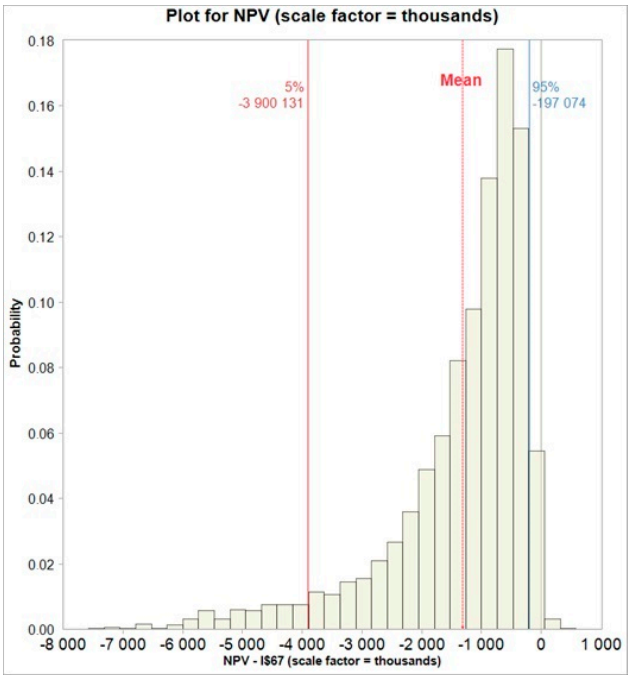
An analysis of economic efficiency was also carried out for the power plant (power units) capacity of around 200 MW (3 times decrease). The NPV, with investment outlays of 253 million Euro for the entire CCS system, including pipelines, construction of the cavern, storage, and monitoring infrastructure, also with the same CO_2 allowances prices distribution, dropped significantly, amounting to −1.322 million Euro (Figure 13).

Does underground CO_2 sequestration offer a lifeline for coal technologies, Polish energy security, and the energy sector as a whole? The evidence suggests that it does. However, more comprehensive and detailed analyses are necessary in this area. These analyses should include the expansion of criteria related to energy transmission capacity, specifically addressing the timing and scale of future transmission needs. While this criterion may initially appear marginal due to the repowering of existing generation sites, it becomes significant in the context of evolving energy flow dynamics within the grid. This is particularly relevant given the potential for onshore and offshore wind turbines and power plants to be located closer to Poland's northern regions.



NPV distribution statistics, euro	
Location	
Mean	−350,321
Minimum	−6,879,804
Maximum	2,270,863
Spread	
St. dev.	1,327,991
Variance	2×10^{12}
Risk ratio	−58.27
CofV	−3.79
Shape	
Skewness	−1.44
Kurtosis	5.52
Percentiles	
5%	−3,083,514
95%	1,184,901

Figure 12. The NPV distribution and its basic statistics. Source: own study.



NPV distribution statistics, euro	
Location	
Mean	−1,322,642
Minimum	−7,573,873
Maximum	314,890
Spread	
St. dev.	1,175,550
Variance	2×10^{12}
Risk ratio	−2.74
CofV	−0.89
Shape	
Skewness	−1.81
Kurtosis	6.56
Percentiles	
5%	−3,900,131
95%	−3,217,083

Figure 13. NPV distribution for the energy unit with nominal power at 200 MW el. Source: own study.

The findings indicate that results are highly sensitive to variations in key decision variables. Consequently, effective planning for the development of a CO_2 pipeline network necessitates the establishment of a dedicated network operator and a cost-sharing mechanism among multiple stakeholders through the provision of relevant services.

Future research should prioritize a detailed evaluation of capital investments, operating costs, and potential savings associated with emission reductions. Additionally, incorporating a comparative analysis of alternative technologies will provide a broader understanding of how CCS performs in terms of cost, efficiency, and sustainability. Developing criteria for selecting units for modernization and CCS deployment will be crucial for optimizing implementation strategies. Further exploration of the impacts of environmental changes, along with associated investments and measures in other energy sectors, will enhance the robustness and comprehensiveness of the study.

Some limitations of the study include the following:

- The long-term environmental and geological uncertainties associated with underground CO_2 sequestration.
- The influence of CO_2 pricing and political factors on the adoption and viability of CCS technologies.

5. Conclusions

Poland is facing an energy transformation. In connection with this, the possibilities of a new methodical approach to maintenance (sequence of shutdowns vs. repowering, modernizations), including coal assets (mines) to maintain the generating capacity of coal-fired power plants, were analyzed. In this respect, the analysis covered an example power unit with a capacity of 600 MW el. located close to the mine, for which key technical, energy, and financial values of the appropriate CCS unit were determined. The analysis assumed that waste carbon dioxide could be stored in salt formations (caverns), the potential location of which, as a function of distance from the power plant, was the subject of detailed analyses. The studies assumed that the entire project would be financed by a single entity without sharing the transport and storage infrastructure, which was associated with charging the full cost of CO_2 capture, transport, and storage in the rock mass.

The analysis showed that at the assumed distribution of CO_2 emission allowances price, and assuming the production scale and emissions, transport and storage costs, and necessary investment outlays (453 million Euro), the scenario with CO_2 capture and sequestration is profitable. The resulting NPV amounted to 147 million Euro, with an annual updated value of differential cash flow of 38 million Euro. The implementation of this strategy may constitute an important perspective on stable energy generation for coal-fired power plants operating in Poland. Before their final liquidation, which may take place after 2049 (the expected date of the end of coal mining in Poland), this scenario should be seriously considered, especially keeping in mind that the sharing of transport and storage infrastructure will improve the individual efficiency of CO_2 storage processes for each party. The publication also shows that the limit of effective carbon dioxide storage is a distance of 170 km from the power plant (for the adopted assumptions). It has also been shown that a decrease in the price of CO_2 emission allowances, i.e., a key decision parameter, by almost 20 Euro/Mg CO_2 causes a decrease in the NPV by almost 500 million Euro. This is a significant value. Therefore, selecting the right model for future CO_2 prices is crucial in planning the strategy for CCS with storage in salt caverns.

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Nomenclature

CAD	Canadian dollar
CCS	Carbon capture and storage
CF	Cash flow
CO2f	CO_2 emission factor, kg CO_2
DAM	Day-Ahead Market
dP	Length of the pipeline transporting CO_2, kg
ECCO2	Emission costs of CO_2
Ep	Unit cost of electricity, euro/MWh
EPr	Energy production, MWh/y
CFPP	Capacity factor of the power plant, h
CO2f	Emission CO_2 factor, Mg/MWh
CPP	Power unit, MW
CTD	Coal transport distance, km
IISD	International Institute for Sustainable Development
LHV	Calorific value, MJ/kg
MCO2	Mass of CO_2 produced, Mg
MCO2C	Mass of CO_2 capture, Mg
Mp_CO2	Market prices of CO_2 emission allowances, euro/Mg
nel	Efficiency of the coal power plant
NPV	Net present value, Euro
P	Productivity of the power unit with and without a CCS infrastructure, h/year
TCC	Cost of coal transport
TCCO2	Cost of CO_2 transport
TGE	Polish energy market, Towarowa Giełda Energii (in Polish)
UCCO2	Utilization costs of CO_2 storage and monitoring
uCCT	Unit cost of coal transport, euro/Mg
uCC_CO2	Unit cost of carbon dioxide capture, euro/Mg CO_2
uCS_CO2	Unit costs of CO_2 storage and monitoring, euro/Mg CO_2
uCT_CO2	Unit cost of CO_2 transport, euro/Mg CO_2

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