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Influence of the CCS systems in power plants on electricity price

***Abstract**. One of the ways to reduce the carbon dioxide emission in power plants can be capturing and sequestrating CO_2. This paper uses the available data about investment and operating costs to analyze the influence of the CCS technologies on the cost of electricity production and its price under risk conditions.*

***Streszczenie** Jednym ze sposobów redukcji emisji dietlenku węgla w elektrowniach może być wychwytywanie i sekwestracja CO_2. W artykule wykorzystano dostępne dane o kosztach inwestycyjnych i eksploatacyjnych w celu analizy wpływu technologii CCS na koszty wytwarzania energii elektrycznej i jej cenę w warunkach ryzyka **(Wpływ systemów CCS w elektrowniach na cenę energii elektrycznej)**.*

Keywords: power plant, CCS technology, investment efficiency.
Słowa kluczowe: elektrownia, technologia CCS, efektywność inwestycji.

Reducing CO_2 emissions in power engineering

The EU countries develop common projects for controlling climate changes, concentrating mostly on carbon dioxide emissions reduction. Burning of fossil fuels is the most important source of carbon dioxide. Reduction of the CO_2 emissions [1] can be achieved by improving the efficiency of energy conversion, transport and end-use. Technological improvements in thermal power plants with fossil steam boilers (pulverized coal) make possible to achieve the efficiency on the level of 45% but it seems to be insufficient to achieve deep reductions in the CO_2 emissions. Switching to less carbon–intensive fossil fuels can be effective. Switching from the coal to the natural gas in electricity generation causes a typical emission reduction about 50%, it means 0,4 t CO_2/(MW·h). Of course the supplies of natural gas should be available. Deep reductions in CO_2 emissions could be achieved by switching to nuclear power plants or renewable energy sources, e.g. wind power plants, solar electricity generation, biomass power plants, and geothermal energy used for electricity. Another way to reduce CO_2 emissions in fossil fuel power plants is capturing CO_2 and then storing it for a long time in depleted oil and gas fields, in deep saline formation or in the ocean. Also mineral storage is possible.

Brief characteristic of CCS technologies

At present the CCS technologies [2, 3] are sufficiently developed, at least with respect to the carbon dioxide capture stage, so that they could be applied in power plants. The purpose of CCS technology is to produce a concentrated (nearly pure) stream of carbon dioxide at high pressure to transport and storage. There are three most important approaches to capturing the CO_2 in fossil fuel power plants: post-combustion, pre-combustion, and oxyfuel combustion systems.

The best known technology of capturing CO_2 is the *post-combustion* method of scrubbing it from the exhaust gases. CO_2 is separated from the exhaust gases by absorption using the amine solution, such as monoethanolamine MEA, or by the membrane separation. The methods based on cryogenic or adsorption processes are of lesser importance.

Alternatively, the *pre-combustion* technology of reducing the CO_2 emissions can also be applied. The fuel is converted into CO and H_2 to form a synthesis gas, which is transformed into CO_2 and H_2 (the reaction with water is known as shift conversion). As a result, CO_2 is easy to separate in the flux of the synthesis gas, hydrogen can be used as fuel, and coal is removed before combustion.

In the process of oxygen combustion the fuel burns in oxygen. The temperature is controlled and kept at the level of the regular air burning by means of re-circulating the cooled fumes into the burning chamber. The fumes contain mainly carbon dioxide and water. After liquidizing the steam it is possible to obtain a flux of practically pure carbon dioxide, which can be subsequently transported to the storage site. The main disadvantage of this CCS technology is the large energy expenditure necessary for producing pure oxygen.

Costs of CCS technologies

Two technologies used in fossil fuel power plants are considered: fossil steam boiler with pulverized coal (FSB PC) and integrated gasification combined cycle. The basic component of the CCS technology cost in fossil fuel power plants is the cost of capturing CO_2. For large power plants included in the power system it is the dominant cost, comprising CO_2 compression up to the pressure of about 14 MPa, convenient for pipeline transport. The cost of CO_2 capture depends on the electricity production technology and is estimated as follows [2]: 18÷34 USD/(MW·h) for FSB PC, 9÷22 USD/(MW·h) for IGCC.

The cost of scrubbing CO_2 by means of amines increases the electricity production cost by about 40-70% in modern FSB PC power plants, reducing the CO_2 emissions level by about 85%. In an IGCC plant a comparable decrease in emissions entails the cost rise by about 20-55%.

The typical transport and storage costs are estimated at the level of 0,5÷6 USD/(MW·h) for coal power plants. Lower values of additional cost result from applying the EOR - (Enhanced Oil Recovery) or ECBM - (Enhanced Coal Bed Methane) technologies. The cost of underground storing CO_2 in saline formations or gas fields or oil fields are estimated as 0,5÷8,0 USD/t CO_2.

Table 1 presents the most important data on costs and CO_2 emissions reduction for the main electricity production technologies.

Investment analysis of building a power plant with CCS under risk conditions

The efficiency of investment under risk will be assessed by means of the optimization method described in detail in [4], and selected applications thereof in [3, 5, 6]. It is based on the Bellman equation and employs the net present value NPV indicator. The methodology has been utilized here for the analysis of the investment of building a power plant with the CO_2 Capture and Storage System.

The *NPV* indicator, if the liquidation value of the investment is disregarded, is equal to the discounted cash flows minus the investment cost I born during the time N_b of building the power plant and discounted at the time of launching the operation.

Table 1. CO_2 emissions reduction indicators and electricity production costs without and with CCS. Source: [2]

Item	Unit	FSB PC plant			IGCC plant		
-	-	Min	Max	Average	Min	Max	Average
Emissions rate without CO_2 capture	kg CO_2/(MW·h)	736	811	762	682	846	773
Emissions rate with CO_2 capture	kg CO_2/(MW·h)	92	145	112	65	152	108
Increase in energy intake necessary for CO_2 capture	%	24	40	31	14	25	19
Investment cost without CO_2 capture	USD/kW	1161	1486	1286	1169	1565	1326
Investment cost with CO_2 capture	USD/kW	1894	2578	2096	1414	2270	1825
Electricity production cost without CO_2 capture	USD/(MW·h)	43	52	46	41	61	47
Electricity production cost with CO_2 capture	USD/(MW·h)	62	86	73	54	79	62
Cost of CO_2 avoided	USD/tCO_2	29	51	41	13	37	23

Table 2. Analysis of selected power plants

Technology	Power	Investment value	Rate of utilizing installed power	Electrical energy production	Yearly emissions of CO_2
	MW	Million USD	-	GW·h	thousand t
Coal-fired power plant (FSB PC)	460	964,2	0,7	2820,7	315,9
IGCC power plant	335	611,4	0,7	2054,2	221,9

If the continuous character of cash flows is taken into consideration, the formula for the discounted net present value becomes

(1) $$NPV = V - I = \int_0^{N_e} \pi(t) e^{-rt} dt - I$$

where: r – the discount rate adopted by the investor, N_e – the operation period, $\pi(t)$ – the yearly net balance of income in consecutive years t, i.e. the difference between the actual income $P(t)$ and cost $C(t)$.

The total cost incurred in a year $C(t)$ includes fuel and energy cost, pay cost, environmental fees, repair cost, sales cost, and insurance. It was assumed that the operation generates the cost C, and that the operation can be temporarily suspended, if the value of income P goes down below the cost C. It is possible to re-launch production if the value P exceeds C again. Additional cost incurred by suspending production and the restart cost are both included in C. The income generated by the investment project can be represented as

(2) $$\pi(P) = max[P - C, 0]$$

The value V of the project depends on the value of the income P, which undergoes random variation with a trend (in accordance with the Brown geometrical motion model, the so called diffusion equation). Because of that the investment value will be determined as a function of the income $V(P)$. The income P can be treated as a stochastic variable behaving as in the equation below

(3) $$dP = \alpha P dt + \sigma P dz$$

where α – is the trend coefficient, σ – is the standard deviation.

The investment value at the time t can be represented as a sum of the cash flows within the time period $(t, t+dt)$ and the value of continuation after that time

(4) $$V(P) = \pi(P)dt + \varepsilon\left[V(P + dP)e^{-r\,dt}\right]$$

where: ε – is the expected value.

Applying Ito's lemma and transforming (4) one can obtain the differential equation for the investment value

(5) $$\tfrac{1}{2}\sigma^2 P^2 V''(P) + (r - \delta)PV'(P) - rV(P) + \pi(P) = 0$$

where: $\delta = r - \alpha$.

A method of solving Eq. (5) for the two intervals $P < C$ and $P > C$ as well as a discussion on the solution when $P = C$ was presented in [3, 4]. The solution can be written as

(6) $$V(P) = \begin{cases} K_1 P^{\beta_1} & dla \;\; P < C \\ B_2 P^{\beta_2} + P/\delta - C/r & dla \;\; P > C \end{cases}$$

where: β_1, β_2 - the roots of the equation characteristic of the homogeneous equation, $\beta_1 > 1$, $\beta_2 < 0$, K_1, B_2 - constants.

The value of the investment option $F(P)$ Is the maximal value out of the expected *NPV* of the investment

(7) $$F(P) = max\, \varepsilon\left\{\left[V_T(P) - I\right]e^{-rT}\right\}$$

where: T – is the time at which the investment is to be completed.

In order to find the solution of $F(P)$ dynamic programming was applied. The Bellman equation can be represented as

(8) $$rF\,dt = \varepsilon(dF)$$

Taking Ito's lemma and Eq. (3) into consideration, the Bellman equation (8) can be transformed into

$$\frac{1}{2}\sigma^2 P^2 F''(P)+(r-\delta)PF'(P)-rF=0 \tag{9}$$

Additionally, *F(P)* must meet the boundary conditions

$$\begin{gathered} F(0)=0 \\ F(P^*)=V(P^*)-I \\ F'(P^*)=V'(P^*) \end{gathered} \tag{10}$$

The value of the investment option *F(P)* is the sought optimum investment strategy. Assuming that the value *P* varies in accordance with Eq. (3), the solution for the investment option can be obtained as

$$F(P)=A_1P^{\beta_1}+A_2P^{\beta_2} \tag{11}$$

where: A_1 , A_2 - constants.

This leads to an equation with one unknown value P^*, which can be solved numerically

$$(\beta_1-\beta_2)B_2(P^*)^{\beta_2}+(\beta_1-1)\frac{P^*}{\delta}-\beta_1\left(\frac{C}{r}+I\right)=0 \tag{12}$$

The value P^* is the critical, or threshold value of income, for which the investment of building a power plant is economically feasible under the conditions of risk associated with the future profit. On the basis of the threshold value and the quantity of electrical energy produced in the power plant it is possible to determine the critical value of electricity price above which the investment is profitable.

The construction of two modern power plants with CO_2 capture system has been analyzed: a coal-fired power plant (FSB PC) of power 460 MW and an IGCC power plant of power 335 MW. It was assumed that the FSB PC power plant is equipped with the post-combustion CO_2 capture systems. The analysis makes use of the data contained in tables 1 and 2 for average (reference) power plants.

Table 3. Critical values of the investment in millions of USD and electricity prices in USD/(MW·h) as functions of the risk indicator σ for discount rate r=6%, CO_2 allowance price 25 USD/t CO_2

Technology	Quantity	Unit	Values					
	σ	-	0,05	0,1	0,15	0,2	0,25	0,3
	β_1	-	1,926	1,772	1,622	1,500	1,406	1,333
	β_2	-	-24,926	-6,772	-3,288	-2,000	-1,366	-1,000
Coal-fired power plant (FSB PC) 460 MW	P^*	Million USD	249,3	273,3	302,1	332,2	363,4	395,8
	c_e^*	USD/(MW·h)	88,4	96,9	107,1	117,8	128,8	140,3
IGCC power plant 335 MW	P^*	Million USD	154,5	169,4	187,4	206,3	225,9	246,2
	c_e^*	USD/(MW·h)	75,2	82,5	91,2	100,4	110,0	119,9

Table 4. Critical values of the investment in millions of USD and electricity prices in USD/(MW·h) as functions of the risk indicator σ for discount rate r=8%, CO_2 allowance price 25 USD/t CO_2

Technology	Quantity	Unit	Values					
	σ	-	0,05	0,1	0,15	0,2	0,25	0,3
	β_1	-	2,509	2,217	1,961	1,766	1,620	1,510
	β_2	-	-25,509	-7,217	-3,627	-2,266	-1,580	-1,177
Coal-fired power plant (FSB PC) 460 MW	P^*	Million USD	257,9	281,9	311,2	342,0	373,7	406,5
	c_e^*	USD/(MW·h)	91,4	99,9	110,3	121,2	132,5	144,1
IGCC power plant 335 MW	P^*	Million USD	158,6	173,4	191,6	210,8	230,7	251,2
	c_e^*	USD/(MW·h)	77,2	84,4	93,3	102,6	112,3	122,3

Table 5. Critical values of the investment in millions of USD and electricity prices in USD/(MW·h) as functions of the risk indicator σ for discount rate r=10%, CO_2 allowance price 25 USD/t CO_2

Technology	Quantity	Unit	Values					
	σ	-	0,05	0,1	0,15	0,2	0,25	0,3
	β_1	-	3,069	2,623	2,262	2,000	1,809	1,667
	β_2	-	-26,069	-7,623	-3,929	-2,500	-1,769	-1,333
Coal-fired power plant (FSB PC) 460 MW	P^*	Million USD	266,0	289,5	318,7	349,6	381,6	414,7
	c_e^*	USD/(MW·h)	94,3	102,6	113,0	123,9	135,3	147,0
IGCC power plant 335 MW	P^*	Million USD	162,4	176,8	194,7	213,9	233,8	254,4
	c_e^*	USD/(MW·h)	79,1	86,1	94,8	104,1	113,8	123,8

Table 6. Critical values of the investment in millions of USD and electricity prices in USD/(MW·h) as functions of the risk indicator σ for discount rate r=6%, CO_2 allowance price 50 USD/t CO_2

Technology	Quantity	Unit	Values					
Technology	σ	-	0,05	0,1	0,15	0,2	0,25	0,3
	β_1	-	1,926	1,772	1,622	1,500	1,406	1,333
	β_2	-	-24,926	-6,772	-3,288	-2,000	-1,366	-1,000
Coal-fired power plant (FSB PC) 460 MW	P^*	Million USD	257,5	282,2	311,5	342,2	373,8	406,6
	c_e^*	USD/(MW·h)	91,3	100,0	110,4	121,3	132,5	144,1
IGCC power plant 335 MW	P^*	Million USD	160,2	175,7	194,1	213,3	233,2	253,8
	c_e^*	USD/(MW·h)	78,0	85,5	94,5	103,8	113,5	123,6

Table 7. Critical values of the investment in millions of USD and electricity prices in USD/(MW·h) as functions of the risk indicator σ for discount rate r=8%, CO_2 allowance price 50 USD/t CO_2

Technology	Quantity	Unit	Values					
Technology	σ	-	0,05	0,1	0,15	0,2	0,25	0,3
	β_1	-	2,509	2,217	1,961	1,766	1,620	1,510
	β_2	-	-25,509	-7,217	-3,627	-2,266	-1,580	-1,177
Coal-fired power plant (FSB PC) 460 MW	P^*	Million USD	266,1	290,8	320,7	352,0	384,2	417,5
	c_e^*	USD/(MW·h)	94,3	103,1	113,7	124,8	136,2	148,0
IGCC power plant 335 MW	P^*	Million USD	164,4	179,7	198,3	217,9	238,1	258,9
	c_e^*	USD/(MW·h)	80,0	87,5	96,5	106,1	115,9	126,1

Table 8. Critical values of the investment in millions of USD and electricity prices in USD/(MW·h) as functions of the risk indicator σ for discount rate r=10%, CO_2 allowance price 50 USD/t CO_2

Technology	Quantity	Unit	Values					
Technology	σ	-	0,05	0,1	0,15	0,2	0,25	0,3
	β_1	-	3,069	2,623	2,262	2,000	1,809	1,667
	β_2	-	-26,069	-7,623	-3,929	-2,500	-1,769	-1,333
Coal-fired power plant (FSB PC) 460 MW	P^*	Million USD	274,2	298,4	328,2	359,7	392,3	425,8
	c_e^*	USD/(MW·h)	97,2	105,8	116,4	127,5	139,1	151,0
IGCC power plant 335 MW	P^*	Million USD	168,2	183,0	201,5	221,1	241,3	262,3
	c_e^*	USD/(MW·h)	81,9	89,1	98,1	107,6	117,5	127,7

It was stipulated that the power plants operate with the ratio of utilizing the power installed is *n*=0,7, on the basis of which the yearly amount of electricity produced and the CO_2 emissions were determined, and consequently, the cost of electricity production including the CCS system cost was calculated. It was also assumed that the efficiency of CO_2 capture is 85%. In the calculations of the total cost of electricity production the following partial costs were taken into account: for the FSB PC technology the average cost of CO_2 capture of 26 USD/(MW·h), the transportation and storage cost of 3 USD/(MW·h), and for the IGCC technology the average CO_2 capture cost of 15,5 USD/(MW·h), the transportation and storage cost of 3 USD/(MW·h) as well as the emissions allowance price in two levels 25 USD/t CO_2 and 50 USD/t CO_2. The exploitation period is N_e=50 years. Other parameters included in the calculations are the discount rate *r* equal 6%, 8% and 10%, and the trend coefficient α=3% (hence δ equal 3%, 5% and 7% respectively). The calculations were performed for selected values of the standard deviation for income within the interval σ=0,05÷0,3. The greater value of σ represents the higher risk associated with the fall of income.

For the assumptions presented above the threshold value of the electricity price is

$$c_e^* = \frac{P^*}{P_i\, n\, T_r} \tag{13}$$

where: P_i - is the installed power, MW, T_r - is the yearly period, T_r =8760 h.

The critical value P^* of the investment project was determined by solving Eq. (12). The results of the calculations are presented in tables 3÷8. The critical values c_e^* of the electrical energy price increase together with the increase in risk and exceed the cost of electricity production given in table 1 and equal to 73 USD/(MW·h) for FSB PC and 62 USD/(MW·h) for IGCC, respectively. The influence of discount rate and emissions allowance price on the critical electricity prices is rather weak but the influence of risk is relatively strong.

Conclusions

The analysis of the prospective large-scale implementation of the CCS technology indicates that this is rather a distant possibility in terms of time. The CCS technologies increase the cost of electrical energy production and decrease the economical efficiency of a power plant. Besides, the problem of storing CO_2 has not be successfully solved yet, as it is believed that storing CO_2 can be potentially hazardous for the environment. Taking all the arguments above into account, it can be stated that the test implementations of the CCS systems in power plants are useful and necessary. EU will support 10-12 demonstration CCS projects up to 50% of investment cost. It seems to be the right decision to develop such projects, since conventional combustion power plants based on hard and brown coal will prevail for several decades [7, 8]. Striving towards lowering the cost of advanced solutions and, consequently, towards applying the zero-emission technology and carbon dioxide sequestration on a large scale should be a priority policy in power industry.

The analysis presented in this paper of economic feasibility of building a power plant with carbon dioxide capture system takes into consideration the changing cost and income as well as the risk associated with their values in the future. The growing risk of lowering income in the future, reflected in the growing value of the standard deviation σ, causes increase in the threshold value P^* of the income generated by the investment project, and at the same time, increase in the threshold value c_e^* of the electrical energy price for the power plants under consideration.

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