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Large power plants with low CO_2 emission – economic feasibility analysis including risk

***Abstract**. The carbon dioxide emission of power plants can be reduced by advances in technology, increasing efficiency of power production, using low carbon emission fuel, and sequestrating CO_2. Alternative technologies of power generation could be nuclear or natural gas power plants. Each of the above-mentioned methods of reducing CO_2 emissions involves large investment and operating costs. This paper uses the available data to analyze the influence of the low carbon emission technologies on the cost of electricity production under risk conditions.*

Streszczenie.** Emisję dwutlenku węgla w elektrowniach można obniżyć poprzez postęp w technologiach, zwiększenie sprawności wytwarzania energii elektrycznej, wykorzystanie paliw o niskiej emisji oraz sekwestrację CO_2. Alternatywnymi technologiami wytwarzania energii elektrycznej mogą być elektrownie jądrowe lub Każda z metod redukcji emisji CO_2 wymaga dużych nakładów inwestycyjnych i sporych kosztów eksploatacyjnych. W artykule przedstawiono wyniki badań wpływu niskoemisyjnych technologii wytwarzania na koszty produkcji energii elektrycznej w warunkach ryzyka. **(Niskoemisyjne elektrownie systemowe – ekonomiczna analiza wykonalności z uwzględnieniem ryzyka)

Keywords: power plant, investment, feasibility analysis, risk analysis.
Słowa kluczowe: elektrownia, inwestycja, analiza wykonalności, analiza ryzyka.

Introduction

The EU countries develop common projects for controlling climate changes, concentrating mostly on carbon dioxide emissions reduction, as CO_2 emissions due to fossil fuel burning are considered to be one of the main causes of the greenhouse effect. Reducing greenhouse gas emissions seems to be important contribution to mitigation of the global warming.

In the document of the Commission of European Communities [1] the main assumption of energy policy is formulated: "*Energy accounts for 80% of all greenhouse gas (GHG) emission in the EU; it is at the root of climate change and most air pollution. The EU is committed to addressing this – by reducing EU and worldwide greenhouse gas emissions at a global level to a level that would limit the global temperature increase to 2°C compared to pre-industrial levels."* [1]. So the strategic objective of Europe's energy policy is at least a 20% reduction of greenhouse gases by 2020 compared to 1990.

Reducing CO_2 emissions in power engineering

Coal and natural gas are the most important fuels in electricity generation. They account about 50% of the EU's electricity supply. Coal combustion produces almost two times more the emissions of CO_2 compared to natural gas fired power plants (see Table 1). Even so the fossil fuels will remain important part of the EU energy balance. Developing clean coal technologies will be necessary. The strategic energy technology plan (SET plan) [2] assumes supporting development of a new generation of low carbon technologies and increasing research to reduce cost and improve performance of the CCS systems.

The comparison of emission data in Table 1 indicates advantages of nuclear, biomass and natural gas as fuels of electricity generation. Nuclear energy is one of the cheapest sources of energy with low emission. The electricity production in these power plants also has relatively stable costs. The next generation of nuclear reactors should even reduce production costs. New nuclear power plants could produce electricity at 4 € cents per kWh. The fourth generation fission nuclear reactors and future fusion technology improve the competitiveness, safety and security of nuclear electricity, as well as reduce the level of waste [1].

CO_2 emissions from power plants can be reduced in several ways: by changing the electricity production technology from conventional, fossil fuel technology to technologies employing non-emission or low CO_2, emission energy sources, such as nuclear, or renewable sources; by increasing the efficiency of electricity production, and by CO_2 sequestering. At present the main lines of development of the CO_2 emissions reduction technology are methods of capturing CO_2 from exhaust gases and oxygen combustion. The majority of experts believe that the implementation of these technologies will be possible after 2025 [3].

The CCS (*Carbon dioxide Capture and Storage*) technology consists in isolating and capturing CO_2 from combustion gases, and its subsequent transport and permanent storage (sequestration) in isolation from the atmosphere. Possible methods of storing carbon dioxide include geological storage in oil fields, gas fields, coal seams, saline formations, ocean storage (directly or at the floor of the ocean), and mineral storage. Mineral carbonatization [4] is the reaction of CO_2 with minerals, such as serpentynite, olivine, or talc. The chemical bond is of permanent type.

Prospective optimum strategies for the development of power industry must include the CO_2 emissions reduction technology, which in turn contribute to increase in investment and operating cost of electricity production. Due to high uncertainty connected to this kind of cost, it is necessary to employ sophisticated methods for selecting optimum investment strategy under risk.

Brief characteristics of the CCS technologies

Among the known methods of CO_2 separation the most important ones include physical and chemical absorption, physical adsorption, membrane separation, and cryogenic separation [4, 5, 6].

The chemical absorption process takes place in the absorption column in which the solvent has contact with cooled and filtered exhaust gases. Carbon dioxide is absorbed by the solvent and subsequently released in the desorber. Then, CO_2 is compressed and in such a form it can be transported. Substances used as absorbers can be amines, e.g. mono-ethanolamine (MEA) or diethanolamine (DEA), ammonium hydroxide, or potassium bicarbonate.

Adsorption involves the process of physical attraction between a gas and solid substances such as activated carbon, alumina, zeolites or aluminum and silica gel.

The membrane separation technologies seem to be quite promising in power industry. The CO_2 flux from exhaust gases permeates through a membrane and dissolves on the other side of the membrane in the absorption liquid, such as mono-ethanolamine.

The cryogenic fractioning process consists in compressing and cooling exhaust gases. Liquid CO_2 gets separated due to different condensation conditions of particular exhaust components.

At present the CCS technologies are sufficiently developed, at least with respect to the carbon dioxide capture stage, so that they could be applied in power plants. Practically, however, only the amine adsorption technology is available and suitable for fossil fuel power plants. As far as the long-term underground storage of carbon dioxide is concerned, it is actually an untried technology and up to now no large power plant operated with the full CCS system. The implementation of CCS in a modern conventional power plant will make it possible to reduce CO_2 emissions by 80÷90% [6]. Additional energy needed for capturing and compressing CO_2 will increase the energy consumption by 11÷40%. In this way, installing the CCS system will cause rise in the cost of electricity production. According to estimations presented in [6] the cost will go up by 21÷91% depending on the technology and distance between the power plant and CO_2 storage location. At present storage sites are underground geological formations: unminable coal seams, oil and gas fields, or oceans. As predicted by IPCC [6], the CCS technology can reduce the total CO_2 emissions by 10÷55% by the year 2100. On the other hand, as was mentioned, capturing and sequestrating carbon dioxide increases the investment and operating costs of power plants. Storing CO_2 by means of Enhanced Oil Recovery (EOR) technology makes it possible to obtain additional amount of oil from the oil field, which ultimately decreases the electricity production cost. The increase of the prices of natural gas and oil makes the EOR technology more effective.

At present the best known technology of capturing CO_2 is that of scrubbing it from the exhaust gases. Here the *post-combustion* method is the most popular, in which CO_2 is separated from the exhaust gases by absorption using the amine solution, such as 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. Power plants employing the oxygen burning technology (oxyfuel) are referred to as zero-emission plants, since carbon dioxide is a stream of exhaust gas, and not a fraction captured and isolated before or after the combustion. The main disadvantage of this CCS technology is the large energy expenditure necessary for producing pure oxygen.

A CCS technology of the future, which is currently being tested, and which will be applicable in the fluidized bed combustion is the Chemical Looping Combustion (CLC). The method uses metal oxides, which after being introduced into the fluidized bed enter into chemical reactions with the fuel, thereby forming solid metal particles and a mixture of carbon dioxide and steam. When the steam is liquidized, the carbon dioxide can be sequestrated. The metal particles are oxidized in another fluidized bed, used mainly for heat generation and recovery of metal oxides, which are subsequently reintroduced to the CLC process.

CCS technology costs

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 are estimated as follows [6]: 18÷34 USD/(MW·h) for FSB PC, 9÷22 USD/(MW·h) for IGCC and 12÷24 USD/(MW·h) for NGCC.

The cost of scrubbing carbon dioxide by means of amines increases the electricity production cost by about 40-70% in modern FSB PC power plants or natural gas 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 data is to be treated with caution as it is only approximate.

The typical transport and storage costs are estimated at the level of 0,5÷6 USD/(MW·h). Lower values of additional cost, which may even become income, 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 2 presents the most important data on costs and CO_2 emissions reduction for the main electricity production technologies.

Nuclear power plants

Advanced nuclear light water reactors generation III are used in commercial application. Nuclear technology has been improved generally by better use of fuel and passive safety systems. Well known construction are ABWR, System 80+, APWR and AP 600. Evolutionary reactors of Generation III+ with passive safety systems, e.g. ACR-1000 (Advanced CANDU Reactor), AP 1000, ESBWR and EPR are the next step of the development. Investors could consider construction of EPR (European Pressurized Reactor, 1600 MW) by AREVA and Siemens AG (SWR-1000), ABWR (Advanced Boiling Water Reactor, 1350 MW) and ESBWR (Economic Simplified Boiling Water Reactor, 1550 MW) by General Electric, AP1000 by Westinghouse Electric Company, CANDU 6 (CANada Deuterium Uranium, PHWR), Canada and WWER 1000 (Water-Water Energetic Reactor, PWR), Russia.

The cost of electricity in nuclear power plants depends on investment cost. The Moody's Investors Service (MIS) estimates overnight cost in nuclear power plant on the level about 5 400 Euro/kW.

Investment cost, so called turn-key cost, given by world nuclear agencies are in the interval 4500÷5400 Euro/kW [7]. The comparison analysis of overnight cost in [8] indicates the world average value is equal to 4100 USD/kW. The total investment cost included interest of capital, so called interest during construction are equal 3 600÷4 200 Euro/kW according to [8] and to the Eurelectric estimates for EPR technology.

The cost of capital is calculated assuming interest rate of commercial credit equal to 7 %, and cost of own capital equal to 10,5 %. The next assumption is that about 70 % of investment cost comes from the loan. It implies the cost of capital 8,05 % as a result of calculation. It means that a discount rate could be about 8 %.

The cost of fuel in nuclear power plants constitutes from 16% to 28% of variable costs. The cost of nuclear fuel should be estimated as 12,5 USD/(MW·h) [7] and the operation cost about 138 PLN/(MW·h) [7]. So, the variables cost are about 173 PLN/(MW·h) (exchange rates taken in calculation 4 PLN/Euro and 2,8 PLN/USD).

Significantly lower estimate of electricity cost is given by [8] based on operating characteristics of US nuclear power plants in the period 1995÷2009. The average cost of electricity production is equal to 22 USD/(MW·h), it means about 62 PLN/MW·h.

The licenses of the nuclear reactors have been extended to 60 years and the power plant has to prepare funds for decommissioning (in the USA about 300 million USD).

Table 1. Basic data of power plants (source [1])

Energy sources	Technology	Cost of electricity in 2005 (source IEA)	Projected cost of electricity in 2030 with €20÷30/t CO_2 (source IEA)	GHG emissions	Efficiency
-	-	€/(MW·h)	€/(MW·h)	kg CO_2/(MW·h)	%
Natural gas	Open cycle Gas Turbine (GT)	45-70	55-85	440	40
	Natural Gas Combined Cycle (NGCC)	35-45	40-55	400	50
Coal	Pulverised Fuel with flue gas desuphurisation (PF)	30-40	45-60	800	40-45
	Circulating Fluidised Bed Combustion (CFBC)	35-45	50-65	800	40-45
	Integrated Gasification Combined Cycle (IGCC)	40-50	55-70	750	48
Nuclear	Light Water Reactor (LWR)	40-45	40-45	15	33
Biomass	Biomass Generation Plant (BGP)	25-85	25-75	30	30-60

Investment analysis of building a large power plant under risk conditions

The efficiency of investment under risk will be assessed by means of the optimization method described in detail in [9], and selected applications thereof in [10]. 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. 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, 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 [9, 10]. 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, $\beta_1 > 1$, $\beta_2 < 0$, $K_1\ i\ B_2$ - constants.

The value of the investment option is marked as $F(P)$. It 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

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

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

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

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

(11) $$F(P) = A_1 P^{\beta_1} + A_2 P^{\beta_2}$$

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

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

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 c_e^* above which the investment is profitable

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

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

Results of calculation

The constructions of modern power plants without and with CO_2 capture system and nuclear power plant have been analyzed: a conventional FSB PC power plant of power 460 MW, an IGCC power plant of power 335 MW, a NGCC power plant of power 400 MW and nuclear power plant with LWR of power 1600 MW. It was assumed that the fossil fuel power plants are equipped with the post-combustion CO_2 capture systems. The analysis makes use of the data contained in Table 2 for average (reference) power plants. The values of the investment projects have been established. It was stipulated that the fossil fuel power plants operate with the ratio of utilizing the power installed is n=0,7 and the nuclear power plant with n=0,9, 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), 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), and for the NGCC technology the average cost of CO_2 capture of 18 USD/(MW·h), the transportation and storage cost of 3 USD/(MW·h) as well as the emissions allowance (or Certified Emission Reduction CER) prices in the range from 10 USD/t CO_2 to 110 USD/t CO_2. The exploitation period is N_e=50 years. Other parameters included in the calculations are the discount rate r=8% and the trend coefficient α=3% (hence δ=5%). The calculations were performed for selected values of the standard deviation for income within the interval σ=0,03÷0,18. The greater value of σ represents the higher risk associated with the fall of income.

Table 2. Data of selected power plants [6]

Technology	Power	Investment cost	Emissions rate	Rate of utilizing installed power	Variable electricity production cost
	MW	USD/kW	kg CO_2/(MW·h)	-	USD/(MW·h)
Combustion FSB PC power plant	460	1286	762	0,7	28,8
Combustion FSB PC power plant with CCS	460	2096	112	0,7	57,8
IGCC power plant	335	1326	773	0,7	43,3
IGCC power plant with CCS	335	1825	108	0,7	61,8
NGCC power plant	400	568	367	0,7	29,4
NGCC power plant with CCS	400	998	52	0,7	50,4
Nuclear power plant LWR (min)	1600	5600	-	0,9	22
Nuclear power plant LWR (max)	1600	7000	-	0,9	62

Table 3. Critical values of the electricity prices c_e*in USD/(MW·h) in nuclear power plant as functions of the risk indicator σ

Technology	Quantity	Unit	Values					
	σ	-	0,03	0,06	0,09	0,12	0,15	0,18
Nuclear power plant LWR (min)	c_e^*	USD/(MW·h)	80	83	88	94	101	108
Nuclear power plant LWR (max)	c_e^*	USD/(MW·h)	135	140	148	158	169	181

Table 4. Critical values of the electricity prices c_e* in USD/(MW·h) in fossil fuel power plants as functions of the risk indicator σ and price of CO_2 allowances

CO_2 allowance price	Quantity	Unit	Values					
USD/(t CO_2)	σ	-	0,03	0,06	0,09	0,12	0,15	0,18
Combustion FSB PC power plant 460 MW								
10	c_e^*	USD/(MW·h)	54	56	59	63	67	71
30	c_e^*	USD/(MW·h)	69	72	76	80	85	90
50	c_e^*	USD/(MW·h)	85	88	93	98	103	108
70	c_e^*	USD/(MW·h)	100	104	110	115	121	126

Combustion FSB PC power plant with CCS 460 MW								
10	c_e*	USD/(MW·h)	88	91	96	102	108	115
30	c_e*	USD/(MW·h)	90	93	99	105	111	118
50	c_e*	USD/(MW·h)	92	96	101	107	114	120
70	c_e*	USD/(MW·h)	94	98	104	110	116	123
IGCC power plant 335 MW								
10	c_e*	USD/(MW·h)	69	72	76	80	85	90
30	c_e*	USD/(MW·h)	85	88	93	98	103	108
50	c_e*	USD/(MW·h)	101	105	110	116	121	127
70	c_e*	USD/(MW·h)	116	121	127	133	139	145
IGCC power plant with CCS 335 MW								
10	c_e*	USD/(MW·h)	88	91	96	102	108	114
30	c_e*	USD/(MW·h)	90	94	99	105	111	117
50	c_e*	USD/(MW·h)	92	96	101	107	113	120
70	c_e*	USD/(MW·h)	95	98	104	110	116	122
NGCC power plant 400 MW								
10	c_e*	USD/(MW·h)	41	43	45	47	50	52
50	c_e*	USD/(MW·h)	56	58	61	64	66	69
90	c_e*	USD/(MW·h)	71	74	77	80	83	86
110	c_e*	USD/(MW·h)	78	81	85	88	91	94
NGCC power plant with CCS 400 MW								
10	c_e*	USD/(MW·h)	65	67	71	75	79	83
50	c_e*	USD/(MW·h)	67	70	73	77	81	85
90	c_e*	USD/(MW·h)	69	72	76	80	84	88
110	c_e*	USD/(MW·h)	70	73	77	81	85	89

The threshold values c_e* of the electricity price of the investment projects were determined by solving equations (12) and (13). The results of the calculations are presented in Tables 3 and 4. The critical values c_e* of the electrical energy price increase together with the increase in risk.

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. 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 [11, 12]. Striving towards lowering the cost of advanced solutions and, consequently, towards applying the zero-emission technology and CO_2 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 and a nuclear power plant 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.

The electricity is produced in the NGCC power plant with the lowest critical values of electricity price. The CO_2 allowance price about 110 USD/(t CO_2) makes that the NGCC power plant with the CCS technology is more efficient than without the CCS. Also the low c_e* values are calculated for FSB PC power plant but only for CO_2 allowance price not greater than 10 USD/(t CO_2). The allowance price between 50 to 70 USD/(t CO_2) causes that the CCS technology is worthy to install in the FSB PC power plant. The critical values c_e* in nuclear power plant are greater than c_e* values in fossil power plants but greater values of allowance prices change that relationship.

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