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The costs of CC(U)S adaptation: The case of Russian power industry

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Abstract

In the context of the Climate Agenda, CC(U)S technologies are promising decarbonization options, but they are not widespread. The costs of CC(U)S are still high, and economic assessment of such initiatives for different sites and regions are of particular interest. This paper is aim to analyze the main approaches to costing CC(U)S, as well as the economic assessment of the CO_2 capture option implementation on coal-fired power plant in the Murmansk region (Russia). The paper presents a brief analysis of CC(U)S costing approaches and focuses on economic assessment of CO_2 capture at Apatitskaya coal-fired power plant, determining such indicators as Levelized cost of electricity and Cost of CO_2 captured. The calculations have shown that the cost of CO_2 captured at power plant in the Murmansk region is relatively high (263 USD per tonne). The main reasons are high capital costs, lack of tax incentives and project support. Also, the reasons are lack of economies of scale and high energy penalty. Monetization of CO_2, state support of CC(U)S, scaling technologies with accompanying cost reductions can be the basis for improving the economics of such projects.
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1. Introduction

Carbon dioxide (CO_2) emissions continued an upward trend in the last decades. To achieve the goal stated in the Paris Agreement [1], a significant global effort to reduce CO_2 emissions is required in the coming decades [2]. In this context, science is looking towards promising low-carbon options, industry is moving towards decarbonization, and states are launching initiatives to meet climate goals.

Global decarbonization is a complicated and poorly predictable process. Known decarbonization options include energy efficiency, electrification, wind and solar energy, hydrogen-based solutions, bioenergy, and others together

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with limiting the use of fossil fuels and applying additional mitigation measures such as CC(U)S (carbon capture, utilization and storage) [3,4].

Fossil fuels play a dominant role in the global energy mix (82% of primary energy use in 2021 [5]). In the near future, according to most experts, the situation will not change significantly [6,7], even though fossil fuels account for the most of current anthropogenic CO_2 emissions [8]. Power industry is the largest CO_2 stationary source of emissions worldwide [8], and coal-fired power plants contribute relatively 42% of the total energy-related emissions [9]. Therefore, CC(U)S technologies, which can "prolong the life" of fossil fuels, are assigned one of the key roles in moving to carbon neutrality [10,11]. The Intergovernmental Panel on Climate Change (IPCC) and International Energy Agency (IEA) confidently list CC(U)S as mandatory decarbonization measures [3,4].

The main application examined so far for CC(U)S has been its use in power generation, as well as in oil and gas industry. The reason for CC(U)S spreading in the oil and gas industry is the possibility of using CO_2 to enhance oil recovery (CO_2-EOR). Deployment of CO_2 capture technologies in fossil fuel power stations is a measure to reach a compromise between the growing energy consumption and the impossibility of rapid energy transition in many countries. As for the other industries, in most cases they have the potential to use various low carbon options to decarbonize their operations, including changing energy sources, diversification towards low carbon solutions, etc. Operating fossil fuel power stations have a mature technology chain and do not have the same flexibility, as other industries, due to the complexity of changing technological processes [8]. Moreover, the main function of power plants is to produce electricity, so business model changes become virtually impossible. Renewable energy sources are still unable to provide a sufficient and stable level of electricity production, so reducing the carbon intensity of existing fossil fuel power stations without significant changes in the basic processes seems possible through the integration of CC(U)S technologies.

According to Global CCS Institute [12], in 2022 there are 29 active commercial CC(U)S projects in the world, where carbon dioxide is captured from industrial sources. Most of the projects (14) are implemented in the U.S., as well as in China and Canada (4 in each country). The number of CC(U)S projects around the world is growing faster than ever. From the end of 2020 to September 2021, the growth of capacity was around 48% (up to 111 million tonnes of CO_2 per year) [12,13]. Today, according to the latest data, there are no active CC(U)S projects in Russia.

Given the major role played by fossil fuels (including coal) in supplying energy in the world, as well as the long way to the changing energy systems, the continued use of fossil fuels is a most likely base scenario in many countries, including Russia. Coal-fired power plants provide about 14.3% of Russia's electricity generation [14], and often such plants are the only source of energy in a particular region (particularly in remote one). The ability to adapt CO_2 capture options on coal-fired power plants in Russia, as well as economic feasibility of such solutions are a major focus of the research.

The paper is aim to analyze the main approaches to costing CC(U)S, as well as the economic assessment of the CO_2 capture option implementation on coal-fired power plant in the Murmansk region (Russia). It should be noted that this paper is the first attempt to make such an economic assessment for CC(U)S projects in Russia.

2. Literature review and the design of the study

CC(U)S technologies are not economically feasible, widespread and mature, so there is a wide range of approaches to their economic assessment. The CC(U)S cost calculation is the subject of many studies. While international organizations provide detailed approaches of CC(U)S cost estimation, based on their own experience and calculation methodologies [15,16], various authors attempt to standardize these approaches by identifying specific features of each individual approach, offering common metrics and terminology [17–19]. There is no unification: developed approaches are applied for specific purposes and industries.

As mentioned above, power sector, particularly coal-fired power plants, is one of the most widespread sectors for CC(U)S implementation, but the viability of such projects is still questionable. In addition to the economic assessment of implemented CC(U)S projects at power plants [20], researchers try to conduct a technical and economic assessment of particular power plants modernization cases in countries where carbon-intensive fuels play a significant role in the energy balance, such as China [21,22], Poland [23,24], Australia [25].

The main research method is desk study. The materials of the study are the data presented in the open sources by such organizations as the IPCC, the IEA, the Global CCS Institute, the Kearney consulting agency, BP, etc., as well as the materials presented in scientific papers on the topic. Methods of systematic, comparative and critical analysis, decomposition method and method of analogy were also used in this work. Economic assessment was carried out with the use of methods for calculating the Levelized cost of electricity and Cost of CO_2 captured.

3. Cost methods

The high cost of CC(U)S is the main obstacle to their deployment. Although the cost of CO_2 capture has been decreasing over the past decade and will continue to do so through learning curves [26], CC(U)S costs are still high. Over the past eight years, 14 potentially large CC(U)S projects have been cancelled, including 11 for economic reasons [27].

In order to assess the cost of CO_2 capture at power plant in Russia, we analyzed the main approaches used to assess the cost of the full technological chain of CC(U)S.

A common approach is determining the cost of 1 tonne of CO_2 avoided. This approach is used to assess known decarbonization options and allows comparing both different decarbonization options and different CC(U)S chains among themselves [27]. For CC(U)S technologies, cost of 1 tonne of CO_2 avoided is quite high. For example, in cement industry, CO_2 capture costs can reach 200 USD per tonne of CO_2 [10], and in coal and gas-fired power plants – 270–290 USD per tonne of CO_2 [28].

CC(U)S cost assessment is also carried out separately by stages of the technological chain (capture, transport, storage). The total cost of CC(U)S is composed of the following components: (1) the cost of CO_2 capture at the source of emissions; (2) the preparation of CO_2 for transport (depending on the method of transportation); (3) the transport of CO_2; (4) injection of CO_2 underground and monitoring the storage site [26]. Capture options typically account for about 75% of the total CC(U)S cost, transportation and storage for about 25% [27].

As the cost of CC(U)S cycle will vary from industry to industry mostly due to the different cost of capture, the latter is the key parameter for assessing CC(U)S costs by industries. Natural gas processing, ethanol and ammonia production can be considered as relatively inexpensive from this point of view, while power generation, cement and steel industry can be considered as expensive [10,28,29].

When assessing the cost of CC(U)S in different sectors, another approach is used — the division of all industries into energy and industry with a difference in methods of calculating costs. This is explained by the fact that CC(U)S activities were originally focused on energy facilities, but in the last decade began to actively develop in carbon-intensive industries [30]. It is possible to note, that partial pressure of gas in power industry reaches essentially lower values, than at many industrial sources [26]. This directly affects a large cost of capturing and, accordingly, the whole process of CC(U)S at power facilities.

Since the main product of the electric power industry is electricity, which is also used to operate the capture units, it becomes possible to consider the cost of CC(U)S operation as a reduction in the final volume of electricity production. This allows using specific indicators in relation to the power industry, such as the Levelized Energy Cost (LEC) or Levelized Cost of Energy (LCOE) [31]. Since the purpose of this work is to assess the cost of capture at power station, this approach will be used for the following calculation.

4. Economic assessment

The cost assessment of the capture technology implementation at a coal-fired power plant under the conditions of Russia was carried out. Apatitskaya power plant, located in the Murmansk region, was chosen as a research case. According to its technological design the power plant relates to pulverized-coal (PC) unit. This design is currently dominant worldwide; it is characterized by higher environmental emissions into the atmosphere than other options — fluidized bed and coal gasification [32].

The capture method implemented at such facilities is mostly post-combustion capture using chemical solvents [26]. Post-combustion of the three best-known capture technologies (pre-combustion, post-combustion, oxy-fuel combustion) is the most suitable process for implementation to the existing operating plants. This is due to less need for changes to existing production processes and plant renovations, which results in less overall investment and operating costs [33].

The cost assessment was based on the calculation of the increase in the LCOE indicator due to the implementation of the CO_2 capture system. The indicator is the value of the increase in the average estimated production cost of 1 unit of electricity throughout the life cycle of the power plant, and is calculated as the ratio of all construction and maintenance costs of the capture facilities to the capacity of the power plant (formula (1)) [17]. The advantages of the LCOE metric are the ability to compare different low-carbon solutions to each other, as well as wide spread of metric and its transparency for different stakeholders. Despite this, experts recognize that this metric is only suitable for simplified economic evaluation, but not for investment decisions making, because it does not take into account market and financial factors of the project [34].

$$LCOE = \frac{\sum_i \frac{I_i + O\&M_i}{(1+r)^i}}{\sum_i \frac{Q_i}{(1+r)^i}} \quad (1)$$

I_i– initial investment costs, (USD);
$O\&M_i$ – operating and maintenance costs, (USD);
Q_i– electricity generation, (MWh/year);
i – project lifespan, (years);
r – discount rate, (%).

Input data for the calculation are presented in Table 1.

Table 1. Input data.
Source: Created by the authors.

Indicator	Unit	Value	Source
Installed capacity of power plant	MW	230	Production of electrical energy [35]
Annual electricity capacity	Million kWh	449.6	Production of electrical energy [35]
Average CO_2 emission	kg/kWh	1.01	How much carbon dioxide is produced per kilowatthour of U.S. electricity generation? [36]
Capture rate	%	90	A review of cost estimates for carbon capture and storage in the power sector [37]
Energy penalty	kWh/kg CO_2	0.31	Carbon Capture Retrofit Analyses [38]
Coal price	USD/t	18.3	Traders warn of a rise in coal prices to peak levels [39]
Electricity price	USD/MWh	10.6	Order of the Federal Antimonopoly Service of December 13, 2021 №1392/21 [40]
Ruble exchange rate	RUB/USD	60.0	
Project lifespan	years	30	
Discount rate	%	12	

It is known that the annual power generation at Apatitskaya power plant is 449.6 million kWh [35]. Assuming that the average emission rate for coal plants of this design is about 1.01 kg/kWh, we can assume that the annual amount of emissions is about 454 000 tonnes per year. Assuming a 90% capture rate, we can estimate that the annual amount of captured emissions would be 409 000 tonnes of CO_2.

Capture plants require a significant amount of electricity to operate them. Since electricity is the main product of the power industry, some of it can be used to keep the capture plants running. Thus, the plant with post-combustion capture will have the same coal consumption rate, but the net power outputs of the plant will be lower. It is necessary to take into account this reduction in the final power output at the facility. Taking into account the cost of CO_2 capture and compression units operation - 0,31 kWh/ kg CO_2, the final output of electricity to consumers will be about 322 million kWh (∼28% loss, which is close to other similar cases) [41].

We will use a scaled approach to determine the capital costs. Formula (2) shows the nonlinear growth connection between plant capacity and the amount of capital investment [26]. According to formula (2), when the average capital cost of a capture unit at a coal-fired power plant with a capacity of 1400 thousand tonnes of CO_2 per year is 1000 million USD [28], then a unit with a capacity of 409 thousand tonnes of CO_2 per year is 422 million USD.

$$Cost\ of\ plant\ A = Cost\ of\ plant\ B \left(\frac{Capacity\ of\ plant\ A}{Capacity\ of\ plant\ B}\right)^n \quad (2)$$

$Cost\ of\ plant\ A, B$ – capital investment costs for projects A, B respectively, (USD);
$Capacity\ of\ plant\ A, B$ – capture capacity for projects A, B respectively, (tonne);
n – ranges from 0.6 (single train) to 0.8 (multiple trains in parallel).

Operation and maintenance costs of the capture unit are usually divided into energy and non-energy costs. Non-energy costs for coal-fired power plants are assumed to be approximately equal to 4% of capital investments [28] - 16.9 million USD per year. Energy costs can be calculated through the consumption rate of energy resources for 1 tonne of CO_2 captured. In kind it is 0.16 MWh of electricity and 0.094 tonne of coal [28]. Thus, the costs of electricity and coal for the considered power plant are approximately 1.69 and 1.72 USD per tonne of CO_2 respectively; multiplying this value by the annual power plant capacity (409 thousand tonnes of CO_2), we get the annual costs - 1.4 million USD. Consequently, the annual cost of O&M will be 18.3 million USD.

So, according to formula (1), the increase in LCOE would be 0.23 USD for the production of 1 kWh of electricity.

If the costs are accounted only at the stage of capture, the indicator "cost of CO_2 captured" becomes particularly relevant. In contrast to the "cost of CO_2 avoided" metric, "cost of CO_2 captured" does not take into account the amount of emissions produced by capture facilities, and that may misrepresent the understanding of cost per unit of environmental effect. However, in the projects involving sale of captured CO_2, this metric allows to compare its cost with the market price and assess the economic viability of the project [42]. The essence of the method is to compare the cost of production on the site using CC(U)S and the same site without CC(U)S and to determine the costs of tonne of CO_2 captured by dividing the value of the cost difference by the amount of tonnes of captured emissions. Knowing the change in LCOE before and after the implementation of capture units, we can determine the cost per tonne of CO_2 captured using formula (3).

$$Cost\ of\ \mathrm{CO_2}\ captured = \frac{LCOE_{CCS} - LCOE_{ref}}{\left(\frac{tonne_{\mathrm{CO_2}}}{U}\right)_{ref} - \left(\frac{tonne_{\mathrm{CO_2}}}{U}\right)_{CCS}} \tag{3}$$

$(LCOE)_{CCS}$ – levelized cost of electricity with CC(U)S, (USD/kWh);
$(LCOE)_{ref}$ – levelized cost of electricity without CC(U)S, (USD/kWh);
$(tonne_{\mathrm{CO_2}}/U)_{ref}$ – amount of CO_2 emissions per unit of product without CC(U)S, (tonne/kWh);
$(tonne_{\mathrm{CO_2}}/U)_{CCS}$ – amount of CO_2 emissions per unit of product with CC(U)S, (tonne/kWh).

The amount of CO_2 emissions per unit of production without CC(U)S is 1.01 tonnes per kWh. Taking into account the remaining after-capture emissions of 45 thousand tonnes per year and the reduced final output, the amount of CO_2 emissions per unit of production with CC(U)S will be 0.14 tonnes per kWh. Thus, the cost of CO_2 captured for the current project will be 263 USD per tonne.

5. Discussion and conclusions

The study has showed that there is a range of approaches to assessing costs of CC(U)S. The power industry should be called "expensive" in terms of CC(U)S adaptation costs; however, CC(U)S deployment in this sector is critical for the balanced development of the energy sector.

There have already been attempts to calculate the carbon capture costs at coal-fired power plants in the academic discussion. Most of the calculation results are significantly lower than the results obtained in this research [33]. However, it is difficult to compare calculation results obtained in different research, because the input parameters and the technologies considered differ from case to case. Moreover, existing scientific papers present detailed project calculations [21,22], while this paper presents the first attempt at an aggregated cost calculation for Russian CC(U)S project.

The costs level of CC(U)S is primarily affected by significant amounts of capital investment. Cost reduction for specific cases and countries can be achieved through widespread development of technologies, learning curves, modularization, and economies of scale. Operating costs consist mainly of the fuel cost for the operation of capture units. The costs of electricity and coal are relatively cheap in Russia, but these advantages are still not enough to make the cost of CO_2 capture competitive in comparison with international experience. According to the calculation results we see that the cost of CO_2 captured is high (263 USD per tonne).

To date there have been two examples of commercial capture projects at coal-fired power plants around the world — Boundary Dam and Petra Nova. According to IEA, cost of CO_2 capture decreased from 110 USD per tonne at Boundary Dam (2014) to 65 USD per tonne at Petra Nova (2017) [43]. Projects' revenues come from selling CO_2 to oil and gas companies for CO_2-EOR operations (10–35 USD per tonne of CO_2 [44]), and from tax credits. Despite additional tax incentives, the Petra Nova project was suspended in 2020 for economic reasons.

The calculated LCOE indicator for Apatitskaya power plant (263 USD per tonne) is high as compared to the considered cases. This is due to high capital costs, as well as the lack of economies of scale (small capacity plants), and high energy penalty (mostly more than 20% for post-combustion capture).

The cost of electricity for the final consumers in the Murmansk region is around 0.01 USD per kWh (2022). Consequently, it is not possible to include additional costs for CO_2 capture in this price (0.23 USD per kWh).

Given the lack of carbon tax regulation and support for CC(U)S initiatives in Russia, the economic viability of such projects requires at least finding buyers of captured CO_2. In northern regions of Russia, the most realistic scenario is selling CO_2 to oil and gas companies to implement CO_2 – EOR options, but there are no oil fields in the Murmansk region. Transportation over long distances will significantly increase the cost of CO_2 captured.

In Russia, within the framework of the national climate policy, various instruments of carbon regulation are being developed and tested. Development of product and sector-related benchmarks is in progress; it is expected that for the energy sector, greenhouse gas benchmarks will be set in 2023. Regulatory documents in the field of climate policy are being improved and supplemented. At the same time, carbon regulation experiments are being carried out in some regions of Russia in 2022. These make it possible to consider carbon capture projects as viable in the future.

About 40 projects for CO_2 capture at power industry are in the stage of development around the world [45], moreover, Boundary Dam continues to operate, which means that such projects can be viable. However, such projects require a certain set of factors that determine their viability: advanced capture technology, tax incentives, large volumes of capture capacity for economies of scale, a developed transportation system, etc., as well as the presence of nearby consumers of captured CO_2.

The calculated part of the study was conducted using open data sources from similar cases. We admit that this may lead to inaccuracies in the calculations, but it is the only available approach for making preliminary calculations for Russian conditions.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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