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OVERVIEW OF CARBON CAPTURE, UTILISATION AND STORAGE TECHNOLOGIES TO ENSURE LOW-CARBON DEVELOPMENT OF ENERGY SYSTEMS

Abstract. *Carbon dioxide CO_2 is a component of air that is responsible for the growing global warning and greenhouse gases emissions. The energy sector is one of the main sources of CO_2 emissions in the world and especially in Ukraine. Carbon capture, utilization and storage (CCUS) is a group of technologies that play a significant role along with renewable energy sources, bioenergy and hydrogen to reduce CO_2 emissions and to achieve international climate goals. Nowadays there are thirty-five commercial CCUS facilities under operation around the world with a CO_2 capture capacit up to 45 million tons annually. Tougher climate targets and increased investment provide new incentives for CCUS technologies to be applied more widely. CCUS are applications in which CO_2 is captured from anthropogenic sources (power generation and industrial processes) and stored in deep geological formations without entering atmosphere or used in various products using technologies without chemical modification or with conversion. The article discusses the use of various technologies of CO_2 capture (post-combustion capture, pre-combustion capture and oxy-combustion capture), CO_2 separation methods and their application in the global energy transition to reduce the carbon capacity of energy systems. Technical and economic indicators of CO_2 capture at different efficiencies for coal and gas power plants are given. Technologies of transportation and storage of captured carbon dioxide and their economic indicators are considered. The directions for the alternative uses of captured CO_2, among which the main ones are the production of synthetic fuels, various chemicals and building materials, are also presented and described in the paper. The possibility of utilization captured CO_2 in the production of synthetic fuel in combination with Power-to-Gas technologies was studied.*

Keywords: greenhouse gases emissions, fossil fuels, CO_2 capture technologies, capture efficiency, synthetic fuel.

1. Introduction

According to the analysis of the International Energy Agency (IEA) [1], one of the key technologies for putting the world's energy systems on the path of sustainable low-carbon development and achieving international climate goals will be the capture, use and storage of carbon (carbon capture, utilization and storage – CCUS). The IEA Energy Technology Outlook 2020 report [2] highlights the central role that CCUS, along with renewable energy sources, bioenergy and hydrogen, should play in the global energy transition. CCUS is the only group of technologies that contributes both to the direct reduction of greenhouse gas (GHG) emissions in key sectors and the removal of carbon dioxide (CO_2) to balance unavoidable emissions. In the short to medium term, fossil fuels will still play an important role in the global economy, so achieving carbon neutrality requires the use of CCUS technologies to reduce carbon dioxide emissions until innovative low, zero or negative emission energy technologies are introduced. One of the advantages of CO_2 capture technologies is that they can be used to modernize existing industrial facilities.

The purpose of the article is to review the application of CCUS technologies in the energy industry as a whole, to analyze the implementation of carbon dioxide capture from the combustion of fossil fuels in thermal power plants (TPPs), and to investigate the possibility of using captured CO_2 in the production of synthetic fuels.

2. Methods and materials

CCUS technologies provide carbon dioxide capture, transportation and long-term storage without exposure to the atmosphere or use as raw materials in various industries. CO_2 capture is possible from point sources (power plants, industrial plants) burning fossil fuels or biomass for fuel, and directly from the atmosphere. If the CO_2 obtained as a result of capture is not used on site, it is transported in a compressed form by pipeline, ship, rail or road transport to the place of use or places of permanent storage in deep geological formations, which are salt aquifers or depleted oil and gas fields.

Today, there are thirty-five commercial CCUS facilities in operation around the world, capable of capturing almost 45 million tons of CO_2 annually [3]. According to the IEA, in 2021, two-thirds or 28.5 million tons of CO_2 were captured at gas processing facilities. Another third of captured CO_2 is produced in the production of fertilizers, chemicals, synthetic fuels, electricity, bioethanol, hydrogen, steel and cement. Currently, CO_2 capture has been implemented in several TPPs working on fossil fuels. The first such facility in 2014 was one of the blocks of the Boundary Dam TPP (Saskatchewan, Canada) operating on brown coal. Capture capacity is 1 million tons of CO_2 per year. The second TPP CO_2 capture facility was launched in 2017 at unit 8 of a coal-fired power plant in Texas, USA (Petra Nova project) with the ability to capture up to 1.4 million tons of CO_2 per year. Captured CO_2 has been used to improve reservoir oil recovery in oil production, but since May 2020, due to low oil prices associated with the economic effects of Covid-19, capture operations have been suspended. In 2021, 150,000 t/year CO_2 capture was implemented at Unit No. 1 of the Guohua Jinjie coal-fired TPP in Shaanxi Province (China), which became the first commercial application of CCUS in China's power sector. All projects are modernization of existing coal-fired power plants.

Tougher climate targets and increased investment provide new incentives for CCUS technologies to be applied more widely. Over the past decade, CCUS adoption has tripled. It is planned to put into operation about 200 new CCUS facilities by 2030 with a total capture volume of more than 220 million tons of CO_2 annually, of which about 70 million tons of CO_2 will be captured in electricity generation (currently about 2.5 million tons) after the introduction of CCUS technologies at more than 40 power plants around the world [3].

Today, traditional technologies for CO_2 capturing from point sources, which are TPPs, industrial enterprises for the production of iron and steel, cement, fertilizers, as well as plants for the processing of natural gas, the production of synthetic fuels and hydrogen, have become the mainstream. There are various types of carbon dioxide capture systems: from combustion products for power plants (post-combustion capture, pre-combustion capture and oxy-combustion capture, i.e. combustion of fuel enriched with oxygen) and industrial separation of CO_2 in industrial processes [4].

The most common post-combustion capture technology is where CO_2 is separated from flue gases, which generated from fuel combustion [5–8]. For this, liquid solvents (aqueous solutions of amines or ammonia) are used, which react chemically with CO_2 present in the flue gas stream (5–15%), without reacting with other components of the flue gas. After regeneration, as a result of heating, the mixture of solvent and CO_2 decomposes, pure CO_2 is formed, and the solvent is returned for reuse. Post combustion capture technologies capture up to 90% of CO_2.

Pre-combustion CO_2 capture technology involves the conversion of fuel to syngas using a steam reforming process [9, 10]. As a result, the primary fuel is first converted into a mixture of carbon monoxide CO and hydrogen H_2, and after steam treatment, into a mixture of CO_2 and H_2. The resulting mixture is separated into hydrogen and carbon dioxide in the same way as in the separation of CO_2 after combustion. The resulting gaseous hydrogen is a carbon-free energy carrier and can be used as fuel in power plants and industrial plants. The initial fuel conversion makes this capture technology more complex and more expensive than post-combustion capture, but due to the high CO_2 concentration (15–60%) and high pressure, a smaller unit is required to separate the CO_2. Pre-combustion capture technologies are mainly used in Integrated Gasification Combined Cycle (IGCC) processes [11, 12] and can achieve over 90% CO_2 capturing.

The technology of CO_2 capturing after oxygen-enriched fuel combustion differs from conventional technology by using oxygen instead of air during the combustion process, resulting in a flue gas consisting mainly of CO_2 and water vapor, with CO_2 concentrations reaching more than 80% [13]. When the flue gas is gradually cooled and condensed, the captured CO_2 is dried and, after compression, is transported to a place of storage or use.

This technology allows to capture to 100% CO_2, but requires equipment to separate nitrogen from the air to obtain pure oxygen before combustion, which complicates this technology and requires significant additional costs.

All of the above technologies require a stage of separation of CO_2 from flue streams. More advanced and common separation methods are chemical absorption and physical separation of CO_2. Membranes and cycles of cycles – chemical or calcium cycle – can also be used [14]. The choice of a specific separation technology depends on many factors – the initial and final expected concentration of CO_2, operating pressure and temperature, composition and speed of the smoke flow, integration with other equipment, cost indicators.

The process of generating electricity with CO_2 capture requires about 10–40% more energy compared to conventional generation. For combined-cycle plants, energy costs increase by 11–22%, for coal blocks – by 24–40%, for integrated gasification plants with a combined cycle – by 14–25% [15], which leads to an increase in the cost of electricity production.

Studies by the Global CCS Institute [16] on the current and likely future costs of CO_2 capturing in power generation have shown that the cost of electricity with CO_2 capture (which used for the first time) increases the least at integrated gasification combined cycle technology – by 45% and more – at coal combustion — by 60–70%. The cost of capturing decreases in downstream applications as technology advances and becomes commercialized. Thus, the cost of CO_2 capturing at the Petra Nova coal plant (USA), which was put into operation in 2017, is approximately \$65/t [1]. This is 30% less than at the Boundary Dam coal plant (Canada), which began operation in 2014, and where CO_2 capture was first used in power generation. Studies have shown that the next CO_2 capture facility, similar to Boundary Dam, can be built with a 67% lower capital cost and achieve a capture cost of \$45/tCO_2 with a capture efficiency of 90% [17].

Most modern CCUS systems capture about 90% of the CO_2 generated from point sources. Higher capture efficiency to achieve zero emissions requires a specially designed process and the use of larger and more energy-intensive separators, which increases the cost of capture accordingly. For most modern technologies, it is possible to increase the capture efficiency up to 99%. The IEA Greenhouse Gas Program has studied the impact of post-combustion capture technology (the main one today for power plants) with different capture efficiencies on the cost of electricity production and the CO_2 avoided cost for coal-fired TPPs and TPPs with a natural gas combined cycle (NGCC) [18]. It showed a fairly insignificant increase in the levelised cost of electricity (LCOE) and the CO_2 avoided cost, while achieving almost zero emissions, compared with the corresponding indicators when CO_2 capturing with an efficiency of 90%.

Increasing the efficiency of CO_2 capture from 90% to 99% for a coal-fired power plant with ultra-supercritical parameters leads to an increase in the cost of electricity generation by 8% and in the CO_2 avoided cost by 6%. But the smallest increase in LCOE cost and in CO_2 avoided cost (respectively 2% and 1.5%) to achieve zero emissions can be obtained by co-combustion of coal and 10% of biomass in a standard post-combustion capture process with 90% efficiency. In this case, biomass (wood chips, wood pellets) is mixed with coal and directly burned in the existing coal-fired boiler. The additional costs associated with modification, operation and maintenance are negligible compared to the costs of fuel handling (transportation, processing, and storage) and maintenance of the system as a whole. Table 1 shows technical and economic indicators for ultra-supercritical combustion of coal at different CO_2-capture rates, as well as for co-combustion with biomass (10%) at 2015 prices [18]. The cost of coal in the calculations is 2.5 EUR/GJ and the cost of biomass is 3.5 EUR/GJ.

For a gas-fired TPP, an increase in CO_2 capture efficiency from 90% to 99% leads to an increase in the present cost of electricity and in the CO_2 avoided cost by 7% and 8%, respectively. Table 2 shows the technical and economic characteristics for gas combustion at different CO_2-capture rates [18]. The cost of gas in the calculations is 5 EUR/GJ.

Important to the implementation of CCUS technologies are the safe transport of captured CO_2 to a place of storage or use and its cost. The two main ways are pipelines and ships. Road and rail transport is possible but at a high cost. Today the total length of CO_2 pipelines across the world is 9000 km [19]. Transportation of CO_2 through pipelines has been practiced for many years, is the cheapest way and has received the most implementation to date. Since the early 1970s in the US and Canada, pipelines have been used to transport CO_2 to oil fields for enhanced oil recovery. As a result, a great deal of experience has been accumulated in the reliable application of pipelines for transporting CO_2. With a nominal distance of 250 km, the cost of transporting CO_2 through pipelines is (1-8) USD/t [2]. There has not yet been a large-scale use of ships

Table 1. Techno-economic assessment for ultra-supercritical coal-fired TPP at different CO_2-capture rates [18]

Indicator	Combustion without capture	Combustion with capture			
		Standard capture after combustion			Co-combustion with biomass (10%)
		90%	95%	99%	90%
Total output power, MW	900	900	900	900	900
Own needs, MW	83	266.1	276.7	299.3	266.1
Useful output power, MW	817	633.9	623.3	600.7	633.9
CO_2 emissions, t/h	604	61	30	6.5	0
Intensity of CO_2 emissions, t/MW·h	0.736	0.092	0.045	0.007	0.000
Capture of CO_2, t/h	0	543	574	597.5	543
Total capital investments, mln of Euros	1343	1681	1689	1698	1714
Specific capital costs, EUR/kW	1647	2654	2712	2830	2704
Annual fixed operating expenses, mln of Euros	37.67	46.33	46.51	46.725	47.13
Annual variable operating costs, mln of Euros	7.54	20.05	22.77	23.90	20.05
LCOE, EUR/MWh	51.6	87.0	89.7	94.0	88.7
CO_2 avoided cost, EUR/t	–	55.0	55.2	58.3	55.8

for transporting CO_2. Technologically, this type of transport will be similar to the transportation of liquefied petroleum and natural gases. Transportation of CO_2 by ships (cost over $20/t) makes this type of transportation economically attractive over distances of more than 750 km, when the cost of transportation through pipelines increases significantly [20]. According to the Global Institute CCS [16], the cost of transportation together with CO_2 storage is in the range of (7–12) USD/t.

Storage involves the injection of captured CO_2 into porous geological formations more than 800 m below the earth's surface, where the CO_2 is in a dense liquid state. These deep geological reservoirs must be capped with an impermeable layer of rock to seal and prevent CO_2 from escaping into the atmosphere. Suitable storage places include salt beds and depleted oil and gas fields. Technologies for injection of CO_2 into geological formations are developed and well studied [21, 22]. Geological

Table 2. Techno-economic assessment for gas-fired TPP with NGCC at different CO_2-capture rates [18]

Indicator	Combustion without capture	Combustion with capture		
		90%	95%	99%
Total output power, MW	890	890	890	890
Own needs, MW	12	162	170	199
Useful output power, MW	878	728	720	691
CO_2 emissions, t/h	310	30.2	15.8	2.9
Intensity of CO_2 emissions, t/MW·h	0.349	0.0373	0.0176	0.000
Capture of CO_2, t/h	0	279.4	293,8	306.7
Total capital investments, mln of Euros	835.7	1172.8	1177.4	1185.3
Specific capital costs, EUR/kW	939	1611	1629	1716
Annual fixed operating expenses, mln of Euros	29.16	39.67	39.815	40.04
Annual variable operating costs, mln of Euros	3.41	11.92	12.31	12.82
LCOE, EUR/MWh	52.9	77.6	78.9	82.7
CO_2 avoided cost, EUR/t	–	79.3	78.6	85.5

storage of CO_2 requires much the same methods used in the oil and gas industry, as the process is very similar to underground gas storage. The current and projected cost of CO_2 storage varies significantly depending on the rate of CO_2 injection, the characteristics of geological reservoirs and their location. The cost of developing new storage locations is significantly uncertain. Depleted oil and gas fields using existing wells are expected to provide cheap CO_2 storage. At the same time, the cost of storage in practice can be quite low, and in cases of using CO_2 for enhanced oil recovery, even negative, taking into account additional income from oil production. According to the IEA [1], more than 60% of CO_2 storage in the United States has a cost of less than \$10/t, and about 20% less than \$15/t. Offshore storage of CO_2 is much more expensive – (15–55) USD/t.

In addition to storage, CCUS technologies provide for the utilization of CO_2, i.e. its use as raw material to a range of products and services. Injection of captured CO_2 into producing fields for enhanced oil recovery is an example of combining CO_2 storage with its use. Both direct use, when CO_2 does not change chemically and transformation into another product are possible.

To date, the world uses approximately 230 million tons of CO_2. The greatest consumption of CO_2 occurs in the production of fertilizers (125 million tons) and in the oil and gas industry for enhanced oil recovery (70–80 million tons). Currently, there is a development of new directions for the use of CO_2, among which the main ones are the production of synthetic fuels, the production of various chemicals in the structure of which carbon is present (polymers, ethylene and methanol) and the production of building materials, where CO_2 is used as a substitute for water in concrete or as their raw material component (cement, building aggregates) [23].

To reduce the carbon capacity of energy systems, there is considerable interest in using captured CO_2 to produce synthetic fuels, covering a range of well-known commercial products – methane, methanol and syngas (a gas mixture of carbon monoxide and hydrogen). They can be used directly as a fuel or as an intermediate for the production of other fuels (diesel, gasoline, jet fuel). The fuel obtained from CO_2 can be used both in the transport sector and in other sectors of the economy, including industry, electricity and heat generation.

Carbon dioxide is a stable compound with a low energy state. To turn it into a high-energy fuel, a large amount of external energy is required. The overall conversion efficiency is about 50% and differs for different types of fuel. The most mature CO_2 conversion pathways use energy in the form of hydrogen. To decarbonize the power industry, it is necessary to use «green» hydrogen, obtained by electrolysis from renewable energy sources, to produce low-carbon synthetic fuels from captured carbon dioxide. Dependence on natural conditions makes the process of obtaining electricity from renewable energy sources intermittent and unstable, which requires its balance for the stable operation of the electrical network and the use of reserve shunting capacities and means of long-term storage of large amounts of electricity. Power-to-Gas (PtG) technology contributes to solving this problem and provides an alternative to the introduction and use of energy storage mechanisms. PtG envisages in the first stage the use of excess electricity from renewable sources to produce hydrogen H_2 by electrolysis of water, and then, in the second stage, the conversion of the produced hydrogen together with CO_2 from an external source through methanation into synthetic methane CH_4 or grid-compatible synthetic natural gas. Methanation is a mature technology which is already widely applied in industrial processes [24]. Schematically, PtG technology can be represented as follows (Fig. 1) [25].

The widespread use of hydrogen obtained as a result of the first stage of PtG is still constrained by the need to develop new equipment and create an appropriate infrastructure. An alternative is the two-stage application of PtG technology, which makes it possible to obtain synthetic methane, which, as a substitute for natural gas, can be pumped into the gas network or stored in gas storage facilities with their high volumetric potential. It does not require additional investment in infrastructure and utilizes the captured CO_2 [26].

It should be noted that Power-to-Gas technology is under research and its widespread adoption is expected in the medium and long term. To date, there are more than 100 diverse PtG pilot and demonstration projects, indicating a growing interest in the technology [27]. About half of the projects are looking at a two-stage methanation technology to convert excess electricity into a substitute for natural gas. Most of the research projects are in Germany, Denmark, USA and Canada. An example of a commercial application of PtG is the Audi E-gas syngas plant in Werlte (Germany), which has been operating since 2013 [28]. A 6 MW industrial plant produces by catalytic methanation about 1000 tons of synthetic methane per year from 2800 tons of captured CO_2 from the biogas plant and hydrogen obtained by alkaline electrolysis from renewable

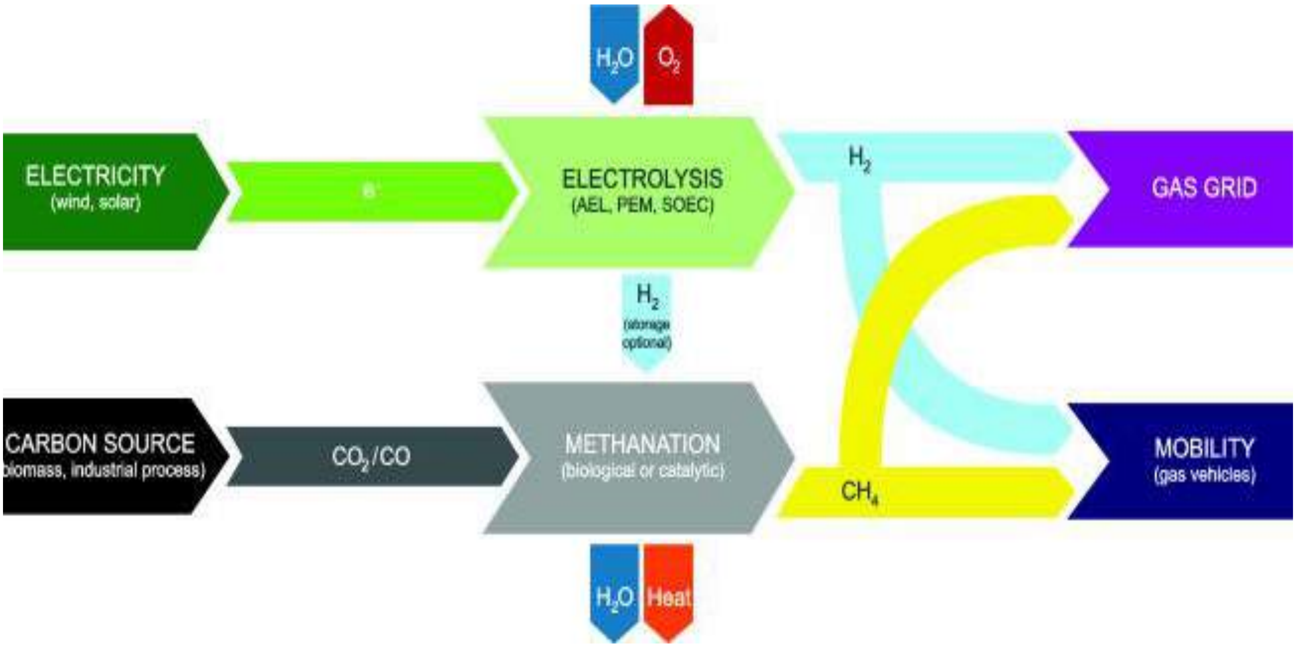

Fig. 1. Schematic of PtG Technology

sources. The resulting synthetic gas is fed into the city's gas network.

The main cost components for the production of synthetic methane from CO_2 are the capital costs of equipment for electrolysis and methanation, the cost of hydrogen, electricity and captured CO_2. According to the IEA [23], the cost of producing synthetic methane from carbon dioxide today in most world regions is several times higher than their fossil counterparts. The major cost driver is electricity, which accounts for 40 to 70 percent of production costs. Therefore, competitive production of methane from CO_2 is possible with a low average cost of electricity, sufficient CO_2, and high fossil fuel prices. Also, the cost of producing fuel from CO_2 is affected by emission pricing policies and restrictions on the use of fossil fuels. Over time, the cost of producing fuel from CO_2 is expected to decrease due to a significant reduction in capital costs for electrolysis and methanation technologies [29] and the availability of cheap renewable energy and CO_2, which will lead to the competitiveness of the cost of producing synthetic methane.

The technical and economic performance of synthetic natural gas production is also affected by the location of renewable energy sources, an electrolyzer for hydrogen production, water and carbon dioxide sources. Placement of the electrolyzer next to the source of captured CO_2 (TPP) makes it possible to refuse the transportation of hydrogen, but requires the transfer of electricity from renewable source to the electrolyzer. Alternatively, the electrolyzer can be located near a wind farm (WPP) or solar (PV) station (subject to the availability of a water source). In this case, there is a need for a pipeline to transport hydrogen to a synthetic natural gas plant, which may be located near a TPP with CO_2 capture. Such a layout was considered in [29] for calculating the cost of producing synthetic natural gas: hydrogen is produced from wind energy by electrolysis near wind farms and is supplied by a special pipeline to the suburbs, where there is a TPP that captures CO_2 and a synthetic gas production plant. Synthetic gas obtained as a result of methanation at the plant is compressed and pumped into the city's gas distribution network for further use by residential and commercial consumers. The feasibility study carried out in [30] showed that the cost of producing synthetic natural gas largely depends on the cost of hydrogen and, to a lesser extent, on the power utilization factor. With a capacity utilization factor of 90% and a hydrogen cost of \$3/kg, the cost of syngas production is \$124/MWh, with 75% of this cost coming from hydrogen, 14% from capital costs, 5.5% from for operating costs and 5.5% for the cost of CO_2, which is assumed to be \$40/t. With a reduction in the capacity factor to 65%, the cost of producing synthetic natural gas increases slightly – to more than 132 USD/MWh. At the same time, the increase in the cost of hydrogen has a significant impact on the cost of syngas production – approximately 188 and 252 US dollars per MWh at hydrogen prices of 5 and 7 US dollars per kg, respectively (at a capacity utilization factor of 90%).

3. Results and discussion

Studies have shown that carbon dioxide capture in industrial facilities and power plants can significantly reduce greenhouse gas emissions from the combustion of fossil fuels. Most modern CCUS systems capture CO_2 from point sources with an efficiency of 90%. Increasing the capture efficiency to achieve zero emissions in power plants requires little additional cost. To date, the vast majority of captured CO_2 is stored in geological formations (salt beds and exhaustible oil and gas fields). This trend under the IEA NetZero scenario will continue in 2030 – more than 95% of the captured CO_2 will be stored and less than 5% will be used [31], which is associated with significant uncertainty in the scale of CO_2 use, the development of markets and technologies, as well as dependence on support within the policy.

The combination of CCUS and Power-to-Gas technologies produces carbon-neutral synthetic natural gas from green hydrogen and captured carbon dioxide. The cost of production is largely dependent on the cost of hydrogen. Comparison of the cost of producing synthetic natural gas with natural gas prices in North America (20–30 US$/MWh) shows that it is several times higher. For the European gas market, where the price of natural gas has recently exceeded 100 EUR/MWh, and sometimes reaches 200 EUR/MWh, the cost of synthetic natural gas can be competitive in the medium term, especially with the projected decline in the price of hydrogen, received from renewable energy sources. The future use of captured CO_2 is still very uncertain given the early stage of technology development for many applications. The analysis shows that the production of synthetic fuels has the greatest potential for using captured CO_2 due to the huge size of the market.

4. Conclusions

CCUS technologies are promising technologies for reducing the carbon footprint of energy systems and will play a key role in the global energy transition. Fossil fuels will continue to play an important role in the production of electricity and heat in the next 10-15 years, and therefore CCUS technologies are indispensable for reducing CO_2 emissions and achieving carbon neutrality.

The introduction of CCUS technology in the power generation is at an early stage. The first large-scale facility was launched less than 10 years ago. To date, there are only a few such facilities in the world and they are capable of capturing approximately 2.5 million tons of CO_2 per year. But in the period up to 2030, according to the plans of the IEA, the active introduction of new CCUS facilities is expected at more than 40 power plants with a total amount of capturing about 70 million tons of CO_2 annually.

To date, the main and cheapest capture technology after combustion is based on chemical absorption with a capture efficiency of 90%. Achieving zero CO_2 emissions by increasing capture rates to more than 99% does not require significant additional costs, and co-firing of coal with biomass (10%) is the most cost-effective carbon neutral option.

The use of captured CO_2 is small scale and uncertain given the early stage of technology development and dependence on policy support. Synthetic fuel production has the greatest potential for using captured CO_2. The combination of Power-to-Gas and CCUS technologies results in carbon-neutral synthesis gas.

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ОГЛЯД ТЕХНОЛОГІЙ УЛОВЛЮВАННЯ, ВИКОРИСТАННЯ ТА ЗБЕРІГАННЯ ВУГЛЕЦЮ ДЛЯ ЗАБЕЗПЕЧЕННЯ НИЗЬКОВУГЛЕЦЕВОГО РОЗВИТКУ ЕНЕРГЕТИЧНИХ СИСТЕМ

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Анотація. *Двоокис вуглецю CO_2 є компонентом повітря, що відповідає за зростання глобального потепління та викидів парникових газів. Енергетичний сектор є одним із основних джерел викидів CO_2 у світі та особливо в Україні. Уловлювання, утилізація та зберігання вуглецю (CCUS) є групою технологій, які разом з відновлюваними джерелами енергії, біоенергетикою і воднем відіграють важливу роль у зменшенні викидів CO_2 і досягненні міжнародних кліматичних цілей. На сьогодні в світі працює тридцять п'ять комерційних об'єктів CCUS із потужністю уловлювання до 45 млн т CO_2 щорічно. Посилення кліматичних цілей і збільшення інвестицій надають технологіям CCUS нові стимули для більш широкого застосування. Уловлювання, утилізація та зберігання вуглецю – це програми, в яких CO_2 уловлюється з антропогенних джерел (виробництво електроенергії та промислові процеси) та зберігається в глибоких геологічних формаціях без потрапляння в атмосферу або використовується в різних продуктах за допомогою технологій без хімічної модифікації або з перетворенням. У статті розглядається використання різних технологій уловлювання (після спалювання, до спалювання і спалювання збагаченого киснем палива), методів сепарації CO_2 та їх застосування в глобальному енергетичному переході для зменшення вуглецевої ємності енергетичних систем. Наведено техніко-економічні показники уловлювання CO_2 при різній ефективності для вугільних та газових електростанцій. Розглянуто технології транспортування і зберігання уловленого двоокису вуглецю та їх економічні показники. В роботі також представлені та описані напрями альтернативного використання уловленого CO_2, серед яких основними є виробництво синтетичного палива, різних хімікатів і будівельних матеріалів. Досліджено можливість використання уловленого CO_2 при виробництві синтетичного палива у комбінації з технологіями Power-to-Gas.*

Ключові слова: викиди парникових газів, викопні палива, технології уловлювання CO_2, ефективність уловлювання, синтетичне паливо.

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