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Carbon Capture and Utilization through Biofixation: A Techno-Economic Analysis of a Natural Gas-Fired Power Plant †

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Abstract: With the increasing global concern regarding climate change and the need to reduce greenhouse gas emissions, carbon capture and utilization (CCU) technologies are seen as one of the primary steps toward large-scale decarbonization prospects. In this context, a thorough assessment of each CCU pathway is required from both the techno-economic and environmental perspectives. In this work, the potential of carbon biofixation through microalgae cultivation is evaluated through the preliminary technical design and calculation of plant economics in the case of the Turakurgan natural gas-fired combined cycle power plant located in the eastern part of Uzbekistan. The primary data used in this study are obtained from the open access project report of the targeted power station, along with recently published literature sources. According to the results, although the purchase and installation costs of photobioreactors require significant investments in the capital costs, the technology would still be cost competitive as long as there is a carbon tax imposition of around USD 50 per ton of CO_2 emissions. However, CO_2 biofixation can be relatively more suitable compared to benchmark absorption, particularly in low-CO_2-concentration conditions. Future research will involve a more comprehensive examination of CO_2-based microalgae cultivation and its comparison with chemical absorption and membrane-assisted separation techniques.

Keywords: carbon capture; CO_2 utilization; carbon biofixation; microalgae cultivation; CO_2 bio-product; NGCC power plant; Uzbekistan

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1. Introduction

When it comes to fighting against the escalating threats of climate change, primarily driven by anthropogenic CO_2 emissions, specifically by fossil fuel combustion, urgent actions need to be taken toward carbon reduction at both global and national scales. The fossil fuel-fired power generation sector, a major contributor to greenhouse gas emissions, is the first target to initiate the decarbonization plans [1]. In this context, the Republic of Uzbekistan, hereinafter referred to as Uzbekistan, also plays a key role in the CO_2 emission profile of Central Asian countries. Uzbekistan, as a member of Paris Agreement, announced its first NDC plan for CO_2 emission reduction by 10% per unit of GDP by 2030, with a base year of 2010, followed by a further reduction by 35% within the previously planned period. Apart from that, Uzbekistan also has an ambition of reaching net zero emissions in its power sector by 2050. This target can be achieved by switching to renewable energy sources (RESs) in combination with CCSU technology [2–4].

The fossil fuel dependency in the energy sector of Uzbekistan is substantial, accounting for more than 40% of the country's total CO_2 emissions. The majority of fossil fuel-fired power plants burn natural gas as a primary fuel responsible for an almost 80% of CO_2 emissions of the power sector [2]. While conventional natural gas-fired power plants offer a cleaner alternative to coal-fired plants, their emissions remain a significant concern. Among natural gas-fired power plants, most of the power plants operate in combined cycle mode. Natural gas combined cycle (NGCC) power plants, which utilize a combination of gas and steam turbines, offer higher efficiency and lower emissions compared to their conventional counterparts. However, even NGCC plants emit substantial amounts of CO_2, necessitating the implementation of CCSU technologies to further reduce their environmental impact [5].

There are several methods and techniques for CO_2 capture from power plants, each being related to one of the pre-, post-, and oxy-fuel combustion methods. Among them, the post-combustion carbon capture (PCC) technique is considered the most mature, as it can be retrofitted to existing power plants with minor modifications. PCC offers a range of CO_2 capture approaches, including chemical and physical absorption, adsorption, membrane separation, cryogenic separation, and CO_2 biofixation [6]. Each of these methods has its own advantages and disadvantages, and the choice of method depends on factors such as the flue gas composition, desired capture efficiency, resource availability, geolocation, and economic considerations.

As for the PCC from NGCC power plant, the main challenge is the relatively low concentration of CO_2 in the flue gas at around 4 vol% compared to conventional natural gas-fired (8–9%) and coal-fired (12–14%) power generation exhausts [5]. In this case, while the energy-intensive nature and high costs of many PCC techniques can be seen as disadvantages, CO_2 algae cultivation emerges as a feasible candidate for implementing CCSU in NGCC power plants due to not only its suitability but also the simultaneous capability for utilization as biomass and subsequent bioproducts. Apart from that, NGCC flue gas is rather cleaner than coal-fired exhausts, containing mainly H_2O, CO_2, N_2, O_2, and trace amount of NO_x and SO_x, which eliminates the need for flue gas pre-treatment for biofixation as some algae cultures can simply tolerate them [7].

CO_2 biofixation is a biological process in which CO_2 is captured and converted into organic compounds by living organisms, such as plants, algae, and certain bacteria [8]. Incorporating microalgae-mediated biofixation for carbon capture and utilization (CCU) presents a promising solution for reducing CO_2 emissions from thermal power plants. As highlighted in the review by Scapini et al. [9], microalgae have demonstrated significant potential in biofixating CO_2 through photosynthesis at rates 10–50 times higher than terrestrial plants. Key species such as *Chlorella*, *Scenedesmus*, and *Arthrospira* are particularly effective in capturing CO_2 directly from industrial flue gases while tolerating high concentrations of pollutants like nitrogen oxides (NO_x) and sulfur oxides (SO_x) [9]. Additionally, microalgal biorefineries, as part of the bio-CCU strategies, offer a promising platform for transforming waste CO_2 into economic assets, thus contributing directly to global sustainability initiatives [10]. Algae cultivation can also be highly effective for wastewater treatment and the removal of toxic pollutants. For example, microalgal–bacterial systems biofixate carbon along with efficiently removing nitrogen and organic carbon from wastewater, offering a sustainable method for treating industrial effluents while simultaneously producing valuable biomass [11].

There were several studies dealing with CCSU application in thermal power plants through PCC biofixation. For instance, Gharanjik et al. explored the use of various microalgae strains for CO_2 capture directly from flue gas emitted by the Neka thermal power plant. The study focused on three microalgae species, *Spirulina* sp., *Chlorella vulgaris*, and *Scenedesmus obliquus*, and compared their ability to biofixate CO_2, grow, and accumulate lipids under different CO_2 concentrations (0.03%, 2%, and 5%). The findings suggest that

Chlorella vulgaris is highly efficient in CO_2 biofixation and lipid production, making it suitable for biodiesel production. This research highlights the potential of using flue gas from power plants as a direct source of CO_2 for microalgae cultivation without pre-treatment [12]. Oliveira et al., investigated the economic viability of biofixation for CO_2 emissions from Portuguese NGCC power plant flue gas using microalgae *Chlorella vulgaris* in a closed-loop photobioreactor [13]. According to the summary of their results, algal-based CO_2 fixation can be economically viable despite the large investment requirement. In addition, Llamas et al. also studied the techno-economic aspects of algae cultivation using power plant flue gas, testing both open raceway pond and closed photobioreactors [14]. They emphasized different biomass market value and biomass production in these two different techniques. Based on their results, as long as there is a carbon cost of EUR 50 per ton of CO_2, the technology can compete with other pathways. Furthermore, there are several other research studies and investigations that have been conducted on CO_2 biofixation in studies of microalgae characteristics and performances [15–17]. However, most of those investigations either focused on CO_2-based bioproducts or algae characteristics. Considering that this pathway requires detailed data such as the location, resource, water or wastewater, and land availability, and the real characteristics of NGCC flue gas, this study aims to evaluate the CO_2 biofixation and its techno-economic and environmental viability to the specific Turakurgan NGCC power plant located in Uzbekistan.

2. Methodology

Several processes and their interdependence must be taken into account while implementing a biological CCSU unit in the Turakurgan NGCC power plant. The present investigation proposes extracting flue gases directly from the power plant's exhaust, bypassing the stack, and then introducing them into an adjacent microalgae cultivation system. This method eliminates the need to vent flue gases into the atmosphere. To facilitate this process, the microalgae production unit must be built near the power plant, as the flue gases cannot be transported over long distances. Figure 1 below shows the locations of the large-scale power plants in Uzbekistan (left) and the selected Turakurgan NGCC power plant (right). Table 1 provides the flue gas stream characteristics at the stack.

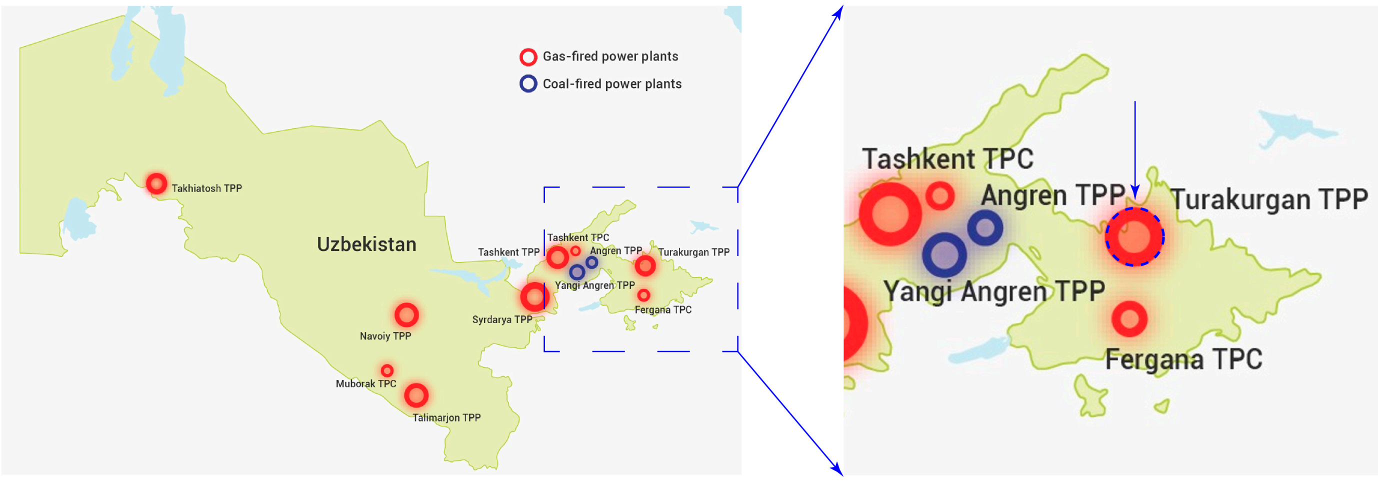

Figure 1. Locations of the large-scale power plants in Uzbekistan (**left**) and the selected Turakurgan NGCC power plant (**right**).

Table 1. Flue gas characteristics at the stack of the power plant.

Parameters		Compositions (mol%)	
Flue gas exit mass flowrate (kg/s)	707	N_2 O_2	0.76 0.12
Flue gas exit temperature (°C)	104	CO_2 H_2O	0.04 0.077
Flue gas exit pressure (kPa)	98.1	Argon (Ar) Nitric oxide (NO_x)	0.002 0.001

The process begins with an NGCC power plant that generates flue gas, which undergoes pre-treatment before being directed into photobioreactors for algae cultivation (see Figure 2). In these reactors, algae fix the CO_2 from the flue gas, aided by solar radiation and water. The wet algae product is then sent for further treatment and processing, leading to the final algae product, while treated wastewater and oxygen-rich gas are released as byproducts.

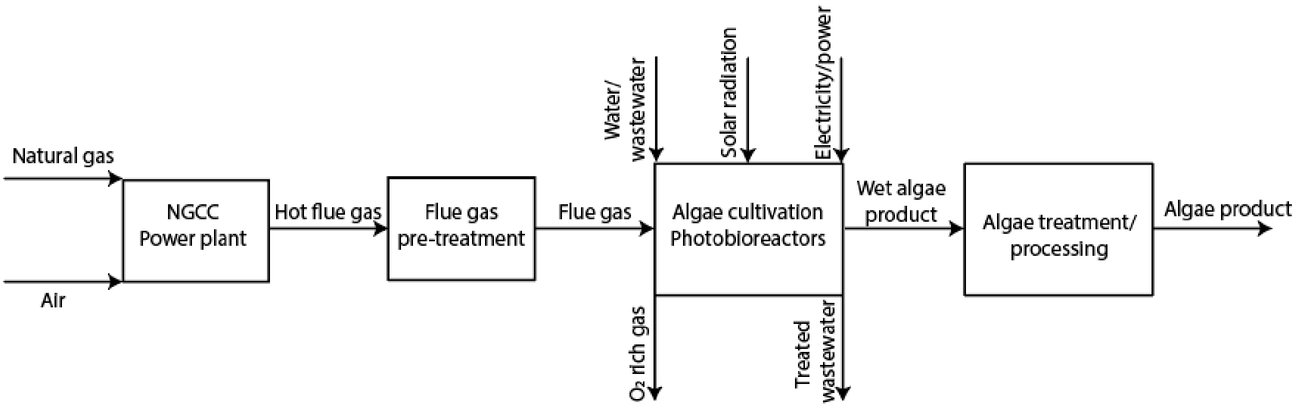

Figure 2. General process flow diagram of CO_2 biofixation through algae cultivation.

Table 2 provides the dimensions of the main equipment used in the CO_2 biofixation process through microalgae cultivation. The total volume of the photobioreactors is 946,583 m^3, with each individual photobioreactor having a volume of 320 m^3, a length of 1629 m, and a diameter of 0.5 m. There are 2958 photobioreactors in total. Additionally, the direct contact cooler has a volume of 1700 m^3, and the mixing tank for each photobioreactor holds 27 m^3.

Table 2. The dimensions of the main equipment.

CO_2 Biofixation through Microalgae Cultivation	Units	Dimensions
Total volume of photobioreactors	m^3	946,583
Photobioreactor's individual volume	m^3	320
Number of photobioreactors	-	2958
Length of each photobioreactor	m	1629
Diameter of each photobioreactor	m	0.5
Direct contact cooler volume	m^3	1700
Mixing tank volume for each photobioreactor	m^3	27

As for the technical assessment, there has not been any large-scale CO_2 biofixation plant with a closed pond system. Therefore, we used general chemical engineering principles and the literature data to estimate the techno-economic performance of the plant to identify the viability and competitiveness of the plant. The main parameters, assumptions, and considerations for technical analysis of the plant are as follows [7,13,18–20]:

- For algal CO_2 fixation, flue gas with a CO_2 concentration of 2–5 vol% is enough.

- Several studies indicate that 1 kg of microalgal biomass can fix roughly 1.80 to 2 kg of CO_2.
- Raceway ponds capture CO_2 at an efficiency of around 10%, significantly less than greenhouses (35%) and photobioreactors (up to 75%).
- *Chlorella vulgaris* microalgae culture is considered to have a CO_2 fixation rate of between 3.4 and 6.2 g/L/day (average 4.8 g/L/day).
- Trace elements like NO_X in flue gas can act as nutrients for microalgae, eliminating the need for scrubbing.

The mass balance of the process is provided in Figure 3, showing each 1 m^3 volume of the photobioreactors. The carbon fixation rate in the literature varies significantly, ranging from 0.2 to 30 kg/m^3 per day, depending on the characteristics of the flue gases mentioned above. A conservative value of 2.9 kg/m^3 per day was chosen as a less favorable scenario to account for potential difficulties in carbon uptake within the system. Biomass productivity is considered to be 1.5 kg/m^3/day, with a specific growth rate of 1.93 kg CO_2/kg biomass/day.

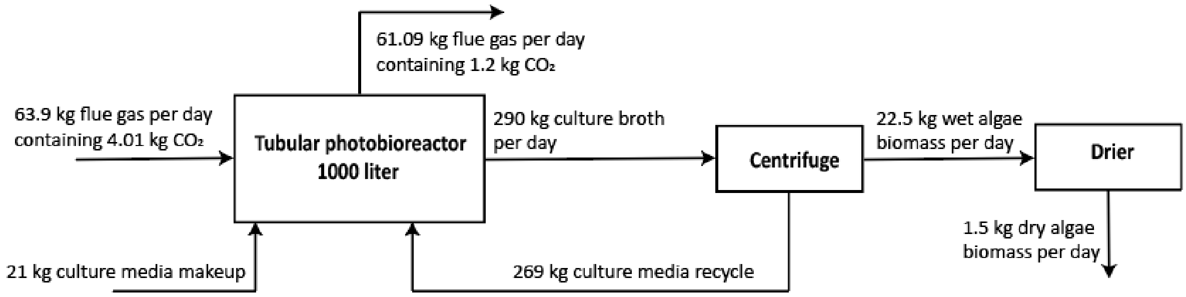

Figure 3. Mass balance of the process.

In terms of the economic estimation, the net present value of the CO_2 fixation plant is used to evaluate the economic viability of this route (Equation (1)). Sensitivity analysis is also employed to estimate the required carbon allowance in different costs as a profit for the fixation plant.

$$\sum_{i=1}^{n} \frac{CF_i}{(1+r)^i} - Total\ CAPEX \quad (1)$$

where: n is the life of the project in years, CF_i is the calculated net cash flow for the ith period, and r is the discount rate. As for CF_i, it is calculated as the total annual revenue (TAR) subtracting the total OPEX using the following expressions (Equation (2)):

$$TAR - (Fixed\ OPEX + Variable\ OPEX) \quad (2)$$

Apart from that, there are several assumptions and considerations for economic estimation, which are provided below in Table 3.

Table 3. Assumptions and considerations for economic estimation of the CO_2 fixation plant [13,14,21].

	Description	Costs
CAPEX	Annual interest rate (%)	12
	Plant economic life (years)	15
	Each photobioreactor cost (EUR/m^3)	2000
	Other supportive instruments and land cost	20% of CAPEX
OPEX	Fixed OPEX including control and maintenance, labor, etc.	3% of total CAPEX
	Water cost (EUR/m^3)	≈Pumping cost
	Electricity cost (EUR/kWh)	0.08
	Each batch process duration (days)	10
	Number of working days in a year	300

Table 3. *Cont.*

	Description	Costs
Revenue	Algal biomass cost unprocessed (EUR/t)	500–1000 (average of 750)
	Oxygen rich gas cost	Not included
	CO_2 allowance and CO_2 tax and CO_2 cost (EUR/t of CO_2)	0–100

3. Results and Discussion

The techno-economic estimation results of CO_2 biofixation through microalgae cultivation with 450 MW Turakurgan NGCC power plant flue gas are obtained in this study.

Given the massive levels of CO_2 emissions for biofixation, the microalgae cultivation system will also need to be at a very large scale. However, from the first glance, according to the rough estimation, it can be viable as long as there is a driver of using CO_2 from power plant flue gas, such as carbon tax imposition. Apart from that, the results are also highly dependent on the biomass production facility, quality, and cost.

Table 4 provides a comprehensive summary of the techno-economic indicators for the CO_2 biofixation plant under a carbon allowance of EUR 50 per ton of CO_2 and a biomass production cost of EUR 750 per ton. The results emphasize the dual benefits of the biofixation system, namely effective CO_2 removal and substantial biomass production.

Table 4. Different tuning results for techno-economic estimation at a CO_2 allowance of 50 EUR/ton CO_2 and produced biomass cost of 750 EUR/ton.

	Main indicator	Results
Total investment cost	Photobioreactor cost (million EUR)	1514.533
	Infrastructure to support PBR tube vessels (million EUR)	32.522
	Storage tanks for water/culture medium recycling (million EUR)	51.453
	Centrifuge for microalgae biomass harvesting (million EUR)	7.863
	Combined oxygen and temperature control in PBR (million EUR)	8.398
	Microfiltration/sanitization system for freshwater and culture medium (million EUR)	20.505
	Direct contact cooler cost (million EUR)	4.257
	Blower for flue gas pressure increase (million EUR)	3.635
	Total CAPEX (million EUR)	1893.167
	Annualized CAPEX (million EUR)	277.963
Fixed OPEX	Labor cost (million EUR/year) Equipment and maintenance (million EUR/year) Insurance and others (million EUR/year)	56.795
Variable OPEX	Water cost (million EUR/year) Electricity cost (million EUR/year)	4.724
	Culture media (nutrients) cost (million EUR/year)	16.603
	Total OPEX (million EUR/year)	21.327
Total revenue	Biomass produced (Mton/year)	425.962
	CO_2 avoided (Mton/year)	823.527
	Biomass revenue cost (million EUR/year)	319.472
	Carbon allowance cost (million EUR/year)	41.176
	Total annual revenue (million EUR/year)	360.648
Total annualized cost (million EUR)		356.084
Net Present Value (million EUR)		31.084

The techno-economic indicators emphasize the dual benefits of the biofixation system: effective CO_2 removal and substantial biomass production. With an annual CO_2 removal of 823,527 tons and biomass production of 425,962 tons, the system not only mitigates carbon emissions but also generates valuable biomass, contributing to the overall revenue. Despite a very high costs of CAPEX, the project achieves a positive NPV of EUR 31.084 million at a

CO_2 allowance of EUR 50/ton, demonstrating that the economic returns from the biomass revenue and CO_2 removal allowances can offset the initial and ongoing expenses. On the other hand, the NPV analysis, as depicted in Figure 4, illustrates the financial performance of the carbon biofixation project under various carbon tax scenarios. The NPV represents the difference between the present value of cash inflows and the present value of cash outflows over the project's lifetime.

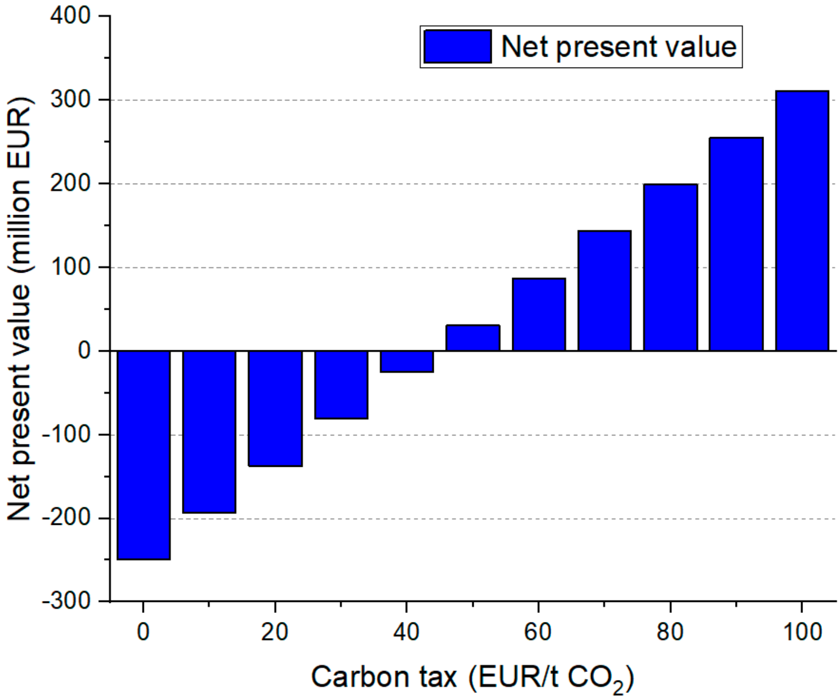

Figure 4. Net present value in response to the different carbon tax costs.

The analysis reveals that without a carbon tax, the project would incur significant financial losses, as indicated by the negative NPV in a EUR 0/t CO_2 tax scenario. However, introducing a carbon tax dramatically shifts the economic landscape, turning the NPV positive at around EUR 50/t CO_2 and continuing to increase with higher taxes.

These findings highlight the importance of economic incentives such as carbon taxes and CO_2 allowances in promoting CCU technologies. The positive NPV at a moderate carbon tax level suggests that policy frameworks encouraging higher carbon taxes could substantially enhance the financial attractiveness of CCU projects, facilitating wider adoption and contributing to climate change mitigation efforts.

4. Conclusions

This study assessed the feasibility of using microalgae cultivation for carbon capture and utilization (CCU) by designing a preliminary technical plan and calculating the economics of a system implemented at the Turakurgan natural gas power plant in eastern Uzbekistan.

This study underscores the critical role of carbon taxes and financial incentives in the viability of CCU projects. Higher carbon tax levels significantly enhance the NPV, suggesting that economic policies are pivotal in driving the adoption of sustainable technologies. Moreover, the production of biomass as a by-product provides a valuable revenue stream, further bolstering the economic case for CCU implementations in natural gas-fired power plants. Overall, while large-scale microalgae cultivation is necessary to handle significant CO_2 emissions, a few factors make it potentially viable. Firstly, a carbon tax on power plant emissions could incentivize capturing CO_2 for biofixation. Secondly, the success of this approach depends heavily on optimizing biomass production facilities for both high yields and cost-effectiveness.

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Abbreviations

NGCC	Natural gas combined cycle
NDC	Nationally determined contribution
GDP	Gross domestic product
NPV	Net present value
CCSU	Carbon capture, storage, and utilization
CCU	Carbon capture and utilization
RES	Renewable energy sources
PCC	Post-combustion carbon capture
CAPEX	Capital expenditure
OPEX	Operational expenditure

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