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Review

The Changing Role of CO_2 in the Transition to a Circular Economy: Review of Carbon Sequestration Projects

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Abstract: Despite the diversity of studies on global warming and climate change mitigation technologies, research on the changing role of CO_2 in the industrial processes, which is connected with the introduction of circular economy principles, is still out of scope. The purpose of this review is to answer the following question: Is technogenic CO_2 still an industrial waste or has it become a valuable resource? For this purpose, statistical information from the National Energy Technology Library and the Global CCS Institute databases were reviewed. All sequestration projects (199) were divided into three groups: carbon capture and storage (65); carbon capture, utilization, and storage (100); and carbon capture and utilization (34). It was found that: (1) total annual CO_2 consumption of such projects was 50.1 Mtpa in 2018, with a possible increase to 326.7 Mtpa in the coming decade; (2) total amount of CO_2 sequestered in such projects could be 2209 Mt in 2028; (3) the risk of such projects being cancelled or postponed is around 31.8%; (4) CO_2 is a valuable and sought-after resource for various industries. It was concluded that further development of carbon capture and utilization technologies will invariably lead to a change in attitudes towards CO_2, as well as the appearance of new CO_2-based markets and industries.

Keywords: CO_2 sequestration; CCS; CCUS; CCU; industrial waste; resource; circular economy

1. Introduction

The problem of global warming has been widely discussed in the recent decades [1,2]. One of the key reasons is an exponential growth of technogenic greenhouse gas emissions, mainly CO_2. To slow this growth, many so-called global warming (climate change) mitigation technologies [3,4] are currently being implemented. Despite some doubts [5,6], one of such promising technologies is CO_2 sequestration (Figure 1), with its subsequent use or disposal in geological formations [7].

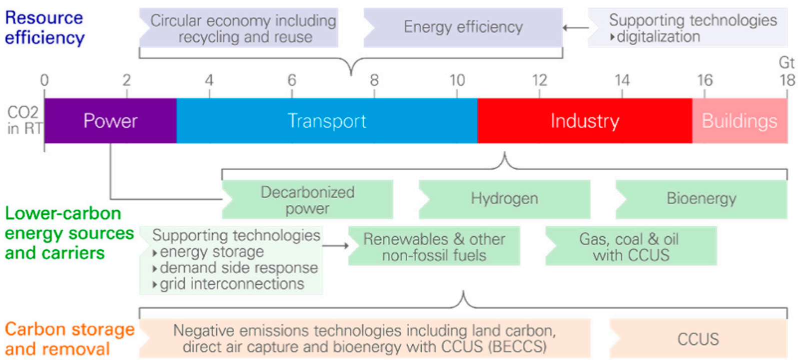

Figure 1. Improvements for further substantial reductions in CO_2 emission [8]. Acronyms: RT = BP's rapid transition scenario (all possible CO_2 reduction measures for power, transport, industry, and buildings); CCUS = carbon capture, utilization, and storage.

CO_2 sequestration is a cluster of technologies [9,10], which can be divided into three groups: carbon capture and storage (CCS); carbon capture, utilization, and storage (CCUS); and carbon capture and utilization (CCU). In literature, there are different definitions and distributions of such projects within these three groups. In this regard, we propose the following division (Figure 2).

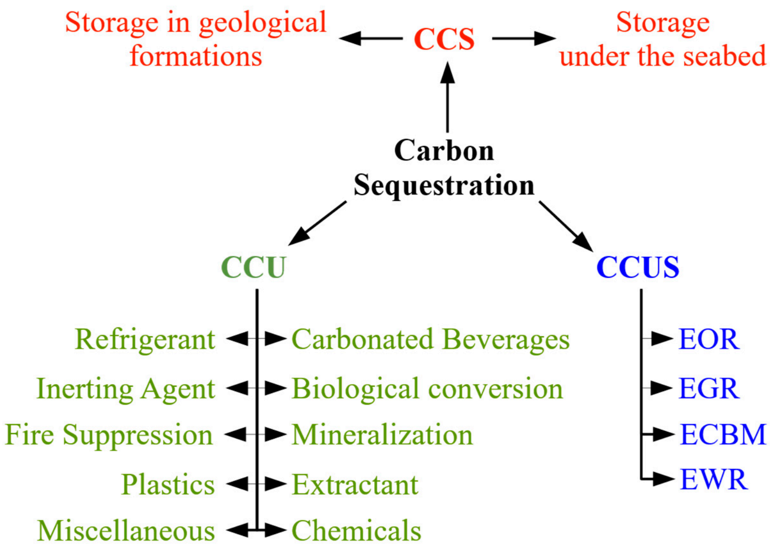

Figure 2. Cluster of carbon sequestration technologies. Acronyms: EOR = enhanced oil recovery; EGR = enhanced gas recovery; ECBM = enhanced coalbed methane; EWR = enhanced water recovery; CCS = carbon capture and storage; CCU = carbon capture and utilization.

According to Figure 2, CCS involves capture and disposal of CO_2 in any geological formation or method of offshore storage [11], with no other uses. CCUS involves projects that use CO_2 to improve the efficiency of natural resource extraction processes (oil, natural gas, underground water, geothermal energy, etc.). After the extraction stage, CO_2 is stored under the ground. CCU projects involve capture and use of CO_2 in the manufacturing process as a raw material or chemical agent [12] (i.e., these projects assume the "storage" of CO_2 in various goods).

Despite the fact that the capture phase is a part of all these options, they have different goals, implementation principles, effects, risks, and prospects [13]. In addition, the shift from one option to another leads to a change in perception of CO_2; it becomes not just a waste, but a resource that is useful in many industries, which is a clear example of the transition from a linear to a circular economy. This situation is rarely discussed in the scientific literature, despite the fact that it determines the need to revise the existing principles of various industries organization, mechanisms of carbon markets regulation, and a common understanding of the role of CO_2 in the global economy. Thus, the aim of this paper is to show and discuss the changing role of CO_2 in the development of sequestration technologies and the transition from a linear to a circular economy, as well as to generalize the existing experience when comparing different sequestration technology options.

2. Literature Review

2.1. Analysis of CO_2 Sequestration Options

There are various studies devoted to the analysis of the considered sequestration options. Singh et al. [14] analyzed different power generation options (coal and natural gas) with and without CCS. The results showed that despite the reduction in CO_2 emissions, fossil-fuel-based energy generation is associated with other negative environmental impacts that must be taken into account. Significant reduction in CO_2 emission was confirmed by Akash et al. [15]; however, this study also showed that the use of CCS in power generation affects construction expenditure, and consequently, the cost of electricity caused by the lack of additional economic effects. Odenberger et al. [16] showed that various CCS options (offshore and onshore storage) could have a significant impact on the development of energy in Europe in the coming decades. However, it is noted that CCS has serious competition from alternative low carbon energy generation options. Moreover, Pihkola et al. [17] concluded that CO_2 utilization may become a more attractive option for industry, despite the potential for CCS to take a certain position in the energy strategy of Finland.

An analysis of the current CCUS-enhanced oil recovery (EOR) status in China was carried out by Zhen and Lijiao [18]. It was concluded that CCUS-EOR is the optimal CO_2 sequestration option for China; however, its further development requires careful state regulation. The economic assessment of CCUS-enhanced coalbed methane (ECBM) technology was carried out by Yu et al. [19]. The authors identified key factors that have the most significant impact on the economic efficiency of such projects. An approach to assessing the technical and economic efficiency of CCUS-ECBM projects is proposed by Kim et al. [20]. The results showed that coalbed methane can become a serious competitor to a natural gas. An assessment of the efficiency of geothermal energy production (GEP) using CCUS was carried out by Buscheck et al. [21]. However, because of the early stage of CCUS-GEP development, further research in this area is required to confirm the economic value of such projects.

Different CCU options were evaluated by Schlögl et al. [22]. A visible emphasis is placed on the need to improve the regulation system of CO_2-based industries, which is also confirmed by other studies [23]. The business model for power-to-methanol (combined CCU and renewable energy technologies) projects was proposed by González-Aparicio et al. [24]. Economic assessment showed that this combination may become a so-called “win-win” solution, which could be competitive in the energy market. The study by Muthuraj and Mekonnen [25] showed the results of a technology readiness level assessment for CO_2-based co-polymers and polymers blend (CCU) manufacturing. The authors noted that these technologies are at an early stage of development; however, in the near future they could be used in many areas, including the processing of plastic wastes. Chauvy et al. [26] also described the assessment of various CCU technology readiness levels and a novel method for selecting optimal short- and medium-term CCU options.

Cuéllar-Franca and Azapagic [27] analyzed 27 studies related to CCS, CCUS, and CCU to compare the environmental impact of each option. The authors concluded that the positive global warming mitigation potential of CCU is much higher than CCS and CCUS. At the same time, the negative environmental impacts of CCS and CCUS (acidification, eutrophication, toxicity potential) are much higher compared to most CCU technologies. Zhang et al. [28] proposed a roadmap for the implementation of various CO_2 sequestration options in China. The authors concluded that the most effective options for the Chinese economy are CCUS-EOR and onshore saline aquifers. The study by Li et al. [13] was also devoted to China and showed that large-scale deployment of sequestration technologies will require significant improvements in regulatory frameworks.

Viebahn et al. [29] described an ecological and economic assessment of CCS (offshore and onshore) and CCUS-ECBM development potential. The results showed that the success of sequestration projects significantly depends on the successful experience of developed countries in this area. There are also a number of constraints, such as the high cost of technology, competition from renewable energy, and the long-term implementation period. Another study by the same authors [30] was based on the same methodology but aimed at China, and also included CCUS-EGR and CCUS-EOR. Key factors for the successful deployment of such projects are the presence of state support, as well as improvement of the methodology for assessing CO_2 storage potential. The relevance of such studies was also noted by Peck et al. [31], who showed a number of decision points that help to determine optimal methods of CO_2-EOR storage capacity estimation. The valuation of CCS and CCUS was carried out by Wilberforce et al. [32]. The results showed that despite the significant pace of development, as well as government support, such projects still have limited competitiveness in the energy market.

A combination of CCS and CCU technologies in Rotterdam (ROAD and OCAP projects) was described by Ros et al. [33]. According to the project, anthropogenic CO_2 will be captured in Maasvlakte power plant 3 for further storage in the depleted gas reservoir under the North Sea. At the same time, this project will satisfy seasonal demand for CO_2 from the agricultural industry to enhance crop growth. This combination is a relatively novel approach for global industry. Patricio et al. [34] proposed a method of choosing optimal pairs of CO_2 sources and CO_2 consumers for implementation of CCUS or CCU technological chains. The distance of transportation, purity, and volume of the required CO_2 were chosen as the main criteria. The proposed approach allows one to make an express assessment of the possibility to implement various sequestration technology options in a region.

The literature review shows that CCS and CCUS have been studied in more details because of the relative maturity [35] of these technologies (Table 1). As an example, it is necessary to mention EOR, which is one of the most widespread CCUS options [36] because of the relatively high technical efficiency of the deployment methods, such as carbonated water injection [37]. However, it is necessary to keep in mind that CCU options are at different stages of development. While most are at the research stage, there are examples of CCU that started at the end of the last century (e.g., Bellingham Cogeneration Facility). Given the accelerating rate of technology development, it is expected that the position of CCU will be strengthened in the coming years. This will be determined by the possibility of diversifying existing and planned enterprises through the addition of advanced CO_2 utilization technologies, as well as creation of new competitive CO_2-consuming enterprises.

Table 1. Readiness level of several sequestration technologies.

Technology	Technology Readiness Level (TRL) *		
	[36]	[35]	[26]
CCS			
Ocean storage	Concept (TRL2)	-	-
Mineral storage	Proof of concept (Lab test) (TRL3)	-	-
Depleted oil and gas fields	Demonstration (TRL7)	-	-
Saline formation	Commercial (TRL9)	-	-
CCUS			
CO_2-EGR	Demonstration (TRL7)	Mostly demonstration	-
CO_2-EOR	Commercial (TRL9)	Mostly demonstration	-
CCU			
CO_2 utilization in general	Pilot plants (TRL6) **	-	-
Enhanced commodity production	-	Research/mass market ***	-

Table 1. *Cont.*

Technology	Technology Readiness Level (TRL) * [36]	[35]	[26]
CO_2 mineralization	-	Mostly demonstration	Demonstration scale/system operations (TRL 7–9)
Chemical Production	-	Mostly research	-
CO_2 to fuels	-	Mostly research	-
Conversion by microalgae	-	-	System commissioning/ system operations (TRL 8–9)
Microbial conversion	-	-	Demonstration scale (TRL 7)
Hydrogenation of CO_2	-	-	Demonstration scale/system operation (TRL 7–9)
Organic synthesis of polycarbonates and urea	-	-	System operations (TRL 9)

Note: * Scale from 1 (initial) to 9 (mature). Methodology depends on the source. ** CCU reflects a wide range of technologies, most of which have been demonstrated conceptually at the lab scale. The list of technologies is not intended to be exhaustive. *** Depending on industry.

2.2. CO_2 in the Transition to a Circular Economy

The development of sequestration technologies has been associated with the transition from a linear to a circular economy in several studies [38–40]. Despite this, a significant aspect of this transition has been missed—the development of waste management and waste processing technologies, which are also typical for many other industries [41]. This is important because in the framework of CCS projects, CO_2 is nothing more than a waste that needs to be effectively "stored";, however this is not the case in CCUS and CCU.

On the other hand, studies associated with waste management are mostly focused on solid wastes [42,43], with the exception of the nuclear industry [44]. The emergence of CCU technologies is to some extent a unique and innovative step, which adds a processing option to the traditional methods used to combat gaseous waste (capture and storage [45]). Thus, without attention from the researchers to the comprehensive development of waste management (including gaseous wastes and air quality control [46]) as part of the transition to a circular economy, a knowledge gap will appear in the coming years.

Another unexplored issue is the changing role of CO_2 in the development of sequestration technologies [47]. At the beginning of the century, companies were focused on carbon tax reduction rather than on using CO_2 [48]. However, currently there is a rapid development of cost-effective technologies for CO_2 processing [49,50]. At the same time, CO_2 acts as a raw material for the production of not only new, but also existing products [51], which means that it can take a share of already formed markets (Table 2). The potential to enter existing and new markets is one of the key factors that determines the interest of industry and investors in CCUS and CCU technologies. Consequently, with the development of new, and improvement of existing, CO_2 utilization technologies, the rate of deployment of sequestration projects will increase, which is a positive trend in the context of sustainable development. This situation requires a revision of the attitude towards CO_2 and justification of its role in the world economy, not as a waste but as a useful resource [52] that will lead to the formation of the so-called CO_2 economy [53,54].

Table 2. Potential markets for CO_2-based products.

CO_2-based product	Production, Mt/y	Potential CO_2 Utilization (Mt CO_2/y) [26]	Unit price (USD/ton) [55]	Potential CO_2 Utilization (gigatons) in 2030 [49]	Potential Annual Revenue (billion USD) in 2030 [49]
Methane	1100–1500 [26]	3000–4000	200–250		
Urea	180 [56]	132.3	370–450		
Calcium carbonate	113.9 [57]	50	30–350		
Ethanol	80 [26]	152.88	480–530		
Methanol	65 [26]	89.245	460–500	0.005–0.05	1–12
Formalgehyde	62 [26]	25.73	490–1000		
Others*	71.17	47.128			
Aggregates				0.3–3.6	15–150
Fuels				1.07–2.1	10–250
Concrete				0.6–1.4	150–400
Polymers				0.0001–0.002	2–25

* See details in [26].

3. Materials and Methods

3.1. Projects Analysis

Generalized data on CO_2 sequestration trends are presented in a significant number of scientific and review papers. However, these papers do not divide projects into CCS, CCUS, and CCU. In addition, it is often unknown what source of data was used to build the trends.

In this regard, in order to compare the trends of CCS, CCUS, and CCU development, an analysis of completed, active, and planned projects in this area was performed. Two databases were chosen as primary sources of information: National Energy Technology Laboratory (NETL, https://www.netl.doe.gov/) and Global CCS Institute (GCCSI, https://co2re.co/FacilityData). Other databases were considered as auxiliary sources of information, or were not used due to incomplete data. The decision on the selection of primary data sources was based on the following criteria (Table 3):

Table 3. Comparison of sequestration projects databases.

Database	Open Access	Number of Projects	Projects Description	Last Update
National Energy Technology Laboratory	Yes	305	Yes	2018
Global CCS Institute	Yes	176	Yes	2018–2019
Knoema Large-Scale Carbon Capture Projects Database	No	Around 50	No information	2018
Statista Global Large-Scale Sequestration Projects	No	No information	No information	2017
ZeroCO_2.no Database	Yes	207	Yes	2013 (2016 for the USA, 2014 for the UK)
Opendatasoft.com Large-Scale Carbon Capture Projects Database	Yes	44	Yes (limited)	No information
MIT CCS Technologies Database	Yes	Around 100	Yes	2016
Third Way Database	Yes	301	Yes (limited)	2018
SCOT Project Database	Yes	212 (CCUS and CCU)	Yes (limited)	No information

(1) Open access. Similar databases that provide only paid access to their content (e.g., Statista) were not considered in this paper, although they are shown in the comparative table.

(2) Number of projects. The NETL database is the largest known to authors. It is also important that chosen databases contain information on projects of all sequestration options, unlike, for example, the SCOT project database.

(3) Completeness of data (project description). NETL and GCCSI databases contain brief descriptions of all projects, but they are not exhaustive. In this regard, additional information was taken primarily from ZeroCO_2 and CCST MIT databases.

(4) Relevance of data (the last update). The most relevant database is the GCCSI. The NETL database takes the second place. It seems likely that the SCOT database is also updated regularly, however, it is currently running in test mode (project descriptions are incomplete or unreliable).

During database comparison, authors faced a number of problems associated with different names being used for the same projects, different information about the implementation period, and heterogeneity of quantitative data. In this regard, the analysis was performed manually by matching and searching for duplicate records by country, period of implementation, and types of technological chains. Key steps of analysis are shown in Table 4.

Table 4. Key steps of the databases analysis.

Steps	NETL	GCCSI
Data collection	305 projects	176 projects
Project classification: CCS, CCUS, and CCU	The description of each project was studied. If the information was not sufficient, other databases and publicly available information (case studies, reports, articles, etc.) were used.	
Removal of projects not suitable for current study	Removed: "Terminated"; and "Hold"; status *, type "Capture"; only, Zero Capture/Storage Amount, no utilization/storage aim of the project (191 in total). *"Terminated"; and "Hold"; projects (97 in total) were removed from the main data set, but are shown in Table 7.*	Removed: Test Centers, only Capture, unsuitable "other initiatives";, initiatives with zero CO_2 capacity (57 in total).
Determination of key projects' characteristics for further analysis	The following characteristics were considered for comparison: title of the project, country, start date, end date, type of project (CCS/CCUS/CCU), volume of CO_2 disposal/utilization.	
Search for missed data	As with project classification, third-party data sources were used. One of the problems faced by the authors is the lack of sufficient information about new and small-scale CCU projects, which was only partially solved.	
Databases merging and removal of duplicates	Due to the heterogeneity of the databases, the analysis was carried out manually, by searching for information on each project. During merging of databases, 34 repeats were identified (out of 233 records).	
Calculation of CCS, CCUS, and CCU capacities	Total number of projects–199, including 81 from NETL and 118 from GCCSI. Among these projects, 33 were defined as "Potential"; and moved to a separated dataset. Total annual capacity was calculated as a sum of all project capacities in this group (CCS, CCUS, CCU).	

Abbreviations: NETL = National Energy Technology Laboratory; GCCSI = Global CCS Institute/.

3.2. Changing Role of CO_2: Theoretical Aspects.

It is often mentioned in the literature that the development of sequestration technologies is interrelated with the transition from a linear to a circular economy [47]. However, there is no mention of any boundaries between the individual stages of this transition and the emergence of the technological chains discussed in this study. We assume that the stages of waste management methodologies can be designated as particular stages of this transition [58]. Thus, the qualitative part of the study is aimed to show and discuss the changing role of CO_2 in the context of waste management development and the transition from a linear to a circular economy. For this purpose, two main tasks were accomplished.

(1) Based on the literature analysis, a generalized retrospective map of waste management development was constructed, showing the transition from a linear to a circular economic model, as well as the stages of emergence of sequestration technologies. When constructing the map, we noted that the development of sequestration technologies can be correlated with the stages of waste management development, both in time and in essence.

(2) Based on the analysis of CO_2 project databases (Section 3.1), trends (completed and active projects) and perspectives (active and planned projects) of CCS, CCUS, and CCU in the context of sustainable development and a circular economy were identified.

4. Results and Discussion

4.1. Projects Analysis

Analysis of databases showed an imbalance in the geographical distribution of CO_2 sequestration projects (Table 5), which is due to a significant number of factors, ranging from the history of the industrial development of the region and ending with the state regulation of environmental issues. The leading country is the United States (78 projects out of 166), where the first sequestration project was also launched (CCUS-EOR, Kelly–Snider oil field, Texas, 1972). The second largest number of projects is in China (20 projects), which is the world's largest CO_2 emitter. More than half of the projects are in North America (92), 22 are in Europe, 31 in Asia, and 21 in other countries. In total, 73 completed and 93 active projects were identified.

Table 5. Distribution of projects by country.

Country	Completed			Active			Total
	CCS	CCUS	CCU	CCS	CCUS	CCU	
Algeria	1	0	0	0	0	0	1
Australia	5	0	1	2	0	2	10
Brazil	0	1	0	0	3	1	5
Canada	2	4	0	1	5	1	13
China	0	6	1	1	7	5	20
Croatia	0	0	0	1	0	0	1
Cross-country	1	0	0	0	0	5	6
Denmark	1	0	0	0	0	0	1
England	0	0	0	1	0	0	1
France	1	0	0	1	0	1	3
Germany	2	0	0	0	0	0	2
Iceland	1	0	0	1	0	0	2
India	0	0	0	0	0	1	1
Italy	0	0	0	1	0	0	1
Japan	1	1	0	1	1	1	5
Mexico	0	0	0	0	1	0	1
Netherlands	0	2	0	1	0	1	4
Norway	0	0	0	2	0	0	2
Poland	0	2	0	0	0	0	2
Romania	0	0	0	0	1	0	1
Saudi Arabia	0	0	0	0	1	1	2
Spain	0	0	0	2	0	0	2
Taiwan	0	0	0	1	0	0	1
United Arab Emirates	0	0	0	0	1	0	1
United States	17	24	0	1	30	6	78
Total	32	40	2	17	50	25	

There is also a visible difference in project execution periods (Table 6; Appendix A, Leading countries). Given that a significant number of them are pilot and demonstration studies, it is natural that 25% of them were executed within a three-year period. The following table shows that the median execution period for different sequestration options differs slightly; however, a large number of the longest projects (15 and more years) are CCUS (70%). This is because of the relative maturity of CCUS-EOR technologies, as well as the early emergence of the first projects in this area.

Table 6. Distribution of projects by lifetime period.

Years	Completed			Active			Total
	CCS	CCUS	CCU	CCS	CCUS	CCU	
1	6	9	1	2	0	1	19
2	3	8	0	1	2	2	16
3	5	10	0	0	2	0	17
4	4	5	0	0	1	3	13
5	2	5	1	1	3	2	14
6	6	2	0	1	1	2	12
7	4	2	0	1	7	2	16
8	1	1	0	0	1	0	3
9	3	3	0	1	3	2	12
10	2	1	0	1	5	4	13
11	1	1	0	0	3	4	9
12	0	0	0	3	2	1	6
13	0	0	0	0	2	0	2
14	0	2	0	0	2	0	4
15 and more	0	2	0	1	5	2	10
Median	5	3	3	8	9	9	

CCUS is the leader in terms of CO_2 sequestration volume (Figure 3). Since 2009, there has been a rapid growth in CCUS and CCU sequestration volumes, while CCS has shown a stable trend. In general, the existing projects allow sequestration of about 53.9 Mtpa, and the total amount of utilized and stored CO_2 in these projects since 1972 is 631 million tons.

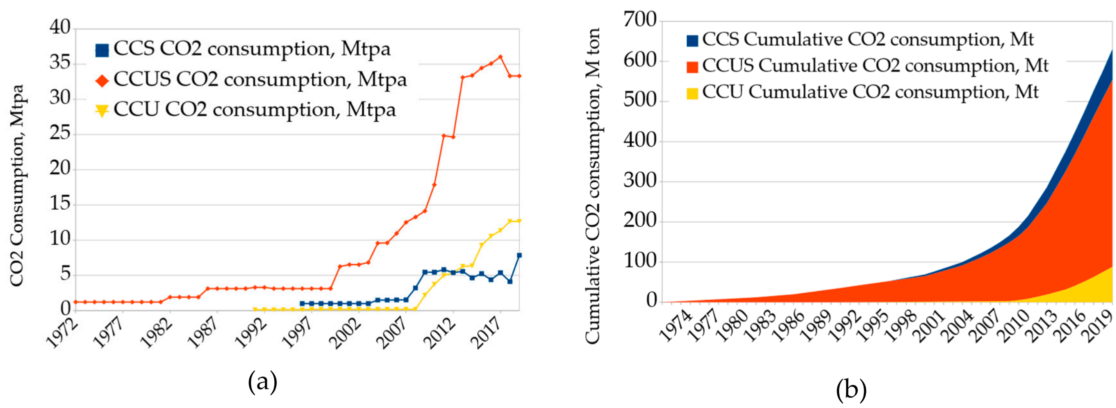

Figure 3. Retrospective trends of CO_2 consumption by sequestration options (**a**) and shares of sequestration options in total cumulative CO_2 consumption (**b**).

During databases analysis, 33 projects were defined as Planned (Table 7). CCS has the highest planned annual capacity, followed by CCUS, and lastly by CCU. The same is true for the total number of projects. Despite such results, we have many doubts about their reliability.

Table 7. Planned capacity of CO_2 sequestration projects.

Country	CCS		CCUS		CCU	
	Number of Projects	Planned Capacity (Mtpa)	Number of Projects	Planned Capacity (Mtpa)	Number of Projects	Planned Capacity (Mtpa)
Australia	3	9.830			2	1.004
Belgium					1	0.120
Canada			2	1.750		
China	2	1.010	6	6.310		
Indonesia	1	0.010				
Ireland	1	2.500				
Netherlands					2	5.000
Norway	1	0.800				
South Africa	1	0.010			1	0.100
South Korea	2	2.000				
United Kingdom	6	10.500				
United States			1	4.200	1	0.030

Firstly, according to the NETL database, out of 305 projects, 97 (31.8%) were cancelled or postponed (Table 8) because of various reasons, such as negative public perception, non-compliance with environmental requirements, and lack of financial resources. With the strengthening of CCUS and CCU positions, this trend will only intensify with respect to CCS projects [59]. Secondly, there is a huge lack of statistical data on CCU projects because of their small scale compared to CCS and CCUS (see SCOT project database). Thus, the potential capacity of CCU is still an open question that requires further development and dissemination of these technologies, as well as reliable statistics on implemented and planned projects.

Table 8. Distribution of cancelled and postponed projects by country.

Country	Postponed	Cancelled	Country	Postponed	Cancelled
Algeria	1	0	Italy	1	1
Australia	2	9	Malaysia	1	0
Bulgaria	1	0	Netherlands	2	3
Canada	5	3	Norway	3	1
China	3	1	Poland	0	2
Denmark	1	0	Scotland	1	4
Finland	0	1	United Arab Emirates	1	0
France	1	0	United Kingdom	1	5
Germany	2	3	United States	9	29

Despite this, it can be concluded that in the coming years, there will be new projects for each of the considered sequestration options, and annual CO_2 consumption will grow rapidly (Figure 4), which is a positive trend in the context of sustainable development.

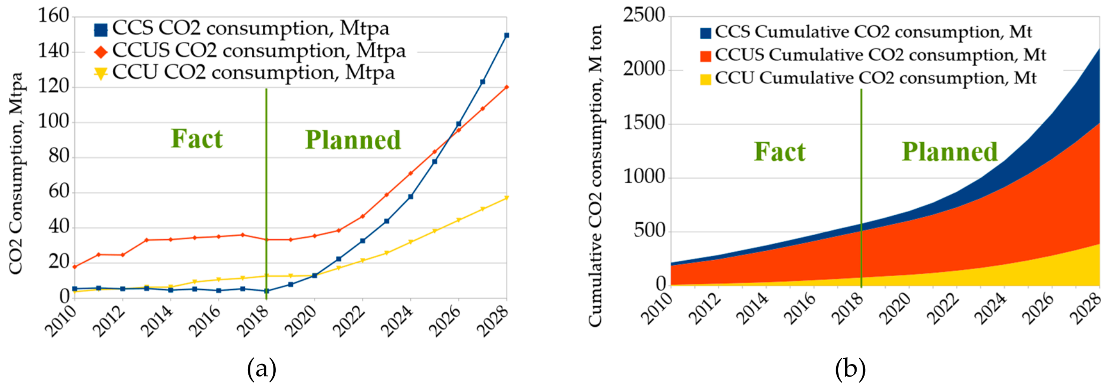

Figure 4. Planned trends of CO_2 consumption by sequestration options (**a**) and shares of sequestration options in total planned cumulative CO_2 consumption (**b**).

4.2. Changing Role of CO_2 in the Transition to a Circular Economy.

The theory of the influence of CO_2 on global warming processes was formed from the early 19th to the second half of the 20th century [60]. In the context of sustainable development and evolution of waste management, this period belongs to the so-called linear economy (Figure 5).

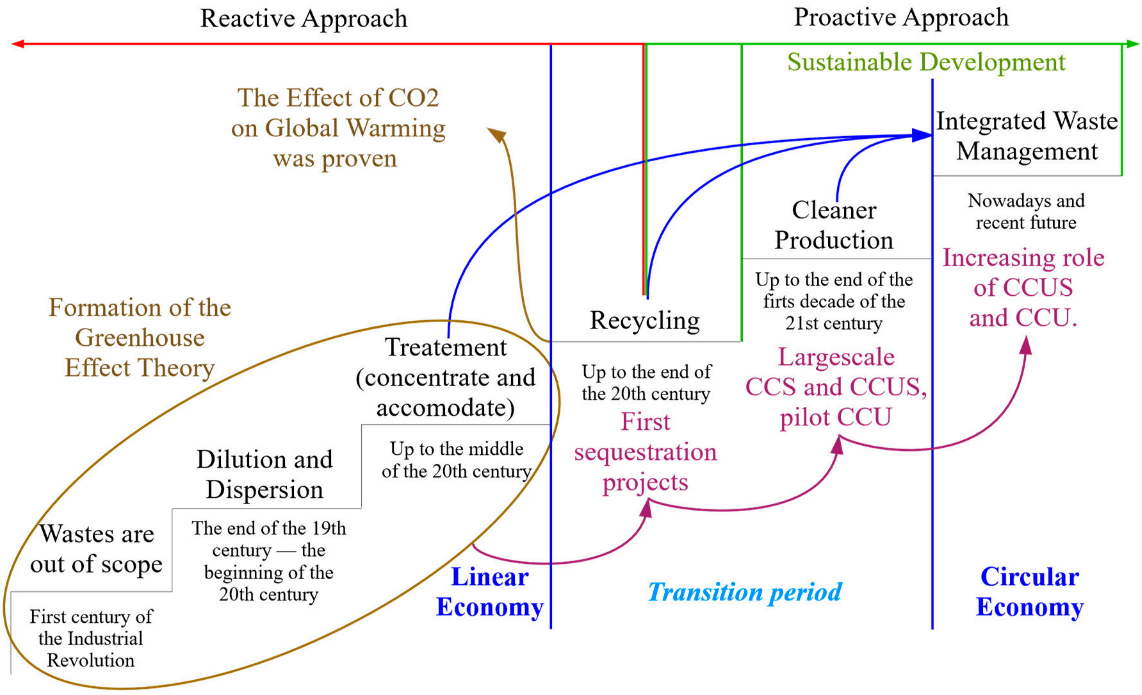

Figure 5. The relationship between sequestration project development and the transition to a circular economy.

Industrial activity during this period did not set mandatory tasks to improve the efficiency of the secondary use of resources, including waste [61]. Moreover, the technologies of that period were not sufficiently developed to find cost-effective ways of handling gaseous waste.

However, in the second half of the 20th century a transition period began. At this stage, technical and organizational approaches aimed at improving the efficiency of waste processing began to develop. As a rule, the transition stage is not shown in scientific papers, but it was during this period that the first CO_2 sequestration projects began to appear.

Based on the databases analysis, it was found that the first projects related to CO_2 sequestration were aimed at EOR (Val Verde NG Plants, USA, 1972; Enid Fertilizer, USA, 1982; Rangely Webber, EOR, USA, 1986; Mitchell Energy Bridgeport Plant, USA, 1991). These projects predate the United Nations Framework Convention on Climate Change (UNFCCC) [62], which is often marked as the starting point in the fight against global warming. This indicates the potential economic efficiency of such projects, even during periods of falling oil prices, which were observed after 1979 [63].

In 1991, the currently active Bellingham Cogeneration Facility project (USA) was launched, from which captured CO_2 is used in the food and beverage industry. Despite the fact that today such a project seems relatively simple from a technological point of view [34], it belongs to the CCU category.

CCS projects began to appear only after UNFCCC due to the lack of any other economic initiatives. The first and largest CCS project in the world was Sleipner (Norway), which was launched in 1996. After this, at least two new projects (according to the databases) began to appear annually. At the same time, the need for companies to create not only environmental but also economic effects [64] determined the high growth rates of CCUS and CCU projects since 2010 (Figure 3a). Today, such projects are becoming important links in the transition to circular economies in the energy sector [65], in cement production [66,67], in the chemical industry [68], and others [69–71].

In the context of this transition, it is necessary to consider not just the technological feasibility of CO_2 use, but also the analysis of created economic value, as well as a project's financial self-sufficiency (Figure 6).

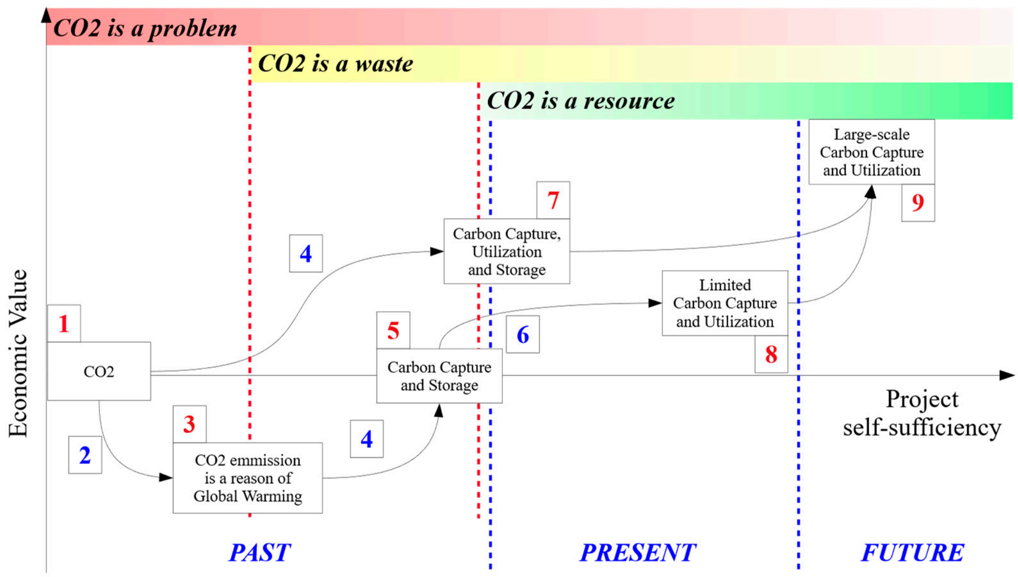

Figure 6. Changing role of CO_2 in the development of sequestration projects.

These factors are essential for the sustainable long-term development of any industry [72], as they reflect the ability of projects to operate and provide value in the market without state support [73], which is necessary for any innovative technology at the initial stage. These two factors are decisive when comparing the prospects of CCS, CCUS, and CCU; however, there are no comprehensive and reliable estimates of these factors in the scientific literature. Despite this, it is possible to generalize and to unite two processes: the development of sequestration technologies and the transition to a circular economy (Figure 7). This combination shows the increase in economic value and in project self-sufficiency, which resulted after intensification of CCU and CCUS large-scale deployment.

Figure 7 shows an explanation of each transition and each step, which are marked in Figure 6. Only CCU and CCUS have signs of self-sufficiency, providing them with long-term development without requiring additional government support. In addition, considering the rapid development of CCU technologies, it seems logical that their next stage of large-scale implementation will be to unite the CCUS and CCU technological chains [74]. The combination of two various cost-effective technologies can increase the economic stability of cross-industrial projects and their financial attractiveness, which is one of the main conditions for further large-scale development [75].

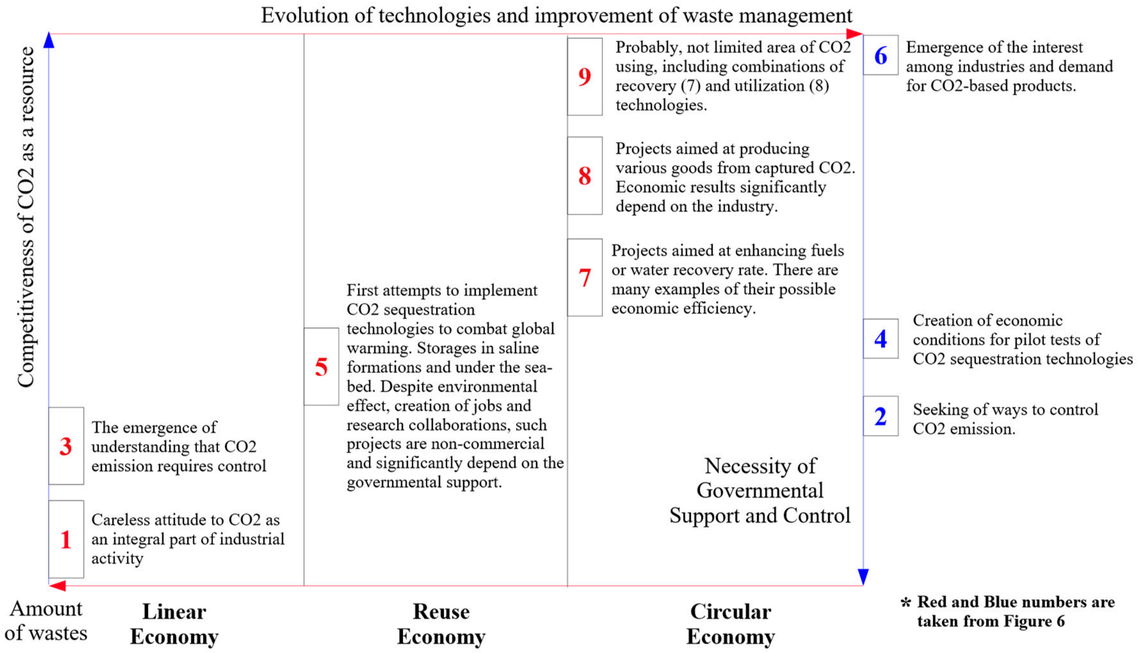

Figure 7. Conceptual vision of CO_2 sequestration options development.

To summarize the comparison between considered CO_2 sequestration options, it is necessary to show their compliance with the basics requirements of a circular economy. For this purpose, we built a comparative scheme, which shows the key principles of each option (Figure 8). The circular economy and integrated waste management concepts assume at least three production stages that must be implemented when using a resource [76,77]: reduce (limitation of technogenic CO_2 emission), reuse (using CO_2 in its initial form, instead of storing it), and recycle (processing CO_2-based products to create something new). Considering the specifics of CO_2 as a resource, it seems necessary to add to this list a summarizing aspect—recovery, as an ability of technology to convert wastes into resources, which could serve a useful purpose for replacing other materials.

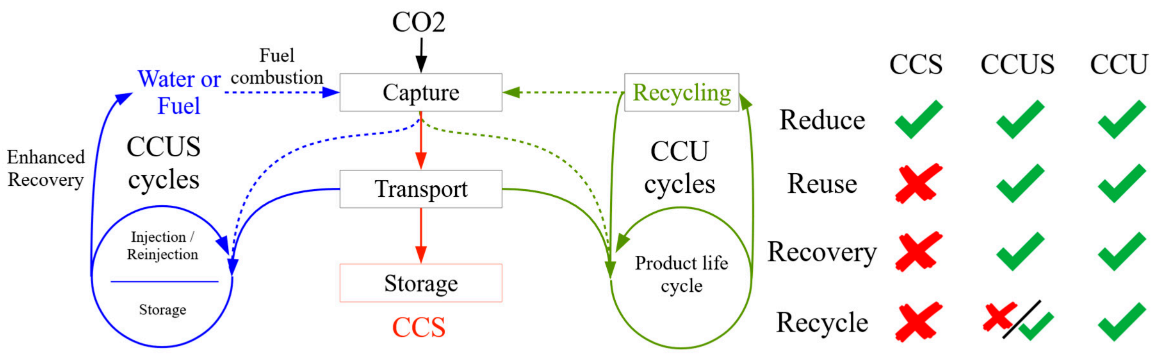

Figure 8. Compliance of CO_2 sequestration options with the principles of a circular economy.

As the figure shows, all the mentioned activities are possible only in the framework of CCU. However, it should be noted that CCUS, to a certain extent, also involves recycling, as enhanced natural resources can be processed using carbon capture technologies. Only CCS does not include any cyclic processes (in terms of CO_2 use), which allows one to attribute such projects to a linear economy.

5. Conclusions

The growth of anthropogenic CO_2 emissions is a global challenge for the modern economy. To combat it, a range of low-carbon technologies have been developed, one of which is CO_2 sequestration with further storage (CCS, CCUS) or utilization (CCUS, CCU).

Analysis of NETL and GCCSI databases showed that currently in the world, there are no less than 74 completed, 92 active, and 33 planned projects. Among them, 65 are related to CCS, 100 to CCUS, and 34 to CCU. More than half of the projects are in North America (92), 22 are in Europe, 31 in Asia, and 21 in other countries.

Over the 47-year period of sequestration projects, there has been an advanced trend of cumulative CO_2 consumption for CCUS projects (from 1.2 Mt in 1972 to 432.9 Mt in 2018), compared to CCS (from 1 Mt in 1996 to 68.7 Mt in 2018) and CCU (from 0.1 Mt in 1991 to 75.6 Mt in 2018). At the same time, since 2009 there has also been an increase in the growth rate of CCU projects' cumulative CO_2 consumption (+5 Mt in 1991–2009 and +70.6 Mt in 2009–2018). According to NETL and GCCSI databases, the number of CCS projects may increase greatly in the next decade, which will allow them to take the first place in total annual CO_2 consumption (from 4.1 Mtpa in 2018 to 149.6 Mtpa in 2028), compared to CCUS (from 33.3 Mtpa in 2018 to 120.2 Mtpa in 2028) and CCU (from 12.7 Mtpa in 2018 to 56.9 Mtpa in 2028). However, it is necessary to keep in mind two things. Firstly, there is a risk of cancellation of planned projects, which is about 31.8 %. Secondly, reviewed databases are not an absolutely exhaustive source of information. There are many small-scale projects that together can influence the trend of total annual CO_2 consumption of CCU. Despite this, the presented review of the largest projects seems to be sufficient to determine the general vector of CO_2 sequestration development.

CCS, CCUS, and CCU, despite their classification as CO_2 sequestration technologies, have different principles of CO_2 management and organizational features. These features allow one to draw a clear line between CCS (as a technology of a linear economy) and the two others. The line between CCUS and CCU is not so obvious and could be determined through an analysis of risks (such as the possibility of CO_2 leakage from storage, or environmental impact of underground disposal) and benefits (regional and social effects). In general, they are very similar technologies that comply with the principles of a circular economy.

As a rule, environmental projects (including CCS) have insufficient economic efficiency, which hinders their large-scale development. However, CCUS and CCU have significant economic potential, both in established and potential markets.

The global practice of sequestration project implementation is based on the attitude to CO_2 as an industrial waste. However, pilot and commercial CCUS and CCU projects show the need to revise this approach. In the present conditions and in the near future, CO_2 will become a resource that will be demanded by various sectors of the global economy. These changes will require new regulatory approaches for CO_2-based industries and markets, and should become one of the key topics for further research in this area.

The main limitations of this study are related to the lack of information on the research topic. The first significant limitation is the lack of a complete and objective CO_2 sequestration project database. This is especially true for CCU projects, which are not as actively covered in the scientific literature because of their small scale and the immaturity of several technologies. The second limitation is a small number of studies on gaseous waste management. Waste management methodology mainly focuses on solid wastes. Despite this, we believe that the current review could be useful for studies in this area as a base for further discussion on the changing role of CO_2 in the global economy.

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Appendix A

Table A1. Distribution of projects by lifetime period in leading countries (by number of projects).

Country	Status	Option	Lifetime Period, Years															Total
			1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**>=15**	
United States	Active	CCS			1													**1**
		CCUS			1		1	1	7	1	3	4	1	1	2	1	7	**30**
		CCU		1				1				1	2				1	**6**
	Completed	CCS	6	2	2	1			3		2		1					**17**
		CCUS	6	5	5	2	2	1					1				2	**24**
		CCU																**0**
China	Active	CCS	1															**1**
		CCUS		1	1		1					2				1	1	**7**
		CCU		1							1	1	1	1				**5**
	Completed	CCS																**0**
		CCUS	2		1	1	1				1							**6**
		CCU					1											**1**
Canada	Active	CCS					1											**1**
		CCUS		1				1		1	1				1			**5**
		CCU	1															**1**
	Completed	CCS						1			1							**2**
		CCUS		1		1	1				1							**4**
		CCU																**0**
Australia	Active	CCS	1											1				**2**
		CCUS																**0**
		CCU							1			1						**2**
	Completed	CCS			1		1	1				2						**5**
		CCUS																**0**
		CCU	1															**1**
		Total	**18**	**12**	**12**	**5**	**9**	**6**	**11**	**2**	**10**	**11**	**6**	**3**	**3**	**2**	**11**	

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