Review

Current Developments of Carbon Capture Storage and/or Utilization—Looking for Net-Zero Emissions Defined in the Paris Agreement

Maria João Regufe , Ana Pereira , Alexandre F. P. Ferreira, Ana Mafalda Ribeiro and Alírio E. Rodrigues

LSRE-LCM-Laboratory of Separation and Reaction Engineering-Laboratory of Catalysis and Materials, Associate Laboratory, Faculdade de Engenharia, Universidade do Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal; ajmp@fe.up.pt (A.P.); aferreir@fe.up.pt (A.F.P.F.); apeixoto@fe.up.pt (A.M.R.); arodrig@fe.up.pt (A.E.R.)

* Correspondence: mjregufe@fe.up.pt

Citation: Regufe, M.J.; Pereira, A.; Ferreira, A.F.P.; Ribeiro, A.M.; Rodrigues, A.E. Current Developments of Carbon Capture Storage and/or Utilization—Looking for Net-Zero Emissions Defined in the Paris Agreement. *Energies* **2021**, *14*, 2406. <https://doi.org/10.3390/en14092406>

Academic Editor: Attilio Conventi

Received: 22 March 2021

Accepted: 9 April 2021

Published: 23 April 2021

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

Abstract: An essential line of worldwide research towards a sustainable energy future is the materials and processes for carbon dioxide capture and storage. Energy from fossil fuels combustion always generates carbon dioxide, leading to a considerable environmental concern with the values of CO₂ produced in the world. The increase in emissions leads to a significant challenge in reducing the quantity of this gas in the atmosphere. Many research areas are involved solving this problem, such as process engineering, materials science, chemistry, waste management, and politics and public engagement. To decrease this problem, green and efficient solutions have been extensively studied, such as Carbon Capture Utilization and Storage (CCUS) processes. In 2015, the Paris Agreement was established, wherein the global temperature increase limit of 1.5 °C above pre-industrial levels was defined as maximum. To achieve this goal, a global balance between anthropogenic emissions and capture of greenhouse gases in the second half of the 21st century is imperative, i.e., net-zero emissions. Several projects and strategies have been implemented in the existing systems and facilities for greenhouse gas reduction, and new processes have been studied. This review starts with the current data of CO₂ emissions to understand the need for drastic reduction. After that, the study reviews the recent progress of CCUS facilities and the implementation of climate-positive solutions, such as Bioenergy with Carbon Capture and Storage and Direct Air Capture. Future changes in industrial processes are also discussed.

Keywords: CO₂ emissions; CCS; CCUS; global facilities

1. Introduction

Due to the Industrial Revolution, fossil fuels (coal, oil and gas) were unlocked as a new energy resource. Their excessive use has led to several negative impacts such as global climate change [1].

Figure 1 presents the surface air temperature anomalies between 1979 and 2020. For example, comparing with September 2016, September 2019 was the warmest month in the data record, which was 0.57 °C warmer than the average temperature from 1979–2010 [1].

Natural causes are also responsible for this effect. However, greenhouse gases from human activities including population growth, deforestation, agriculture, urbanization (urban heat islands), and the resulting changes in consumption patterns are responsible for more than 95% of global warming [2]. The greenhouse contribution in the temperature variation is evident, responsible for about 1 °C, more than other anthropogenic sources and natural variations.

The principal greenhouse gas related to global climate change is carbon dioxide (CO₂). Other gases, in minor quantities, are also responsible, such as methane (CH₄), water vapor (H₂O), nitrous oxide (N₂O) and fluorinated gases (F-gases), specially hydrofluorocar-

bons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF₆), and nitrogen trifluoride (NF₃) [3,4].

Figure 1. Global mean surface air temperature anomalies in the 1979–2020 period (adapted from Service [1]).

In order to combat climate change and achieve decarbonization, several methods have been studied and implemented: a massive development of clean energies (renewable energy sources); fossil fuel consumption reduction by switching to lower-carbon alternatives, e.g., coal to gas; energy efficiency increase in industrial applications and the power sector, particularly in technologies used to convert fossil fuels into energy; carbon capture and utilization/storage techniques [2,5–7]. The employment of all of the options mentioned above will be required because CO₂ emission abatement became a global priority. However, at the current state of development, the levels of risks and the costs, non-fossil fuel energy alternatives cannot meet our need for energy fed by fossil fuels. Additionally, any quick change to non-fossil energy sources, even if this action was possible, would result in large disruptions to the existing energy supply infrastructure with substantial consequences to the global economy [8].

In the Paris Agreement, 196 parties decided to establish a long-term goal to keep the worldwide average temperature increase below 2 °C above pre-industrial levels and limit the increase to 1.5 °C, since this would significantly reduce the risks and effects of climate change [9–11]. Consequently, to obtain a sustainable low carbon future, global CO₂ levels should be drastically reduced by promoting the actions and investments needed. This limitation in the worldwide temperature implies immediate and decisive actions on climate change to avoid some of the worst climate impacts and reduce the chances of extreme weather occurrences around the world.

Thus, to meet mid to long-term CO₂ emissions targets, cost-effective CO₂ capture from fossil fuel use and subsequent sequestration options need to be evaluated, as well as the utilization of (captured) carbon dioxide as a feedstock for new products. Figure 2 shows the CO₂ life-cycle considering two pathways: carbon capture and storage (CCS) and carbon capture and utilization (CCU).

Figure 2. Analysis of life-cycle of CO₂ with capture and storage, and capture and utilization from main sources pathways (based on Sekera and Lichtenberger [12] and Bui et al. [13]).

Broadly recognized as having an enormous potential to meet climate change targets, CCS and CCUS appear as solutions to deliver low carbon heat and power, decarbonize the industry, and, more recently, facilitate the net removal of CO₂ from the atmosphere [14].

This article aims to review the overall CCS and CCUS strategies implemented to fulfil the climate change ambition established in the Paris Agreement of 2015. The approach to obtain a climate-neutral—an economy with net-zero greenhouse gas emissions—implies large changes in all the economic sectors, as well as energy, transport, industry, and agriculture.

First, the values of actual CO₂ emissions are presented, and it is analyzed the impact of COVID-19 in the first quarter of 2020. After that, Carbon Capture and Storage and Carbon Capture, Utilization, and Storage strategies to combat CO₂ emissions are described. CO₂ capture technologies, classified into three groups, precombustion, oxy-fuel and post-combustion systems, are presented as well as the leading technologies used for CO₂ capture. CCUS's current development, focusing on the facilities and projects working in Europe, is presented.

Two commonly used technologies of climate-positive solutions are briefly described, which are bioenergy with carbon capture and storage (BECCS) and direct air capture (DAC). In conclusion, the future of industrial processes, that use fossil fuels as raw materials and release CO₂ emissions, is analyzed.

2. CO₂ Emissions

In 2019, global energy-related CO₂ emissions reached 33 gigatonnes (Gt), approximately [15]. This resulted mainly from a sharp decline in CO₂ emissions from the power sector in advanced economies (Australia, Canada, Chile, European Union, Iceland, Israel, Japan, Korea, Mexico, Norway, New Zealand, Switzerland, Turkey, and United States.), because of the expanding role of renewable sources (mainly wind and solar photovoltaic systems), fuel switching from coal to natural gas, and higher nuclear power output. However, the total emissions, in the rest of the world, increased.

Figure 3 shows the gigatonnes of CO₂ emitted by developed countries, the rest of the world, and total emissions from 1990 until 2019 [16].

Figure 4 shows the global greenhouse gas emissions (%) by sector in 2020 [16]. The economic sector which had the highest share of carbon dioxide emissions from fossil fuels and cement was the power sector. With a 44% of emissions, this was more than the combined share of both industry and surface transport. These three sectors of the economy make up the majority of the world's CO₂ emissions.

Covid-19 had an enormous impact on energy demand and, therefore, on CO₂ emissions. The drastic curtailment of global economic activity and mobility during the first quarter of 2020 pushed down global energy demand by about 3.8% compared with the first quarter of 2019 [15]. CO₂ emissions were about 5% lower in Q1 2020 than in Q1 2019, almost twice as large as all previous declines since the end of World War II. By sectors, emissions from coal, oil, and natural gas declined about 8, 4.5, and 2.3%, respectively. By

regions, a considerable decrease of CO₂ emissions was observed: −8% in China, −8% in the European Union (EU), and −9% in the United States [15]. However, this decline was punctual; it will not be enough to resolve climate change problems.

Figure 3. CO₂ emissions by countries for a period from 1990 until 2019 (adapted from Agency [16]).

Figure 4. Global greenhouse gas emissions by sector in 2020 (adapted from Tiseo [17]).

In April 2020, McKinsey Global Institute published an overview of several scenarios of projected global CO₂ emissions that helps to understand the future. Climate Action Tracker [18] also provide these data. The scenarios are shown in Figure 5, where global CO₂ emissions in each scenario are projected. All pathways include energy-related emission, industry-process emissions (e.g., from cement production), emissions from deforestation and waste, and negative emissions (e.g., from reforestation and carbon-removal technologies such as bioenergy with carbon capture and storage, and direct air carbon capture and storage). Emissions from biotic feedbacks (e.g., from permafrost thawing, wildfires) were not considered. The red lines represent warming projections if policies are not applied: the lower bound is a “continued growth” pathway based on the IEA’s World Energy Outlook 2019 current policies scenario; the higher bound is based on IPCC’s Representative Concentration Pathway 8.5 [19]. It is possible to observe the need for immediate reduction of GHG emissions.

Figure 5. Projected global CO₂ emissions per scenario (adapted from Climate Action Tracker [18]).

According to this study, if no changes are applied, the continued growth will lead to about 120 Gt equivalent of CO₂ emitted per year in 2050. However, to achieve the 1.5 °C pathway of the Paris Agreement, the CO₂ emissions should be 0 Gt by then.

3. Carbon Capture (Utilization) and Storage (CCUS or CCS)

Basically, carbon capture and storage (CCS) consists of the separation and concentration of CO₂ from power generation plants or industrial processes, its pressurization and transportation, via ship or pipeline, to specific locations where it should be permanently stored deep underground, in geological formations (depleted oil or gas reservoirs or deep saline aquifers) [20,21]. This technology has been identified as a priority, being a critical emissions reduction technology that can be applied across the energy system, expecting to play an essential role in meeting the global warming targets [22–24].

CCS is often used interchangeably with the term Carbon Capture, Utilization, and Storage (CCUS). The difference between the two terms presented is the ‘utilization’ word, which refers to the use of carbon for other applications. CCUS can contribute to almost one-fifth of the emissions reductions needed across the industry sector. CCUS will play a key role in reducing CO₂ emissions from fossil-fuel-based power generation and is the only option available to reduce direct emissions from other industrial point sources significantly [25]. It was estimated that the use of CCUS would address up to 32% of global CO₂ emissions reduction by 2050 [26]. More than 28 Gt of CO₂ could be captured from industrial processes until 2060, the majority of it from the cement, steel, and chemical subsectors [27].

CCS and CCUS technologies are developed slowly, mainly as a result of high costs and unsupportive policy and regulatory frameworks in many countries [28].

The economic penalty of the capture is the crucial obstacle to CCS/CCUS implementation. The efficiency of the CO₂ capture must be increased in the capture step of the processes, as it is estimated that the capture step is responsible for 60% to 80% of the overall CCS/CCUS economic penalty [8,20]. The capture part of the process represents the main promise for cost reduction and focuses on most of the research efforts. CCS or CCUS is far from the ideal solution because it does not directly use green fuels. Still, it is the only technology capable of maintaining the utilization of the existing power plants.

In these types of processes, CO₂ capture technologies can be classified into three groups: pre-combustion systems, post-combustion systems, and oxy-fuel or oxy-combustion processes. The first and second systems depend on whether carbon dioxide is removed before or after fuel is burned. In the third, pure oxygen rather than air is used for combustion [3]. Figure 6 shows a brief scheme of methods for carbon capture.

Figure 6. Scheme of methods for carbon capture (adapted from IPCC [29]).

In the production processes, namely in activities related to CO₂ and other harmful greenhouse gases, even in coal power plants, it is important to reduce the emissions. For that, energy production changes as technology advances. Energy companies and industries use several technologies. This way, Industry 4.0 and the external environment force the energy companies to constantly adjust goals [2,30]. Oxy-combustion capture is still under development and is not yet commercial. Reduction of NO_x, SO_x, Hg emissions, and methods of exhaust gas dedusting are also important.

3.1. Pre-Combustion

In power plants, in oil, gas, and chemical industries processes, where CO₂ is produced, the pre-combustion CO₂ capture can be used [3]. Technologies that separate this gas from gas streams have been used for many decades. The main objective of the industries is CO₂ removal to meet the required downstream product specifications, whether natural gas, hydrogen, or chemicals.

In pre-combustion CO₂ capture systems, the fuel source is decarbonized before combustion. More recently, in anticipation of the requirements to limit CO₂ emissions, plants design have been improved to convert the gas produced from gasification to hydrogen and CO₂ and remove CO₂ before the combustion of the hydrogen-rich gas in the turbine [31]. The gasification or partial oxidation process combines the reacting coal with steam and oxygen at high pressure and temperature. The product is a gaseous fuel consisting mainly of carbon monoxide and hydrogen, called synthesis gas or syngas.

After this, syngas is converted to more hydrogen and carbon dioxide by adding steam at a lower temperature. This is the Water Gas Shift Reaction (WGS) (Equation (1)). Before the combustion of the hydrogen-rich gas in the gas turbine, the CO₂ is captured. The concentration can be in the range of 15–60% (dry basis/% volume), and the total pressure is typically 2–7 MPa [3,31,32]:

$$\Delta H = -40.6 \text{ kJ mol}^{-1}$$

The WGS reaction is the desired route for industrial applications, most commonly in conjunction with the Fischer-Tropsch (FT) reaction to synthesize hydrocarbon fuels from syngas. The conditions used for the FT reaction lie in the range of 200–375 °C; lower temperatures for long-chain alkanes and higher temperatures for shorter [32].

When compared with post-combustion process, CO₂ presents a higher concentration in the pre-combustion gas stream (>20% in the H₂ + CO₂ stream vs. 5–15% in a post-combustion flue gas stream). Then, CO₂/H₂ separation is somewhat more straightforward than the CO₂/N₂ separation in the post-combustion process due to the difference in molecular weights and molecular kinetic diameters [33].

CO₂ and H₂ can be separated using several technologies. Solvent-based CO₂ capture can be applied by chemical or physical (such as the Selexol and Fluor processes) absorption of CO₂ from syngas into a liquid carrier and regenerating the absorption liquid by increasing the temperature or reducing the pressure to break the absorbent-CO₂ bond [34]. Sorbent, membrane, and hybrid systems that combine attributes from multiple technologies are under investigation to reduce costs and energy penalties, as well as, to improve performance [35].

3.2. Oxy-Combustion

The oxy-combustion processes were designed to remove the bulk nitrogen from the air before combustion. A combination of oxygen (95% of purity, approximately) and recycled flue gas is used for the fuel combustion. A mixture with CO₂ and H₂O is generated by recycling the flue gas, and this mixture is ready for sequestration without stripping of the CO₂ from the gas stream [36]. The flame temperature is controlled by the amount of recycled flue gas. No chemical solvent or physical sorbent is required to separate CO₂ from the flue gas due to the high concentration in the stream. The carbon dioxide rich flue gas would then be delivered by pipeline to be sequestered.

This system was developed as an alternative to the more conventional post-combustion process in coal-fired power plants. The main reason is the reduced cost of oxy-combustion when compared with post-combustion. However, although good results were obtained in laboratory scale and pilot plants, commercial plants use is still scarce [3].

3.3. Post-Combustion

Post-combustion CO₂ capture systems have been used for many decades, and in this process, the CO₂ is captured from the products of burning fossil fuels (coal, natural gas, or oil) or combustion exhaust gases. The flue gas passes through a liquid solvent, solid adsorbent, membrane, or another medium, depending on the method/technology, allowing the separation of the CO₂ from the mixture. After that, CO₂ can be transported and stored.

The drawback of post-combustion carbon capture is the low carbon dioxide concentration in the flue gases, which leads to a relatively high energy penalty and high costs of carbon capture. On the other hand, pre-combustion strives to reduce these penalties by decarbonizing the process stream before combustion, resulting in more favorable conditions and more flexible implementation, significantly reducing capture costs [37].

Several technologies can be applied for separating or capturing CO₂ from a mixture of gases in an industrial process. The purification step and the technical approach used depend on the gas stream conditions, such as temperature, pressure, and concentration, and on the product purity required.

The captured and purified gas will be transported to its final destination. In the case of CCS, a pipeline is necessary to transport captured CO₂ for a storage site. When CCU is applied, a spur on the pipeline can take a slipstream from the main flow to be diverted to the chemicals or synthetic fuels plant. At the end of the supply chain, a minor quantity of CO₂ could still be emitted or stored [38].

3.4. Technologies for CO₂ Capture

Figure 7 shows technical approaches available for CO₂ separation and capture.

Figure 7. Technical options for CO₂ capture processes (adapted from Songolzadeh, Ravanchi and Soleimani [21]).

The most common process used to separate the CO₂ from natural gas, refinery off-gases, and synthesis gas processing is absorption technology [39]. This is characterized by using a liquid/solvent that selectively absorbs CO₂ from a gas stream. Afterwards, the solvent can be regenerated through a stripping or regenerative process by heating and/or pressurization [40]. Absorption processes can be chemical absorption, used in pre-combustion or post-combustion capture, or physical absorption, primarily used in pre-combustion capture. Selexol (with dimethyl ethers of polyethylene glycol solvent), Rectisol (with methanol solvent), and Purisol (with N-methyl-2-pyrrolidone as solvent) are the most common physical processes. Typical chemical solvents are primary amines such as monoethanolamine (MEA) and 2-amino-2-methyl-1-propanol (AMP), secondary amines such as diethanolamine (DEA), and ternary amines such as methyldiethanolamine (MDEA) [39,41]. However, in this type of process, gas streams are required at high pressure. Plants for CO₂ capture with processes based on chemical absorption using MEA solvent were developed over 75 years ago to remove acidic gas impurities like H₂S and CO₂ from natural gas streams. Afterwards, the process was adapted to treat flue gas streams, and with this technology, about 85 to 95% of the CO₂ is captured, and a product stream of CO₂ can be produced with a purity higher than 99% [42].

The major challenges for CO₂ capture from flue gases by absorption processes are the sizeable volumetric flow rates at atmospheric pressure with large amounts of CO₂ at low partial pressures (10–15% of CO₂) at 40 °C. Then, the process presents several disadvantages, which are the high energy consumption due to the high thermal energy required, around 4.0 GJ/t of CO₂ captured [41] (considering 30 wt% MEA and 90% CO₂ removal), the presence of SO_x and NO_x contaminants, and the high oxygen partial pressure, which hinders the implementation of amine absorption process [43]. Besides, it leads to corrosive product formation due to the solvents' thermal and oxidative solvent degradation. There are many studies about processual alternatives to reduce the costs involved in power plants to reduce the operating costs. Besides the physical and chemical absorption methods discussed above, other methods could be implemented, as verified in Figure 7.

Gas separation through adsorption processes can be used in pre- and post-combustion capture and are promising alternative separation techniques characterized by solid adsorbents capable of reversibly capturing CO₂. Novel adsorbent materials for CO₂ capture with specific properties can adsorb large amounts of CO₂ to be used or stored, being these materials instruments for CO₂ utilization and storage. Adsorbents are porous solids and have a large surface area per unit mass. Each type of molecule or component creates different interactions with the adsorbent surface, leading to an eventual separation [44].

There are many types of adsorbents, which could be applied to CO₂ capture by physical adsorption processes, including activated carbons, carbon fibers, zeolites [45], metal-organic frameworks [46], and organic-inorganic hybrid materials [47,48]. The adsorbent should be chosen taking into account economic and operational criteria, which are (i) high adsorption capacity for the target gas component, i.e., CO₂, leading to the reduction of the adsorbent quantity and process equipment size; (ii) high CO₂ selectivity, representing a high adsorption capacity ratio between CO₂ and the other components in the stream, such as, nitrogen; (iii) fast adsorption and desorption kinetics; (iv) good physical and chemical stability during the cycles and regeneration steps; (v) be regenerable by modest pressure decrease or temperature increase, leading to the minimization of the operating energy costs. Furthermore, the adsorbent should ideally also have robust performance in the presence of moisture and other contaminants that may be present in the gas stream to treat. Then, there are essential features that should be considered for a successful operation of adsorbent material, such as composition, particle size, pore size, and pore connectivity.

Depending on the regeneration method, adsorption processes can be denominated as pressure swing adsorption (PSA), temperature swing adsorption (TSA), and electrical swing adsorption (ESA) [49,50].

Cryogenic carbon capture utilizes the principle of separation based on the cooling of CO₂ to low temperature. The CO₂ is separated from the flue gas mixture after cooling this gas below -73.3°C at atmospheric pressure. After this, CO₂ is pressurized and delivered at pipeline pressure. Cryogenic separation can be applied for post-combustion processes in two different ways. In one of these methods, CO₂ can be de-sublimated to solid CO₂ on the heat exchangers, further heated and pressurized to obtain liquid CO₂ in the recovery stage. Clodic and Younes [51] proposed this type of separation. Tuinier et al. [52] proposed another method, with the use of packed beds for de-sublimation of CO₂. CO₂ is recovered from the packing material by feeding a fresh gas stream to increase the temperature and enhance the concentration of the CO₂ recovered from the packed bed [53]. It may be a good technique because it does not involve any additional chemicals in the separation process. However, the high compression power requirements for this method are the major disadvantage [54].

Membranes are another potential alternative to conventional solvent absorption technology. The difference in physical and/or chemical interactions between gases and membrane materials is responsible for the CO₂ separation. The method presents many advantages, such as reduced equipment size, lower energy requirements, simplicity in the process, among others. Nevertheless, in the post-combustion process, particularly in the CO₂/N₂ separation, due to the relatively low CO₂ concentration and pressure, the driving force for membranes to perform appropriately is weak, making their implementation difficult [55].

Another potential technique for removing CO₂ from flue gases is microalgae. Microalgae are microscopic organisms that typically grow suspended in water and are driven by the same photosynthetic process as higher plants [56].

Microalgal cells are sunlight-driven cell factories that can convert carbon dioxide into raw materials for producing biofuels (e.g., biohydrogen, biodiesel, and bioethanol), animal food chemical feedstocks, and high-value bioactive compounds [56].

The ability of these cells to absorb CO₂ can be applied as an attractive alternative for CO₂ sequestration. CO₂ fixation and storage via microalgae are essentially photosynthesis, transforming water and CO₂ into organic compounds without extra energy addition or consumption and secondary pollution.

Hydrate-based CO₂ capture (HBCC) technology emerges as a potential solution for CO₂ capture from gas streaming, e.g., from CO₂/N₂ or from CO₂/H₂ of fossil fuel power plants. This technology is based on the hydrate cages formation by water molecules at high pressure and low temperature, where CO₂ molecules stay enclathrated, allowing their separation. It is estimated that this technology could have a cost reduction of CO₂ capture of about 45% when compared with the chemical absorption technology [57]. Recently, studies involving hydrate-base CO₂ capture and storage have increased [58,59].

3.5. Current Progress of CCUS Facilities

Since 1972, CCS has been applied to capture CO₂ from an extensive range of sectors and industries [7]. Typically, the progress of technology development contains a series of scale-up steps: first, laboratory scale or bench; second, pilot-scale; third, demonstration-scale; fourth, commercial scale. Currently, there are eighteen large-scale facilities in operation in the world, five under construction, and twenty in various stages of development [14] (see Table 1).

Table 1. Current development progress of technologies in terms of technology readiness level (TRL): carbon capture; transport; storage; and utilization (adapted from Bui [13], Consoli [14]).

Technology Readiness Level	Current Development
TRL1	Concept
TRL2	Formulation
Ocean Storage
TRL3	Proof of concept (lab tests)
Ionic Liquids-Post-combustion
BECCS Power
Low T separation-Pre-combustion
Membranes dense inorganic (CO ₂ separation)
Mineral storage
TRL4	Lab prototype
Oxy-combustion gas turbine (water cycle)
TRL5	Lab-scale plant
Membranes dense inorganic (H ₂ separation for reformer)
TRL6	Pilot plant
Membranes polymeric (power plants)
Biphasic solvents-Post-combustion
Chemical looping combustion (CLC)
Calcium carbonate looping (CaL)
CO ₂ utilization (non-EOR)
TRL7	Demonstration
Membranes polymeric (NG industry)
Pre-combustion IGCC + CCS
Oxy-combustion coal power plant
Adsorption-Post-combustion
BECCS industry
DAC
Depleted oil & gas fields
CO ₂ -EGR

Table 1. Cont.

Technology Readiness Level	Current Development
TRL8	Commercial Refinement required
TRL9	Commercial
Post-combustion amines (power plants)
Pre-combustion NG processing
Transport on-shore & off-shore pipelines
Transport ships
Saline formations
CCUS

Notes: BECCS corresponds to bioenergy with CCS, IGCC corresponds to integrated gasification combined cycle, EGR corresponds to enhanced gas recovery, EOR corresponds to enhanced oil recovery, NG corresponds to natural gas; CO₂ utilization (non-EOR) reflects a wide range of technologies, most of which have been demonstrated conceptually at the lab scale. C–Capture; T–Transport; U–Utilization; S–Storage.

3.6. Global Facilities of CCUS

More than 30 new integrated CCUS facilities have been announced since 2007, mostly in the United States and Europe, although projects are also planned in China, Australia, Korea, the Middle East and New Zealand [60]. One of them was developed by Svante [61]. Started in 2007, Svante designed and built a CO₂ capture facility to capture half a tonne of carbon per day. This technology captures carbon dioxide from flue gas, concentrates it, then releases it for safe storage or industrial use, in 60 s. Today, Svante has several industrial-scale carbon capture projects and collaborations.

Another application example is Air Products. This company possesses solutions for CO₂ capture from fossil fuel conversion before it reaches the atmosphere. The technology has designed and constructed a large-scale system to capture CO₂ from steam methane reformers, which are located within the Valero Refinery in Port Arthur (TX, USA). Air Products has a technology that already separate, purify and transport CO₂ from natural gas reforming, management of syngas from gasification, and oxyfuel combustion in markets such as steel and glass [62].

The Global CCS Institute provides a database of CCUS facilities operating in the world. This organization establishes as large-scale integrated CCSU facilities in its database comprising the capture, transport, and storage of CO₂ at a scale of at least 800 kt of CO₂ annually for a coal-based power plant, or at least 400 kt of CO₂ annually for other emission-intensive industrial facilities (natural gas-based power generation is included). The remaining facilities and initiatives in the database are mentioned as in advancement/deployment status [63]. The last update of the database refers to October 2019.

Currently, there are several CCS facilities in Europe, and they can be classified in three different classes:

- (1) Commercial Carbon Capture and Storage Facilities—CO₂ can be captured and transported to be permanently stored; have economic lives similar to the host facility whose CO₂ is captured; must support a commercial return while operating and meet regulatory requirements;
- (2) Carbon Capture and Storage Hubs—Commercial facilities although not having a full-chain (capture, transport and storage) operation; several models are considered, combining multiple capture facilities, or CO₂ transport and storage;
- (3) Pilot and Demonstration Facilities—CO₂ is captured for testing, developing or demonstrating CCS technologies/processes; CO₂ captured may or may not be transported for permanent storage; A commercial return during operation is not expected.

Taking into account this classification, actually in Europe (accessed data at 1st of April 2021), there are 13 commercial CCS Facilities, two CCS Hubs (one in The Netherlands and

another one in United Kingdom), and 29 Pilot and Demonstration facilities [63]. Figure 8 shows the map of the worldwide distribution of CCUS facilities, focusing on Europe.

Figure 8. Worldwide distribution of CCUS facilities divided by categories, expanded in Europe (adapted from Institute [63]).

Table 2 summarises the commercial CCS facilities that are working in Europe. Other facilities are under study in test centers or the pilot or demonstration phase. Table A1 to Table A4 (in the Appendix A) summarise these facilities.

Table 2. Summary of large-scale commercial CCS facilities that are working in Europe (Notes: Status: ED—Early Development; AD—Advanced Development; O—Operational; C—Completed; In C—In Construction; Data: represents the starting year of the project; Mtpa—Million tonnes per annum; tpa—tonnens per annum; tpd—tonnes per day).

Name	Status	Country	Data	Industry	Observations
Acorn Scalable CCS Development	ED	UK	2020s	Oil Refining	Scale-up of the pilot project Acorn (Minimum Viable CCS Development)
Caledonia Clean Energy	ED	UK	2024	Power generation	CO ₂ capture would be 3 Mtpa and transported via re-purposed pipeline for geological storage in the North Sea of Scotland
Drax BECCS Project	ED	UK	2027	Power generation	Aims to capture 4 Mtpa from one (660 MW) of the biomass-fired power lines at the UK's biggest power station by 2027
Ervia Cork CCS	ED	Ireland	2028	Power generation and refining	CO ₂ captured initially from the two-modern gas-fired, combined-cycle gas turbine power stations and Ireland's only oil refining business; transported via a pipeline network to sites in the Kinsale Gas Field
Hydrogen to Humber Saltend (H2H)	ED	UK	2026–2027	Hydrogen production	H2H Saltend is in development to produce blue hydrogen via a new build 600 MW autothermal reformer to decarbonize Triton Power's gas-fired power plant; up to 1.4 million tonnes of CO ₂ will be captured.
Hydrogen 2 Magnum (H2M)	ED	Netherlands	2004	Power generation	H2M produce hydrogen to be used in gas power plant in Eemshaven, Germany, Equinor, Vattenfall and Gassunie

Table 2. Cont.

Name	Status	Country	Data	Industry	Observations
HyNet North West	ED	UK	Mid 2020s	Hydrogen Production	CO ₂ is planned to be captured from the Hydrogen Production & Carbon Capture plant, and transported, together with captured CO ₂ from existing nearby industrial sites
Langskip CCS–Fortum Oslo Varme	AD	Norway	2024	Waste Incineration	It is in construction to capture about 0.4 Mtpa of CO ₂ by 2024 from its cement production plant in southern Norway; the offshore Aurora area has been evaluated as original storage site and will involve a combined ship and pipeline transportation system.
Net Zero Teesside	ED	UK	2020s	Various	Cluster of leading energy-intensive companies to examine the opportunity to build one of Europe's first CCS equipped industrial zones in Tees Valley, UK; starts with a capture capacity of 0.8 Mtpa, that could grow up to 10 Mtpa; CO ₂ transported via pipeline to an offshore site in the North Sea
Northern Gas Network H21 North of England	AD	UK	2026	Hydrogen production	H21 aims to convert the UK gas grid from natural gas (methane) to zero-carbon hydrogen
Norway Full Chain CCS	AD	Norway	2023–2024	Various	Aim of 0.8 Mtpa; Capture CO ₂ studies are being undertaken by two proponents involved in cement production and a waste-to-energy recovery plant, both in southern Norway; CO ₂ would be transported via ship and pipeline to an offshore in the Smeaheia area
Port of Rotterdam CCUS Backbone Initiative (Porthos)	AD	Netherlands	2023	Various	The ambition is to store 2 Mtpa from 2023 on, a total that will run up to 5 Mtpa by 2030
Sleipner CO ₂ Storage	O	Norway	1996	Natural Gas Processing	The Sleipner CO ₂ storage facility was the first (since 1996) in the world to inject CO ₂ into a dedicated geological storage (located offshore in Norway); Approximately 0.85 Mtpa is injected and over 17 Mtpa has been injected since inception to 2019
Snohvit CO ₂ Storage	O	Norway	2008	Natural Gas Processing	CO ₂ is captured at an LNG facility on the island of Melkoya, Norway; designed to capture 0.7 Mtpa, and CO ₂ is transported via pipeline back to the Snohvit field offshore, where more than 4 Mtpa has been stored to date since 2008
The Clean Gas Project	ED	UK	2025	Power generation	Natural gas will be used to generate power via a Combined Cycle Gas turbine gas-fired generation station, with CO ₂ captured and transported by pipeline for storage in a formation under the Southern North Sea

As demonstrated with the set of works in development presented in Table 2, great efforts have been made to apply capture, storage, and utilization processes in plants. However, there are only a few large-scale CCS plants in operation in Europe so far. This is related to a series of obstacles preventing this technology from being adopted more widely. In most European countries, the nature of the challenges can be political, economic, technical, and social [64–67].

- Political: lack of political commitment with CCS by some member states;

- Economic: high investment, high operational costs, lack of competitiveness compared with other low carbon technologies; no financial compensation for the additional capital and operating costs associated with CCS; Long-term funding commitments from various public and private sources ensure the continuity of research programs which are necessary for the development of CO₂ utilization;
- Technical: lack of infrastructures for transport and storage;
- Social: CCS is unknown for the overall public; resistance to CO₂ storage concept; environmental risks concerning health and water pollution.

Efforts have been made to combat these barriers. As mentioned, to reach the targets defined in the Paris Agreement, immediate/prompt action would be required to reduce CO₂ emissions. Processes related to CCS can be classified as carbon-positive, near carbon-neutral, or carbon-negative. Carbon positive corresponds to the majority of the processes, which still emit CO₂ for the atmosphere. Carbon-neutral and carbon-negative emissions are responsible for zero carbon emissions (neutral) and CO₂ emissions reduction to the atmosphere. Examples of the “negative” processes able to capture CO₂ are Bioenergy with Carbon Capture and Storage (BECCS) and Direct Air Capture (DAC).

4. Climate Positive Solutions

4.1. Bioenergy with Carbon Capture and Storage (BECCS)

Bioenergy has always been present in the world and used by humans to produce heat. Bioenergy is used in vehicles as fuel (bioethanol) and provides electricity by burning biomass [14]. BECCS is part of the broader CCS technology and is emerging as one of the most advanced technologies to decarbonize emission-intensive industries and sectors and enable negative emissions [14]. This is a group of different technologies to produce energy from biomass and CO₂ storage.

This process using biomass as a fuel source because biomass feedstock draws down CO₂ from the atmosphere through photosynthesis. Biomass is burned (combusted or converted) to biofuel, using digestion or fermentation processes. The heat generated can be used for electricity generation or industrial applications, such as cement, pulp and papermaking, waste incineration, steel and iron, and petrochemical. Conversion leads to gaseous (when digestion is applied) or liquid (when fermentation occurs) fuels production. In the liquid case, it leads to the production of bioethanol. Then, CO₂ is captured from a biomass energy conversion and permanently stored in a suitable geological formation. At the end of the process, the CO₂ emitted during bioenergy production, the CO₂ transported, converted, and utilized should be lower than the CO₂ stored to achieve the primary target-negative emissions. Figure 9 presents a scheme of the BECCS.

Figure 9. Scheme of bioenergy and carbon capture and storage (BECCS) (adapted from Consoli [14]).

The Global CCS Institute (2019 data) [14] reports the existence of five facilities (one large-scale and four small-scale) actively operating using BECCS technologies worldwide. Approximately 1.5 million tonnes of CO₂ per annum (Mtpa) are captured by these facilities. Table 3 shows a description of these BECCS facilities and the planned projects.

Table 3. Brief description of BECCS facilities operating today and planned projects (Notes: Mtpa—million tonnes per annum; tpa—tonnes per annum; tpd—tonnes per day).

Operating Today—Five Facilities in USA
Illinois CCS (USA)—1 Mtpa
Ethanol is produced from corn at its Decatur plant, producing CO ₂ as part of the fermentation process
Kansas Arkalon (USA)—200,000 tpa
CO ₂ is compressed and piped from an ethanol plant in Kansas to Booker and Farnsworth Oil Units in Texas for EOR
Bonanza CCS (USA)—100,000 tpa
CO ₂ is compressed and piped from an ethanol plant in Kansas to nearby Stewart Oil field for EOR
Husky Energy CO ₂ Injection (Canada)—250 tpd
CO ₂ is compressed and trucked from an ethanol plant (Saskatchewan) to nearby Lashburn and Tangleflags oil fields for EOR
Farnsworth (USA)—600,000 tonnes
CO ₂ is compressed from an ethanol plant (Kansas) and fertiliser plant (Texas) and piped to Farnsworth oil field for EOR
Planning—One facility in Asia and Two facilities in Europe
Mikawa Power Plant (Japan)
Retrofit of a 49-MW unit power plant (Omuta, Fukuoka Prefecture) to accept 100% of tonne of biomass with a CO ₂ capture facility. Current situation: identify a secure offshore storage site
Drax Power Plant (UK)
Biomass power generation pilot (North Yorkshire): high potential to develop CO ₂ capture and storage
Drax Power Plant (UK)
BECCS integration into waste-to-energy and a cement plants:
Plant: plans to capture 400,000 tpa of CO ₂ (Klemetsrud waste-to-energy) Currently co-fires up to 30% biomass and plans to capture up to 400,000 tpa of CO ₂ (Norcem Cement plant)
CO ₂ will be sent to a storage site (Norwegian North Sea) from waste-to-energy and cement plants

Note: Mtpa is million tonnes per annum of CO₂; tpa is tonnes per annum of CO₂; tpd is tonnes per day of CO₂.

4.2. Direct Air Capture (DAC)

Industrial applications containing air capture technology are not new and have existed since 1930 [68].

In contrast to carbon dioxide capture from sources, such as cement or biomass plants, direct air capture (DAC) is a technology that captures CO₂ directly from the ambient air and generates an enriched stream of CO₂ for storage or use. The process can be denominated as physical or chemical separation. Figure 10 presents a scheme of the DAC process.

Figure 10. Scheme of DAC (adapted from Gutknecht [69]).

It is common to divide the DAC process into three different classes, regarding the approach to separate CO₂ from the air: chemical, cryogenic, and membranes [70].

Two technology approaches are being used to extract CO₂ from the atmosphere in the chemical systems: liquid systems (liquid solvents) and solid systems (solid sorbents) direct air capture. In the cryogenic processes, CO₂ is removed from the air by freezing as a by-product of cryogenic oxygen separation. Membranes are used to separate CO₂ from the air and seawater. Chemical systems are the preferred processes of DAC used by companies.

Liquid systems pass air through chemical solutions, which removes the CO₂ while returning the rest of the air to the environment. For example, a typical process used is when sodium hydroxide is the solvent applied (used in the pulp and paper industry). CO₂ reacts with sodium hydroxide (NaOH) and precipitates sodium carbonate (Na₂CO₃), which produces a highly pure gaseous CO₂ stream when heated; after that, sodium hydroxide is recycled from sodium carbonate.

The reaction occurs between NaOH and CO₂, as presented in Equation (2):

$$\Delta H = -105 \text{ kJ/mol}$$

This process has a high potential to obtain high loadings of CO₂ over a wide range of operating conditions and system designs because of the strong binding energy associated with the reaction presented in Equation (2). A disadvantage is the high energy requirements for releasing the CO₂ during the regeneration stage [20].

Figure 11 shows a brief scheme of this process.

Figure 11. Brief scheme of a liquid solvent process used for capturing CO₂ from air, using NaOH as the absorber (adapted from Mazzotti et al. [71]).

Solid direct air capture technology makes use of solid sorbent filters that chemically bind with CO₂. When the filters are heated, they release the concentrated CO₂, which can be captured for sequestration or utilization.

However, CO₂ in the air is approximately 300 times (~400 ppm) more dilute than in flue gas from a coal-fired power plant, which results in a costly process to separate CO₂ with the same end purity as the one obtained in the CO₂ captured from fossil fuel power plants [72]. Figure 12 shows a brief scheme of the DAC process.

At present, few companies are involved in the DAC field, all designing or using different technologies of DAC, and different markets are focused.

Figure 12. Schematic representation of the DAC process (adapted from Sinha and Realff [73]).

Carbon Engineering Ltd. (CE, Vancouver, BC, Canada) uses liquid alkali metal oxide sorbents regenerated by heat at around 800 °C. CE uses natural gas to power its machines, co-capturing CO₂ from the flue gas stream of the burned natural gas in addition to atmospheric capture [74,75].

Global Thermostat (GT, New York, NY, USA) is a US company which uses a solid amine-based sorbent material for CO₂ capture from air, regenerated at around 80–100 °C [76].

Also, using DAC design, Climeworks AG (Zurich, Switzerland) capture CO₂ with a system based on an adsorption-desorption process with alkaline-functionalized adsorbents. The adsorption is performed at ambient conditions while the desorption occurs using a temperature-vacuum-swing (TVSA) process. The pressure decrease and the temperature increase from 80 to 120 °C, allow to release the CO₂ [76]. The enriched stream of CO₂ is produced at 1 bar with a purity of >99.8%. If the relative humidity on the feed is high, the H₂O is also extracted from the air as a by-product [77]. The first commercial DAC plant was presented in 2017 in Switzerland from Climeworks, with a capacity for 900 t of CO₂ captured per year from the air.

Currently, in Europe, in the United States (US), and in Canada, there are more than 15 DAC plants operating worldwide, most of them are small and sell CO₂ captured for use (in carbonated drinks, for example). However, the first large-scale DAC plant has been developed in the US by a Carbon Engineering Ltd. and Occidental Petroleum partnership. The plant will capture up to 1 MtCO₂ (metric tonnes of CO₂) per year for EOR. This unit could become operational as early as 2023 [76]. Table 4 presents the companies that are working to commercialize DAC systems nowadays.

Several studies have been presented with direct air capture applications to obtain climate change mitigation, some more optimistic than others. Creutzig, et al. [78] estimates that DAC will reach 1 Gt of CO₂ per year in 2050. Fasihi, et al. [79] presents an estimative of about 7 Gt of CO₂ captured per year in the energy system, and about 8 Gt of CO₂ captured per year in carbon dioxide removal in the same year.

Today, the costs involved in direct air capture systems are approximately 510 € per tonnes of CO₂ captured [80].

The transition to a net-zero energy system, in which the amount of CO₂ released to the atmosphere is equivalent to the amount being removed, is highly dependent on the carbon removal processes. The application of decarbonization strategies in the several sectors as aviation and heavy industry would be very difficult. In these cases, carbon removal technologies can be the key for an effective transition. In the 2030 Sustainable Development Scenario, it was defined that CO₂ capture by direct air capture should reach almost 10 Mt of CO₂ per year (in 2030) [76].

Table 4. Companies Working to Commercialize Systems of Direct Air Capture technology [72].

Company	Type of System	Type of Technology	Type of Regeneration	Purity/ Application	Scale
Carbon Engineering Ltd.	Liquid solvent	Potassium hydroxide solution/calcium carbonation	Temperature	99%	Pilot 1 tonne per day
Climeworks	Solid sorbent	Amine-functionalized filter	Temperature or vacuum	99%w /dilution depending on the application	Demonstration 900 tonne per year
Global Thermostat	Solid sorbent	Amine-modified monolith	Temperature and/or vacuum	99%	1000 tonne per year
Infinitree	Solid sorbent	Ion-exchange sorbent	Humidity	3–5% algae	Laboratory
Skytree	Solid sorbent	Porous plastic beads functionalized with benzylamines	Temperature	Air purification, greenhouses	Appliance

5. Industrial Processes

Industrial processes are responsible for raw materials conversion into useable products, which results in energy consumption and CO₂ emissions. For this conversion, fossil fuels continue to satisfy most of the industrial energy demand. However, these processes can be transformed to meet global climate changes. The industrial CO₂ emissions can be categorized into four main groups [27]:

- Energy-related emissions: combustion of coal, oil, and natural gas (considering biomass with an emission factor of zero);
- Process emissions: associated with chemical and physical reactions, such as the production of aluminum, ferroalloys, lubricants and paraffins, and fuels through coal and gas-to-liquid processes, etc.;
- Direct emissions: all emissions associated with industrial processes, except the electricity, heat, and steam purchases (energy-related emissions plus process emissions);
- Indirect emissions: all emissions “out of the facilities”, including electricity, heat and steam purchased.

Industry is responsible for about one-quarter of CO₂ emissions from energy and industrial processes, being 90% of the direct GHG emissions from industrial production, and 40% of global energy demand, especially in cement, in iron and steel and in chemicals industries, which are the most challenging for emissions reduction. Between 1990 and 2017, industrial CO₂ emissions increased 70%. According to Clean Technology Scenario (CTS), consistent with the Paris Agreement defined targets, more than 28 Gt of CO₂ must be captured from industrial facilities until 2060 [27]. CCUS can be a critical factor in the industry decarbonization action. CCUS technologies will contribute to a reduction of 21 Gt of CO₂ of emissions (27%) in the period of 2017–2060, from the cement (18%, capturing 5 Gt of CO₂), iron and steel (15%, capturing 10 Gt of CO₂), and chemical subsectors (38%, capturing 14 Gt of CO₂) [27].

Several industrial sectors produce CO₂ at different temperatures, concentrations, purities, pressures, and volumes, and for all of them, carbon dioxide capture technologies could be applicable. This will be vital for energy-intensive industries, such as those listed below to capture carbon if the EU is to reach its climate targets. These industry subsectors consider iron and steel, chemicals and petrochemicals, cement, pulp and paper, aluminium, and other industries such as ceramics and glass production.

The costs involved in CO₂ capture vary greatly by point source and by capture technology. Costs range from 15 USD per tonne of carbon dioxide (USD/t of CO₂) to 60 USD/t of CO₂ for concentrated CO₂ streams (e.g., natural gas processing and bioethanol production through fermentation), or from 40 USD/tCO₂ to 80 USD/tCO₂ for coal- and gas-fired power plants. The costs can be over USD 100/t of CO₂ for smaller or more dilute point sources (e.g., industrial furnaces) [27].

The current status of industrial sectors is encouraging. Several works are in development today, especially involving the CO₂ capture from high-purity CO₂ sources.

6. Conclusions

International climate obligations, especially the values established in the Paris Agreement, require detailed monitoring and reporting of greenhouse gas emissions, which allowed to observe the increase of CO₂ emissions over time. These scary numbers allow understanding the immediate need to act to reduce the emissions. In this regard, CO₂ capture, utilization, and storage have demonstrated a high potential to be used to reduce global warming potential from power plants. CCS/CCUS has many challenges to overcome. For that, continuous advancement of knowledge is essential to improve the economic and environmental feasibility and technologies potential. As can be seen, several projects are under study to improve the capture of CO₂ and utilization/storage. In the future, some technologies may offer a range of potential opportunities for a sustainable global industry, supporting the climate change objectives, the circular economy, renewable energy deployment, the evolution of CO₂ capture systems, among others. With the 1.5 °C pathway of the Paris Agreement, CO₂ emissions should be 0 in 2050. Therefore, there is still a long path ahead.

Author Contributions: Conceptualization, M.J.R.; Writing—original draft preparation, M.J.R.; Writing—review and editing, M.J.R., A.P., A.F.P.F., A.M.R. and A.E.R.; Visualization, M.J.R.; Supervision, A.F.P.F., A.M.R. and A.E.R. All authors have read and agreed to the published version of the manuscript.

Funding: This work was financially supported by: Base Funding-UIDB/50020/2020 of the Associate Laboratory LSRE-LCM-funded by national funds through FCT/MCTES (PIDDAC). Financial support of NORTE-01-0145-FEDER-000006 FCT-Fundação para a Ciência e Tecnologia under CEEC Institucional program is also acknowledged.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Conflicts of Interest: No conflict of interest.

Nomenclature

AMP	2-Amino-2-methyl-1-propanol
BECCS	Bioenergy with Carbon Capture and Storage
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilization
CCUS	Carbon Capture, Utilization, and Storage
DAC	Direct Air Capture
DEA	Diethanolamine
EGR	Enhanced Gas Recovery
EOR	Enhanced Oil Recovery
ESA	Electrical Swing Adsorption
HBCC	Hydrate-based Carbon Dioxide Capture
IGCC	Integrated Gasification Combined Cycle
MDEA	Methyl diethanolamine
MEA	Monoethanolamine
PSA	Pressure Swing Adsorption
TSA	Temperature Swing Adsorption
TVSA	Temperature-Vacuum Swing Adsorption

Appendix A

Table A1. Summary of other CCS facilities that are working in Europe.

Name	Status	Country	Data	Industry	Observations
CATO Programme	O	The Netherlands	2004	Various	Responsible for covering the full CCS chain and addressing both fundamental and applied topics including regulation and safety and public perception
CO ₂ FieldLab Project	C	Norway	-	N/A	Project is led by Sintef Petroleum Research, with the purpose of testing the sensitivity of a variety of monitoring systems by observing the migration of small amounts of injected CO ₂ in the shallow subsurface
CO ₂ MultiStore Joint Industrial Project (JIP)	C	UK	2012	N/A	Project is led by Scottish Carbon Capture and Storage with joint funding and expert support from CCS project developers and public corporations, to support the development of multi-use regional CO ₂ storage assets
Hisarna Pilot Plant (Reducing CO ₂ Emissions in Steelmaking)	O	The Netherlands	2007	Iron and Steel Production	A coal-based Hisarna smelting reduction process in steelmaking industry was developed by Tata Steel, Rio Tinto and ULCOS partners, and it has been operational since 2011. CO ₂ emissions were reduced by 20%, and can be 80% lower when CCS is applied
QICS Project	C	UK	2010	N/A	Project led by the Plymouth Marine Laboratory, to quantify and monitor Environmental Impacts of Geological Carbon Storage involved in the assessment and monitoring of the first controlled release of CO ₂ into seabed sediments

Table A2. Summary of pilot and demonstration mode CCS facilities in Europe.

Name	Status	Country	Data	Industry	Observations
ELCOGAS Pre-combustion Carbon Capture Pilot Project: Puertollano	C	Spain	2010	Power Generation	A pilot plant was integrated into the Puertollano IGCC plant in Spain to test the feasibility of pre-combustion technology to capture CO ₂ in an IGCC environment that uses solid fossil fuels and wastes as feedstock; operational tests occurred in 2010/2011
Aberthaw Pilot Carbon Capture Facility	C	UK	2013	Power generation	A pilot-scale plant at the Aberthaw power station in South Wales UK tested the Cansolv integrated CO ₂ and SO ₂ removal system during 2013/2014 First fully commercial CCS facility in the iron and steel industry, and involves the CO ₂ capture via a new build CO ₂ Compression facility using high purity CO ₂ produced as a by-product of the direct reduced iron-making process at the Emirates Steel Industries factory in Mussafah. The compression facility has a capture capacity of 0.8 Mtpa. The CO ₂ is captured and is transported via pipeline to Abu Dhabi National Oil Company ADNOC oil reservoirs for EOR
Abu Dhabi CCS (Phase 1 being Enirates Steel Industries)	O	United Arab Emirates	2016	Iron and Steel Production	Initiate a low cost full chain CCS project in the North East of Scotland; cluster of capture, transport and storage infrastructure; CO ₂ is separated from natural gas and vented, adjacent to an offshore transport pipeline, which connects to a well understood offshore basin, rich in storage opportunities
Acorn (Minimum Viable CCS Development)	AD	United Kingdom	2021–2022	Various	

Table A2. Cont.

Name	Status	Country	Data	Industry	Observations
Brindisi CO ₂ Capture Pilot Plant	C	Italy	2010	Power Generation	A pilot-scale plant at the Brindisi power plant in south-eastern Italy tested a number of solvent technologies during 2010–2012
Buggenum Carbon Capture (CO ₂ Catch-up) Pilot Project	C	The Netherlands	2011	Power Generation	A pilot-scale plant at the Willem-Alexander power plant in The Netherlands (now closed) undertook a CO ₂ capture testing and R&D program between 2011 and 2013
C2A2 Field Pilot-Le Havre	C	France	2013	Power Generation	A pilot-scale plant at the Le Havre power plant in France tested a specific carbon capture technology during parts of 2013 and 2014
CarbFix Project	O	Iceland	2012	Power Generation	Study of injection of pure CO ₂ and a gas mixture of CO ₂ and H ₂ S, dissolved in water, into basaltic formations; pilot tests in 2012 injected over 200 tonnes of CO ₂ from a geothermal power plant
CASTOR	C	Denmark	2006	Power Generation	Tests of three solvents in a post-combustion pilot plant located at the coal-fired Esbjerg power plant in Denmark
CEMCAP	C	Norway	2015	Cement Production	Prepare the ground for large-scale implementation of CO ₂ capture in the European cement industry; designed to strengthen and complement the Norcem and ECRA CCS projects; technical development, including technology demonstration in a simulated industrial environment.
CESAR	C	Denmark	2008	Power Generation	Project for the post-combustion capture work undertaken at the coal-fired Esbjerg pilot plant in Denmark under the CASTOR project; modifications to the Esbjerg pilot plant were undertaken during 2008, after which a three test campaign was conducted covering a benchmark and two novel solvents
CIUDEN: CO ₂ Capture & Transport Technology Development Plant	C	Spain	2012	Power Generation	The Hontomin Technology Development Plant—CO ₂ Capture & Transport the CIUDEN Technology Development Center, successfully completed the full CO ₂ capture process, using oxy-combustion in the circulating fluidized bed CFB boiler with the compression and purification unit
CIUDEN: CO ₂ Storage Technology Development Plant	O	Spain	2015	N/A	The Hontomin Storage Technology Development Plant—the site includes one injection well and a monitoring well; 10,000 tonnes of CO ₂ are planned to be injected in the period 2017–2020
CO ₂ Capture Test Facility at Norcem Brevik	C	Norway	2013	Cement Production	A real cement flue gas at the Brevik plant in Norway was used to test three different post-combustion technologies, while investigations on a fourth technology were performed offsite based on a pilot installed at Stuttgart University; tests were done from 2013 to 2017 and aimed to demonstrate the CO ₂ capture from a cement plant, to improve understanding of these technologies for large-scale application
DMX TM Demonstration in Dunkirk	AD	France	2022	Iron and Steel Production	Designed by Axens, started in 2020 at the ArcelorMittal steelworks site in Dunkirk; able to capture 0.5 metric tonnes of CO ₂ an hour from steelmaking gases by 2022

Table A2. Cont.

Name	Status	Country	Data	Industry	Observations
Drax bioenergy carbon capture pilot plant	O	United Kingdom	2019	Power Generation	The CO ₂ capture pilot plant captures 1 tpd from the Drax power station unit, which runs 100% biomass feedstock
ELCOGAS Pre-combustion Carbon Capture Pilot Project: Puertollano	C	Spain	2010	Power Generation	A pilot plant was integrated into the Puertollano IGCC plant in Spain to test the feasibility of pre-combustion technology to capture CO ₂ in an IGCC environment that uses solid fossil fuels and wastes as the main feedstock
Ferrybridge Carbon Capture Pilot (CCPilot100+)	C	United Kingdom	2011	Power Generation	Involves the capture of 100 tpd of CO ₂ from a flue gas stream at the Ferrybridge power station; designed to test the application of an amine-based, post-combustion capture process under realistic operating conditions
Geothermal Plant with CO ₂ Re-injection	C	Croatia	2018	Power Generation	A hybrid geothermal system is used, utilizing the energy potential of hot brines with dissolved natural gases to deliver combined heat and power at its Draškovec development; is expected to supply 17–18 MW of power; CO ₂ separation, capture and injection capacity is at around 50,000 tpa
K12-B CO ₂ Injection Project	C	The Netherlands	2004	Natural Gas Processing	CO ₂ is captured at the offshore natural gas production facility at the K12-B gas field and injected back into the depleted gas reservoir; cumulative injection in 2017 was over 100,000 tonnes
Karlshamn Field Pilot	C	Sweden	2009	Power Generation	One of a number of test facilities used by Alstom to test the viability of its Chilled Ammonia Process for CO ₂ capture and involved the capture of around 30 tpd of CO ₂
Ketzin Pilot Project	C	Germany	2004	Power Generation and Hydrogen Production	The first geological CO ₂ storage project on the European mainland and one of the largest storage pilot projects in the world; constituted by three phases, over 67,000 tonnes of CO ₂ were injected between 2008 and 2013, and post-injection and site behavior monitoring completed in 2017
La Pereda Calcium Looping Pilot Plant	C	Spain	2012	Power Generation	In operation in 2012, undertook three European funded ‘projects’ or test campaigns, testing the viability of post-combustion capture by calcium looping, 1.7 MWth
Lacq CCS Pilot Project	C	France	2010	Power Generation	A storage-focused project of global significance that injected 51,000 tonnes of CO ₂ over a 39 month period from 2010 to 2013; including a comprehensive monitoring plan
LEILAC—Low Emissions Intensity Lime and Cement Project	In C	Belgium	2020’s	Cement Production	Designed, built and operated a pilot plant to: Direct Separation calcining technology can work at the temperatures necessary to process limestone for the lime and cement industries; capture over 95% of the CO ₂ emissions from both industries without significant energy or capital penalty
Renfrew Oxy-fuel (Oxycoal 2) Project	C	United Kingdom	2007	Power Generation	Consisted of an initial oxy-fuel technology mapping phase followed by testing of a 40-MWth oxy-fuel burner at Renfrew, Scotland, under realistic operating conditions and included testing adaptation from air-firing to oxy-fuel firing on pulverized coal; the pilot facility completed 20 test days

Table A2. Cont.

Name	Status	Country	Data	Industry	Observations
Schwarze Pumpe Oxy-fuel Pilot Plant	C	Germany	2008	Power Generation	The 30 MWth Schwarze Pumpe oxy-fuel pilot was the world's first large-scale testing of the entire oxy-fuel combustion technology chain; In 2014, it was discontinued research into coal-fired power with CCS; the pilot plant captured and liquefied 11,000 tonnes of CO ₂ ; Around 1500 tonnes of CO ₂ from the Schwarze Pumpe oxy-fuel capture pilot plant were injected
STEPWISE Pilot of SEWGS Technology at Swerea/Mefos	O	Sweden	2017	Iron and Steel Production	The Sorption Enhanced Water Gas Shift reaction SEWGS process is to be demonstrated at a CO ₂ capture rate of 14 tonnes per day; the pilot plant is fed with blast furnace gas from the adjacent steel plant of SSAB; the test facility was launched in September 2017
Wilhelmshaven CO ₂ Capture Pilot Plant	C	Germany	2012	Power Generation	CO ₂ capture from a side stream of the Wilhelmshaven coal-fired power station; designed to capture 70 tpd of CO ₂ at full capacity; achieved 4500 h of operation in the first quarter of 2014

Table A3. Summary of CCS facility tests centers in Europe.

Name	Status	Country	Data	Industry	Observations
Technology Centre Mongstad (TCM)	O	Norway	2012	Oil Refining	The demonstration test facility comprises two capture units, one designed for amine-based solvents and the other for chilled aqueous ammonia
UKCCSRC Pilot-scale Advanced Capture Technology (PACT)	O	United Kingdom	-	Power Generation	PACT facilities bring together a range of integrated pilot-scale and accompanying specialist research and analytical facilities, supported by leading academic expertise; post-combustion pilot is installed and is jointly operated by the Universities of Leeds and Sheffield

Table A4. Summary of CO₂ utilization facilities in Europe.

Name	Status	Country	Data	Industry	Observations
ArcelorMittal Steelanol Ghent	In C	Belgium	2020	Iron and Steel Production	ArcelorMittal Steelanol Ghent
Port Jérôme CO ₂ Capture Plant	O	France	2015	Hydrogen Production	Port Jérôme CO ₂ Capture Plant
Twence Waste-to-energy CO ₂ Capture and Utilisation	O	The Netherlands	2014	Waste Incineration	Twence Waste-to-energy CO ₂ Capture and Utilisation

References

- Climate Change Service. Surface Air Temperature for September 2019. Available online: <https://climate.copernicus.eu/surface-air-temperature-september-2019> (accessed on 14 March 2021).
- Borowski, P.F. Nexus between water, energy, food and climate change as challenges facing the modern global, European and Polish economy. *AIMS Geosci.* **2020**, *6*, 397–421. [CrossRef]
- Folger, P. *Carbon Capture: A Technology Assessment*; Congressional Research Service: Washington, DC, USA, 2013; p. 3.
- Lallanilla, M. Greenhouse Gas Emissions: Causes & Sources. Available online: <http://www.livescience.com/37821-greenhouse-gases.html> (accessed on 26 May 2016).
- Jefferson, M. Energy policies for sustainable development. In *World Energy Assessment: Energy and the Challenge of Sustainability*; Communications Development Incorporated: Washington, DC, USA, 2000.
- Green, C.; Byrne, K. Biomass: Impact on Carbon Cycle and Greenhouse Gas Emissions. *Encycl. Energy* **2004**, *1*, 223–236. [CrossRef]
- Quadrelli, R.; Peterson, S. The energy-climate challenge: Recent trends in CO₂ emissions from fuel combustion. *Energy Policy* **2007**, *35*, 5938–5952. [CrossRef]

8. Olajire, A.A. CO₂ capture and separation technologies for end-of-pipe applications—A review. *Energy* **2010**, *35*, 2610–2628. [CrossRef]
9. Masson-Delmotte, V. *Global Warming of 1.5 °C*; IPCC—Intergovernmental Panel on Climate Change: Geneva, Switzerland, 2019; ISBN 978-92-9169-153-1.
10. Masson-Delmotte, V.P.; Zhai, H.-O.; Pörtner, D.; Roberts, J.; Skea, P.R.; Shukla, A.; Pirani, W.; Moufouma-Okia, C.; Péan, R.; Pidcock, S.; et al. *Global Warming of 1.5 °C. An IPCC Special Report on the Impacts of Global Warming of 1.5 °C above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*; IPCC: Geneva, Switzerland, 2018.
11. Foley, A.; Smyth, B.M.; Pukšec, T.; Markovska, N.; Duić, N. A review of developments in technologies and research that have had a direct measurable impact on sustainability considering the Paris agreement on climate change. *Renew. Sustain. Energy Rev.* **2017**, *68*, 835–839. [CrossRef]
12. Sekera, J.; Lichtenberger, A. Assessing Carbon Capture: Public Policy, Science, and Societal Need. *Biophys. Econ. Sustain.* **2020**, *5*, 14. [CrossRef]
13. Bui, M.; Adjiman, C.S.; Bardow, A.; Anthony, E.J.; Boston, A.; Brown, S.; Fennell, P.S.; Fuss, S.; Galindo, A.; Hackett, L.A.; et al. Carbon capture and storage (CCS): The way forward. *Energy Environ. Sci.* **2018**, *11*, 1062–1176. [CrossRef]
14. Consoli, C. *Bioenergy and Carbon Capture and Storage*; Global CCS Institute: Docklands, Australia, 2019.
15. International Energy Agency. Global Emissions in 2019. Available online: <https://www.iea.org/articles/global-co2-emissions-in-2019> (accessed on 18 March 2021).
16. International Energy Agency. *Global Energy Review 2020*; International Energy Agency: Paris, France, 2020. Available online: <https://www.iea.org/reports/global-energy-review-2020> (accessed on 18 March 2021).
17. Tiseo, I. Global Distribution of CO₂ Emissions from Fossil Fuel and Cement by Sector 2020. Available online: <https://www.statista.com/statistics/1129656/global-share-of-co2-emissions-from-fossil-fuel-and-cement/> (accessed on 18 March 2021).
18. Climate Action Tracker. 2100 Warming Projections. Available online: <https://climateactiontracker.org/global/temperatures/> (accessed on 18 April 2021).
19. CarbonBrief—Clear on Climate. Explainer: The high-emissions ‘RCP8.5’ global warming scenario. Available online: <https://www.carbonbrief.org/explainer-the-high-emissions-rcp8-5-global-warming-scenario> (accessed on 3 September 2020).
20. Pires, J.C.M.; Martins, F.G.; Alvim-Ferraz, M.C.M.; Simões, M. Recent developments on carbon capture and storage: An overview. *Chem. Eng. Res. Des.* **2011**, *89*, 1446–1460. [CrossRef]
21. Songolzadeh, M.; Ravanchi, M.T.; Soleimani, M. Carbon Dioxide Capture and Storage: A General Review on Adsorbents. *World Acad. Sci. Eng. Technol.* **2012**, *6*, 213–220.
22. International Energy Agency. Carbon Capture, Utilisation and Storage. Available online: <https://www.iea.org/fuels-and-technologies/carbon-capture-utilisation-and-storage> (accessed on 3 August 2020).
23. Marocco Stuardi, F.; MacPherson, F.; Leclaire, J. Integrated CO₂ capture and utilization: A priority research direction. *Curr. Opin. Green Sustain. Chem.* **2019**, *16*, 71–76. [CrossRef]
24. Romasheva, N.; Ilinova, A. CCS Projects: How Regulatory Framework Influences Their Deployment. *Resources* **2019**, *8*, 181. [CrossRef]
25. Global CCS Institute. *The Global Status of CCS*; Summary report; Global Carbon Capture and Storage Institute Ltd.: Melbourne, Australia, 2015; Available online: https://www.globalccsinstitute.com/wp-content/uploads/2018/12/Global-Status-Report_2015_Summary.pdf (accessed on 3 August 2020).
26. International Energy Agency. *Energy Technology Perspectives*; International Energy Agency: Paris, France, 2017. Available online: <https://www.iea.org/topics/energy-technology-perspectives> (accessed on 18 March 2021).
27. International Energy Agency. Transforming Industry through CCUS. 2019. Available online: <https://www.iea.org/reports/transforming-industry-through-ccus> (accessed on 18 March 2021).
28. Dindi, A.; Quang, D.V.; Vega, L.F.; Nashef, E.; Abu-Zahra, M.R.M. Applications of fly ash for CO₂ capture, utilization, and storage. *J. CO₂ Util.* **2019**, *29*, 82–102. [CrossRef]
29. IPCC. *IPCC Special Report on Carbon Dioxide Capture and Storage*; Prepared by Working Group III of the Intergovernmental Panel on Climate Change; Metz, B.O., Davidson, H.C., de Coninck, M.L., Meyer, L.A., Eds.; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2005; p. 442.
30. Nota, G.; Nota, F.D.; Peluso, D.; Toro Lazo, A. Energy Efficiency in Industry 4.0: The Case of Batch Production Processes. *Sustainability* **2020**, *12*, 6631. [CrossRef]
31. Global CCS Institute. *CO₂ Capture Technologies*; Global Carbon Capture and Storage Institute: Canberra, Australia, 2012; pp. 1–13.
32. Pastor-Pérez, L.; Baibars, F.; Le Sache, E.; Arellano-García, H.; Gu, S.; Reina, T.R. CO₂ valorisation via Reverse Water-Gas Shift reaction using advanced Cs doped Fe-Cu/Al₂O₃ catalysts. *J. CO₂ Util.* **2017**, *21*, 423–428. [CrossRef]
33. Rackley, S.A. *Carbon Capture from Power Generation*, 2nd ed.; Carbon Capture and Storage; Elsevier: London, UK, 2017; ISBN 9780128120415.
34. U.S. Department Energy. Pre-Combustion CO₂ Capture. Available online: <https://www.energy.gov/fe/science-innovation/carbon-capture-and-storage-research/carbon-capture-rd/pre-combustion-carbon> (accessed on 15 August 2020).
35. National Energy Technology Laboratory Post-Combustion CO₂ Capture. Available online: <https://www.netl.doe.gov/coal/carbon-capture/post-combustion> (accessed on 1 April 2021).

36. Buhre, B.J.P.; Elliott, L.K.; Sheng, C.D.; Gupta, R.P.; Wall, T.F. Oxy-fuel combustion technology for coal-fired power generation. *Prog. Energy Combust. Sci.* **2005**, *31*, 283–307. [CrossRef]
37. Wong, S. *Module 3—CO₂ Capture: Pre-Combustion (Decarbonisation) and Oxy-Fuel Technologies*; Global CCS Institute: Docklands, VIC, Australia, 2011; Volume 1, pp. 45–54. Available online: <https://www.globalccsinstitute.com/archive/hub/publications/114711/building-capacity-co2-capture-and-storage-apec-region> (accessed on 3 August 2020).
38. Armstrong, K.; Styring, P. Assessing the Potential of Utilization and Storage Strategies for Post-Combustion CO₂ Emissions Reduction. *Front. Energy Res.* **2015**, *3*. [CrossRef]
39. Bhowan, A.S.; Freeman, B.C. Analysis and Status of Post-Combustion Carbon Dioxide Capture Technologies. *Environ. Sci. Technol.* **2011**, *45*, 8624–8632. [CrossRef]
40. Leung, D.Y.C.; Caramanna, G.; Maroto-Valer, M.M. An overview of current status of carbon dioxide capture and storage technologies. *Renew. Sustain. Energy Rev.* **2014**, *39*, 426–443. [CrossRef]
41. Luis, P. Use of monoethanolamine (MEA) for CO₂ capture in a global scenario: Consequences and alternatives. *Desalination* **2016**, *380*, 93–99. [CrossRef]
42. Walspurger, S.; Van Dijk, H.A.J. *EDGAR CO₂ Purity: Type and Quantities of Impurities Related to CO₂ Point Source and Capture Technology: A Literature Study*; The Energy Research Centre of The Netherlands: Petten, The Netherlands, 2012.
43. Samanta, A.; Zhao, A.; Shimizu, G.K.H.; Sarkar, P.; Gupta, R. Post-Combustion CO₂ Capture Using Solid Sorbents: A Review. *Ind. Eng. Chem. Res.* **2012**, *51*, 1438–1463. [CrossRef]
44. Grande, C.A. Advances in Pressure Swing Adsorption for Gas Separation. *ISRN Chem. Eng.* **2012**, *2012*, 13. [CrossRef]
45. Regufe, M.J.; Ribeiro, A.M.; Ferreira, A.F.P.; Rodrigues, A. CO₂ Storage on Zeolites and Other Adsorbents. In *Nanoporous Materials for Gas Storage*; Kaneko, K., Rodríguez-Reinoso, F., Eds.; Springer: Singapore, 2019; pp. 359–381.
46. Yang, H.; Li, J.-R. Metal-Organic Frameworks (MOFs) for CO₂ Capture. In *Porous Materials for Carbon Dioxide Capture*; Lu, A.-H., Dai, S., Eds.; Springer: Berlin/Heidelberg, Germany, 2014; pp. 79–113.
47. Regufe, M.J.; Tamajon, J.; Ribeiro, A.M.; Ferreira, A.; Lee, U.H.; Hwang, Y.K.; Chang, J.-S.; Serre, C.; Loureiro, J.M.; Rodrigues, A.E. Syngas Purification by Porous Amino-Functionalized Titanium Terephthalate MIL-125. *Energy Fuels* **2015**, *29*, 4654–4664. [CrossRef]
48. Lu, C.; Bai, H.; Wu, B.; Su, F.; Hwang, J.F. Comparative study of CO₂ capture by carbon nanotubes, activated carbons, and zeolites. *Energy Fuels* **2008**, *22*, 3050–3056. [CrossRef]
49. Regufe, M.J.; Ferreira, A.F.P.; Loureiro, J.M.; Rodrigues, A.; Ribeiro, A.M. Development of Hybrid Materials with Activated Carbon and Zeolite 13X for CO₂ Capture from Flue Gases by Electric Swing Adsorption. *Ind. Eng. Chem. Res.* **2020**, *59*, 12197–12211. [CrossRef]
50. Regufe, M.J.; Ferreira, A.F.P.; Loureiro, J.M.; Rodrigues, A.; Ribeiro, A.M. Electrical conductive 3D-printed monolith adsorbent for CO₂ capture. *Microporous Mesoporous Mater.* **2019**, *278*, 403–413. [CrossRef]
51. Clodic, D.; Younes, M. A new Method for CO₂ Capture: Frosting CO₂ at Atmospheric Pressure. In *Proceedings of the Greenhouse Gas Control Technologies—6th International Conference, Kyoto, Japan, 1–4 October 2002*; Gale, J., Kaya, Y., Eds.; Pergamon: Oxford, UK, 2003; pp. 155–160.
52. Tuinier, M.J.; van Sint Annaland, M.; Kramer, G.J.; Kuipers, J.A.M. Cryogenic CO₂ capture using dynamically operated packed beds. *Chem. Eng. Sci.* **2010**, *65*, 114–119. [CrossRef]
53. Nanda, S.; Reddy, S.N.; Mitra, S.K.; Kozinski, J.A. The progressive routes for carbon capture and sequestration. *Energy Sci. Eng.* **2016**, *4*, 99–122. [CrossRef]
54. Hart, A.; Gnanendran, N. Cryogenic CO₂ capture in natural gas. *Energy Procedia* **2009**, *1*, 697–706. [CrossRef]
55. Kenarsari, S.D.; Yang, D.; Jiang, G.; Zhang, S.; Wang, J.; Russell, A.G.; Wei, Q.; Fan, M. Review of recent advances in carbon dioxide separation and capture. *RSC Adv.* **2013**, *3*, 22739–22773. [CrossRef]
56. Klinthong, W.; Yang, Y.-H.; Huang, C.-H.; Tan, C.-S. A Review: Microalgae and Their Applications in CO₂ Capture and Renewable Energy. *Aerosol Air Qual. Res.* **2015**, *15*, 712–742.
57. Yang, M.; Song, Y.; Jiang, L.; Zhao, Y.; Ruan, X.; Zhang, Y.; Wang, S. Hydrate-based technology for CO₂ capture from fossil fuel power plants. *Appl. Energy* **2014**, *116*, 26–40. [CrossRef]
58. Zheng, J.; Chong, Z.R.; Qureshi, M.F.; Linga, P. Carbon Dioxide Sequestration via Gas Hydrates: A Potential Pathway toward Decarbonization. *Energy Fuels* **2020**. [CrossRef]
59. Matsuo, S.; Umeda, H.; Takeya, S.; Fujita, T.A. Feasibility Study on Hydrate-Based Technology for Transporting CO₂ from Industrial to Agricultural Areas. *Energies* **2017**, *10*, 728. [CrossRef]
60. International Energy Agency, CCUS in Clean Energy Transitions. Available online: <https://www.iea.org/reports/ccus-in-clean-energy-transitions/a-new-era-for-ccus> (accessed on 18 March 2021).
61. Svante. Capturing Carbon Economically, Today. Available online: <https://svanteinc.com/carbon-capture-technology/> (accessed on 18 March 2021).
62. Air Products. Carbon Capture. Available online: <https://www.airproducts.com/company/innovation/carbon-capture#/> (accessed on 18 March 2021).
63. Global CCS Institute. Facilities Database. Available online: <https://co2re.co/FacilityData> (accessed on 4 August 2020).

-
64. Townsend, A.; Gillespie, A. *Scaling Up the CCS Market to Deliver Net-Zero Emissions*; Global CCS Institute: Docklands, Australia, 2020; Available online: <https://www.globalccsinstitute.com/wp-content/uploads/2020/04/Thought-Leadership-Scaling-up-the-CCS-Market-to-Deliver-Net-Zero-Emissions-Digital-6.pdf> (accessed on 18 March 2021).
 65. Budinis, S.; Krevor, S.; Dowell, N.M.; Brandon, N.; Hawkes, A. An assessment of CCS costs, barriers and potential. *Energy Strategy Rev.* **2018**, *22*, 61–81. [CrossRef]
 66. Karayannis, V.; Charalampides, G.; Lakioti, E. Socio-economic Aspects of CCS Technologies. *Procedia Econ. Financ.* **2014**, *14*, 295–302. [CrossRef]
 67. Stigson, P.; Hansson, A.; Lind, M. Obstacles for CCS deployment: An analysis of discrepancies of perceptions. *Mitig. Adapt. Strateg. Glob. Chang.* **2012**, *17*, 601–619. [CrossRef]
 68. Ranjan, M.; Herzog, H.J. Feasibility of air capture. *Energy Procedia* **2011**, *4*, 2869–2876. [CrossRef]
 69. Gutknecht, V. Awesome Extractors. Available online: https://mag.ebmpapst.com/en/industries/refrigeration-ventilation/awesome-extractors_12472/ (accessed on 6 August 2020).
 70. Sandalow, D.; Friedmann, J.; McCormick, C.; McCoy, S. Direct Air Capture of Carbon Dioxide. 2018. Available online: https://www.globalccsinstitute.com/wp-content/uploads/2020/06/JF_ICEF_DAC_Roadmap-20181207-1.pdf (accessed on 18 March 2021).
 71. Mazzotti, M.; Baciocchi, R.; Desmond, M.J.; Socolow, R.H. Direct air capture of CO₂ with chemicals: Optimization of a two-loop hydroxide carbonate system using a countercurrent air-liquid contactor. *Clim. Chang.* **2013**, *118*, 119–135. [CrossRef]
 72. Ocean Studies Board and National Academies of Sciences Engineering, and Medicine. *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*; The National Academies Press: Washington, DC, USA, 2019.
 73. Sinha, A.; Realff, M.J. A parametric study of the techno-economics of direct CO₂ air capture systems using solid adsorbents. *AIChE J.* **2019**, *65*, e16607. [CrossRef]
 74. Keith, D.W.; Holmes, G.; St. Angelo, D.; Heidel, K. A Process for Capturing CO₂ from the Atmosphere. *Joule* **2018**, *2*, 1573–1594. [CrossRef]
 75. Carbon Engineering Ltd. Direct Air Capture. Available online: <https://carbonengineering.com/our-technology/> (accessed on 18 March 2021).
 76. Beuttler, C.; Charles, L.; Wurzbacher, J. The Role of Direct Air Capture in Mitigation of Anthropogenic Greenhouse Gas Emissions. *Front. Clim.* **2019**, *1*, 10. [CrossRef]
 77. International Energy Agency. *Direct Air Capture*; International Energy Agency: Paris, France, 2020. Available online: <https://www.iea.org/reports/direct-air-capture> (accessed on 9 April 2021).
 78. Creutzig, F.; Breyer, C.; Hilaire, J.; Minx, J.; Peters, G.; Socolow, R. The mutual dependence of negative emission technologies and energy systems. *Energy Environ. Sci.* **2019**, *12*, 1805–1817. [CrossRef]
 79. Fasihi, M.; Efimova, O.; Breyer, C. Techno-economic assessment of CO₂ direct air capture plants. *J. Clean. Prod.* **2019**, *224*, 957–980. [CrossRef]
 80. Sandalow, D.; Friedmann, J.; Aines, R.; McCormick, C.; McCoy, S.; Stolaroff, J. *Industrial Heat Decarbonization Roadmap*; ICEF–Innovation for Coal Earth Forum: Tokyo, Japan, 2019.