energies

MDPI

Article

An Assessment of CO_2 Capture Technologies towards Global Carbon Net Neutrality

Amith Karayil, Ahmed Elseragy and Aliyu M. Aliyu *

School of Engineering, University of Lincoln, Brayford Pool, Lincoln LN6 7TS, UK;
amith.karayil@arcadis.com (A.K.); ahmed.elseragy@bue.edu.eg (A.E.)
* Correspondence: AAliyu@lincoln.ac.uk

Abstract: Carbon dioxide, the leading contributor to anthropogenic climate change, is released mainly via fossil fuel combustion, mostly for energy generation. Carbon capture technologies are employed for reducing the emissions from existing huge point sources, along with capturing them from direct air, to reduce the existing concentration. This paper provides a quantitative analysis of the various subtypes of carbon capture technologies with the aim of providing an assessment of each from technological, social, geo-political, economic, and environmental perspectives. Since the emissions intensity and quantity, along with the social–political–economic conditions, vary in different geographic regions, prioritising and finding the right type of technology is critical for achieving ambitious net-zero targets. Four main types of carbon capture technology were analysed (adsorption, absorption, membrane, and cryogenic) under four scenarios depending on the jurisdiction. The Technique for Order of Preference by Similarity to Ideal Solution (also known as the TOPSIS method) was used to establish a quantitative ranking of each, where weightages were allocated according to the emissions status and economics of each depending on the jurisdiction. Furthermore, forecasting the trends for technology types vis à vis carbon neutral targets between 2040 and 2050 was carried out by applying regression analysis on existing data and the emissions footprint of major contributing countries. The study found the membrane score to be the highest in the TOPSIS analysis in three of the four scenarios analysed. However, absorption remains the most popular for post-combustion capture despite having the highest energy penalty per ton of CO_2 capture. Overall, capture rates are well short of projections for carbon neutrality; the methodology put forward for prioritising and aligning appropriate technologies and the region-by-region analysis will help highlight to technocrats, governments, and policymakers the state of the art and how to best utilise them to mitigate carbon emissions—critical in achieving the net-zero goals set at various international agreements on climate change.

Keywords: absorption; adsorption; energy penalty; membrane capture; net-zero

check for updates

Citation: Karayil, A.; Elseragy, A.; Aliyu, A.M. An Assessment of CO_2 Capture Technologies towards Global Carbon Net Neutrality. *Energies* **2024**, *17*, 1460. https://doi.org/10.3390/en17061460

Academic Editor: Qi Liu

Received: 25 February 2024
Revised: 11 March 2024
Accepted: 13 March 2024
Published: 18 March 2024

1. Introduction

Greenhouse gas emissions have been scientifically linked to global warming, resulting in a rise in sea levels and subsequent climate change. This happens due to the ability of greenhouse gases to trap the infrared radiation in the Earth's atmosphere. Carbon dioxide makes up more than three-fourths of greenhouse gas emissions, followed by methane and nitrous oxide. Anthropogenic greenhouse gas emissions have resulted in climate change, manifested by global warming and rising sea levels. Carbon dioxide makes up around 76% of greenhouse gas emissions. Methane, which contributes around 16%, comes primarily from farming and agriculture. The detailed breakdown of greenhouse emissions is shown in Figure 1.

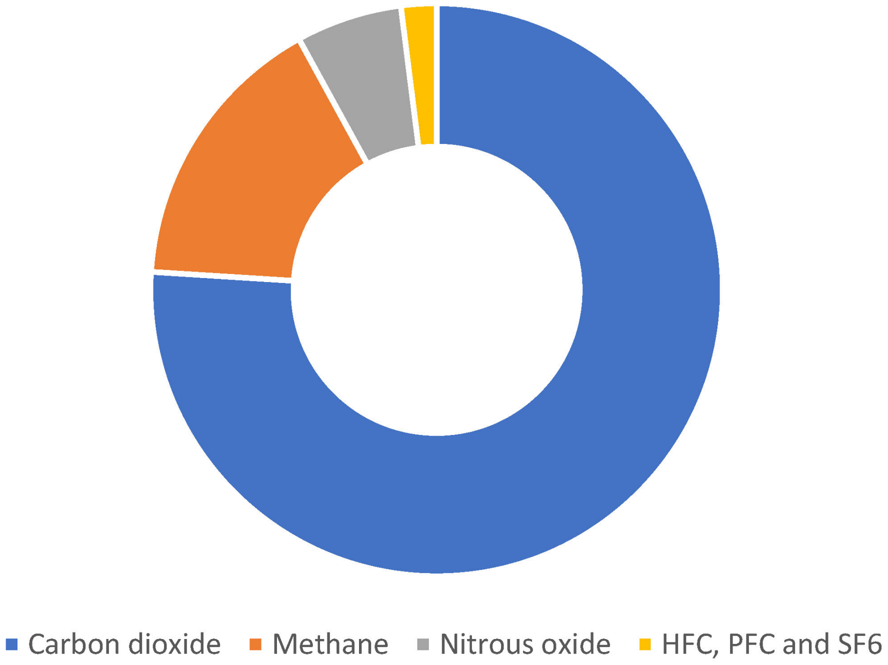


Figure 1. Greenhouse gas emissions breakdown by compound [1].

Perceiving the gravity of the situation, the UK, along with other members of the G7, have committed to a 2050 net-zero goal. This has been reiterated by the UK government's ten-point plan [2]. It points out the need for investments in carbon capture, usage, and storage. Around 200 countries agreed on the Paris Climate Treaty in 2015, aiming to "limit global warming to well below 2, preferably to 1.5 degrees Celsius, compared to pre-industrial levels" [3]. Capture technologies could either be oxyfuel combustion, post-combustion, or pre-combustion. In this article, the focus will be on post-combustion carbon capture. Although there are several types of post-combustion carbon capture processes in various stages of technological development, their performance criteria, such as capture efficiency, cost, and energy consumption, are spread on a wide range. This paper assesses these capture routes to identify their metrics. The TOPSIS method will be used to rank these technologies based on the metrics. Understanding the technology priority for their country and aligning their carbon-neutral agenda accordingly will accelerate the journey towards a global net-zero goal.

We hence study the main post-combustion carbon capture technologies, absorption, membrane, adsorption, and cryogenic carbon capture technology (Figure 2 showing their sub-classifications), with an aim to carry out a comparative analysis of these technologies. This is conducted in terms of four parameters: scalability, capture cost, recovery rate, and energy consumption. Detailed analysis of transportation, storage or seabed sequestration, and utilisation of captured carbon falls outside the scope of this research. The Technique for Order of Preference by Similarity to the Ideal Solution method (otherwise known as TOPSIS) is then used to analyse these metrics and rank them for four different typical cases: developing countries with high emissions, developing countries with low emissions, developed countries with high emissions, and developed countries with low emissions.

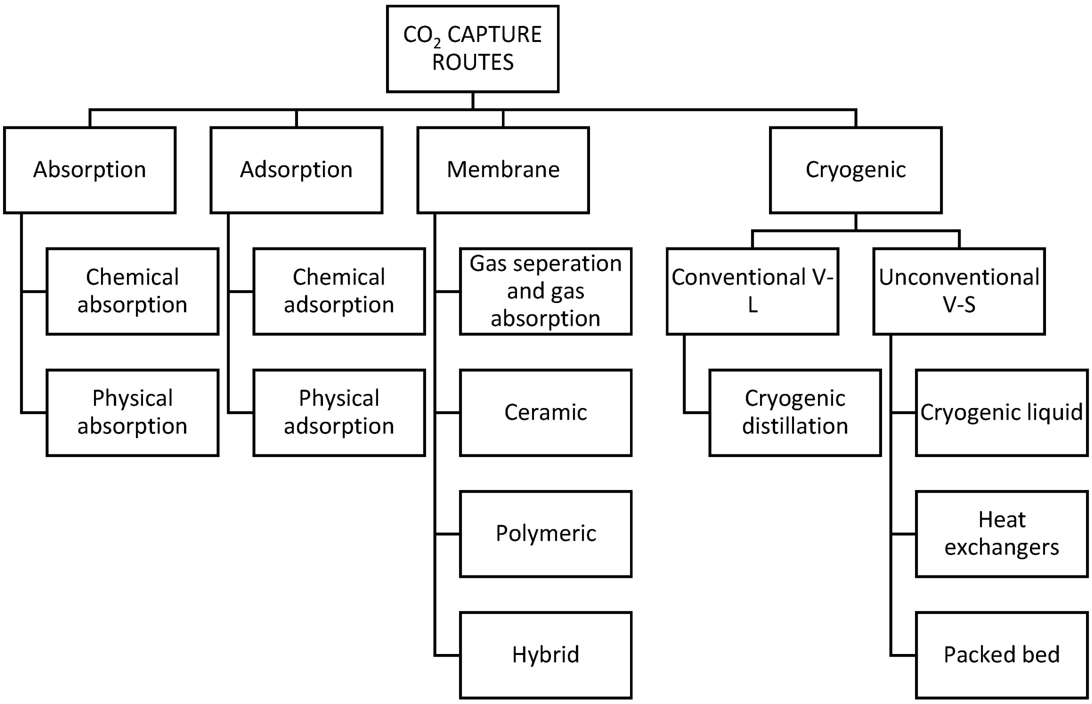


Figure 2. Different routes for carbon capture. Based on Ref. [4].

2. Research Methodology

2.1. Overall Strategy

Since the purpose of this research is to comparatively analyse different technologies, a secondary research method is adopted. Once the research topic is defined, all available data sources related to the topic are examined. Books, academic journals, and industry websites are used to gather, validate, and organise the data. External secondary research methodology is employed since the information collected is not from in-house data sources. Data were collected from online library databases DOAJ, SCOPUS, Web of Science, EBSCO host, ScienceDirect, and Google Scholar. Using the keywords and search criteria mentioned in the literature review section helped in narrowing down the search. Keywords such as 'types of carbon capture', 'assessment', 'absorption and adsorption', 'membrane', 'chemical looping', 'cryogenic carbon capture', and 'comparative analysis' were used. Search results were further refined and narrowed down by selecting the source type and year of publication date range. Out of the 184 relevant papers collected from these sources, 117 papers were shortlisted and used for referencing in this article. Once the relevant information was gathered and organised, data were compared and analysed. A detailed literature review helped to deduce four main metrics related to carbon capture types: capture rate, technology readiness level, capture cost, and energy consumption.

Since there are multiple criteria involved in this decision making, the TOPSIS method was used to rank the technologies. Four different typical cases were considered: developing country with high emissions, developing country with low emissions, developed country with high emissions, and developed country with low emissions. Weightages for these four parameters are given accordingly to formulate a weighted normalised matrix. The ideal best and ideal worst values are calculated for each type. Euclidean distances to the ideal best and ideal worst values are calculated. These values are then used to calculate the performance score for each carbon capture type. Figure 3 visually shows the methodology. The TOPSIS method indicated at the bottom of the schematic is described in more detail in the next section.

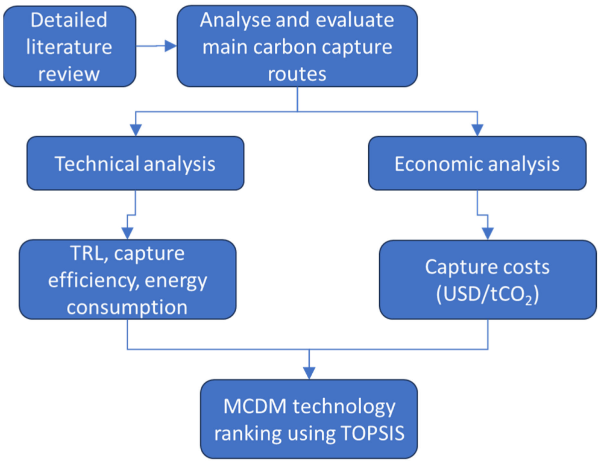


Figure 3. Flowchart visualising the research methodology used in this article.

2.2. Multi-Criteria Decision Method—The TOPSIS Technique

This study aims to prioritise and rank four main types of carbon capture technology: absorption, adsorption, membrane separation, and cryogenic carbon capture. Four different cases are considered for this technology prioritisation: developing countries with high emissions, developing countries with low emissions, developed countries with high emissions, and developed countries with low emissions. Most countries will fit one of these cases and have already made a commitment to net zero by this mid-century [5]. Metrics are given weightages for each case considering their emissions status and economics.

Four main metrics are analysed for each capture route: technology readiness level (TRL), capture efficiency or the percentage of CO_2 removed from the flue gas, energy consumption for capture, and cost of capture. A decision matrix is formed with the metrics for each carbon capture route. The normalised matrix is calculated using Equation (1) given below. The formula for calculating the normalised matrix is as follows:

$$\overline{\mathrm{x}}_{\mathrm{ij}} = \frac{X_{ij}}{\sqrt{\sum_{i=1}^{n} {X_{ij}}^2}} \tag{1}$$

where $\overline{\mathrm{x}}_{\mathrm{ij}}$ denotes the elements of the normalised matrix, and X_{ij} denotes the elements of the decision matrix. In this formula, the denominator is the square root of squared sums of the values in that column. Each value in the decision matrix is then divided by this denominator to obtain a normalised matrix. The normalised matrix is then multiplied with the weightage to obtain the weighted normalised matrix shown in Equation (2). Weightage is shown in the first row of the decision matrix. Multiplying this with the values in the same column in the normalised matrix would give the elements of the weighted normalised matrix, denoted by V_{ij}.

$$V_{ij} = \overline{X}_{ij} \times W_j \tag{2}$$

where W_j denotes the weightage for that metric. This weightage is given based on the emissions intensity and affordability for each case. The next step is identifying the ideal best and ideal worst values for each metric. It may be noted that for metrics such as TRL and capture efficiency, a higher value would be considered the ideal best, whereas for energy penalty and cost, a lower value would be considered the ideal best. V+ denotes the ideal best values, and v− denotes the ideal worst values for each metric. Equations (3) and (4) are used for calculating Euclidean distance from the ideal best and ideal worst. The formula for calculating the Euclidean distance from the ideal best is as follows:

$$\mathrm{s}_{\mathrm{i}}^{+} = \sqrt{\sum_{j=1}^{m} \left(v_{ij} - v_j^{+}\right)^2} \tag{3}$$

where v_{ij} denotes elements of the normalised matrix, and v_j^+ denotes the ideal best value for that metric. Similarly, the formula for calculating the Euclidean distance from ideal worst is

$$\mathrm{s}_{\mathrm{i}}^{-} = \sqrt{\sum_{j=1}^{m} \left(v_{ij} - v_j^{-}\right)^2} \tag{4}$$

v_{ij} denotes elements of the normalised matrix, and v_j^- denotes the ideal worst value for that metric. Equation (5) to calculate the performance score is

$$\mathrm{P}_{\mathrm{i}} = \frac{\mathrm{s}_{\mathrm{i}}^{-}}{\mathrm{s}_{\mathrm{i}}^{+} + \mathrm{s}_{\mathrm{i}}^{-}} \tag{5}$$

Here, the denominator is the sum of the Euclidean distance from ideal best ($\mathrm{s}_{\mathrm{i}}^{+}$) and ideal worst ($\mathrm{s}_{\mathrm{i}}^{-}$). The numerator is the Euclidean distance from the ideal worst. The option with the highest performance score could be considered the best available solution. In this study, we consider four different cases, with varying weightage on metrics depending on the varying income level and carbon footprint.

3. Results and Discussion

In this section, the various technologies used to achieve post-combustion carbon capture will be assessed. These are absorption, adsorption, membrane separation, and cryogenic methods. Analysis will be carried out to evaluate their strengths, weaknesses, and energy consumption. TOPSIS will then be used to rank them as the most promising technologies for post-combustion carbon capture towards achieving net-zero CO_2 emissions by 2040.

3.1. Absorption

Absorption is the main technique currently used for carbon capture and is the most mature and deployed system in industry. Absorption could be broadly classified into physical and chemical absorption processes. Chemical absorption includes using chemical reactions to separate carbon dioxide. Physical absorption involves mass transfer at the interface [6]. Physical absorbents are generally derived from Selexol and Rectisol. Physical absorption depends on the solubility of CO_2 in the solvent and is preferred at higher pressures [7].

3.1.1. Chemical Absorption

The main advantage of chemical absorption is its high absorption capacity [8]. Amine-based carbon capture mainly works on an absorption–regeneration loop. The solvent in the absorber reacts with the carbon dioxide in the flue gas from the plant. This CO_2-rich solvent is then transferred to a stripper to regenerate CO_2 at high temperatures. This will reverse the process to release CO_2, and this cycle is repeated. The amine method can recover 85–95% CO_2 from flue gas. Piperazine is noted to have a high resistance to degradation. Using solvent blends would assist in enhancing absorption properties. It has been found that blending piperazine with monoethanolamine can enhance the absorption rate since piperazine is faster than monoethanolamine [9]. Chemical absorption is the most widely deployed industrially for post-combustion carbon capture. Readers can find a lot of material on classifications in the open literature. Hence, they will not be repeated here.

3.1.2. Physical Absorption

Physical absorption methods are useful for small temperatures and large pressures of the separated gas. In the coal gasification process, chemically inert solvents such as Selexol, Rectisol, and Purisol are used [9,10]. There are many existing commercial processes (see Figure 4), such as the Selexol Process, Rectisol Process, Purisol Process, Morphysorb Process, and Fluor Process. The absorbents are diethyl ether or propylene glycol for the Selexol Process, methanol for the Rectisol Process, N-Methylpyrrolidone for the Purisol

Process, morpholine for the Morphysorb Process, and propylene carbonate for the Fluor Process [11]. The merits and demerits for different physical absorption carbon capture are shown in Table 1.

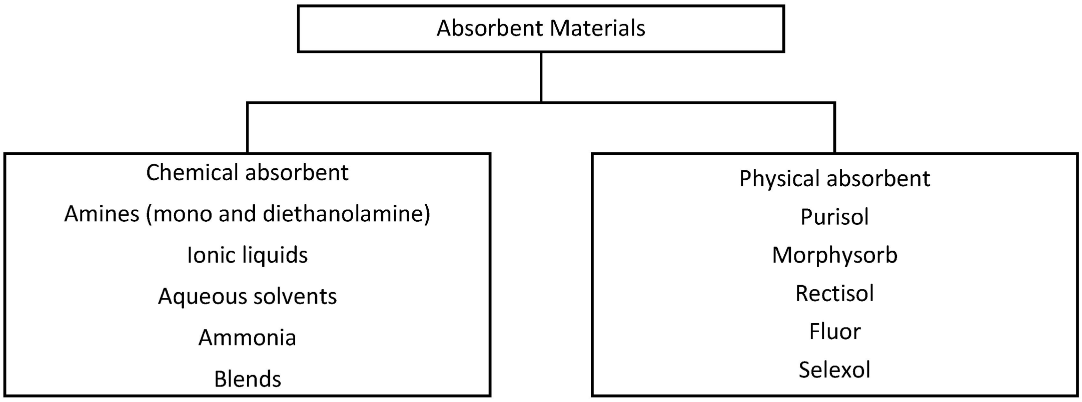


Figure 4. Carbon capture absorbent classification [6].

Table 1. Merits and demerits of different physical absorption processes [12].

Process	Advantages	Disadvantages
Selexol	Hydrogen sulphide selectivity is high. No washing is required to recover solvent. High stability. Pollution level in exhaust will be low [13] Capable of moisture removal. Minimal capital and operational expenditures [14].	Reduced absorption rate at low temperature [15]. CO_2 concentration should be high for efficient operation [14].
Rectisol	Efficiency is high. Enable simultaneous capture of H_2S and CO_2. No solvent wastage [13]. Reduced energy penalty. Stable and resistant to corrosion [14].	Expensive due to complex process [14,16].
Purisol	Can be used for both H_2S and CO_2 removal [13].	Low efficiency and stability for solvent [13].
Morphysorb process	High absorption and corrosion-resistant solvent. Reduced Capex and Opex. Energy efficient.	Technology readiness level is low.
Fluor process	High absorption and resistance to corrosion [14].	Expensive. Contactor technology is not mature [14].

3.2. Adsorption

In the adsorption carbon capture process, a rigid surface is used to remove CO_2 from the flue gas. There are mainly two types of adsorption: physical adsorption and chemical adsorption [12]. Pressure swinging (PSA) or temperature swinging (TSA) is used to release and revive the adsorbent material [17]. In TSA, the saturated adsorbent is heated (using hot air or steam) to the temperature range at which the physical or chemical bond is broken to release the adsorbed species, whereas in PSA, pressure is reduced to achieve the same effect [12]. Table 2 shows the advantages and disadvantages of various types of adsorbents.

Table 2. Merits and demerits of major adsorbents [18].

Type of Adsorbents	Merits	Demerits
Zeolite	Highly porous. Stability with high capture rate.	Susceptible to corrosion.
Activated carbon [19]	Compact and economical. High stability and corrosion resistance	Efficient only at high carbon dioxide concentration. Prior water separation is required.
Amine-functionalised adsorbents [20]	Works at low flue gas pressure. High capture capacity.	Not stable at high operating temperatures.
Metal–Organic Framework [19]	High capture capacity and efficiency.	Costly and susceptible to corrosion.
Alkali-metal-based oxides [21]	Cheap and available. Works on a wide temperature range.	Low stability and capture capacity.

3.2.1. Physical Adsorption

In physical adsorption, porous materials like activated carbon, zeolites and metallic oxides are used [22]. Even though zeolites are hydrophilic, they have strong adsorption properties for carbon dioxide capture. Study [23] indicates that water could weaken the compound interactions. Metal ions in the metal–organic framework (MOF) are helpful in creating strong coordination bonds. Research [24] suggests that an optimum adsorbent should have fast kinetics, low heat capacity, high selectivity, and adsorption capacity. Although porous carbon is thermally stable and cheap, its application is limited to treating pressured gases [25]. Zeolites are another widely used physical adsorbent.

3.2.2. Chemical Adsorption

Chemical modification would help improve adsorption and selectivity. Due to reduced heat capacity, adsorbents have less regeneration heat. Low capture capacity, along with an increase in cost, is another drawback of this technology [11]. They could be further classified into amine-impregnated and amine-grafted materials [24].

3.3. Membrane Separation

This is usually carried out in a scheme consisting of two stages. At first, the flue gas is cooled down via an absorber before sending it to the membrane. The permeate is then sent to the second membrane, while the remaining is recirculated as a sweep [26]. There are various types of membrane separation processes: (a) Gas separation and gas absorption membranes. This separation process involves passing flue gas via separation membranes and absorption membranes. In the gas separation membrane, flue gas is in contact with the part of the membrane with high pressure, while CO_2 is separated from the other side with low pressure. In a gas absorption system, a microporous membrane enables gas flow and absorption [10]. (b) Ceramic, polymeric, and hybrid membranes. Permeability and selectivity are the main characteristics to keep in mind when selecting this type of membrane. Three important subtypes are polymeric membranes (organic), ceramic membranes (inorganic), and hybrid membranes [27]. Recent studies (including [28]) indicate that membranes like PRISM, Polaris, PolyActive, PermSelect, and Medal [28] could be used for post-combustion capture. Experiments on metal–organic frameworks (MOFs) might offer advantages like large surface areas, adjustable pore sizes, and controllable pore-surface properties [27].

3.4. Cryogenic Carbon Capture

Carbon dioxide separation from the flue gas mixture is carried out using condensation and desublimation to obtain a high recovery rate [29]. The process includes freezing carbon dioxide prior to solid gas separation. The main types of cryogenic carbon capture methods are shown in Figure 5. Different cryogenic methods are used for two regions. Conventional liquid–vapour separation is used for above 193 K, and non-conventional solid–vapour separation is for regions under the black solid curve.

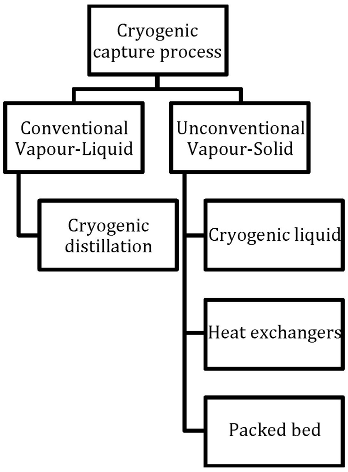


Figure 5. Cryogenic carbon capture separation types [30].

3.4.1. Conventional Cryogenic-Based Vapour–Liquid Separation

This gas-to-liquid separation prevents clogging due to solid formation. Heavier hydrocarbons are used to avoid carbon dioxide solidification. Carbon dioxide purification units would require techniques for water elimination to steer clear of ice plugging [30]. Holmes and Ryan [31] originally proposed this cryogenic distillation for the purification of natural gas. The feed gas is cooled by a precooler, which is again chilled down by a heat exchanger. The distillation column consists of vapour–liquid contact devices. Condensed carbon dioxide, which is gathered at the bottom, is then transported to a separator. Purified carbon dioxide is then extracted from the separator [32].

3.4.2. Unconventional Cryogenic-Based Vapour–Solid Separation

Low energy consumption, when compared to conventional separation, is an advantage for vapour–solid separation. Study [33] shows that for a gas with 70% carbon dioxide concentration, energy consumption for a cryogenic packed bed is considerably low when compared to conventional cryogenic distillation. The different options to achieve these cold temperatures are heat exchangers, cryogenic liquids, and packed beds [33].

3.4.3. Heat Exchangers

Heat exchangers mainly include coil–wound heat exchangers, plates, multi-stream plates, fin, and regenerative types. Defrosting would be required to optimise pressure loss on the gas side circulation [33]. This switching between frosting and defrosting conditions could become an operational challenge.

3.4.4. Cryogenic Liquid

Flue gas is in direct contact with cryogenic liquid. Carbon dioxide would be dissolved in the cryogenic liquid and later become slurry. Final filtration would provide pure carbon dioxide [34]. The contacting liquid could be reused since the solid carbon dioxide is filtered. Recent study [34] indicates that energy consumption of 0.74 MJ/kg CO_2 is required to attain a 90% capture rate.

3.4.5. Packed Beds for Cryogenic Capture

Nitrogen at cryogenic temperature is filled in a packed bed prior to feeding flue gas. Carbon dioxide will be desublimated to become frost. Once the column is saturated, a regeneration step is required to avoid frost from the packed beds. Multiple packed beds are operated in parallel to continue capture, regeneration, and cooling steps. Numerical analysis [35] reveals a cooling duty range from 1.2 to 2.6 MJ/kg CO_2. They were also proposed [36] instead of operating multiple beds in cycles. This prevents excessive CO_2 frost formation on the column.

3.5. Strengths, Weaknesses, Opportunities, and Threats (SWOT) Analyses

Studies [9,23,37] propose that using biphasic solvents and water-free solvents would considerably reduce the energy consumption of the process. Research [38] indicates that a capture efficiency of up to 95% could be achieved by using ethylene glycol-based solvent mixtures. As per [39], using deep eutectic solvents could decrease corrosion, require low energy consumption for regeneration, and lessen the solvent vapour pressure. Studies [40,41] indicate some drawbacks to chemical absorption technology, which include high equipment corrosion rate, low carbon dioxide loading capacity, amine degradation, high energy penalty, and large equipment size. Disadvantages of aqueous amine absorption also include a low gas–liquid contact area. Table 3 highlights the strengths, weakness, opportunities, and threats associated with different carbon capture routes.

Table 3. SWOT Analysis.

	Absorption	**Adsorption**	**Membranes**	**Cryogenic**
Strengths	High carbon capture efficiency. Could be used to filter out other pollutants as well. Easily adaptable at power stations and other point sources. Availability of cheap solvents. Suitable for high-temperature applications	Sorbents could be regenerated and reused. Low cost of sorbents. Mature technology.	Energy-efficient and eco-friendly. High purity and recovery of CO_2. Short startup time and low energy requirement. Low-cost separation of CO_2.	High carbon recovery rate. Could be used to filter out other pollutants as well. Easily adaptable at power stations and other point sources. Energy required for compression can be saved.
Weaknesses	Solvent degradation. Increased energy consumption for regeneration. Amines are prone to corrosion. Solvent regeneration efficiency. Huge plant equipment size. Large capital cost for high-performance sorbent.	Frequent regeneration would lead to quick replacement. Less carbon capture capacity. Huge energy consumption for regeneration.	Membranes have strict temperature requirements. Susceptible to corrosion. Low selectivity for CO_2 capture. High capital expense. High carbon concentration is required in flue gas.	Moisture removal from flue gas is required. Substantial energy requirements for cryogenic process. High installation cost. Not economical when carbon dioxide concentration is low
Opportunities	Cheap solvent availability with high capture capacity. Amine absorption is the most widely used technology in carbon capture. Recent progress in technology readiness levels. Advanced amines and Ionic liquids.	Development in composite adsorbents. Low-cost reusable sorbents make this technology promising. Noncorrosive. Gas products are dry.	High commercial availability and separation efficiency. Development in composite hollow-fibre membranes, mixed matrix membranes, and hybrid membrane–cryogenic processes. Low cost of separation and energy requirements could drive this technology in the future. Low footprint, good for offshore use.	Long track record for industrial CO_2 recovery. Captured carbon dioxide could be used for industrial purposes. High purity of product increases the economic value.

Table 3. *Cont.*

	Absorption	Adsorption	Membranes	Cryogenic
Threats	Large capital costs and high energy penalties would be challenging. Potential corrosion issues. Amine degradation. Environmental impact	Achieving optimum operating temperature. Low technology readiness level. Increased energy penalty along with periodic sorbent regeneration.	Energy intensive. Low selectivity and temperature sensitivity. Requires multiple stages of removal and compression. Operational issues like low fluxes and fouling.	High energy consumption and installation costs could serve as a deterrent for this technology. Only viable for high carbon dioxide concentration. Subzero temperature requirement.
References	[11,12,42,43]	[11,12,30]	[29,43,44]	[32,35,45]

Adsorption processes for carbon capture are usually carried out using specialised materials which are activated to be micro- and nanoporous. Once adsorbed, the material needs to be regenerated, and this is carried out by a process known as temperature swing adsorption (TSA). TSA processes have been found to be most effective for low CO_2 concentrations. If the carbon dioxide partial pressure is high, pressure swing adsorption (PSA) is preferred [46]. Due to less requirement for adsorbent regeneration, study [17] argues PSA would be more appealing. Advantages of adsorption include less energy penalty with an economical regeneration process, higher stability, and high loading capacity [47]. Study [48] indicates that the adsorption efficiency of zeolites is determined by the density of charge, size, and molecular arrangement of positively charged ions. Metal–organic frameworks (MOF) have generated interest because of their tuneable opening surface and increased area of contact [49]. MOFs have extraordinary adsorption capacity while dealing with pure carbon dioxide at high pressure [50]. The main drawback for most physical adsorbents is low carbon dioxide selectivity.

Membrane processes have the advantages of low cost, mechanical stability, and high gas flux [51]. However, low selectivity is one of the drawbacks of polymeric membranes. Although ceramic membranes have high selectivity, their production is more difficult [27]. Hybrid membranes combine the advantages of both polymeric and ceramic membranes.

For cryogenic carbon capture processes, the main disadvantage is the high energy demand that would be more than half of the plant's operating costs. High purity of recovered carbon and operating capability at atmospheric pressure are advantages of this process. This comparative analysis is the result of comparing data obtained for each carbon capture route. The main parameters used to measure these technologies are technology readiness level (TRL), capture cost, energy consumption, and carbon recovery rate (Table 4).

Table 4. Comparative analysis of different carbon capture routes showing variability in capture costs at different locations.

Technology	Absorption	Membrane	Adsorption	Cryogenic
Technology Readiness Level	4.1	4	3.6	3.7
Capture Cost/tCO_2	USD 40–100	USD 15–55	USD 50–150	USD 55–130
CO_2 recovery	60–95%	60–90%	80–95%	99.99%
Energy consumption (GJ/tCO_2)	2.3–9.2 GJ/tCO_2	0.5–6 GJ/tCO_2	4–6 GJ/tCO_2	2.4–5.2 GJ/tCO_2
References	[11,12,42,43]	[29,43,44]	[11,12,30]	[32,35,45]

3.6. Assessment

All carbon capture technologies incur energy penalties. Scalability or the technology readiness level varies considerably across these different types of technology. While some carbon capture technologies are already in commercial-scale operation, some are still being developed and tested in laboratories. Capture efficiency, or the percentage of carbon dioxide captured successfully from the flue gas, is another decisive factor for prioritising the technologies. Retrofitting a carbon capture unit on an existing power plant and building a new power plant with an inbuilt capture unit would have different economic impacts. The Levelised Cost of Energy or LCOE measures the average net cost of energy along with the average capital and operational expense involved in carbon capture units. All the above parameters should be given weightage while selecting the optimum technology. Detailed assessments (under the headings shown in Figure 6) would consider these critical technical and economic factors in the decision-making process. A comprehensive review of all these factors would enable the governments and other stake holders to make an informed decision.

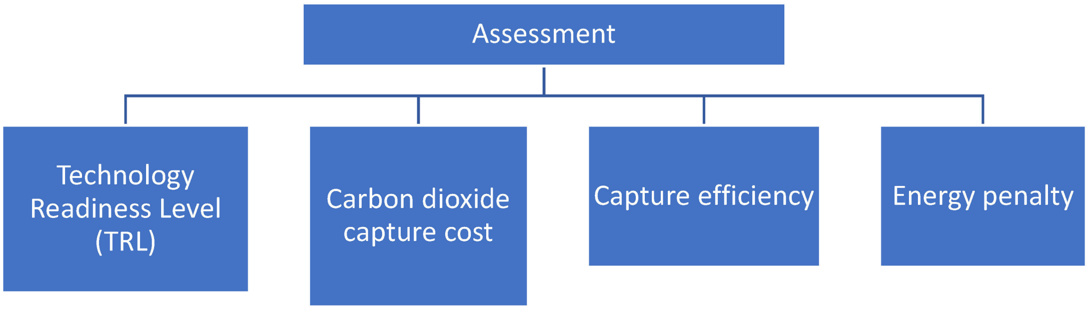


Figure 6. The four metrics considered for the assessment of capture methods.

3.6.1. Technology Readiness Level

The technology readiness level (TRL) is used by many institutions to assess the readiness of a technology for the market. It was pioneered by the US National Aeronautics and Space Administration (NASA) and adopted by other US organisations such as the Electric Power Research Institute (EPRI) and the Department of Energy (DOE). A variation of it was standardised by the European Union (EU) and used worldwide. A technology in the conceptual stage would have a TRL score of 1, while a fully tested commercial service would have a TRL score of 9. As per the EPRI definition [52], TRL stages 1–3 would fall under research, 4–6 would be development, and 7–9 would be the demonstration phase (Table 5). Following this framework, EPRI assigned TRL levels to different carbon capture technologies. The EPRI study [52] concluded that absorption is the most mature carbon capture technology.

Table 5. Technology readiness level score.

Demonstration	9	Normal commercial service
	8	Commercial demonstration, full-scale deployment in final form
	7	Sub-scale demonstration, fully functional prototype
Development	6	Fully integrated pilot tested in a relevant environment
	5	Sub-system validation in a relevant environment
	4	System validation in a laboratory environment
Research	3	Proof-of-concept tests, component level
	2	Formulation of the design
	1	Basic principles observed, initial concept

EPRI has evaluated over 100 post-combustion carbon capture technologies [53]. TRL ranking is shown in the histogram in Figure 7. The vertical axis shows the number of post-combustion carbon capture technologies reviewed, while the horizontal axis shows the TRL score. Almost 60% of the technology are absorption-based, followed by membrane and adsorption.

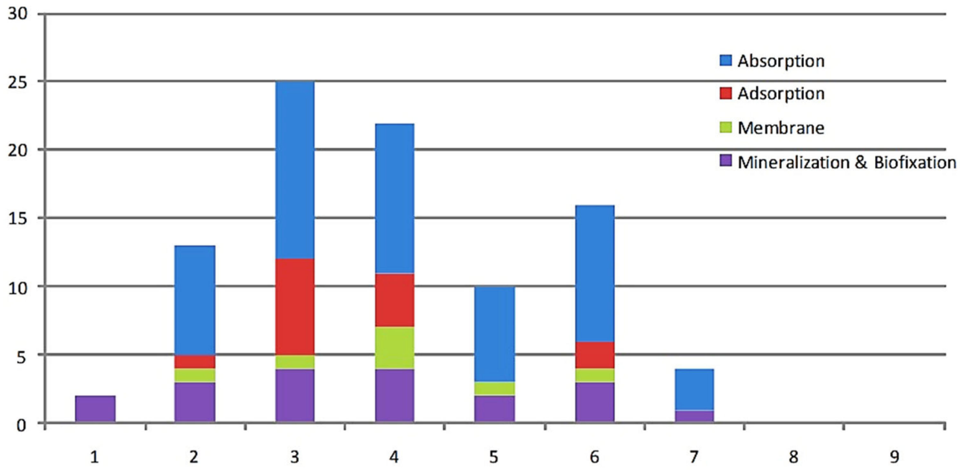


Figure 7. Technology readiness level of various CC technologies (horizontal axis) versus number of technologies reviewed (vertical axis).

Study [33] indicates that the technological readiness level of moving packed bed cryogenic carbon capture technology is TRL 3. Other sub-types of cryogenic carbon capture technology are also in the early phase of development. Most advanced cryogenic carbon capture technology uses heat exchangers followed by bio-methane liquefaction with a TRL score of 6 [33].

Absorption carbon capture is already widely used in petrochemical and other industries. Its ease of operation, along with economy of scale, has made it a favourable choice for natural gas treatment [54]. The existing main challenge for this technology is considerable energy consumption for solvent regeneration. Incremental improvements in this technology occurs by modifying the solvent and using corrosion inhibitors [55]. The current research focus is on reducing regeneration heat for the system [56]. It has been observed that increasing solvent concentration along with using solvents with low-reaction kinetics helps to reduce required regeneration energy. Using amine blends such as Cansolv [57] by Shell has helped in process optimisation. Methods such as using catalysts to enhance the absorption rate are still a long way from commercialisation. Other examples of absorption types with low TRL include piperazine [58] and carbonic anhydrase [54]. Ongoing research on amine solvents includes siloxanes [59] and ionic liquids [60].

Significant experience in industrial gas separation [52] has been an advantage for absorption technology when compared to membrane and adsorption carbon capture technologies. Figure 7 shows that for TRL 3, TRL 4, and TRL 6, there is a significant dominance of absorption carbon capture technology. For TRL 3 and 4, relatively new chemicals such as ionic liquids and solvents [52] are used for absorption, while those in TRL 6 use mature chemicals such as amines. However, considering the technology readiness level for all sub-types of absorption carbon capture technology, the Electric Power Research Institute (EPRI) has assigned the average TRL value as 4.1 [52].

Adsorption capture technologies are less commonly used in chemical industries when compared to absorption-based processes. Successfully developing a commercial-scale adsorption-based capture system requires the technological development of adsorbent materials along with the corresponding progress in process design [61]. Economical and humidity-inert adsorbent development shows progress in some studies released by the University of Wyoming [62]. Detailed cost–benefit analyses are required to verify the performance of these latest adsorbent techniques to justify their higher cost. Initial studies at the University of Berkeley [63] are aligned in this direction. The use of metal Oxide frameworks (MOFs), along with organic molecules, is being undertaken at the University of California [64]. It may be noted that all these advancements are in the laboratory validation stage, thereby determining its technology readiness level at 3 and 4 [54]. Bench scale testing is already in progress at Ohio State University [65], where adsorbents are integrated with sophisticated process designs for carbon capture. The overall technology readiness level assigned by EPRI for adsorption technology is 3.6 [52].

The usage frequency of membrane separation in chemical processes is low when compared with absorption and adsorption carbon capture processes. Honeywell [66] is using a polymeric membrane for carbon separation for natural gas processing. An important technical challenge faced by membrane technology in coal-fired power plants is the particulate depositing on the membrane, causing significant permeability decrease [67] over time. Another technical challenge is the requirement for a large membrane area. Since relative pressure from the flue gas is low, accommodating this large membrane area raises significant design challenges. However, the relatively low energy penalty [43] is a driving force for the advancement of membrane separation technology. Considering the overall progress in membrane separation, EPRI has assigned a technology readiness level of 4 [52].

Several sub-types of cryogenic carbon capture process are in different stages of technical development. For packed bed cryogenic technology [35], the cold energy source is liquid nitrogen gas. Therefore, the advancement of this technology is limited to the availability of liquid nitrogen gas. Although this technology can avoid high-pressure drops, its development is still at the lab scale [68]. The limitation of anti-sublimation technology is that it is dependent on liquefied natural gas as its cold energy source. Now in the pilot demonstration stage [69], its lower energy consumption makes it a promising technology for the future. Cryocell technology [70] is only suitable for high carbon concentrations. The high energy requirement for compression is another limitation of this technology. High installation cost is the main hindrance to the growth of distillation cryogenic technology [71]. The main advantage of distillation technology is that compression costs can be avoided. Stirling cooler technology has the advantage of low energy penalty [72]. Research [73] indicates that this technology is still at the lab scale. Since most of the cryogenic carbon capture technologies are in component-level testing or system validation stage, EPRI has assigned an overall technology readiness level of 3.7 [52] for cryogenic carbon capture technology.

Although the TRL framework provides an overview of the scalability and commercial feasibility of the technology, it does not show the information needed to assess the progress required [52] to move on to the next stage. The technology readiness level, as calculated by EPRI, for main carbon capture types is shown in Table 6.

Table 6. Overall TRL for capture routes.

Type of Capture Technology	Overall TRL	References
Absorption	4.1	[52,54]
Adsorption	3.6	[52,54]
Membrane	4	[52,54]
Cryogenic	3.7	[52,54]

3.6.2. Capture Efficiency

The carbon dioxide capture efficiency or recovery rate is a determining factor while prioritising the technologies. The recovery rate varies with the pressure of flue gas and the type of fuel used. It may also be noted that increasing the capture efficiency often happens at the expense of increased capture cost and energy penalty. Therefore, process optimisation is required to consider the overall benefit. Absorption carbon capture technology has a great recovery rate when compared with other post-combustion carbon capture technologies. Research [74] indicates that monoethanolamine sorbents have an efficiency of over 90% for carbon dioxide absorption. A successful pilot plant testing [75] was carried out with a monoethanolamine-based absorption system. Other studies [76] with piperazine and ionic liquid sorbents have also shown promising capture efficiency. Although piperazine reacts faster than monoethanolamine, it is more expensive, and development is still under process. Studies [11,12,42,43] suggest an overall carbon dioxide recovery rate of 60–95% for absorption capture. Research [77–79] indicates that adsorption technology has lower capture efficiency when compared to cryogenics and absorption carbon capture. Study [80] indicates that pressure swing adsorption has succeeded in achieving more than 85% efficiency in carbon dioxide recovery. Temperature swing adsorption [81] has been shown to achieve a more than 80% recovery rate. Various research [11,12,30,82] have indicated a recovery rate of 80–95% for adsorption carbon capture.

Membranes with high efficiency [29,83] achieved a recovery rate of 82–88%. Polymeric [83], metallic [84], and ceramic membranes have shown more separation efficiency than absorption systems [85]. Low carbon dioxide concentration and pressure are critical factors affecting the capture efficiency of the membrane system. A study on polymeric membranes [86] shows that increasing the recovery rate would require an additional 50% increase in capture cost. Facilitated [87] transport membrane was successful in achieving more than 90% capture efficiency. Multi-stage [88] membrane systems could also achieve 90% capture efficiency in power plants. An overall capture efficiency of 60–90% was achieved for membrane separation carbon capture technology in various studies [29,43,44]. Cryogenic carbon capture technologies generally have a very high carbon capture rate. A gas separation process called cryogenic distillation [85] could achieve a 90–95% carbon dioxide recovery rate. Operating temperature is a critical factor in determining the capture efficiency of a cryogenic carbon capture system. When maintaining cryogenic [34] temperature, carbon dioxide concentration in the air from the capture unit exhaust would be less than that of ambient air. Cryogenic-packed beds have recorded a 99% [35] carbon dioxide recovery rate. Controlled freeze zone [89] using natural gas sources also succeeded in achieving a 98–99% recovery rate. The external cooling loop cryogenic process [90] was able to achieve 95.6% capture efficiency. Experiments at coal-fired power plants with the anti-sublimation cryogenic process [69] showed a 90% carbon dioxide recovery rate. The recovery and capture rates of different cryogenic capture technologies is summarised in Tables 7 and 8 respectively.

Table 7. Recovery rate for types of cryogenic capture routes.

Type of Cryogenic	Recovery Rate	Reference
Packed bed	99%	[35]
Anti-sublimation	90%	[69]
Controlled freeze zone	98–99%	[89]
External cooling loop	95.6%	[90]
Stirling cooler	85%	[91]

Table 8. Overall capture rate for types of carbon capture.

Type of Capture Technology	Overall Capture Rate	References
Absorption	60–95%	[11,12,42,43]
Adsorption	80–95%	[11,12,30,82]
Membrane	60–90%	[29,43,44]
Cryogenic	99.99%	[32,35,45]

3.6.3. Capture Cost

Although there are numerous studies [45,92–94] investigating the economic aspects of carbon capture, a significant difference in cost estimation could be observed. This could be partly due to the difference in assumptions and cost assessment methods along with the variety of capture technologies and cases studied. Different scenarios, such as brownfield (retrofitting) projects and Greenfield projects, along with the type of fuel used and the intended capture efficiency, are all determining factors for a scientific cost assessment [93]. Since the scope of the study is to prioritise different carbon capture techniques, carbon storage and transportation costs are not taken into consideration here. Additionally, in many projects, transportation and storage infrastructures are pooled with other entities (factories or power plants). Since the standard assumptions will not fit all situations, the scope of an accurate cost estimate may vary on a case-by-case basis. The cost-estimating framework is dependent on a reference plant without carbon capture to which the plant fitted with carbon capture is compared. The levelised cost of electricity (LCOE) is the unit cost of power generation in a power plant's lifetime. It can be used as a tool to compare unit costs for different types of technologies. Discounted value is taken into consideration while calculating over a period of time [93].

The operation cost for the Purisol process is 30–40% [95], which is less than the Selexol process. The degradation of absorbents is the leading cause of the increase in operational cost for absorption technologies. Study [96] indicates that the overall cost for amine absorption is USD 52–77/tCO_2. A study on exergetic and exergoeconomic analysis of chemical absorption [97] indicates that the capture cost would be 31.8–35 USD per ton of CO_2. The main capital cost components of absorption technology are absorber and stripper. Research [98] indicates that absorber cost comes to around 55%, while stripper cost accounts for 17% of the total capital cost required for the installation. The overall capture cost per ton of CO_2 for absorption carbon capture technology is USD 40–100 [11,12,42,43].

Activated carbon is an attractive physical adsorbent due to its low cost [25]. Amine-based adsorbents have relatively low capture efficiency and high cost. Although highly flammable, propane is a cheaper adsorbent. Study [99] also indicates that calcium-based adsorbents are cheap and widely available. Alkali-based oxides [48] have low cost with high adsorption capacity. Equilibrium-based temperature swing adsorption [100] was estimated to have an operating cost of USD 80–150 per ton of CO_2. This study also demonstrated that cost could be reduced to USD 50–80 per ton of CO_2 by limiting the adsorption capacity. Research [11,12,30,82] indicate that for adsorption carbon capture, the overall cost per ton of CO_2 is USD 50–150. Conversely, membrane carbon capture technology is relatively cheaper when compared with other post-combustion carbon capture technologies. A report by the US Department of Energy [101] indicates a capture cost of USD 15–20 per ton of CO_2. A study [43] on combustion air sweep membranes resulted in a low capture cost of USD 23 per ton of CO_2. This research also found that enhancing the membrane permeability would be even more economical. A study on hybrid membrane systems [44] indicated a cost estimation of USD 25 per ton of carbon dioxide. Research on the two-step membrane separation system [43] indicated the capture cost to be about USD 39 per ton of carbon dioxide. A counter-current sweep carried out in the same study showed a cost of USD 23 per ton of CO_2. Studies [29,43,44] indicate an overall capture cost of USD 15–55 per ton of CO_2.

Although cryogenic carbon capture is expensive when compared to other options, its main advantage is that liquefaction costs can be avoided [32]. Studies [90,102] have found that the enormous energy demand for cryogenic distillation comprises more than 50% of the operating cost. Cryogenic heat exchangers are a main component of huge initial costs. Since the bed size is small, a cryogenic packed bed [32] needs a lower investment for installation than the vacuum pressure swing adsorption process. Several research [32,35,45] indicate an overall capture cost of USD 55–130 per ton of CO_2 for various cryogenic carbon capture methods (see Table 9).

Table 9. Overall capture cost for the various carbon capture methods.

Type of Capture Technology	Overall Capture Cost	References
Absorption	USD 40–100	[11,12,42,43]
Adsorption	USD 50–150	[11,12,30,82]
Membrane	USD 15–55	[29,43,44]
Cryogenic	USD 55–130	[32,35,45]

3.6.4. Energy Penalty

The Purisol absorption process has comparatively low energy [11] consumption. A high energy requirement for regeneration is a disadvantage for chemical absorption. For amine absorption and stripping technology, an overall energy requirement of 0.72 GJ per ton of CO_2 [11] was observed. As per a report from the International Energy Agency [103], regeneration energy is 3.24–4.2 GJ per ton of CO_2. A percentage of 50–80% [104] of energy consumption in chemical absorption is for solvent regeneration. The MEA absorption process has shown an energy usage of 2.5–3.5 GJ per ton of CO_2 [98]. Studies on ammonia-based solvents [105] showed an energy usage of 2.6 GJ per ton of CO_2. An overall energy consumption of 2.3–9.2 GJ per ton of CO_2 for the absorption process can be deduced from various studies [11,12,42,43]. Research on temperature swing adsorption has shown an energy consumption of about 3.2 GJ per ton of CO_2. Energy consumption required for adsorbent regeneration is low. The energy consumption for zeolites is lower than chemical absorbents [106]. Research [46] on pressure vacuum swing adsorption has found low energy consumption. A Rapid Vacuum Pressure Swing Adsorption Process [107] made for a biogas plant has shown an energy consumption of 822.9 KJ/kg. CO_2. A pressure and temperature swing adsorption process experiment using zeolite [108] obtained an energy consumption of 3.8 GJ/t CO_2. Another study on temperature swing adsorption [109] showed a low energy consumption of 0.6638 MWh per ton of CO_2. Various studies [11,12,30,82] show an overall energy consumption of 2.3–9.2 GJ/tCO_2 for adsorption carbon capture technology.

The membrane separation process is a relatively low energy-intensive process with energy consumption of around 0.5–6 GJ [29] per ton of CO_2. A study carried out on a facilitated transport membrane [110] system showed an energy consumption of 0.259–0.796 GJ per ton of CO_2. Another parametric study on single-stage membranes [111] demonstrated an energy consumption of 0.5–1 GJ per ton of CO_2. Study [44] shows improvement in energy efficiency with membrane selectivity. Research [43] also demonstrated an energy saving of 18% when using counter-flow permeate modules. Table 10 shows that an overall energy consumption of 0.5–6 GJ/tCO_2 can be deduced from various studies [29,43,44].

Table 10. Overall energy consumption for types of carbon capture.

Type of Capture Technology	Overall Energy Consumption	References
Absorption	2.3–9.2 GJ/tCO_2	[11,12,42,43]
Adsorption	4–6 GJ/tCO_2	[11,12,30,82]
Membrane	0.5–6 GJ/tCO_2	[29,43,44]
Cryogenic	2.4–5.2 GJ/tCO_2	[32,35,45]

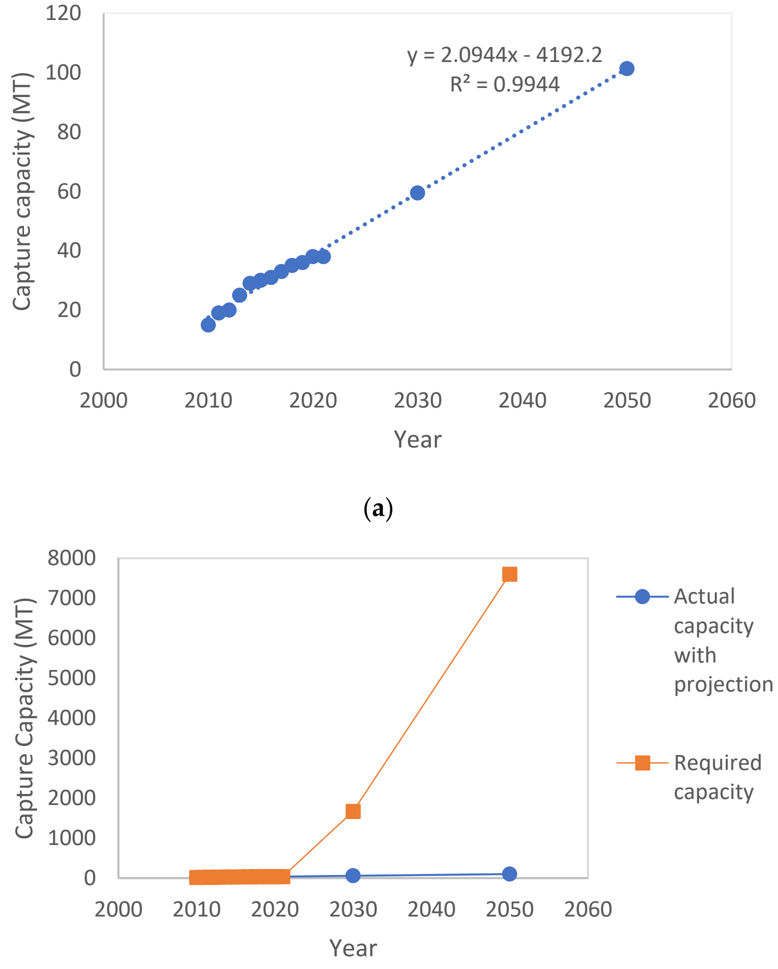
Studies (including [35]) indicate that the energy consumption of a cryogenic packed bed is 22% less than that of a vacuum pressure swing adsorption process (see Table 11). Improving thermal insulation to reduce latent heat loss is a challenge for the cryogenic packed bed process. The external cooling loop system proposed by Baxter [71,112] reduces energy consumption by reusing waste cold energy. Research [113] indicates that the average energy requirement for this process would be 0.98 GJ per ton of CO_2. The energy requirement for the anti-sublimation process [69] is 3.8–7.2% of the plant's efficiency. This study also demonstrated that energy consumption depends on the required capture efficiency and carbon dioxide concentration in the flue gas. Ongoing studies [114,115] are exploring less energy-intensive options by introducing an integrated cryogenic network. An energy analysis [116] demonstrated that the energy consumption of the Stirling cooler system is about 0.55 GJ per ton of CO_2. Low-temperature carbon dioxide could also be used as an energy source for other low-temperature processes.

Table 11. Energy consumption for different types of cryogenic processes.

Type of Cryogenic	Energy Requirement	Reference
Packed bed	1.8 GJ/tCO_2	[35]
Anti-sublimation	1.18 GJ/tCO_2	[69]
Controlled freeze zone	5.2 GJ/tCO_2	[89]
External cooling loop	1.48 GJ/tCO_2	[90]
Stirling cooler	3.4 GJ/tCO_2	[91]

3.7. Carbon Capture Forecast towards Net-Zero

The current capacity of the capture plant, along with a forecast for 2050, is shown in Figure 8a. Capture data for the last decade are obtained from reports [117]. Forecasted value for 2030 and 2050 is obtained via the forecast feature in Microsoft Excel (2021 for Windows). The trend line, the slope of the equation, and the R squared value are also shown in the graph. Figure 8b shows the required carbon capture capacity to achieve the 1.5 °C trajectory and the existing wide gap with the actual capacity. The data for the required capacity are taken from Figure 4 [117]. This gap reiterates the importance of prioritising the carbon capture technology and aligning capture strategies accordingly to achieve the net-zero goal.



(**a**)

(**b**)

Figure 8. (**a**) Actual capture capacity with projection to 2050. Data from Ref. [117] from which we made the projection. (**b**) Actual vs. required capacity with projection to 2050.

3.8. Multicriteria Ranking of Carbon Capture Technologies (Using TOPSIS)

The TOPSIS method assists in multiple criteria decision making based on the Euclidean distance from the ideal best and ideal worst situation. Calculations using TOPSIS allow governments and other stakeholders to decide what typical case they would fit in and align their carbon capture strategies accordingly. This method would serve as a tool for informed decision making while selecting the suitable type of technology for carbon capture. Here, four case studies were analysed, namely 1. developed countries with high emissions; 2. developed countries with low emissions; 3. developing countries with high emissions; 4. developing countries with low emissions. The TOPSIS procedure enumerated in the methodology was applied in each case. The weightages were decided as shown below for Case 1 and subsequent calculations (in Tables 12–16). The other cases (2–4) are given numerically in the Sections A–C.

Table 12. Decision matrix for Case 1.

Capture Route (Weightage)	TRL (0.2)	Capture Efficiency, % (0.5)	Energy Penalty, GJ/tCO$_2$ (0.2)	Cost, USD/tCO$_2$ (0.1)
Absorption	4.1	77.5	5.75	70
Adsorption	3.6	87.5	5	100
Membrane	4	75	3.25	35
Cryogenic	3.7	99.99	3.8	92.5

Table 13. Calculation of the normalised matrix for Case 1.

Capture Route	TRL	Capture Efficiency (%)	Energy Penalty (GJ/tCO$_2$)	Cost (USD/tCO$_2$)
To Absorption	0.531706	0.452872	0.6309	0.446
Adsorption	0.466864	0.511307	0.5486	0.637
Membrane	0.518737	0.438263	0.3566	0.223
Cryogenic	0.479832	0.584292	0.4169	0.589

Table 14. Calculation of the weighted normalised matrix for Case 1.

Capture Route	TRL	Capture Efficiency (%)	Energy Penalty (GJ/tCO$_2$)	Cost (USD/tCO$_2$)
Absorption	0.106341	0.226436	0.1262	0.045
Adsorption	0.093373	0.255653	0.1097	0.064
Membrane	0.103747	0.219132	0.0713	0.022
Cryogenic	0.095966	0.292146	0.0834	0.059

Table 15. Calculation of ideal best V+ and ideal worst V− values for Case 1.

V+	0.106341	0.292146	0.0713	0.022
V−	0.093373	0.219132	0.1262	0.064

Table 16. Calculation of the performance score from the Euclidean distances from ideal best and ideal worst values for Case 1, i.e., $P_i = s_i^- \div (s_i^+ + s_i^-)$.

Capture Route	s_i^+	s_i^-	P_i	Rank
Absorption	0.088	0.024	0.215	4
Adsorption	0.068	0.04	0.369	3
Membrane	0.073	0.069	0.487	2
Cryogenic	0.04	0.085	0.68	1

Case 1 (i.e., developed countries with high emissions) is the typical case, as developed countries tend to have high carbon emissions. A lower weightage is given for cost, and a higher weightage is given for capture efficiency. Cryogenic has the highest performance score, indicating that this would be the type of carbon capture technology suitable for developed countries with high emissions. Secondly, for Case 2. (i.e., developed countries with low emissions), capture efficiency is given a higher weightage with equal weightage considered for all other metrics. Performance score indicates that membrane technology is the most suitable type of carbon capture technology for developed countries with low emissions. In the scenario of Case 3 (developing countries with high emissions), capture efficiency is given a higher weightage with equal weightage considered for all other metrics. Performance score indicates that membrane technology is the most suitable type of carbon capture technology for developing countries with high emissions. Finally, for Case 4. (i.e., developing countries with low emissions), capture cost is given a higher weightage with equal weightage considered for all other metrics. Performance score indicates that membrane technology is the most suitable type of carbon capture technology for developing countries with low emissions. For all typical cases considered, cryogenic is best suited for developed countries with high emissions, while membrane separation is the optimum choice of technology for all other cases. This assumes that there is a low cost of electricity.

A note on the limitations of TOPSIS will be given. The weightages given to different metrics are only indicative, and real values may vary depending on the individual priorities of each nation. The metric data for each technology, such as capture rate, energy consumption, and cost of capture, are obtained from various research papers and are normally indicated as a range with minimum and maximum values. Since applying a range of values is not rational in the TOPSIS method, a median value of this range is chosen for calculation purposes. Correlations between performance criteria should also be considered in decision making. For example, energy consumption is often a function of capture efficiency, and the cost of capture also varies with change in energy consumption.

4. Conclusions

Increased anthropogenic greenhouse gas emissions have been shown to greatly contribute to the changing global climate. Carbon dioxide, the leading contributor, is released mainly via fossil fuel combustion, and carbon capture technology has been identified as key to reducing these emissions prior to an energy transition in the 20–30 years. This study has carried out an extensive assessment of the various sub-types of carbon capture technologies to prioritise their application in different market sectors and geographic locations. The TOPSIS method was used to establish a scientific technology rank for each case where weightages are allotted considering the emissions status and economic conditions of each case. It was found that for developed countries with high emissions, cryogenic capture had the highest ranking, followed by membrane, adsorption, and absorption. However, in the case of developed countries with low emissions, membrane separation had the highest ranking, followed by cryogenic, absorption and adsorption. This is due to capture efficiency being given a higher weightage with equal weightage considered for all other metrics. For developing countries with high emissions, capture efficiency was given a high weightage with a medium weightage for cost, and membrane separation exhibited the highest ranking, followed by cryogenic, absorption and adsorption. Finally, for developing countries with low emissions, capture efficiency was given a medium weightage with a high weightage for cost. Membrane separation had the highest ranking, followed by absorption, cryogenic, and adsorption. While there are many areas of ambiguity when considering the statistics in relation to emissions and capture capacity, the very act of capturing carbon is energy-intensive, and manufacturing the chemicals and solvents required for this process also leaves a carbon footprint. The true value of capture capacity would be the difference between emissions removed and emissions made during the process of removal. Some of the carbon capture technologies are in the initial level of maturity. Research must be carried out to reduce the corrosion rate and energy consumption for absorption technology, enhancing contact area for membrane, surface modification for absorbents, and by-product disposal. Furthermore, cryogenics are known for their high energy consumption and may not be the best over long periods compared to absorption. However, research is needed to develop energy-efficient cryogenic processes. Post-combustion carbon capture is not just limited to these technologies; however, these capture routes were chosen for this study as they are the most widely used ones. There are many more sub-types to each of these routes, many of which are yet to be explored but must be considered to keep the planet on course for carbon neutrality by 2050.

Author Contributions: Conceptualization, A.M.A. and A.E.; methodology, A.M.A. and A.K.; formal analysis, A.K.; data curation, A.K.; writing—original draft preparation, A.K.; writing—review and editing, A.K., A.M.A., and A.E.; visualisation, A.K.; supervision, A.M.A. and A.E. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A. Case 2: Developed Countries with Low Emissions

Table A1. Decision matrix for Case 2.

Capture Route (Weightage)	TRL (0.2)	Capture Efficiency, % (0.5)	Energy Penalty, GJ/tCO$_2$ (0.2)	Cost, USD/tCO$_2$ (0.1)
Absorption	4.1	77.5	5.75	70
Adsorption	3.6	87.5	5	100
Membrane	4	75	3.25	35
Cryogenic	3.7	99.99	3.8	92.5

Table A2. Calculation of normalised matrix for Case 2.

Capture Route	TRL	Capture Efficiency (%)	Energy Penalty (GJ/tCO$_2$)	Cost (USD/tCO$_2$)
Absorption	0.531706	0.452872	0.6309	0.446
Adsorption	0.466864	0.511307	0.5486	0.637
Membrane	0.518737	0.438263	0.3566	0.223
Cryogenic	0.479832	0.584292	0.4169	0.589

Table A3. Calculation of weighted normalised matrix for Case 2.

Capture Route	TRL	Capture Efficiency (%)	Energy Penalty (GJ/tCO$_2$)	Cost (USD/tCO$_2$)
Absorption	0.106341	0.181149	0.1262	0.089
Adsorption	0.093373	0.204523	0.1097	0.127
Membrane	0.103747	0.175305	0.0713	0.045
Cryogenic	0.095966	0.233717	0.0834	0.118

Table A4. Calculation of ideal best and ideal worst value for Case 2.

V+	0.106341	0.233717	0.0713	0.045
V−	0.093373	0.175305	0.1262	0.127

Table A5. Calculation of performance score based on Euclidean distance from ideal best and ideal worst value for Case 2.

Capture Route	Si+	Si−	Pi	Rank
Absorption	0.088	0.041	0.316	3
Adsorption	0.097	0.034	0.258	4
Membrane	0.058	0.1	0.631	1
Cryogenic	0.075	0.073	0.494	2

Appendix B. Case 3: Developing Countries with High Emissions

Table A6. Decision matrix for Case 3.

Capture Route (Weightage)	TRL (0.2)	Capture Efficiency, % (0.5)	Energy Penalty, GJ/tCO$_2$ (0.2)	Cost, USD/tCO$_2$ (0.1)
Absorption	4.1	77.5	5.75	70
Adsorption	3.6	87.5	5	100
Membrane	4	75	3.25	35
Cryogenic	3.7	99.99	3.8	92.5

Table A7. Calculation of normalised matrix for Case 3.

Capture Route	TRL	Capture Efficiency (%)	Energy Penalty (GJ/tCO$_2$)	Cost (USD/tCO$_2$)
Absorption	0.531706	0.452872	0.6309	0.446
Adsorption	0.466864	0.511307	0.5486	0.637
Membrane	0.518737	0.438263	0.3566	0.223
Cryogenic	0.479832	0.584292	0.4169	0.589

Table A8. Calculation of weighted normalised matrix for Case 3.

Capture Route	TRL	Capture Efficiency (%)	Energy Penalty (GJ/tCO$_2$)	Cost (USD/tCO$_2$)
Absorption	0.106341	0.181149	0.1262	0.089
Adsorption	0.093373	0.204523	0.1097	0.127
Membrane	0.103747	0.175305	0.0713	0.045
Cryogenic	0.095966	0.233717	0.0834	0.118

Table A9. Calculation of ideal best and ideal worst value for Case 3.

V+	0.106341	0.233717	0.0713	0.045
V−	0.093373	0.175305	0.1262	0.127

Table A10. Calculation of performance score of the Euclidean distance from ideal best and ideal worst value for Case 3.

Capture Route	Si+	Si−	Pi	Rank
Absorption	0.088	0.041	0.316	3
Adsorption	0.097	0.034	0.258	4
Membrane	0.058	0.1	0.631	1
Cryogenic	0.075	0.073	0.494	2

Appendix C. Case 4: Developing Countries with Low Emissions

Table A11. Decision matrix for Case 4.

Capture Route (Weightage)	TRL (0.2)	Capture Efficiency, % (0.5)	Energy Penalty, GJ/tCO$_2$ (0.2)	Cost, USD/tCO$_2$ (0.1)
Absorption	4.1	77.5	5.75	70
Adsorption	3.6	87.5	5	100
Membrane	4	75	3.25	35
Cryogenic	3.7	99.99	3.8	92.5

Table A12. Calculation of normalised matrix for Case 4.

Capture Route	TRL	Capture Efficiency (%)	Energy Penalty (GJ/tCO$_2$)	Cost (USD/tCO$_2$)
Absorption	0.531706	0.452872	0.6309	0.446
Adsorption	0.466864	0.511307	0.5486	0.637
Membrane	0.518737	0.438263	0.3566	0.223
Cryogenic	0.479832	0.584292	0.4169	0.589

Table A13. Calculation of weighted normalised matrix for Case 4.

Capture Route	TRL	Capture Efficiency (%)	Energy Penalty (GJ/tCO$_2$)	Cost (USD/tCO$_2$)
Absorption	0.106341	0.090574	0.1262	0.178
Adsorption	0.093373	0.102261	0.1097	0.255
Membrane	0.103747	0.087653	0.0713	0.089
Cryogenic	0.095966	0.116858	0.0834	0.236

Table A14. Calculation of ideal best and ideal worst value for Case 4.

V+	0.106341	0.116858	0.0713	0.089
V−	0.093373	0.087653	0.1262	0.255

Table A15. Calculation of performance score based on Euclidean distance from ideal best and ideal worst value for Case 4.

Capture Route	Si+	Si−	Pi	Rank
Absorption	0.108	0.078	0.418	2
Adsorption	0.171	0.022	0.114	4
Membrane	0.029	0.175	0.856	1
Cryogenic	0.147	0.055	0.273	3

References

1. Table 2-8 Inventory of U.S. Greenhouse Gas Emissions and Sinks, 1990 to 2020. United States Environmental Protection Agency. 2020. Available online: https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2020 (accessed on 10 January 2023).
2. Sharma, A.; Johnson, B. *The Ten Point Plan for a Green Industrial Revolution*; Department for Energy Security and Net Zero; Prime Minister's Office, 10 Downing Street; Department for Business, Energy & Industrial Strategy; HM Government, 2020; pp. 1–38.
3. Delbeke, J.; Runge-Metzger, A.; Slingenberg, Y.; Werksman, J. *The Paris Agreement*; United Nations: New York, NY, USA, 2019; pp. 24–45.
4. Madejski, P.; Chmiel, K.; Subramanian, N.; Kus, T. Methods and Techniques for CO$_2$ Capture: Review of Potential. *Energies* **2022**, *15*, 887. [CrossRef]
5. International Energy Agency. *Achieving Net Zero Electricity Sectors in G7 Members*; Organisation for Economic Co-Operation and Development (OECD): Paris, France, 2021.
6. Sreedhar, I.; Nahar, T.; Venugopal, A.; Srinivas, B. Carbon Capture by Absorption—Path Covered and Ahead. *Renew. Sustain. Energy Rev.* **2017**, *76*, 1080–1107. [CrossRef]
7. Chakma, A. Formulated Solvents: New Opportunities for Energy Efficient Separation of Acid Gases. *Energy Sources* **1999**, *21*, 51–62. [CrossRef]
8. Aroonwilas, A.; Tontiwachwuthikul, P. High-Efficiency Structured Packing for CO$_2$ Separation Using 2-Amino-2-Methyl-1-Propanol (AMP). *Sep. Purif. Technol.* **1997**, *12*, 67–79. [CrossRef]
9. Vega, F.; Cano, M.; Camino, S.; Fernández, L.M.G.; Portillo, E.; Navarrete, B. Solvents for Carbon Dioxide Capture. In *Carbon Dioxide Chemistry, Capture and Oil Recovery*; IntechOpen: London, UK, 2018; pp. 142–163. [CrossRef]
10. Sifat, N.S.; Haseli, Y. A Critical Review of CO$_2$ Capture Technologies and Prospects for Clean Power Generation. *Energies* **2019**, *12*, 4143. [CrossRef]
11. Yu, C.-H.; Huang, C.-H.; Tan, C.-S. A Review of CO$_2$ Capture by Absorption and Adsorption. *Aerosol Air Qual. Res.* **2012**, *12*, 745–769. [CrossRef]
12. Theo, W.L.; Lim, J.S.; Hashim, H.; Mustaffa, A.A.; Ho, W.S. Review of Pre-Combustion Capture and Ionic Liquid in Carbon Capture and Storage. *Appl. Energy* **2016**, *183*, 1633–1663. [CrossRef]
13. Jansen, D.; Gazzani, M.; Manzolini, G.; van Dijk, E.; Carbo, M. Pre-Combustion CO$_2$ Capture. *Int. J. Greenh. Gas Control* **2015**, *40*, 167–187. [CrossRef]
14. Sanni, S.E.; Agboola, O.; Fagbiele, O.; Yusuf, E.O.; Emetere, M.E. Optimization of Natural Gas Treatment for the Removal of CO$_2$ and H$_2$S in a Novel Alkaline-DEA Hybrid Scrubber. *Egypt. J. Pet.* **2020**, *29*, 83–94. [CrossRef]
15. Park, S.H.; Lee, S.J.; Lee, J.W.; Chun, S.N.; Bin Lee, J. The Quantitative Evaluation of Two-Stage Pre-Combustion CO$_2$ Capture Processes Using the Physical Solvents with Various Design Parameters. *Energy* **2015**, *81*, 47–55. [CrossRef]
16. Chen, W.-H.; Chen, S.-M.; Hung, C.-I. Carbon Dioxide Capture by Single Droplet Using Selexol, Rectisol and Water as Absorbents: A Theoretical Approach. *Appl. Energy* **2013**, *111*, 731–741. [CrossRef]
17. Ferris, L.E.; Naylor, C.D. Physician Remuneration in Industry-Sponsored Clinical Trials: The Case for Standardized Clinical Trial Budgets. *Can. Med. Assoc. J.* **2004**, *171*, 883–886, Erratum in *Can. Med. Assoc. J.* **2004**, *171*, 1327. [CrossRef]

18. Chao, C.; Deng, Y.; Dewil, R.; Baeyens, J.; Fan, X. Post-Combustion Carbon Capture. *Renew. Sustain. Energy Rev.* **2021**, *138*, 110490. [CrossRef]
19. Modak, A.; Jana, S. Advancement in Porous Adsorbents for Post-Combustion CO_2 Capture. *Microporous Mesoporous Mater.* **2019**, *276*, 107–132. [CrossRef]
20. Hu, X.; Liu, L.; Luo, X.; Xiao, G.; Shiko, E.; Zhang, R.; Fan, X.; Zhou, Y.; Liu, Y.; Zeng, Z.; et al. A Review of N-Functionalized Solid Adsorbents for Post-Combustion CO_2 Capture. *Appl. Energy* **2020**, *260*, 114244. [CrossRef]
21. Wang, S.; Yan, S.; Ma, X.; Gong, J. Recent Advances in Capture of Carbon Dioxide Using Alkali-Metal-Based Oxides. *Energy Environ. Sci.* **2011**, *4*, 3805–3819. [CrossRef]
22. International Energy Agency. *Energy Technology Perspectives 2020—Special Report on Carbon Capture Utilisation and Storage*; Organisation for Economic Co-Operation and Development (OECD): Paris, France, 2020.
23. Boot-Handford, M.E.; Abanades, J.C.; Anthony, E.J.; Blunt, M.J.; Brandani, S.; Mac Dowell, N.; Fernández, J.R.; Ferrari, M.-C.; Gross, R.; Hallett, J.P.; et al. Carbon capture and storage update. *Energy Environ. Sci.* **2014**, *7*, 130–189. [CrossRef]
24. Sayari, A.; Belmabkhout, Y.; Serna-Guerrero, R. Flue Gas Treatment via CO_2 Adsorption. *Chem. Eng. J.* **2011**, *171*, 760–774. [CrossRef]
25. Plaza, M.G.; García, S.; Rubiera, F.; Pis, J.J.; Pevida, C. Post-Combustion CO_2 Capture with a Commercial Activated Carbon: Comparison of Different Regeneration Strategies. *Chem. Eng. J.* **2010**, *163*, 41–47. [CrossRef]
26. Thiruvenkatachari, R.; Su, S.; An, H.; Yu, X.X. Post Combustion CO_2 Capture by Carbon Fibre Monolithic Adsorbents. *Prog. Energy Combust. Sci.* **2009**, *35*, 438–455. [CrossRef]
27. Wang, Y.; Zhao, L.; Otto, A.; Robinius, M.; Stolten, D. A Review of Post-combustion CO_2 Capture Technologies from Coal-fired Power Plants. *Energy Procedia* **2017**, *114*, 650–665. [CrossRef]
28. Kárászová, M.; Zach, B.; Petrusová, Z.; Červenka, V.; Bobák, M.; Šyc, M.; Izák, P. Post-Combustion Carbon Capture by Membrane Separation, Review. *Sep. Purif. Technol.* **2020**, *238*, 116448. [CrossRef]
29. Brunetti, A.; Scura, F.; Barbieri, G.; Drioli, E. Membrane Technologies for CO_2 Separation. *J. Membr. Sci.* **2010**, *359*, 115–125. [CrossRef]
30. Mondal, M.K.; Balsora, H.K.; Varshney, P. Progress and Trends in CO_2 Capture/Separation Technologies: A Review. *Energy* **2012**, *46*, 431–441. [CrossRef]
31. Holmes, I.A.S.; Ryan, J.M. Cryogenic Distillative Separation of Acid Gases from Methane. US Patent US4318723A, 14 November 1979.
32. Song, C.; Liu, Q.; Deng, S.; Li, H.; Kitamura, Y. Cryogenic-Based CO_2 Capture Technologies: State-of-the-Art Developments and Current Challenges. *Renew. Sustain. Energy Rev.* **2019**, *101*, 265–278. [CrossRef]
33. Font-Palma, C.; Cann, D.; Udemu, C. Review of Cryogenic Carbon Capture Innovations and Their Potential Applications. *C* **2021**, *7*, 58. [CrossRef]
34. Jensen, M.J.; Russell, C.S.; Bergeson, D.; Hoeger, C.D.; Frankman, D.J.; Bence, C.S.; Baxter, L.L. Prediction and Validation of External Cooling Loop Cryogenic Carbon Capture (CCC-ECL) for Full-Scale Coal-Fired Power Plant Retrofit. *Int. J. Greenh. Gas Control* **2015**, *42*, 200–212. [CrossRef]
35. Tuinier, M.J.; Annaland, M.v.S.; Kuipers, J.A.M. A Novel Process for Cryogenic CO_2 Capture Using Dynamically Operated Packed Beds—An Experimental and Numerical Study. *Int. J. Greenh. Gas Control* **2011**, *5*, 694–701. [CrossRef]
36. Willson, P.; Lychnos, G.; Clements, A.; Michailos, S.; Font-Palma, C.; Diego, M.E.; Pourkashanian, M.; Howe, J. Evaluation of the Performance and Economic Viability of a Novel Low Temperature Carbon Capture Process. *Int. J. Greenh. Gas Control* **2019**, *86*, 1–9. [CrossRef]
37. 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]
38. Barzagli, F.; Lai, S.; Mani, F. Novel Non-Aqueous Amine Solvents for Reversible CO_2 Capture. *Energy Procedia* **2014**, *63*, 1795–1804. [CrossRef]
39. Mahi, M.-R.; Mokbel, I.; Negadi, L.; Dergal, F.; Jose, J. Experimental Solubility of Carbon Dioxide in Monoethanolamine, or Diethanolamine or N-methyldiethanolamine (30 wt%) Dissolved in Deep Eutectic Solvent (Choline Chloride and Ethylene Glycol Solution). *J. Mol. Liq.* **2019**, *289*, 111062. [CrossRef]
40. Resnik, K.P.; Yeh, J.T.; Pennline, H.W. Aqua Ammonia Process for Simultaneous Removal of CO_2, SO_2 and NO_x. *Int. J. Environ. Technol. Manag.* **2004**, *4*, 89. [CrossRef]
41. Haszeldine, R.S. Carbon Capture and Storage: How Green Can Black Be? *Science* **2009**, *325*, 1647–1652. [CrossRef]
42. Vega, F.; Baena-Moreno, F.M.; Fernández, L.M.G.; Portillo, E.; Navarrete, B.; Zhang, Z. Current Status of CO_2 Chemical Absorption Research Applied to CCS: Towards Full Deployment at Industrial Scale. *Appl. Energy* **2020**, *260*, 114313. [CrossRef]
43. Merkel, T.C.; Lin, H.; Wei, X.; Baker, R. Power Plant Post-Combustion Carbon Dioxide Capture: An Opportunity for Membranes. *J. Membr. Sci.* **2010**, *359*, 126–139. [CrossRef]
44. Lin, H.; He, Z.; Sun, Z.; Kniep, J.; Ng, A.; Baker, R.W.; Merkel, T.C. CO_2-Selective Membranes for Hydrogen Production and CO_2 Capture—Part II: Techno-Economic Analysis. *J. Membr. Sci.* **2015**, *493*, 794–806. [CrossRef]
45. Tuinier, M.J.; Hamers, H.P.; Annaland, M.v.S. Techno-Economic Evaluation of Cryogenic CO_2 Capture—A Comparison with Absorption and Membrane Technology. *Int. J. Greenh. Gas Control* **2011**, *5*, 1559–1565. [CrossRef]

46. Grande, C.A.; Blom, R.; Andreassen, K.A.; Stensrød, R.E. Experimental Results of Pressure Swing Adsorption (PSA) for Pre-Combustion CO_2 Capture with Metal Organic Frameworks. *Energy Procedia* **2017**, *114*, 2265–2270. [CrossRef]
47. Rashidi, N.A.; Yusup, S. An Overview of Activated Carbons Utilization for the Post-Combustion Carbon Dioxide Capture. *J. CO_2 Util.* **2016**, *13*, 1–16. [CrossRef]
48. Wang, Q.; Luo, J.; Zhong, Z.; Borgna, A. CO_2 Capture by Solid Adsorbents and Their Applications: Current Status and New Trends. *Energy Environ. Sci.* **2011**, *4*, 42–55. [CrossRef]
49. Millward, A.R.; Yaghi, O.M. Metal−Organic Frameworks with Exceptionally High Capacity for Storage of Carbon Dioxide at Room Temperature. *J. Am. Chem. Soc.* **2005**, *127*, 17998–17999. [CrossRef]
50. Kuppler, R.J.; Timmons, D.J.; Fang, Q.-R.; Li, J.-R.; Makal, T.A.; Young, M.D.; Yuan, D.; Zhao, D.; Zhuang, W.; Zhou, H.-C. Potential Applications of Metal-Organic Frameworks. *Coord. Chem. Rev.* **2009**, *253*, 3042–3066. [CrossRef]
51. 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]
52. Freeman, B.C.; Bhown, A.S. Assessment of the Technology Readiness of Post-Combustion CO_2 Capture Technologies. *Energy Procedia* **2011**, *4*, 1791–1796. [CrossRef]
53. Global CCS Institute. *CO_2 Capture Technologies—PostCombustion Capture (PCC)*. 2012, pp. 1–16. Available online: https://www.globalccsinstitute.com/resources/publications-reports-research/co2-capture-technologies-post-combustion-capture-pcc/ (accessed on 10 January 2023).
54. Bhown, A.S.; Freeman, B.C. Analysis and Status of Post-Combustion Carbon Dioxide Capture Technologies. *Environ. Sci. Technol.* **2011**, *45*, 8624–8632. [CrossRef] [PubMed]
55. NETL Petra Nova. *W.A. Parish Post-Combustion CO_2 Capture and Sequestration Demonstration Project*; Petra Nova LLC: Thompsons, TX, USA, 2020; p. 12.
56. Que, Z.; Jian, C.; Shujuan, W. Carbon Dioxide Capture from Coal-Fired Power Plants in China. *Summ. Eport NZEC Work Package* **2009**, *3*, 2010-10.
57. Rochelle, G.T.; Goff, G.S.; Cullinane, T. Method for Recovery of CO_2 from Gas Streams. US Patent US7056482B2, 12 June 2003. Available online: https://patents.google.com/patent/US7056482B2/en (accessed on 10 January 2023).
58. Freeman, S.A.; Dugas, R.; Van Wagener, D.H.; Nguyen, T.; Rochelle, G.T. Carbon Dioxide Capture with Concentrated, Aqueous Piperazine. *Int. J. Greenh. Gas Control* **2010**, *4*, 119–124. [CrossRef]
59. Perry, R.J.; Grocela-Rocha, T.A.; O'Brien, M.J.; Genovese, S.; Wood, B.R.; Lewis, L.N.; Lam, H.; Soloveichik, G.; Rubinsztajn, M.; Kniajanski, S.; et al. Aminosilicone Solvents for CO_2 Capture. *ChemSusChem* **2010**, *3*, 919–930. [CrossRef]
60. Bara, J.E.; Carlisle, T.K.; Gabriel, C.J.; Camper, D.; Finotello, A.; Gin, D.L.; Noble, R.D. Guide to CO_2 Separations in Imidazolium-Based Room-Temperature Ionic Liquids. *Ind. Eng. Chem. Res.* **2009**, *48*, 2739–2751. [CrossRef]
61. Sjostrom, S.; Krutka, H. Evaluation of Solid Sorbents as a Retrofit Technology for CO_2 Capture. *Fuel* **2010**, *89*, 1298–1306. [CrossRef]
62. Radosz, M.; Hu, X.; Krutkramelis, K.; Shen, Y. Flue-Gas Carbon Capture on Carbonaceous Sorbents: Toward a Low-Cost Multifunctional Carbon Filter for "Green" Energy Producers. *Ind. Eng. Chem. Res.* **2008**, *47*, 3783–3794. [CrossRef]
63. Demessence, A.; D'alessandro, D.M.; Foo, M.L.; Long, J.R. Strong CO_2 Binding in a Water-Stable, Triazolate-Bridged Metal−Organic Framework Functionalized with Ethylenediamine. *J. Am. Chem. Soc.* **2009**, *131*, 8784–8786. [CrossRef] [PubMed]
64. Deng, H.; Doonan, C.J.; Furukawa, H.; Ferreira, R.B.; Towne, J.; Knobler, C.B.; Wang, B.; Yaghi, O.M. Multiple Functional Groups of Varying Ratios in Metal-Organic Frameworks. *Science* **2010**, *327*, 846–850. [CrossRef] [PubMed]
65. Gupta, H.; Fan, L.-S. Carbonation−Calcination Cycle Using High Reactivity Calcium Oxide for Carbon Dioxide Separation from Flue Gas. *Ind. Eng. Chem. Res.* **2002**, *41*, 4035–4042. [CrossRef]
66. Baker, R.W.; Lokhandwala, K. Natural Gas Processing with Membranes: An Overview. *Ind. Eng. Chem. Res.* **2008**, *47*, 2109–2121. [CrossRef]
67. Pakala, N.R.; Bhown, A.S. Effect of Particulate Matter on Mass Transfer Through Microporous Hollow Fiber Membranes. *J. Membr. Sci.* **1996**, *111*, 71–79. [CrossRef]
68. Lively, R.P.; Koros, W.J.; Johnson, J. Enhanced Cryogenic CO_2 Capture Using Dynamically Operated Low-Cost Fiber Beds. *Chem. Eng. Sci.* **2012**, *71*, 97–103. [CrossRef]
69. Clodic, D.; Hitti, R.E.; Paris, M.D.; Bill, A.; Environment, A.P. CO2 Capture by Anti-Sublimation Thermo-Economic Process Evaluation Center for Energy and Processes. In Proceedings of the 4th Annual Conference on Carbon Capture & Sequestration, Alexandria, VA, USA, 2–5 May 2005.
70. Hart, A.; Gnanendran, N. Cryogenic CO_2 Capture in Natural Gas. *Energy Procedia* **2009**, *1*, 697–706. [CrossRef]
71. Baxter, L.; Baxter, A.; Burt, S. Cryogenic CO_2 Capture as a Cost-Effective CO_2 Capture Process. In Proceedings of the International Pittsburgh Coal Conference, Pittsburgh, PA, USA, 20–23 September 2009; Volume 1, pp. 762–775.
72. Song, C.-F.; Kitamura, Y.; Li, S.-H.; Ogasawara, K. Design of a Cryogenic CO_2 Capture System Based on Stirling Coolers. *Int. J. Greenh. Gas Control* **2012**, *7*, 107–114. [CrossRef]
73. Song, C.F.; Kitamura, Y.; Li, S.H. Evaluation of Stirling Cooler System for Cryogenic CO_2 Capture. *Appl. Energy* **2012**, *98*, 491–501. [CrossRef]
74. Arstad, B.; Blom, R.; Swang, O. CO_2 Absorption in Aqueous Solutions of Alkanolamines: Mechanistic Insight from Quantum Chemical Calculations. *J. Phys. Chem. A* **2007**, *111*, 1222–1228. [CrossRef] [PubMed]

75. Knudsen, J.N.; Jensen, J.N.; Vilhelmsen, P.-J.; Biede, O. Experience with CO_2 Capture from Coal Flue Gas in Pilot-Scale: Testing of Different Amine Solvents. *Energy Procedia* **2009**, *1*, 783–790. [CrossRef]
76. Gurkan, B.E.; de la Fuente, J.C.; Mindrup, E.M.; Ficke, L.E.; Goodrich, B.F.; Price, E.A.; Schneider, W.F.; Brennecke, J.F. Equimolar CO_2 Absorption by Anion-Functionalized Ionic Liquids. *J. Am. Chem. Soc.* **2010**, *132*, 2116–2117. [CrossRef] [PubMed]
77. Yancheshmeh, M.S.; Radfarnia, H.R.; Iliuta, M.C. High Temperature CO_2 Sorbents and Their Application for Hydrogen Production by Sorption Enhanced Steam Reforming Process. *Chem. Eng. J.* **2016**, *283*, 420–444. [CrossRef]
78. Ebner, A.D.; Gray, M.L.; Chisholm, N.G.; Black, Q.T.; Mumford, D.D.; Nicholson, M.A.; Ritter, J.A. Suitability of a Solid Amine Sorbent for CO_2 Capture by Pressure Swing Adsorption. *Ind. Eng. Chem. Res.* **2011**, *50*, 5634–5641. [CrossRef]
79. Bamdad, H.; Hawboldt, K.; MacQuarrie, S. A Review on Common Adsorbents for Acid Gases Removal: Focus on Biochar. *Renew. Sustain. Energy Rev.* **2018**, *81*, 1705–1720. [CrossRef]
80. Takamura, Y.; Aoki, J.; Uchida, S.; Narita, S. Application of High-Pressure Swing Adsorption Process for Improvement of CO_2 Recovery System from Flue Gas. *Can. J. Chem. Eng.* **2001**, *79*, 812–816. [CrossRef]
81. Clausse, M.; Merel, J.; Meunier, F. Numerical Parametric Study on CO_2 Capture by Indirect Thermal Swing Adsorption. *Int. J. Greenh. Gas Control* **2011**, *5*, 1206–1213. [CrossRef]
82. Rodrigues, G.; Raventos, M.; Dubettier, R.; Ruban, S. Adsorption Assisted Cryogenic Carbon Capture: An Alternate Path to Steam Driven Technologies to Decrease Cost and Carbon Footprint (March 18, 2021). International Energy Agency Greenhouse Gas R&D Programme (IEAGHG), 15th Greenhouse Gas Control Technologies Conference 2020 (GHGT-15). Available online: https://ssrn.com/abstract=3820744 (accessed on 10 January 2023).
83. Yave, W.; Car, A.; Funari, S.S.; Nunes, S.P.; Peinemann, K.-V. CO_2-Philic Polymer Membrane with Extremely High Separation Performance. *Macromolecules* **2010**, *43*, 326–333. [CrossRef]
84. Aaron, D.; Tsouris, C. Separation of CO_2 from Flue Gas: A Review. *Sep. Sci. Technol.* **2005**, *40*, 321–348. [CrossRef]
85. 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]
86. Khalilpour, R.; Mumford, K.; Zhai, H.; Abbas, A.; Stevens, G.; Rubin, E.S. Membrane-Based Carbon Capture from Flue Gas: A Review. *J. Clean. Prod.* **2015**, *103*, 286–300. [CrossRef]
87. Hussain, A.; Hägg, M.-B. A Feasibility Study of CO_2 Capture from Flue Gas by a Facilitated Transport Membrane. *J. Membr. Sci.* **2010**, *359*, 140–148. [CrossRef]
88. Zhai, H.; Rubin, E.S. Techno-Economic Assessment of Polymer Membrane Systems for Postcombustion Carbon Capture at Coal-Fired Power Plants. *Environ. Sci. Technol.* **2013**, *47*, 3006–3014. [CrossRef] [PubMed]
89. Kelley, B.T.; Valencia, J.A.; Northrop, P.S.; Mart, C.J. Controlled Freeze Zone™ for Developing Sour Gas Reserves. *Energy Procedia* **2011**, *4*, 824–829. [CrossRef]
90. Ebrahimzadeh, E.; Matagi, J.; Fazlollahi, F.; Baxter, L.L. Alternative Extractive Distillation System for CO_2–Ethane Azeotrope Separation in Enhanced Oil Recovery Processes. *Appl. Therm. Eng.* **2016**, *96*, 39–47. [CrossRef]
91. Song, C.F.; Kitamura, Y.; Li, S.H.; Jiang, W.Z. Parametric Analysis of a Novel Cryogenic CO_2 Capture System Based on Stirling Coolers. *Environ. Sci. Technol.* **2012**, *46*, 12735–12741. [CrossRef]
92. Roussanaly, S.; Berghout, N.; Fout, T.; Garcia, M.; Gardarsdottir, S.; Nazir, S.M.; Ramirez, A.; Rubin, E.S. Towards improved cost evaluation of Carbon Capture and Storage from industry. *Int. J. Greenh. Gas Control* **2021**, *106*, 103263. [CrossRef]
93. Rubin, E.; Booras, G.; Davison, J.; Ekstrom, C.; Matuszewski, M.; McCoy, S.; Short, C. *Toward a Common Method of Cost Estimation for CO_2 Capture and Storage at Fossil Fuel Power Plants*; Global CCS Institute: Canberra, Australia, 2013; pp. 1–36. Available online: https://www.globalccsinstitute.com/resources/publications-reports-research/toward-a-common-method-of-cost-estimation-for-co2-capture-and-storage-at-fossil-fuel-power-plants/ (accessed on 12 December 2022).
94. Hetti, R.K.; Karunathilake, H.; Hewage, K.; Sadiq, R. A Comparison of Carbon Capturing Technologies for Community Energy Systems: A Techno-Economic Assessment. In Proceedings of the 2nd International Conference on New Horizons in Green Civil Engineering (NHICE-02), Victoria, BC, Canada, 24–26 August 2020; pp. 1–5.
95. Gielen, D. CO_2 Removal in the Iron and Steel Industry. *Energy Convers. Manag.* **2003**, *44*, 1027–1037. [CrossRef]
96. Davis, J.; Rochelle, G. Thermal Degradation of Monoethanolamine at Stripper Conditions. *Energy Procedia* **2009**, *1*, 327–333. [CrossRef]
97. Ferrara, G.; Lanzini, A.; Leone, P.; Ho, M.T.; Wiley, D.E. Exergetic and Exergoeconomic Analysis of Post-Combustion CO_2 Capture Using MEA-Solvent Chemical Absorption. *Energy* **2017**, *130*, 113–128. [CrossRef]
98. Abu Zahra, M.; Niederer, J.P.; Feron, P.H.; Versteeg, G.F. CO_2 Capture from Power Plants: Part II. A Parametric Study of the Economical Performance Based on Mono-Ethanolamine. *Int. J. Greenh. Gas Control* **2007**, *1*, 135–142. [CrossRef]
99. Huang, C.-H.; Chang, K.-P.; Yu, C.-T.; Chiang, P.-C.; Wang, C.-F. Development of High-Temperature CO_2 Sorbents Made of CaO-Based Mesoporous Silica. *Chem. Eng. J.* **2010**, *161*, 129–135. [CrossRef]
100. Kulkarni, A.R.; Sholl, D.S. Analysis of Equilibrium-Based TSA Processes for Direct Capture of CO_2 from Air. *Ind. Eng. Chem. Res.* **2012**, *51*, 8631–8645. [CrossRef]
101. James, R.; Zoelle, A.; Keairns, D.; Turner, M.; Woods, M.; Kuehn, N. *Cost and Performance Baseline for Fossil Energy Plants Volume 1: Bituminous Coal and Natural Gas to Electricity*; NETL Rep. Pub-22638; National Energy Technology Laboratory (NETL): Pittsburgh, PA, USA, 2019; Volume 1, p. 598.

102. Li, G.; Bai, P. New Operation Strategy for Separation of Ethanol–Water by Extractive Distillation. *Ind. Eng. Chem. Res.* **2012**, *51*, 2723–2729. [CrossRef]
103. International Energy Agency. *Improvements in Power Generation with Post-Combustion Capture of CO_2*; IEA Greenhouse Gas R&D Programme: Cheltenham, UK, 2004; pp. 1–153.
104. Li, J.; You, C.; Chen, L.; Ye, Y.; Qi, Z.; Sundmacher, K. Dynamics of CO_2 Absorption and Desorption Processes in Alkanolamine with Cosolvent Polyethylene Glycol. *Ind. Eng. Chem. Res.* **2012**, *51*, 12081–12088. [CrossRef]
105. Lombardo, G.; Agarwal, R.; Askander, J. Chilled Ammonia Process at Technology Center Mongstad—First Results. *Energy Procedia* **2014**, *51*, 31–39. [CrossRef]
106. Parshetti, G.K.; Chowdhury, S.; Balasubramanian, R. Biomass Derived Low-Cost Microporous Adsorbents for Efficient CO_2 Capture. *Fuel* **2015**, *148*, 246–254. [CrossRef]
107. Luberti, M.; Oreggioni, G.D.; Ahn, H. Design of a Rapid Vacuum Pressure Swing Adsorption (RVPSA) Process for Post-Combustion CO_2 Capture from a Biomass-Fuelled CHP Plant. *J. Environ. Chem. Eng.* **2017**, *5*, 3973–3982. [CrossRef]
108. Mendes, P.A.; Ribeiro, A.M.; Gleichmann, K.; Ferreira, A.F.; Rodrigues, A.E. Separation of CO_2/N_2 on Binderless 5A Zeolite. *J. CO_2 Util.* **2017**, *20*, 224–233. [CrossRef]
109. Qasem, N.A.; Ben-Mansour, R. Energy and Productivity Efficient Vacuum Pressure Swing Adsorption Process to Separate CO_2 from CO_2/N_2 Mixture Using Mg-MOF-74: A CFD Simulation. *Appl. Energy* **2018**, *209*, 190–202. [CrossRef]
110. Matsumiya, N.; Teramoto, M.; Kitada, S.; Matsuyama, H. Evaluation of Energy Consumption for Separation of CO_2 in Flue Gas by Hollow Fiber Facilitated Transport Membrane Module with Permeation of Amine Solution. *Sep. Purif. Technol.* **2005**, *46*, 26–32. [CrossRef]
111. Bounaceur, R.; Lape, N.; Roizard, D.; Vallieres, C.; Favre, E. Membrane Processes for Post-Combustion Carbon Dioxide Capture: A Parametric Study. *Energy* **2006**, *31*, 2556–2570. [CrossRef]
112. Jensen, M. *Energy Process Enabled by Cryogenic Carbon Capture*; Brigham Young University: Provo, UT, USA, 2015.
113. Safdarnejad, S.M.; Hedengren, J.D.; Baxter, L.L. Plant-Level Dynamic Optimization of Cryogenic Carbon Capture with Conventional and Renewable Power Sources. *Appl. Energy* **2015**, *149*, 354–366. [CrossRef]
114. Maqsood, K.; Ali, A.; Shariff, A.B.; Ganguly, S. Process Intensification Using Mixed Sequential and Integrated Hybrid Cryogenic Distillation Network for Purification of High CO_2 Natural Gas. *Chem. Eng. Res. Des.* **2017**, *117*, 414–438. [CrossRef]
115. Maqsood, K.; Pal, J.; Turunawarasu, D.; Pal, A.J.; Ganguly, S. Performance Enhancement and Energy Reduction Using Hybrid Cryogenic Distillation Networks for Purification of Natural Gas with High CO_2 Content. *Korean J. Chem. Eng.* **2014**, *31*, 1120–1135. [CrossRef]
116. Song, C.; Kitamura, Y.; Li, S. Energy Analysis of the Cryogenic CO_2 Capture Process Based on Stirling Coolers. *Energy* **2014**, *65*, 580–589. [CrossRef]
117. Turan, G.; Zapantis, A.; Kearns, D.; Tamme, E.; Staib, C.; Zhang, T.; Burrows, J.; Gillespie, A.; Havercroft, I.; Rassool, D.; et al. *Global Status of CCS 2021*; Global CCS Institute: Melbourne, Australia, 2021; pp. 1–43.