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Recent Status and Research & Development in the Carbon Capture, Utilization and Storage Technology

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Abstract: The recently rapid extension and expansion of the industrial and energy sector has increased the number of carbon dioxide (CO_2) in our environment. Consequently, many efforts have been concerned in prevention of global warming and mitigate the climate change strategy. In this paper, the current situation of many aspects of carbon capture, utilization and storage (CCUS) technologies were concisely reviewed and discussed. The CCUS technology, using CO_2 separation/capture, storage, utilisation, and sequestration processes, is currently considered as the most applicable method to prevent the emission of CO_2 to the atmosphere and mitigate climate change and global warming. In this review, the source of CO_2 resources and which country that produce its were discussed. It was also reviewed technology types that could be adopted to capture of carbon dioxide with its any advantages and disadvantages. In order to employ those as a cost-effective technologies for the reduction of CO_2 emissions from the use of fossil fuels, research and development in its related processes and materials should put in a highest priority.

Keywords: carbon dioxide, emission, capture, utilization and storage

1. Introduction

Climate change has attracted global attention. Countries in the world began to move by performing out the cooperation between countries and international agreements. This was discussed for the first time at an international conference held in the city of Rio de Janeiro, Brazil in 1992. The last conference was held in the Paris, France in 2015 by conducted the 21st Conference of Parties (COP) and the follow-up instrument of the Kyoto Protocol was formed which agreed on the adoption and implementation of a series of policy decisions foreign policy (decision foreign policy) for member countries involved in the Paris Agreement. The Paris Agreement aims to keep global temperatures below 2 or 1.5 ^{o}C. The advantage of the Paris Agreement is that it fully targets stopping temperature rise, taking into account the different circumstances and capabilities of each country [1], [2].

Carbon dioxide (CO_2) is one of the triggers for the greenhouse effect and global warming [3]. The continuous increase in CO_2 concentrations in the atmosphere will limit the ability of plants and the sea to absorb CO_2 gas, so that CO_2 gas will be trapped in the earth's atmosphere and cause global warming which is characterized by rising earth temperatures, climate shifts, and rising sea levels. The excessive release of CO_2 from industry, power generation and other sources plays a critical role in the global climate and the Earth's life cycle [4]. Two giant CO_2 emission countries are China (6,103.49 MT) and United States (5,975.10 MT) [5]. When we considered the sources of CO_2 by sector, the main contributor for this gas are power generation (power plant) and heat production, industry and construction and transportation.

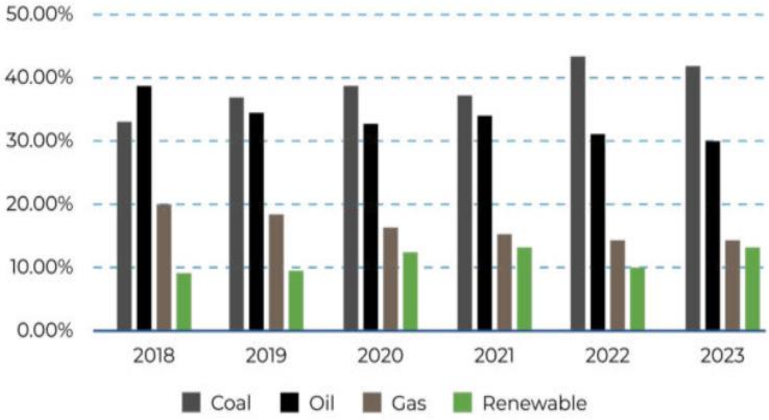
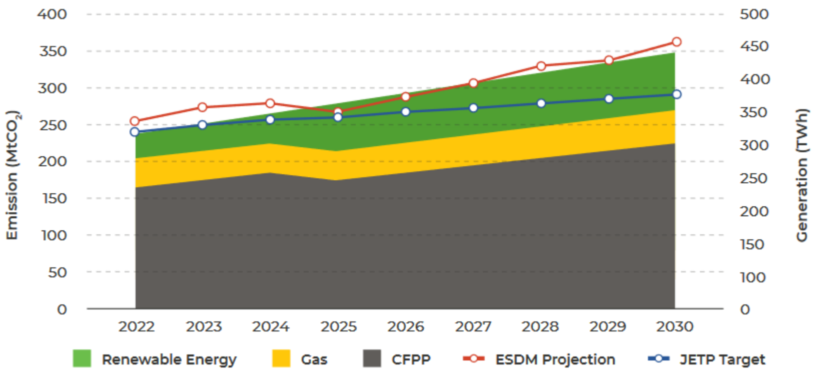


Figure 1. Indonesia primary energy mix [6]

For Indonesia side, share of fossil fuel in a primary energy mix was dominant until quarter 3 of 2022, as shown by **Figure 1**. Moreover, projection for 2023 by linear regression based on the historical trends (without considering any other aspects such as political, technological, and economic aspects) gain the domination of fossil in the primary energy supply, especially for coal. Fortunately, a negative annual growth trend provided by gas and oil. A little increase in year of 2023 due to the spike of energy demand responding to the economic growth during the post-pandemic situation [6].



Note: CFPP: Coal-fired Power Plant; ESDM: Menteri Energi dan Sumber Daya Mineral (Ministry of Energy and Mineral Resources, MEMR); JETP: Just Energy Transition Partnership

Figure 2. Power generation and emission projection [6]

Further, **Figure 2** describes the number of power generation and emission projections until 2030. Since the fossil fuels are sit in higher portion, release in emission increase gradually as a consequent. This is a quite strong fact why development in the carbon capture, utilization and storage (CCUS) technology has to be paid an attention seriously, especially for Indonesia.

Many efforts have been done in the national, regional and international levels to address global warming issue. The barriers have been recognized and studied in order to bring fruitful attempts and future recommendations has been highlighted [6]. A significant idea has also been done through the integrating of climate change issues in Environmental Impact Assessment (EIA). Reviews progress across a range of 19 EIA regimes has been established [7]. In this article the discussion on the recent status and Research & Development in the CCUS technology performed based on the literature review to look inside the existing projects conditions and progress in the R&D.

2. Recent Status of the CCUS Projects

The technology that is currently widely used to reduce the problem of CO_2 emissions is using separation technology including air capture, carbon capture and storage (CCS), and CCSU technologies. Particularly, carbon capture technologies can be operated using several systems: post combustion, pre combustion and oxy combustion [3], [8]-[10]. **Figure 3** presents those three CO_2 capture processes, while the last technology (chemical looping) is still under development and inadequate large scale operation experience [11]. In addition, the CO_2 capture technologies are ready in the market but the cost accounts about 70–80% of the total cost of a complete CCS system including capture, transport and storage [12]. Based on the fact, therefore, it is seen that a hard work in R&D which are focused on the reduction of operating costs and energy consumption is needed.

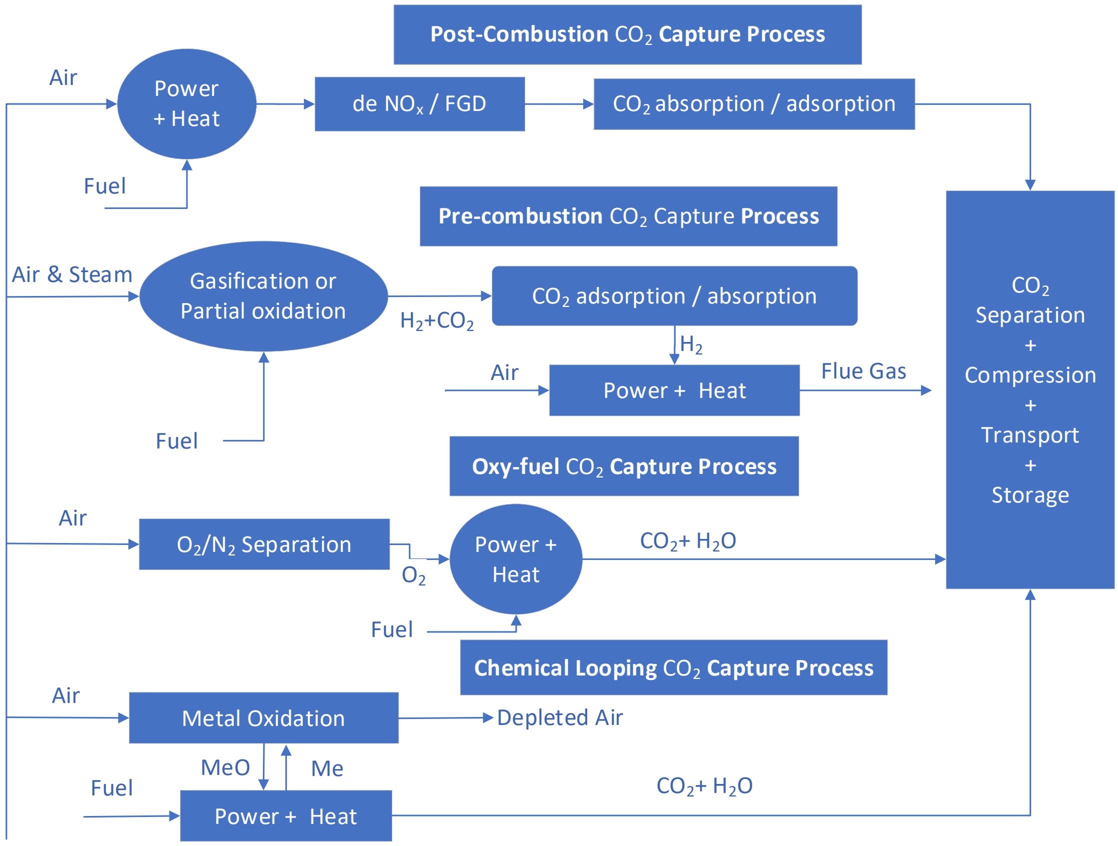


Figure 3. CO_2 capture technologies [11]

It should be known, discussion in this manuscript is focused on the post-combustion system, since the process commonly applied in the field. In this system, capturing of CO_2 is carried out after the fuel combustion process by direct removal of carbon dioxide from the flue gas, which comes from the thermal power plant combustion chamber or other combustion facilities. The system itself can be carried out by various methods including absorption, bio-fixation, membranes, cryogenics and adsorption [13]-[17]. It should be noted that select of the appropriate separation technique depends mainly on several physicochemical properties of the flue gases and the process conditions, that is, temperature, pressure, carbon dioxide concentration, and size of the gas mixture stream. In order to achieve low energy needs, a low carbon footprint and low operating expenses, membrane technology is straightforward to adapt and scale up to the existing power plant [17]. The process shows a good performance, can absorb about 92.5% of CO_2 emissions. Dziejarski et al. (2023) has summarized some advantageous/opportunities and disadvantages/challenges for this system as tabulated in **Table 1** and **Figure 4** presents pathway of the CCS technology of the post-combustion system [17].

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Table 1. Advantageous/Opportunities and Disadvantages/Challenges of Post-combustion Capture [17].

Advantages/ disadvantages	Post-Combustion Capture Characterization
Advantages/ opportunities	Applicable to existing coal-fired power plants as well as new ones (existing technology).
	Extensive research is conducted to enhance sorbents and capturing apparatus.
	Retrofitting existing power-plant designs is a viable option.
	Higher thermal efficiency for conversion to electricity than pre- combustion method.
	Emission of CO_2 is quite low (80-95% CO_2 recovery by adsorption, 90-98% by absorption).
	Extra removal of NO_X and SO_X.
	Use of hybrid processes (membrane-pressure swing adsorption) to optimize CO_2 capture efficiency.
	Increasing the efficiency of pulverized coal systems in the future will result in lower CO_2 emissions and higher plant productivity.
Disadvantages/ challenges	At ambient pressure, the concentration of CO_2 is low (typically 7-14%), which results in large process equipment sizes and high costs - a large volume of gas has to be handled.
	The relatively low CO_2 partial pressure and high temperature of the flue gases offers a design challenge.
	To capture CO_2 at low concentrations in absorption method, powerful chemical solvents must be utilized and regeneration of the solvents to release CO_2 will demand a significant amount of energy.
	The amine technologies in absorption method employed result in a nearly 30% drop in net power production and an 11% fall in efficiency.
	In the absorption method, the corrosivity of amines, the high energy footprint of regeneration, and degradation all contribute to solvent loss and evaporation.
	Absorption method based on MEA is related with expensive capital and operating costs. As a result, certain initiatives that relied on that technology have been shelved.
	Due to the low concentration of CO_2 in the flue gas, the additional cost of power production increases by approximately 60-70% for new infrastructure and by 220-250% for retrofitting.
	Greatly affected by trace impurities (NO_X, SO_X,) in adsorption method.
	Steam extraction reduces the flow to the low-pressure turbine, lowering its efficiency and capacity.
	High pressure drop for adsorption separation process.
	For high capture levels, high performance, circulation volume, and water needs are required.

In post-combustion, removing of CO_2 gas from the flue gas is addressed after combustion process. Post-combustion technology is the preferred option for retrofitting existing power plants. However, the major challenge for post-combustion CO_2 capture is its large parasitic load. Since the CO_2 level in combustion flue gas is normally quite low (i.e. 7–14% for coal-fired and as low as 4% for gas-fired), the energy penalty and associated costs for the capture unit to reach the concentration of CO_2 (above 95.5%) needed for transport and storage are elevated [18]-[20]. It was estimated by U.S. National Energy Technology Laboratory that CO_2 capture in the post-combustion would increase the cost of electricity production by 70% [21]. A recent study reported that the cost of electricity would increase by 32% and 65% for post-combustion in gas and coal-fired plants, respectively [22]. **Table 2** shows selected global CCUS projects from 2013 to 2019 [17]. It is clear that from 15 projects, 7 projects (less than 50%) active right now, 5 projects (1/3 number of projects) terminated and 3 projects hold, planned and potential. No published data for Indonesia about CCUS project.

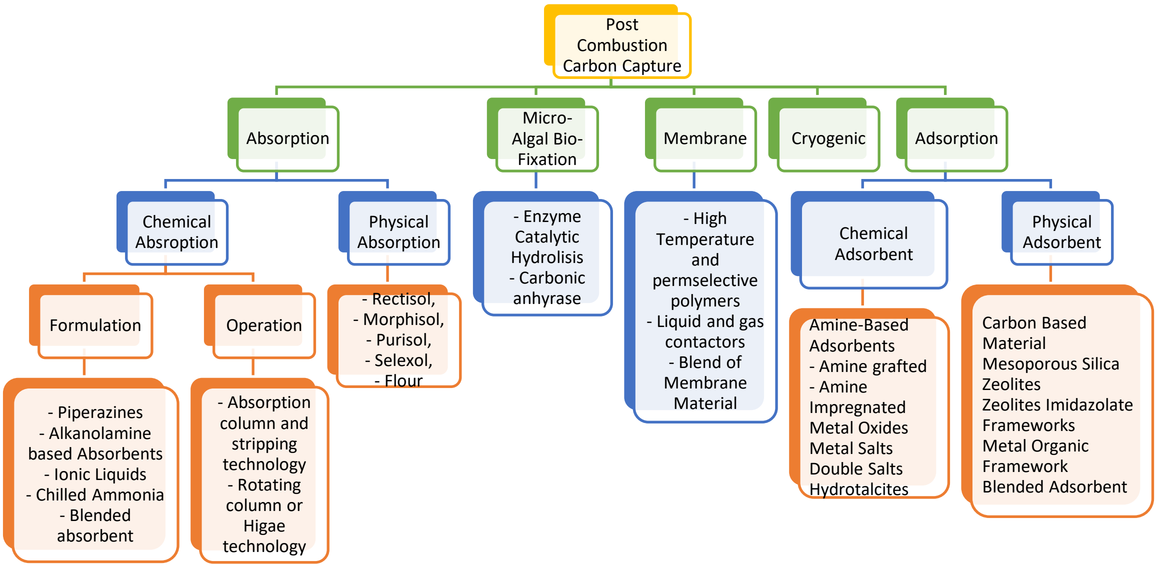

Figure 4. Post combustion carbon capture pathway [16]

Table 2. Wordwide CCUS Projects (2013 – 2019) with Post-combustion Capture Technology [17].

Project name	Country	Starting Year	Overall Status	Plant Size (MW)	Amount of CO_2 Capture/ Stored	Capture/ Stored unit
China Resources Power Integrated CCS Project	China	2019	Planned	-	2,740	MTPD
Large Pilot Testing of Linde	United States	2018	Active	10	-	-
Large Pilot testing of the MTR Membrane post-combustion CO_2 Capture	United States	2018	Active	-	-	-
Uky-CAER Heat-Integrated Transformative CO_2 Capture Process	United States	2018	Active	10	-	-
CATO1-Rotterdam ROAD project	Netherland	2015	Terminated	250	3,014	MTPD
Traiblazer Energy Center	United States	2015	Terminated	600	15,755	MTPD
Boundary Dam Integrated CCS Project	Canada	2014	Active	115	2,740	MTPD
EW Brown Generating Station	United States	2014	Active	0.70	-	-
PureGen Project	United States	2014	Terminated	500	90	% Reduction
RWE nPower-Blyth Post-Combustion Project	United Kingdom	2014	Terminated	2400	8,220	MTPD
Aalborg-Northern Jutland power Station Project	Denmark	2013	Hold	411	4,932	MTPD
Enecogen Cryogenic CO_2 Capture	Netherland	2013	Active	850	24.66	MTPD

Project name	Country	Starting Year	Overall Status	Plant Size (MW)	Amount of CO_2 Capture/ Stored	Capture/ Stored unit
Jamestown BPU	United States	2013	Potential	40	98	% Reduction
RWE nPower-Tilbury Project	United Kingdom	2013	Terminated	1131	90	% Reduction
Veolia Environment CCS Project	France	2013	Active	23	548	MTPD

Note: MTPD = Metric Tons per Day

3. R&D in Separation Projects

Talking on R&D projects absorption and adsorption-based process in post-combustion CO2 capture technology, **Table 3 and Table 4** provide the information on the global level. In absorption methods, R&D projects mostly (more than 50%) terminated in 2022, while for adsorption method R&D is still continue until 2023. Assessment on Technology Readiness Level (TRL) has been conducted by Dziejarski et al. [17], for chemical absorption based on traditional amine solvents is considered to have the TRL of 9. Other chemical absorption technologies use sterically hindered amines shows the TRL 6–9, chilled ammonia stand at the TRL 6–7, water-lean solvent (combine of physical and chemical absorption) reach the TRL 4–7, phase change solvents touch TRL5–6; amino acid-based solvent still in the TRL 4–5; encapsulated solvents and ionic liquids present low the TRL of 2–3. Moreover, physical adsorption (e.g. activated carbon, silica, alumina, MOFs, or zeolites) is now used most often in cement industry (TRL 5–6); chemical industry i.e. ammonia (TRL 5–6), methanol (TRL 7–8) production; and iron and steel sector i.e. direct reduction process (TRL 5–6), smelting reduction process (TR 7–8).

Table 3. R&D Projects Completed in 2020-2022 on Absorption Process in Post-Combustion CO_2 Capture Technology [17].

Type of Solvent	Prime Performer	Project Duration	Operating		CO_2 Recovery [% vol.]	CO_2 Purity [%]	TRL
			Pressure [bar]	Tempera-ture [°C]			
Aminebased solvent	Bechtel National, Inc.	2019-2022	1.089	53.5	80-90	>99	5-7
Water-lean amine solvent	Engineering, LLC	2019-2022	1	40	-	-	6
Amine based solvent	Southern Company Services, Inc.	2019-2022	0.9-1.1	30-60	90	99.9	5-7
Hindered amine - based solvent	University of Illiois	2019-2022	-	-	95	-	5-7
Water-lean solvent	Research Triangle Institute	2018-2022	0.133	34-45	-	-	4
Amine-based solvent	University of Kentucky	2018-2022	1.01	40	90	95	5-6
Water-lean amine solvent	Liquid Ion Solutions, LLC	2018-2022	1.01	40	80	10	3
Ammonium and	SRI International	2018-2022	1	20-40	90	95	3

Type of Solvent	Prime Performer	Project Duration	Operating		CO_2 Recovery [% vol.]	CO_2 Purity [%]	TRL
			Pressure [bar]	Tempera-ture [°C]			
pottasium salt solvent							
Solvents	Linde, LLC	2018-2021	-	-	-	-	6
Water-lean solvent	Pacific Northwest national Laboratory	2018-2021	1	40	90	95	3
Amine-based solvent (MEA)	University of Kentucky Research Foundation	2018-2021	1	40	90	99.9	6
Water-lean solvent	ION Engineering	2018-2019	1.0-1.15	20-50	89-91	-	5-7
Hindered amine-based solvent	University of North Dakota	2018-2019	1	40	95	99.9	5-7
Amine-based solvent	Massachusetts Institute of Technology	2017-2020	1	50	90	99	3

Tabel 4. Completed and Ongoing R&D Project in 2014-2023 on Adsorption in CO_2 Capture Technology [17].

Type of Adsorbent Material	Prime Performer	Project Duration	Operating		CO_2 Recovery [% vol.]	CO_2 Purity [%]	TRL
			Pressure [bar]	Tempera-ture [°C]			
Alkyl – amine coated MOF	Lawrence Berkeley National Laboratory	2017- 2021	0.13	50	90	90	4
Alkalized alumina (Al_2O_3) adsorbent	TDA research Inc.	2014- 2022	1.12	140	90	95	6
Microporous adsorbent	InnoSepra, LLC	2019- 2022	1.15	25-32	90	99	3
Ion exchange amine polymeric resin	TDA research Inc.	2018- 2022	1.1	60	90	95	4
Bi-Layer laminated structured sorbent (MOFs)	Electricore lectricore, Inc.	2019- 2022	1-1.1	40-50	90	90	4
TiO_2/Al_2O_3 on Zeolite 13X	Rensselear Polytechnic Institute	2019-2023	0.15	20	90	95	4
Low-Temp. physical adsorbent	TDA research, Inc.	2018-2023	1.0	30	-	-	6

MOF on MIcrolith in adsorption modules	Precision Combustion, Inc.	2017- 2023	-	30	-	-	4
SIFSIX-2-Cu-I MOF	TDA research	2019-2023	1.0	30	-	-	4
Carbon pellets sorbent	SRI International	2013- 2018	1	20	90	95	3
Amine Functionalized aerogel adsorbent	Aspen Aerogels, Inc.	2013- 2016	0.8	40	90	95	4

In addition, it should be note that a most innovative concept for the separation of CO_2 from the flue gas mixture is a membrane technique. Membrane separation is based on the use of a membrane which are the driving forces including pressure difference, temperature or electric potential on both sides of the membrane. For detail discussion on this technique can be read elsewhere [17].

4. R&D in Storage Projects

R&D in storage section is subsequent run as capturing ones, two of them has already sit in TRL 9, on the other hand some are on the TRL 2, as described by **Table 5**.

Tabel 5. Comparison of CO_2 Storage Methods [17].

Storage Method	Current Status	TRL
Saline Formulations	CO_2 rapid injection at a significant rate (1Mtpa).	9
	Injected CO_2 can be monitored, and storage is permanent.	
	The tools required to identify, appraise are well established.	
	Low economic costs.	
CO_2 - EOR	Proven storage locations.	9
	Maximize oil recovery.	
	More specific monitoring is needed to make sure that the CO_2 injected is being stored permanently.	
CO_2 - EGR	Proven storage locations.	7
	Maximize natural gas and gas condensate recovery.	
	Tight and low-permeability reservoirs.	
Depleted Oil and natural GasField	Technically mature.	7
	Airtight structures.	
	Limited capacity.	
	They have only been applied in demonstration projects.	
Mineral Carbonation (basaltic rock, ultramafic rocks)	High storage potential.	2-6
	Storage is safe and durable.	
	Permeability of rocks is difficult to predict.	
	Majority of tools for conventional CCS cannot be applied to monitor a CO_2 plume in a basalt.	
CO_2 - ECBM	Viable technology and can increase methane production.	2-3
	The produced methane provides revenue to the operation.	
	Injection of CO_2 significantly reduces the permeability of coal - additional costs and increasing operational complexity.	
	ECBM applies only to coal seams which will never be mined.	
Ocean storage	Currently, this method is prohibited by law.	2
	A very risky with unpredictable results.	
	It is at stage of formulation of technological concepts.	

Note: EOR = Enhanced oil recovery; EGR = Enhanced gas recovery; ECBM = Enhanced coal bed methane

5. Conclusion

The conclusions that can be drawn from this paper are as follows:

1. The cost of CO_2 capture technologies accounts for a significant portion (70-80%) of the total cost of a complete CCS system, including capture, transport, and storage. Therefore, research and development efforts should be focused on reducing operating costs and energy consumption.
2. In the field of post-combustion CO_2 capture technology, research and development (R&D) projects have been conducted on absorption and adsorption-based processes. More than half of R&D projects of absorption methods were terminated in 2022, while R&D of adsorption methods is still ongoing until today.
3. Technology readiness level (TRL) assessment conducted indicates that different chemical absorption technologies using various solvents have different TRLs, ranging from 2 to 9. Physical adsorption, utilizing materials like activated carbon, silica, alumina, MOFs, or zeolites, is currently being used in industries such as cement, chemical production (e.g., ammonia and methanol), and the iron and steel sector, with TRLs ranging from 5 to 8.

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