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Achieving Net Zero Emissions Target: Development of Carbon Dioxide Capture, Utilization, and Storage Technologies, Its Challenges and Barriers

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ABSTRACT: Achieving net zero carbon emissions by 2050 is a significant challenge for Indonesia across all sectors. This article presents a review of the current status of carbon dioxide capture, utilization, and storage (CCUS) technologies, covering both commercial-scale applications and ongoing research and development efforts. Performance metrics of these technologies are also included to provide valuable insights for technology selection. However, the challenges and barriers faced by Indonesia in reducing carbon emissions extend beyond technological aspects. Issues related to policy, socio-cultural dynamics, legal frameworks, and human resources also play a critical role. To ensure successful implementation, comprehensive regulations and policies are required at both national and provincial levels, along with extensive public engagement and collaboration among stakeholders.

Keywords: net zero emissions; carbon capture; carbon utilization; carbon storage; carbon emission

1. Introduction

Achieving net-zero carbon emissions is a significant challenge for Indonesia. According to projections based on the Stated Policies Scenario (STEPS), there will be only minimal reductions in the supply of fossil fuels—such as natural gas, oil, and coal—and in CO_2 emissions between 2030 and 2050. To reach the ambitious Net Zero Emissions by 2050 (NZE) target, a wide range of efforts have been initiated by researchers, institutions, corporations, and organizations. These efforts primarily focus on the advancement of carbon capture and storage (CCS) and carbon capture, utilization, and storage (CCUS) technologies. The NZE scenario anticipates that total CO_2 capture will reach 1.2 gigatons (Gt) by 2030, increasing substantially to 6.2 Gt by 2050 (Zhao, 2025). However, Government of Indonesia insist to achieve net zero emission by the year 2060.

Based on our review, the status and research and development (R&D) of CCS/CCUS technologies are discussed. These technologies can generally be categorized into four or five main methods: adsorption, absorption, membrane separation, chemical capture, and possibly cryogenic distillation (Gupta et al., 2024; Li, 2023; Pal et al., 2023; Ma et al., 2022). Among these, adsorption, absorption, and membrane technologies have reached the highest technological readiness level (TRL 9), indicating that they are currently at the commercial stage. The development of CCS/CCUS technologies has been driven by at least seven key factors: scientific innovation, technological innovation, policy innovation, emission reduction goals, equipment manufacturing, technology transfer, and employment opportunities (Mahidin et al., 2023; Ma et al., 2022).

Despite the progress made in CCS/CCUS technologies, significant challenges remain in scaling up these solutions to meet Indonesia's NZE targets effectively. The minimal reduction in fossil fuel supply and CO_2 emissions projected under current policies suggests that existing efforts may be insufficient. Therefore, it is crucial to identify and address the barriers hindering the widespread adoption and optimization of CCS/CCUS technologies. Understanding how to accelerate innovation, enhance policy frameworks, and improve technology transfer will be essential to overcoming these challenges and achieving Indonesia's net-zero ambitions by 2050

This review aims to provide a comprehensive review of the current status, advancements, and challenges in CCS/CCUS technologies, with a particular focus on their role in supporting Indonesia's net-zero emissions goals. By synthesizing recent research and developments, this review

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seeks to identify key opportunities and barriers, thereby offering valuable insights to guide future research, policy-making, and industrial implementation in the pursuit of sustainable carbon management.

2. Current Status Technologies

2.1. Commercial Scale

Carbon capture is one of the most widely recognized methods for managing carbon dioxide emissions, encompassing a range of technologies aimed at achieving climate goals through various approaches. It is particularly known for its effectiveness in capturing CO_2 from stationary sources and permanently storing it to prevent atmospheric release. For specific combustion applications, there are three main capture systems that can be installed to capture CO_2 emissions (pre-, post-, and oxygen-fuel) (Hanson et al., 2025; McLaughlin et al., 2023; Shaw and Mukherjee, 2022; Osman et al., 2021; Leung et al., 2014). It is important to highlight that, as of 2021, there were 135 commercial CCS/CCUS facilities globally, with a combined CO_2 capture capacity of 149.3 million metric tons per year (Mtpa). Most of these facilities are in the United States, accounting for 70 projects. Among the 135 facilities, 27 are currently operational, 4 are under construction, 58 are in advanced stages of development, 44 are in the early stages of development, and 2 are suspended. The number of facilities currently in place is still very small compared to the target set in the Paris Agreement, which is >2000 facilities by 2050. (Dziejarski et al., 2023; Hong et al., 2022; Shen et al., 2022).

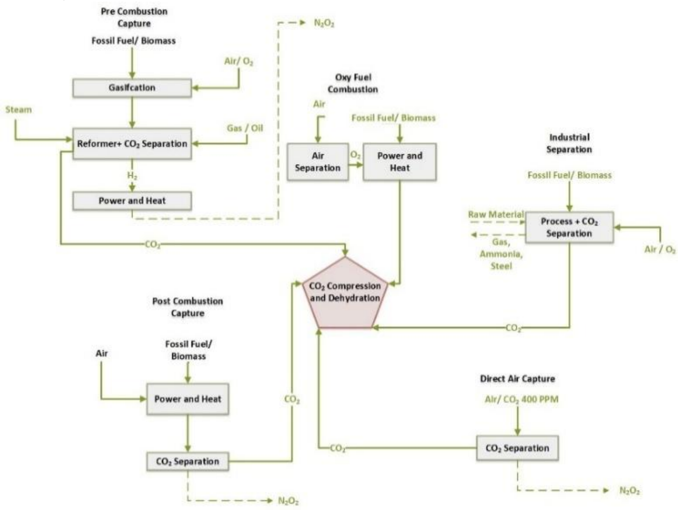

Figure 1. Type of existing CO_2 capture systems

Another widely used technique, often considered the fourth major method, involves capturing CO_2 from industrial process streams. In addition to these four main approaches, there is another emerging technique known as Direct Air Capture (DAC), which captures CO_2 directly from the atmosphere (Dziejarski et al., 2023; Castro-Pardo et al., 2022). DAC is specifically designed for atmospheric CO_2 removal and is not applicable to point-source emissions. While DAC offers the advantage of location flexibility and the potential for negative emissions, it faces significant challenges related to high energy consumption, material requirements, and cost barriers, which currently limit its scalability (Hoseinpoori et al., 2023). Figure 1 presents the five main techniques for CO_2 separation and capture. When DAC is integrated with storage or utilization, the systems are referred to as DACS (Direct Air Carbon Capture and Storage) or DACU (Direct Air Carbon Capture and Utilization), respectively.

Here, performance of several commercial active CCS/CCUS plants specially in pre-, post- and oxy-fuel combustion is discussed. The performance of the plant is defined as the amount of CO_2 captured and stored (Table 1) (Dziejarski et al., 2023; Leung et al., 2014)

2.2. Research & Development Works

When the focus shifts to research and development (R&D), the situation appears quite different. Table 2 shows the achievement of some work on the CCS/CCUS developments (Dziejarski et al., 2023). It is evident that the most superior method/technique is absorption, even though CO_2 recovery little lower than membrane (80-90 vs 80-99).

Absorption-based technology has been claimed as the most advanced technology (Vaz et al., 2022). Another record that supports its superiority is the TRL, reach up 7. The optimal performance for the adsorption method can be achieved through combined processes, such as pressure-temperature swing adsorption and vacuum-temperature swing adsorption, which offer recovery and purity rates exceeding 90%. The combination can improve the capturing selectivity and capacity. Adsorption-based technologies can capture CO_2 in large plants and are mostly applied in natural gas and ethanol processes (Vaz et al., 2022; Ben Mansour et al., 2016). In addition, the surprising fact is that no R&D activity was found in oxy-fuel combustion.

R&D efforts in carbon capture (CC) technologies span a wide range of maturity levels, from early-stage concepts at TRL 1 to pilot-scale demonstrations at TRL 6, covering both separation and storage processes (Mahidin et al., 2023). Dziejarski et al. (2023) described the TRL scale of the CC technologies based on the segments, methods and applications, respectively. For the segments section, the TRL distributed from 2 (formulation) to 9 (commercial). It has been clearly presented that the capture technology sits on the top level (about 54%), followed by the storage of 27%, the transport and storage/utilization of 10.8%, respectively. The utilization technology alone occupied the last position (only 2.7%).

If the review is carried out per stage, then in research activities (TRL 1 to 3), capture technology occupies the top position (45%), the second position is storage technology (33%) and the last is storage/utilization technology (22%). Next for development work (TRL 4 to 6), capture technology is still ranked at the top (67%), storage technology is ranked second (25%), and last is utilization (8%). Finally, for deployment activities (TRL 7 to 9), capture technology is not displaced in the top position with a contribution of 50%, then

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transportation technology appears in second place with a share of 25%, storage and storage/utilization now fill the last position together (12.5% each) (Dziejarski et al., 2023).

Table 1. Performance of selected global CCS/CCUS projects

Type of configuration	Project name and country	Plant size	Amount of CO_2 capture/stored	Unit
Pre-combustion	Great Lakes Energy Research Park - USA	250 MW	350	Metric tons per day
Post-combustion	Boundary Dam Integrated CCS Project - Canada	115 MW	2,740	Metric tons per day
	Enecogen Cryogenic CO_2 Capture – Netherlands	850 MW	24.66	Metric tons per day
	Veolia Environment CCS Project - France	23 MW	548	Metric tons per day
Oxy-fuel combustion	OXYCFB300 Compostilla Project - Spain	323 MW	100,000	Metric tons per day
	South Korea CCS2 - South Korea	300 MW	3,288	Metric tons per day

When the discussion was considered from viewpoint of method, chemical absorption stands at first rank almost in all TRL levels (42% in total), second and third ranks were occupied by adsorption (28.4%) and membrane technique (12.5%), respectively. These three methods have attained TRL 9 (entering the commercial market). Another method that has reached the commercial stage (TRL 9) is physical absorption, in which stay at the fourth rank. Physical adsorption is commonly employed in industrial processes, particularly within ammonia production facilities. Meanwhile, chemical looping combustion (CLC), calcium looping (CaL) and cryogenic methods sit together at the lowest ones (Meylani et al., 2025; Dziejarski et al., 2023; Nyamiati et al., 2023; Rahmah et al., 2022; Ramezani et al., 2022; Mores et al., 2012).

Furthermore, if we look at the economic sector, the use of CCS/CCSU technology is dominant in the cement and iron & steel industries (26% each), followed by application in the power generation sector (18.5%), then in the methanol and ammonia production sectors (11.11% each). The high-value chemical production sector accounts for the smallest share of CC technology deployment, at just 7.4%. Moreover, evidence suggests that only absorption methods have truly entered the commercial stage. The adsorption method itself was only able to reach TRL 8, one step behind (Dziejarski et al., 2023).

Some efforts on utilization of CO_2 are established separately. Among the applications of CO_2 are its use as a solvent in supercritical fluid extraction, a solvent for enhanced oil recovery (EOR), a cooling fluid, a component in food packaging, a propellant in food and beverage products (e.g., carbonated drinks), a raw material in chemical production, and an energy carrier. In general, utilization of CO_2 can be classified in two ways: direct use (without conversion) and with conversion to other products (She et al., 2025; Prajapati et al., 2024; Truong et al., 2024; Dziejarski et al., 2023; Hong et al., 2022; Xie et al., 2022; Pires da Mata Costa et al., 2021; Neeraj and Yadav, 2020). Direct CO_2 utilization involves using CO_2 without altering its chemical structure, typically in applications like greenhouses or carbonated drinks, and is relatively low-cost and low energy. In contrast, indirect utilization converts CO_2 into fuels or chemicals through energy-intensive processes, often requiring advanced technologies and higher investment.

Final step in the CCS/CCUS process is CO_2 storage. For this propose, the captured CO_2 is compressed to pressures exceeding 74 bar, creating conditions that convert the CO_2 into a supercritical or liquid state, prior to its permanent storage. Some storage options are CO_2-EOR application, CO_2-EGR application, CO_2-ECBM application, injection into depleted oil and gas fields, saline formations, basalt and ultramafic rocks, and deep ocean (Oqbi et al., 2025; Dziejarski et al., 2023; Marbun et al., 2023; McLaughlin et al., 2023; Hong et al., 2022; Shiyi et al., 2022; Mahdaviara et al. 2021; Orr Jr., 2018).

Table 2. R&D of selected global CCS/CCUS projects

Type of configuration	Type of method/ technique	CO_2 recovery (% vol.)	CO_2 purity (%)	TRL
Pre-combustion	Adsorption	90	96	6
	Membrane	80-99	95-99.5	3-4
Post-combustion	Absorption	80-90	95-99.9	3-7
	Adsorption	90	90-99	3-6
	Membrane	>60-90	59-99	4-7

In this scope, Indonesia is actively advancing commercial CO_2 storage projects to support its net-zero emissions goals, with notable initiatives including BP's Tangguh CCS project in Papua Barat, which aims to inject over 30 million tonnes of CO_2 in its initial phase and has an ultimate storage potential of around 1.8 Gt (International & Indonesia CCS Forum, 2025). Pertamina is also exploring CCS opportunities in depleted oil and gas reservoirs and saline aquifers, with Indonesia's total estimated geological storage capacity reaching up to 680.57 Gt in saline aquifers and 10.14 Gt in depleted reservoirs (BP Berau Ltd., 2024).

Additionally, a Joint Development and Study Agreement between Chevron and PT Pupuk Indonesia is targeting industrial decarbonization, while Indonesia positions itself as a regional CCS/CCUS hub for Southeast Asia, leveraging its infrastructure and strategic location to support cross-border CO_2 transport and storage.

On the other hand, research activities in Indonesia for CCS/CCUS technology development is still very limited, with some of it conducted or supported by Pertamina. Only a few publications can be collected that report on the activities of several researchers developing adsorbents or absorbent for CO_2 capture (Sussatrio et al., 2024; Tibalia et al., 2021; Yamliha et al., 2013; Apriyanti, 2012).

3. Challenges and Barriers for Indonesia

To encourage and mandate global participation in addressing climate change, the United Nations established the United Nations Framework Convention on Climate Change (UNFCCC). This convention seeks to support negotiations aimed at identifying the most effective approaches to promote development while concurrently addressing climate change and reducing its adverse effects. The two aspects that are the focus are (a) mitigation and (b) adaptation as the main instruments in mitigating the impacts of climate change. One notable form of international commitment is the Paris Agreement, an international accord on climate change aimed at limiting the global average temperature increase to below 2°C above pre-industrial levels.

The Government of the Republic of Indonesia ratified the UNFCCC through Law No. 16 of 2016, which pertains to the ratification of the Paris Agreement under the United Nations Framework Convention on Climate Change (Law of the Republic of Indonesia No.16 of 2016). The ratification of the UNFCCC has the legal consequence that the Government of the Republic of Indonesia is obliged to play an active role in overcoming climate change and global heat. To address this, the Government has implemented various regulations, including the issuance of Minister of Energy and Mineral Resources Regulation No. 16 of 2022, which outlines the procedures for implementing the economic value of carbon in the electricity generation sector (Minister of Energy and Mineral Resources Regulation No.16 of 2022). The efforts made by the Indonesian Government are aimed at reducing carbon emissions.

To support the policies that have been issued, R&D activities in the development of CCS/CCUS technologies must be carried out immediately (Di Vaio et al., 2025). To overcome these challenges and obstacles, a polycentric approach is required, integrating various scales of intervention (e.g., local, national, international), tools (e.g., public investment, partnerships, subsidies), and stakeholders (e.g., public authorities, businesses, citizens). For Indonesia, the challenges and barriers in carbon emission reduction efforts include issues of (1) policy, socio-cultural and legal, (2) human resources, and (3) technology. Public-private partnerships (PPPs) are increasingly being advocated as a solution to address challenges such as limited budget resources, access to technology, and issues related to flexibility in tackling environmental and climate concerns (Casady et al., 2024; McLaughlin et al., 2023).

Additional valuable insights into the challenges in this area stem from modeling the interactions between carbon emissions, urbanization, population growth, energy consumption, and economic development, specifically conducted for the Asia region. Both for urbanization and population growth vs. CO_2 emissions Indonesia sit at rank 4th after Pakistan, India and Bangladesh. Fortunately, for energy use, Indonesia moved to a very good position, ranking 5th from five studied countries (Rehman and Rehman, 2022). Another promising opportunity in the CCUS development is to integrate it with hydrogen production (Lu et al., 2025).

To include social, cultural and legal issues in efforts to reduce carbon emissions, the Government has recently issued various policies including the enactment of Presidential Regulation no. 14 of 2024 concerning the Implementation of Carbon Capture and Storage Activities. This policy has drawn criticism and concern from various segments of society, who fear it could hinder Indonesia's energy transition. The main issue lies in the absence of a clear roadmap for phasing out fossil fuels and decommissioning coal-fired power plants (PLTU). Furthermore, the implementation of CCS/CCUS initiatives raises concerns that oil and gas industry players may exploit these technologies to project an environmentally responsible image, potentially engaging in greenwashing rather than committing to genuine sustainability efforts.

To overcome and reduce carbon emissions, regulations and policies are needed both at the national and regional (provincial) levels (Song et al., 2025; Bang et al., 2024; Lu et al., 2022; Zhang et al., 2022). Apart from that, massive CCS/CCSU socialization efforts are needed from various stakeholders, especially the government and companies. So far, only a few provinces have paid serious attention to the issue of carbon emissions and one of them is Aceh Province which is currently discussing regional regulations related to the CCS/CCUS.

From a technological standpoint, the challenge lies in developing large-scale, low-energy consumption, and cost-effective units for use in low-concentration emission sources (such as coal- and gas-fired power plants, steel mills, cement and chemical industries, and waste incineration), while ensuring continuous safety and risk monitoring (Sovacool et al., 2024; Ma et al., 2022; Fauziawan, 2021).

It is important to highlight that the CCS/CCUS science and technology infrastructure established in advanced regions plays a crucial role in addressing fundamental scientific challenges related to CCS/CCUS, lowering the costs of CCS/CCUS technologies throughout the entire process, ensuring the safety of long-term storage, advancing R&D of cutting-edge technologies, and supporting further commercialization, promotion, demonstration, and talent development. Sharing CCS/CCUS research findings and expertise from advanced regions enables the acceleration of cost and risk reduction, as well as the broader commercial

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implementation of CCS/CCUS in other areas. However, the complexity of geographical, political, and socio-cultural factors poses challenges in directly replicating many technologies and achieving the desired outcomes (Ma et al., 2022).

However, despite Indonesia's vast human and natural resource potential, CCS development in Indonesia faces various obstacles, such as high initial costs, regulatory uncertainty, and limited public awareness. Clear policies, financial incentives, and technological innovation are needed to overcome these obstacles (International & Indonesia CCS Forum, 2025).

4. Conclusion

In conclusion, Indonesia's path to achieving net-zero carbon emissions by 2060 necessitates a multifaceted approach that encompasses technological innovation, robust policy frameworks, and active stakeholder engagement. The successful implementation of carbon capture and storage (CCS) and carbon capture, utilization, and storage (CCUS) technologies is critical, yet it must be complemented by addressing socio-cultural dynamics and legal challenges. By fostering public-private partnerships and aligning efforts with international climate commitments, Indonesia can navigate the complexities of its energy transition while maximizing the potential benefits of CCS/CCUS technologies in mitigating climate change.

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Mahidin: Writing – original draft, Writing – review & editing. **Farid Mulana:** Writing – review & editing. **Mukramah Yusuf:** Writing – review & editing**.** **Adisalamun:** Writing – review & editing**.** **Hisbullah:** Writing – review & editing. **Abdul Hadi:** Writing – review & editing**.** **Nurdin MH:** Writing – review & editing**.** **Faisal Abnisa:** Writing – review & editing.

Declaration of Competing Interest
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability
Not applicable.

References

Agyekum, E. B., Khan, T., Tahir, M., Sultan, S. M., Mbasso, W. F., Rashid, F. L., & Togun, H. (2025). Evolution, trends, and future research directions of carbon capture, utilization and storage – A comprehensive bibliometric and systematic review. *Energy Reports*, 13, 5357–5374. https://doi.org/10.1016/j.egyr.2025.04.063

Apriyanti, E. (2012). Adsorbsi CO2 Menggunakan Zeolit: Aplikasi Pada Pemurnian Biogas. Majalah Ilmiah Universitas Pandanaran, 10(22).

Bang, A., Moreno, D., Lund, H., & Nielsen, S. (2024). Regional CCUS strategies in the context of a fully decarbonized society. *Journal* of Cleaner Production, 477, 143882. https://doi.org/10.1016/j.jclepro.2024.143882

Bashir, A., Ali, M., Patil, S., Aljawad, M. S., Mahmoud, M., Al-Shehri, D., ... & Kamal, M. S. (2024). Comprehensive review of CO_2 geological storage: Exploring principles, mechanisms, and prospects. *Earth-Science Reviews*, 249, 104672. https://doi.org/10.1016/j.earscirev.2023.104672

Ben-Mansour, R., Habib, M. A., Bamidele, O. E., Basha, M., Qasem, N. A. A., Peedikakkal, A., & Ali, M. J. A. E. (2016). Carbon capture by physical adsorption: Materials, experimental investigations and numerical modeling and simulations–A review. *Applied Energy*, 161, 225–255. https://doi.org/10.1016/j.apenergy.2015.10.011

BP Berau Ltd. (2024, 31 Juli). BP building up CCUS, CCS competence in Indonesia (Press release). BP Berau Ltd. https://www.bp.com/en_id/indonesia/home/news/press-releases/bp-building-up-ccus-ccs-competence-in-indonesia.html

Casady, C. B., Cepparulo, A., & Giuriato, L. (2024). Public–private partnerships for low-carbon, climate-resilient infrastructure: Insights from the literature. *Journal of Cleaner Production*, 470, 143338. https://doi.org/10.1016/j.jclepro.2024.143338

Castro-Pardo, S., Bhattacharyya, S., Yadav, R. M., de Carvalho Teixeira, A. P., Mata, M. A. C., Prasankumar, T., & Ajayan, P. M. (2022). A comprehensive overview of carbon dioxide capture: From materials, methods to industrial status. *Materials Today*, 60, 227–270. https://doi.org/10.1016/j.mattod.2022.08.018

Chen, J., Xu, Y., Liao, P., Wang, H., & Zhou, H. (2022). Recent progress in integrated CO_2 capture and conversion process using dual function materials: A state-of-the-art review. *Carbon Capture Science & Technology*, 4, 100052. https://doi.org/10.1016/j.ccst.2022.100052

Dai, Y., Niu, Z., Luo, W., Wang, Y., Mu, P., & Li, J. (2023). A review on the recent advances in composite membranes for CO_2 capture processes. *Separation and Purification Technology*, 307, 122752. https://doi.org/10.1016/j.seppur.2022.122752

Davoodi, S., Al-Shargabi, M., Wood, D. A., Mehrad, M., & Rukavishnikov, V. S. (2024). Carbon dioxide sequestration through enhanced oil recovery: A review of storage mechanisms and technological applications. *Fuel*, 366, 131313. https://doi.org/10.1016/j.fuel.2024.131313

Deng, Q., Ling, X., Zhang, K., Tan, L., Qi, G., & Zhang, J. (2022). CCS and CCUS technologies: Giving the oil and gas industry a green future. *Frontiers in Energy Research*, 10, 919330. https://doi.org/10.3389/fenrg.2022.919330

Di Vaio, A., Chhabra, M., Zaffar, A., & Balsalobre-Lorente, D. (2025). Accounting and accountability in the transition to zero-carbon energy for climate change: A systematic literature review. *Business Strategy and the Environment*. https://doi.org/10.1002/bse.4282

Dziejarski, B., Krzyżyńska, R., & Andersson, K. (2023). Current status of carbon capture, utilization, and storage technologies in the global economy: A survey of technical assessment. Fuel, 342, 127776. https://doi.org/10.1016/j.fuel.2023.127776

Fauziawan, A. F. (2021). Inventory of Greenhouse Gas Emissions in the Waste Sector with First Order Decay in Karangasem Regency. *Eksergi*, 18(1), 18-23. https://doi.org/10.31315/e.v0i0.4534

Gupta, N. C., Tanwar, R., Kaushik, A., Singh, R., Patra, A. K., Sar, P., & Khakharia, P. (2024). Perspectives on CCUS deployment on large scale in India: Insights for low carbon pathways. *Carbon Capture Science & Technology*, 12, 100195. https://doi.org/10.1016/j.ccst.2024.100195

Han, Y., & Ho, W. W. (2021). Polymeric membranes for CO_2 separation and capture. *Journal of Membrane Science*, 628, 119244. https://doi.org/10.1016/j.memsci.2021.119244

Hanson, E., Nwakile, C., & Hammed, V. O. (2024). Carbon capture, utilization, and storage (CCUS) technologies: Evaluating the effectiveness of advanced CCUS solutions for reducing CO_2 emissions. *Results in Surfaces and Interfaces*, 100381. https://doi.org/10.1016/j.rsurfi.2024.100381

Ho, H. J., & Iizuka, A. (2023). Mineral carbonation using seawater for CO_2 sequestration and utilization: A review. *Separation and Purification Technology*, 307, 122855. https://doi.org/10.1016/j.seppur.2022.122855

Hong, W. Y. (2022). A techno-economic review on carbon capture, utilisation and storage systems for achieving a net-zero CO_2 emissions future. *Carbon Capture Science & Technology*, 3, 100044. https://doi.org/10.1016/j.ccst.2022.100044

Hoseinpoori, S., Pallarès, D., Johnsson, F., & Thunman, H. (2023). A comparative exergy-based assessment of direct air capture technologies. *Mitigation and Adaptation Strategies for Global Change*, 28(7), Article 39. https://doi.org/10.1007/s11027-023-10076-3

International & Indonesia CCS Forum. (2025, Maret 30). The potential of Carbon Capture and Storage (CCS) in Indonesia. *International & Indonesia CCS Forum*. https://iiccsforum.com/the-potential-of-carbon-capture-and-storage-ccs-in-indonesia/

Kang, J. N., Wei, Y. M., Liu, L. C., & Wang, J. W. (2021). Observing technology reserves of carbon capture and storage via patent data: Paving the way for carbon neutral. *Technological Forecasting and Social Change*, 171, 120933. https://doi.org/10.1016/j.techfore.2021.120933

Kar, T., & Veluswamy, H. P. (2025). To nip it or let it bloom: Life cycle assessment of lab-scale catalysts used in low-TRL CCUS technologies. *Sustainable Chemistry for Climate Action*, 100057. https://doi.org/10.1016/j.scca.2025.100057

Ketabchi, M. R., Babamohammadi, S., Davies, W. G., Gorbounov, M., & Soltani, S. M. (2023). Latest advances and challenges in carbon capture using bio-based sorbents: A state-of-the-art review. *Carbon Capture Science & Technology*, 6, 100087. https://doi.org/10.1016/j.ccst.2022.100087

Khosroabadi, F., Aslani, A., Bekhrad, K., & Zolfaghari, Z. (2021). Analysis of carbon dioxide capturing technologies and their technology developments. *Cleaner Engineering and Technology*, 5, 100279. https://doi.org/10.1016/j.clet.2021.100279

Leung, D. Y., Caramanna, G., & Maroto-Valer, M. M. (2014). An overview of current status of carbon dioxide capture and storage technologies. *Renewable and Sustainable Energy Reviews*, 39, 426–443.https://doi.org/10.1016/j.rser.2014.07.093

Li, H. (2023). CO2 capture by various nanoparticles: Recent development and prospective. *Journal of Cleaner Production*, 414, 137679. https://doi.org/10.1016/j.jclepro.2023.137679

Lu, H., Xi, D., & Cheng, Y. F. (2025). Hydrogen production in integration with CCUS: A realistic strategy towards net zero. *Energy*, 134398. https://doi.org/10.1016/j.energy.2025.134398

Lu, J., Chen, H., & Cai, X. (2022). From global to national scenarios: Exploring carbon emissions to 2050. *Energy Strategy Reviews*, 41, 100860. https://doi.org/10.1016/j.esr.2022.100860

Ma, J., Li, L., Wang, H., Du, Y., Ma, J., Zhang, X., & Wang, Z. (2022). Carbon capture and storage: History and the road ahead. *Engineering*, 14, 33–43. https://doi.org/10.1016/j.eng.2021.11.024

Mahdaviara, M., Amar, M. N., Hemmati-Sarapardeh, A., Dai, Z., Zhang, C., Xiao, T., & Zhang, X. (2021). Toward smart schemes for modeling CO_2 solubility in crude oil: Application to carbon dioxide enhanced oil recovery. *Fuel*, 285, 119147. https://doi.org/10.1016/j.fuel.2020.119147

Mahidin, M., Mulana, F., Reza, A. A., Dhedia, M. F., Annisak, A., Halimatussakdiah, H., & Hadi, A. (2023). Recent status and research & development in the carbon capture, utilization and storage technology. *Journal of Applied Technology*, 10(1). https://jurnal.usk.ac.id/JAT/issue/view/2200/showToc

Marbun, B. T. H., Sinaga, S. Z., Purbantanu, B., Santoso, D., Kadir, W. G. A., Sule, R., ... & Andhika, B. (2023). Lesson learned from the assessment of planned converted CO_2 injection well integrity in Indonesia–CCUS project. *Heliyon*, 9(8), e18273. https://doi.org/10.1016/j.heliyon.2023.e18505

Meylani, V., Busaeri, N., Radjasa, O. K., Hiron, N., & Mutiara, F. (2025). Comprehensive review of carbon capture technologies for climate change mitigation. *Indonesian Journal of Energy*, 8(1), 62–74 https://doi.org/10.33116/ije.v8i1.211

McLaughlin, H., Littlefield, A. A., Menefee, M., Kinzer, A., Hull, T., Sovacool, B. K., ... & Griffiths, S. (2023). Carbon capture utilization and storage in review: Sociotechnical implications for a carbon reliant world. *Renewable and Sustainable Energy Reviews*, 177, 113215. https://doi.org/10.1016/j.rser.2023.113215

Mores, P., Scenna, N., & Mussati, S. (2012). CO_2 capture using monoethanolamine (MEA) aqueous solution: Modeling and optimization of the solvent regeneration and CO_2 desorption process. *Energy*, 45(1), 1042–1058. https://doi.org/10.1016/j.energy.2012.06.038

Neeraj, & Yadav, S. (2020). Carbon storage by mineral carbonation and industrial applications of CO_2. *Materials Science for Energy Technologies*, 3, 494–500. https://doi.org/10.1016/j.mset.2020.03.005

Nyamiati, R. D., Nurkhamidah, S., Nanda, D. E., Timotius, D., Mahreni, M., Handayani, D. P., ... Krisnabudhi, A. (2023). Current research on the development of carbon separation and capture with polymeric membrane: A state of the art review. *Eksergi*, 20(2), 58–63. https://doi.org/10.31315/e.v20i2.9096

Oqbi, M., Véchot, L., & Al-Mohannadi, D. M. (2025). Safety-driven design of carbon capture utilization and storage (CCUS) supply chains: A multi-objective optimization approach. *Computers & Chemical Engineering*, 192, 108863. https://doi.org/10.1016/j.compchemeng.2024.108863

Orr Jr., F. M. (2018). Carbon capture, utilization, and storage: An update. *SPE Journal*, 23(6), 2444–2455. https://doi.org/10.2118/194190-PA

Osman, A. I., Hefny, M., Abdel Maksoud, M. I. A., Elgarahy, A. M., & Rooney, D. W. (2021). Recent advances in carbon capture storage and utilisation technologies: A review. *Environmental Chemistry Letters*, 19, 797–849. https://doi.org/10.1007/s10311-020-01133-3

Pal, M., Karaliūtė, V., & Malik, S. (2023). Exploring the potential of carbon capture, utilization, and storage in Baltic Sea region countries: A review of CCUS patents from 2000 to 2022. *Processes*, 11(2), 605. https://doi.org/10.3390/pr11020605

Peraturan Menteri Energi dan Sumber Daya Mineral Republik Indonesia Nomor 16 Tahun 2022 tentang Tata Cara Penyelenggaraan Nilai Ekonomi Karbon Subsektor Pembangkit Tenaga Listrik. (2022, 27 Desember). Berita Negara Republik Indonesia Tahun 2022 Nomor 1327. https://peraturan.bpk.go.id/Details/257394/permen-esdm-no-16-tahun-2022

Pires da Mata Costa, L., Micheline Vaz de Miranda, D., Couto de Oliveira, A. C., Falcon, L., Stella Silva Pimenta, M., Guilherme Bessa, I., ... & Pinto, J. C. (2021). Capture and reuse of carbon dioxide (CO_2) for a plastics circular economy: A review. *Processes*, 9(5), 759. https://doi.org/10.3390/pr9050759

Prajapati, M., Thesia, D., Thesia, V., Rakholia, R., Tailor, J., Patel, A., ... & Shah, M. (2024). Carbon capture, utilization, and storage (CCUS): A critical review towards carbon neutrality in India. *Case Studies in Chemical and Environmental Engineering*, 100770. https://doi.org/10.1016/j.cscee.2024.100770

Rahmah, W., Kadja, G. T. M., Mahyuddin, M. H., Saputro, A. G., Dipojono, H. K., & Wenten, I. G. (2022). Small-pore zeolite and zeotype membranes for CO_2 capture and sequestration – A review. *Journal of Environmental Chemical Engineering*, 10(6), 108707. https://doi.org/10.1016/j.jece.2022.108707

Ramezani, R., Di Felice, L., & Gallucci, F. (2022). A review on hollow fiber membrane contactors for carbon capture: Recent advances and future challenges. *Processes*, 10(6), 1152. https://doi.org/10.3390/pr10102103

Rehman, E., & Rehman, S. (2022). Modeling the nexus between carbon emissions, urbanization, population growth, energy consumption, and economic development in Asia: Evidence from grey relational analysis. *Energy Reports*, 8, 5430–5442. https://doi.org/10.1016/j.egyr.2022.03.179

Rui, Z., Zeng, L., & Dindoruk, B. (2025). Challenges in the large-scale deployment of CCUS. *Engineering*, 44, 17–20. https://doi.org/10.1016/j.eng.2024.11.031

Shaw, R., & Mukherjee, S. (2022). The development of carbon capture and storage (CCS) in India: A critical review. *Carbon Capture Science & Technology*, 2, 100036. https://doi.org/10.1016/j.ccst.2022.100036

She, J., Wang, H., & Li, D. (2025, June). Review of carbon capture, utilization, and storage skills status: Future of the decarbonization. In 2025 2nd International Conference on Applied Economics, Management Science and Social Development (AEMSS 2025) (pp. 73–83). Atlantis Press. https://doi.org/10.2991/978-94-6463-752-6_8

Shen, M., Kong, F., Tong, L., Luo, Y., Yin, S., Liu, C., ... & Ding, Y. (2022). Carbon capture and storage (CCS): Development path based on carbon neutrality and economic policy. *Carbon Neutrality*, 1(1), 37. https://doi.org/10.1007/s43979-022-00039-z

Shiyi, Y. U. A. N., Desheng, M. A., Junshi, L. I., Tiyao, Z. H. O. U., Zemin, J. I., & Haishui, H. A. N. (2022). Progress and prospects of carbon dioxide capture, EOR-utilization and storage industrialization. *Petroleum Exploration and Development*, 49(4), 955–962. https://doi.org/10.1016/S1876-3804(22)60324-0

Song, C., Zhao, Z., & Liu, Z. (2025). Evaluation of regional and temporal dynamics in CCUS-hydrogen development policy pathways: A data-driven framework. *Renewable Energy*, 239, 122083. https://doi.org/10.1016/j.renene.2024.122083

Sovacool, B. K., Del Rio, D. F., Herman, K., Iskandarova, M., Uratani, J. M., & Griffiths, S. (2024). Reconfiguring European industry for net-zero: A qualitative review of hydrogen and carbon capture utilization and storage benefits and implementation challenges. *Energy & Environmental Science*. https://doi.org/10.1039/D3EE03270A

Sussatrio, H., Hadiyanto, H. & Widayat, W. (2024). Optimization Of MDEA and MEA Composition as Absorbent for CO2 Removal Process in Gas Production at Field A. *Eksergi*, 21(1), 60–64. https://doi.org/10.31315/e.v21i1

Tibalia, E. M. S. E., Hemawatia, F., Kristiana, B. V., Budianto, G. P. I. (2021). Modifikasi Zeolit Alam menjadi ZSM-5 sebagai Penjerap CO_2. *Eksergi*, 18(2), 60–64. https://doi.org/10.31315/e.v18i2.4725

Truong, T. H., Lin, B. W., Lo, C. H., Tung, C. P., & Chao, C. W. (2024). Possible pathways for low carbon transitions: Investigating the efforts of oil companies in CCUS technologies. *Energy Strategy Reviews*, 54, 101421. https://doi.org/10.1016/j.esr.2024.101421

Undang-Undang Republik Indonesia Nomor 16 Tahun 2016. (2016). Pengesahan Persetujuan Paris atas Konvensi Kerangka Kerja Perserikatan Bangsa-Bangsa mengenai Perubahan Iklim. https://peraturan.bpk.go.id

Vaz Jr., S., de Souza, A. P. R., & Baeta, B. E. L. (2022). Technologies for carbon dioxide capture: A review applied to energy sectors. *Cleaner Engineering and Technology*, 8, 100456. https://doi.org/10.1016/j.clet.2022.100456

Xie, W. H., Li, H., Yang, M., He, L. N., & Li, H. R. (2022). CO_2 capture and utilization with solid waste. *Green Chemical Engineering*, 3(3), 199–209.https://doi.org/10.1016/j.gce.2022.01.002

Yamliha, A., Argo, B. D., & Nugroho, W. A. 2013. Pengaruh Ukuran Zeolite terhadap Penyerapan Karbondioksida (CO2) pada Aliran Biogas. *Jurnal Bioproses Komoditas Tropis*, 1(2). 110

Zhang, K., Lau, H. C., & Chen, Z. (2022). Regional carbon capture and storage opportunities in Alberta, Canada. *Fuel*, 322, 124224. https://doi.org/10.1016/j.fuel.2022.124224

Zhao, Y. (2025). CCUS: A Panacea or a Placebo in the fight against climate change? *Green Energy & Environment*, 10, 239–243. https://doi.org/10.1016/j.gee.2024.10.001.