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The Structural Factors in Advancing CCS/CCUS Technology in Indonesia: A Comprehensive Analysis

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ABSTRACT - Indonesia is currently committed to the global initiative aimed at reducing greenhouse gas emissions, with a target of achieving Net Zero Emissions (NZE) by 2060. The reduction is being pursued through the application of CCS and CCUS technologies. In CCUS, CO_2 is utilized to enhance oil and gas production through Enhanced Oil Recovery (EOR) or Enhanced Gas Recovery (EGR) methods. In contrast, in CCS, CO_2 is captured, transported, and securely stored in geological formations. At the same time, a consistent and affordable energy supply is required to support the achievement of NZE while maintaining economic growth. Ambitious oil and gas production targets are being set by the government to safeguard economic stability. Therefore, CCS/CCUS technologies are considered one of the most viable technical solutions to balance environmental needs with economic conditions. However, the implementation and commercialization of CCS/CCUS in Indonesia still face significant challenges. Several structural factors influencing CCS/CCUS policy implementation are identified in this study. Through structural modeling, CCS/CCUS variables with significant driving power and dependency power are being identified. The final modeling results show that the availability of storage capacity information and technological readiness primarily determine the acceleration of CCS/CCUS implementation. Based on these findings, it is recommended that appropriate policies using a risk-managed approach be adopted by the Indonesian government in the development of CCS/CCUS.

Keywords: carbon, capture, utilization, storage, Indonesia.

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INTRODUCTION

Global warming driven by Greenhouse Gases (GHG) emissions is a critical issue with potentially severe impacts on human society. Thus, both governmental and private sectors must prioritize global GHG emission management through international collaboration. Although the Covid-19 pandemic slowed global economic growth, efforts to reduce GHG emission have continued. Carbon dioxide (CO_2) accounts for approximately 75% of global GHG emissions (IEA 2023), making its management essential. Strategies to reduce CO_2 emissions include Carbon Capture and Storage (CCS) and Carbon Capture, Utilization, and Storage (CCUS), value-chain technologies that separate, transport, and store CO_2 in geological formations such as saline aquifers, depleted oil and gas reservoirs, and coal bed methane seams.

Since oil remains a critical component of global energy supply, oil and gas producers have utilized CO_2 for Enhanced Oil Recovery (EOR) (Wowor et al. 2017). Consequently, the adoption of CCS/CCUS in both developed and developing countries can simultaneously help reduce GHG emissions and meet global energy demands. However, due to the long lead times and high cost associated with CCS/CCUS implementation, immediate policy support from both corporate and governmental sectors is crucial for commercialization. CCS/CCUS can also be integrated with other technologies, such as hydrogen production, bioenergy, and Direct Air Capture, particularly in sectors like cement and fertilizer manufacturing to further reduce CO_2emissions.

Indonesia, a tropical archipelago of over 17,000 islands, is especially vulnerable to climate change due to its vast land area and abundant natural resources. Indonesia is a big CO_2 emitter, contributing 2% of global emissions. Economic growth and continued reliance on fossil fuels are expected to increase future emissions. In 2024, economy in Indonesia grew 5,03% with a government target of 7% long-term growth. The country has committed to reducing GHG emission by 31.89% from business-as-usual levels by 2030 and achieving Net Zero Emissions (NZE) by 2060 or earlier (Yusgiantoro & Prabowo, 2022). Indonesia's energy mix remains heavily dependent on fossil fuels. In 2023, the total primary energy supply reached 1,843 Million Barrel of Oil Equivalent (MBOE), with nearly 90% coming from coal, natural gas, and oil products. Coal is dominant source (736 MBOE), with 57% used for electricity generation (General et al. 2024).

By 2030, Indonesia aims to increase oil production to 1 million barrels per day (bopd) and natural gas output to 12 billion standard cubic feet per day (bscfd), up from 580 thousand bopd and 5.5 bscfd in 2024. This growth goal underscores the need for strategies that enable sustainable economic development while reducing GHG emissions. According to (Sugihardjo 2022), the application of CCUS technologies in Indonesia, especially CO_2-EOR, presents a significant opportunity for both mitigating greenhouse gas emissions and enhancing oil recovery. Indonesia's aging oil fields and abundant CO_2 sources make it a prime candidate for the integration of CCUS, which can simultaneously reduce emissions and improve oil production efficiency. CCS captures, transports, and safely stores CO_2 in geological formations, whereas CCUS can also enhance recovery through EOR or Enhanced Gas Recovery (EGR) (Kristanto et al. 2023). Sunaryo et al. (2023) state that CCS/CCUS technology can use CO_2 to increase oil and gas production through EOR or EGR techniques, in line with that CCS is able to absorb, transport, and store CO_2 safely in geological formations. CCUS technologies, particularly CO_2 injection into geological storage, offer an effective solution for reducing CO_2 emissions (Aziz et al., 2024). Indonesia requires reliable, cheap energy to reach NZE and thrive economically. The Indonesian government has ambitious oil and gas production targets to strengthen the economy, making CCS/CCUS the best technical solution to reconcile environmental and economic aims. The Global CCS Institute (2024) believes Indonesia's extensive oil and gas resources are able to store 13,000 million tons of CO_2, 16% of Euro-Asia's total CO_2 storage. Indonesia ranked first in the 2021 Global CCS Institute Readiness Index for CCS/CCUS technology readiness. Several ASEAN countries are closely monitoring Indonesia's progress (Simanjuntak & Yusgiantoro 2022), as early adoption could provide the country with a significant first-mover advantage in storage and application. Leveraging its long history upstream oil and gas development, Indonesia is well-positioned to lead the CSS/CCUS sector in the region.

Despite these strengths, a notable gap exists in research on the development and application of CCS/CCUS in Indonesia, particularly regarding the integration of structural models. This gap presents a critical avenue for further investigation, as incorporating structural models into the CCS/CCUS framework could optimize deployment strategies and enhance the technology's effectiveness. Addressing this research need would enrich the academic discourse on CCS/CCUS and support evidence-based policy-making. Such advancement would help Indonesia achieve a sustainable, low-carbon economy while safeguarding its energy security and fostering long-term economic growth.

Predicting the future needs, Indonesia requires CCS/CCUS technology to achieve its climate goals. With sufficient government support, the country could become a leader in emission-reduction technology. Highlights the use of CCS/CCUS for power plants and hard-to-abate industries. The government has already invested in technology and initiated projects with international partners (Best et al. 2011; Syahrial et al. 2022).

However, the development of CCS in Indonesian faces several challenges. As a developing nation, Indonesia requires significant investment in technology. Concerns also remain about the safety of sub-terranean CO2 storage. Despite these obstacles, CCS has the potential to reduce emissions in Indonesia and help the country meet its climate targets, provided there is continued investment and project advancement (Kristanto & Yusgiantoro 2023). While CCS/CCUS could significantly reduce Indonesia's emissions, and the government has expressed support for technology, large-scale implementation has yet to begin. Technical, financial, and regulatory difficulties must be addressed before full-scale CCS/CCUS deployment can occur.

Indonesian CCS/CCUS programs remain uncommercialized despite substantial research and pilot project. Multi barriers hinder widespread adoption and technology success in Indonesia will depend on various factors, even under government oversight. This study aims to identify key factors for establishing technical and comprehensive deployment standards in Indonesia. It provides an in-depth analysis to support the strategic use of CCS/CCUS in achieving Indonesia's short- and long-term environmental, energy, and economic objectives. Our model identifies crucial features or key drivers, and it is expected that the findings to guide the creation of CCS/CCUS policies and regulations in Indonesia.

METHODOLOGY

Theory

Deployment Plan of CCS/CCUS

Research on CCS/CCUS technology has been undertaken from both technical and economic perspectives (Tcvetkov, 2021). Given that CCS/CCUS is capital- and technology-intensive, the regulatory framework must align with the technological and economic requirements to enable private sector participation to implement the technology. Recent scholarly works have highlighted advanced studies on macro policy (Scott et al., 2013). The limited adoption of CCS technology is attributable more to political, economic, and societal considerations than to technological shortcomings. Furthermore, it has been argued that CCS/CCUS technology is presently competitive with emerging and renewable technologies (Prabowo & Sihaloho, 2024; Rafiq et al., 2021). Despite this competitiveness, the implementation of CCS/CCUS technology is now competitive with emerging and reviewable technologies for CO2 reduction, generally proceeds through three main stages: the activation phase, the expansion phase and large-scale deployment.

Interpretive Structural Modeling (ISM) is a robust methodology for analyzing complex relationships among factors in various fields, including CCS and CCUS. ISM facilitates structuring and understanding the interdependencies among these factors, which is crucial for strategic planning and decision-making in CCS and CCUS projects (Hsu & Liu 2018). This method involves constructing a visual model that represents the hierarchical relationships among factors, enabling the identification of key drivers and dependencies. The application of ISM in CCS and CCUS can reveal critical factors influencing the success of these technologies and assist in formulating effective implementation strategies (Zhao et al. 2019).

Several studies have examined CCS/CCUS in Indonesia. Adisaputro & Saputra (2017) discuss the implementation in Indonesian energy sector. The multi-region CCS method was developed with South Sumatra and East Java as boundary regions, incorporating five sources and six sinks (Putra et al. 2018). An enhanced approach for CCS target and network design based on pinch analysis has also been proposed (Mualim et al., 2021; Putra et al. 2018). Sutrisno et al. (2021) focus on estimating potential CO_2 emissions from biomass power plants utilizing gasification, firing or co-firing technologies, and recommend suitable carbon capture technologies based on the characteristics of biomass power plants in Indonesia.

Structural models have been employed to analyze CCS implementation by employing ISM to examine the role of stakeholder concerns in effectively deploying CCS in developing Asian Countries (M. Abdullah et al. 2021; Sandbhor & Botre 2014). These studies identify key factors that accelerate CCS technology adoption in certain Asian nations, highlighting the importance of the social dimension in assessing necessary components for advancing CCS projects. Public acceptance emerges as a crucial factor in successful CCS implementation.

METHODOLOGY

ISM is an effective instrument for analyzing intricate systems by elucidating the interconnections among system variables. It is extensively utilized across several domains, including engineering, administration, and social sciences. While powerful, ISM requires experienced judgement to produce accurate and meaningful results (Kumar & Singh 2019). Numerous energy specialists have employed ISM to analyze the behavior of factors in the energy sectors, particularly in relation to government policy (Eswarlal et al. 2011)sustainable supply of clean and affordable renewable energy sources is required if development is to be sustainable, so that it does not cause any environmental problems. The purpose of this paper is to determine the key variables of renewable energy implementation for sustainable development, on which the top management should focus. In this paper, an interpretive structural modeling (ISM. A key strength of ISM lies in its graphical representation of relationship among system factors. is commonly employed to examine intricate socio-economic problems.

A key strength of the ISM is the utilization of a graphical representation to delineate the linkages among various system factors. Typically, the diagram positions dependent variables at the lower end of an axis and driving variables at the upper end, enabling the identification of primary determinants and components that depend on them. This visual approach allows for the assessment of how various components influence one another, highlighting potential points of how various components influence one another, highlighting potential points disruptions could significantly affect system performance.

Expert judgment plays critical role in ISM for several factors. Firstly, the methodology depends on subjective decisions shaped by the experts' knowledge and experience. For instance, when defining system components, experts may differ on what should be included or excluded (Wang 2015). This process may introduce bias, therefore, careful reasoning is required to ensure objective, well-founded criteria. B. Zhang et al. (2008) indicated that experts' prior experience strongly influences variable identification, underscoring the importance of their role in ensuring all relevant aspects are considered.

Secondly, ISM frequently encompasses numerous stakeholders possessing diverse perspectives and interests. Consequently, experts are required to conduct dialogues and ensure that all perspectives are acknowledged. Their role is to assist and support the decision-making process by ensuring that all stakeholders comprehend both the analysis and its implications. In a study conducted by Pla López et al. (2019), expert opinions were employed to ascertain the components of an eco-innovation system. The authors discovered that expert involvement facilitated the resolution of disputes and the formation of a consensus among stakeholders. Ultimately, expert judgment is also crucial for evaluating ISM outcomes. Once the relationships among components are established, it is necessary to involve specialists to assess the implications of these relationships. This may entail determining the most critical factors, assessing those likely to exert the greatest influence, and recommending appropriate actions to address any identified issues (Ma et al. 2019). The authors concluded that expert opinion was essential for identifying crucial components and potential risks. The analytical findings were then utilized to develop a risk management strategy for the platform (Budinis et al. 2018).

Overall, expert judgment is a vital component of ISM, as it enhances the accuracy and validity of the analysis. Experts play an essential role in defining system factors, fostering constructive discourse, and evaluating the analytical outcomes (Yusgiantoro & Prabowo 2023). Consequently, expert judgment is a key element in the application of ISM within our research.

Sample Selection

The factors or key drivers of CCS/CCUS have been identified. Based on this study and literature review, the primary factors relevant to the Indonesian context are:

Government support (A1)

The Indonesian government's support for CCS/CCUS include the policies, efforts, and funds aimed at promoting the implementation of CCS/CCUS technologies to mitigate GHG emissions (Romanak & Dixon, 2022)injection and geological storage outlined the monitoring protocols required for geological CO2 storage as an emissions reduction technology, regulations for CO2 geological storage have been developing and evolving worldwide. The California Air Resources Board Low Carbon Fuel Standard CCS Protocol (LCFS CCSP. Even though relevant government regulations already exist, it is assumed that private sectors still need further regulation to deploy CCS/CCUS. However, this study does not specify the exact type of regulations required.

Financial availability (A2)

The availability of financing for CCS/CCUS in Indonesia pertains to the accessibility of funds and financial resources necessary for the implementation and deployment of CCS/CCUS technology (Prabowo & Rozi 2023). It is assumed that the financial availability reflects the supply and demand side. The supply side represents the costs of deploying CCS/CCUS, while the demand side represents customer willingness to pay for technologies that reduce CO_2 emission.

Strategic Planning (A3)

In Indonesia, strategic planning for CCS/CCUS entails formulating and executing a comprehensive and coordinated strategy for the deployment of CCS/CCUS technologies. This includes the long term goal and roadmap to deploy CCS/CCUS (Dimabuyu, 2023)Utilisation and Sequestration (CCUS. During the process of obtaining expert survey, the National Long-Term Development Plan 2025-2050 has been recently issued. Therefore, many CCS/CCUS experts may not yet have been aware of it.

Skilled manpower (A4)

Skilled manpower for CCS/CCUS in Indonesia denotes the presence and proficiency of trained professionals, technicians, and laborers equipped with the requisite knowledge and abilities to facilitate the implementation and functioning of CCS/CCUS (Chevet et al., 2022). Indonesia has a strong base of CCS/CCUS expertise, as evidenced by studies dating back to the early 2000s.

Sustainable growth (A5)

Sustainable growth in CCS/CCUS entails advancing and applying technologies in a way that balances environmental, economic and social considerations, long-term development (Rubin et al. 2015).

Public awareness (A6)

Public awareness relates to the extent of knowledge and comprehension among the general population about CCS/CCUS, including its advantages and potential risks (Sitinjak et al. 2023). With long-term monitoring programs in place, companies deploying CCS/CCUS can allocate resources to raise public awareness, launch educational campaigns and build community trust in their projects.

Top management support (A7)

Support from top management is essential for the effective implementation of CCS/CCUS technologies, as it affects resource allocation, investment levels, and the prioritization of activities associated with the development and deployment of these technologies (Kim 2022). In Indonesia, the endorsement of top management for CCS/CCUS is crucial for the nation to attain its ambitious objectives for diminishing CO_2 emissions and alleviating climate change. With its full support, a private sector management is able to request for employee collaboration to implement CCS/CCUS.

The efficacy of procedure and implementation (A8)

Effective protocols and execution support are essential for achieving CCS/CCUS projects objectives - GHG reduction, energy security, and economic growth (Z.F. Zhang et al. 2024). Before its commercialization, a CCS/CCUS development project normally progress from desktop studies to pilot projects, then demonstration operations, and finally commercial operations. Streamlined processes reduce costs and speed development, while effective execution ensures compliance with regulations and standards, addressing any concerns or challenges swiftly. With the global race towards NZE by 2050, timely technology deployment is essential for Indonesia to capitalize on its CO2 storage potential.

Storage availability (A9)

The storage availability refers to the presence and accessibility of suitable sites and infrastructure for safe CO_2 sequestration (Li et al. 2022). The efficacy of CCS/CCUS initiatives in Indonesia relies on appropriate storage locations, which may include deep geological formations like saline aquifers or depleted oil and gas fields. However, to assure the integrity of a geological formation to safely store CO_2, comprehensive studies are required to verify storage integrity.

Technological availability (A10)

The technological availability encompasses access to equipment and systems for capturing, transporting and securely storing CO_2 While various CCS/CCUS technologies exist globally, they are at different Technology Readiness Levels (TRLs). Some remain in pilot phases (Prabowo 2024). Many experts are optimistic that the costs of CCS/CCUS technologies will decline in the future.

Stakeholder support (A11)

A CCS/CCUS project is a risk and capital intensive project. Therefore, collaboration and coordination among stakeholders are two key factor to have a successful CCS/CCUS project in Indonesia. Stakeholder support for CCS/CCUS in Indonesia denotes the degree of engagement, collaboration, and dedication from various stakeholders, including governmental bodies, industrial and commercial sectors, academic and research institutions, local communities, and civil society organizations, regarding the advancement, implementation, and management of CCS/CCUS initiatives (M.R.T.L. Abdullah et al. 2021).

Availability of data and information (A12)

The availability of data and information support for CCS/CCUS in Indonesia pertains to the accessibility, quality, and volume of data and information concerning CCS/CCUS projects (Melo et al. 2025). It encompasses data on geological formations, carbon storage capacity, sources of emissions, energy requirements, and other pertinent information essential for the planning, execution, and oversight of CCS/CCUS operations. Much of this information is already available through Indonesian government agencies.

Identify and determine respondents

According to Janes (1988), involving 8 to 15 experts in ISM research is optimal due to the exponential growth in the interaction complexity. Nevertheless, participants selection should prioritize the representativeness of perspectives, focusing on qualitative contributions rather than purely quantitative sampling. The experts were selected to encompass a diverse array of social, environmental, economic, industrial, and legal knowledge. The justification for selecting an expert is predicated on their educational qualifications, field of specialization, years of practical experience, and technological proficiency. Experts were chosen for this study based on the subsequent criteria, such as: 1). Master or PhD degree (for academia); 2). Minimum of five-year experience in CCS/CCUS studies or projects; 3). Knowledge or practical expertise in CCS technology; 4). Strong communication skills; 5). Commitment to the study duration.

Surveys were distributed tto the specialists involved in CCS/CCUS in Indonesia, including government officials, policymakers, investors, technology service providers, and academics. Twenty five respondents provided consistent and thorough replies to the questions. Using a paired comparison method, they were asked: “Do you believe that the variable (subject) ‘i’ directly influences the variable ‘j’?” Divergent responses were resolved using the “minority follows majority” principle (Gan et al. 2018). Contextual relationships among variables were than compiled into a self-interaction matrix.

Construct the structural self-interaction matrix

The subsequent steps are involved in the formulation of ISM, are: 1). Identify variables influencing system performance via literature review and expert consultation; 2). Establish a conceptual relationship among variables based on expert insights; 3). Develop the SSIM to encompass pairwise relationships; 4). Convert the SSIM into a reachability matrix by assigning ‘1’ and ‘0’ to represent pairwise relationships; 5). Apply the transitivity rule which states that if variable ‘A’ leads to variable ‘B’ and ‘B’ leads to variable ‘C,’ then ‘A’ also leads to variable ‘C’; 6). Partition the reachability matrix into various partition levels; 7). Create a directed graph (digraph) showing variable relationships without transitive links; 8). Convert the digraph into ISM model by representing variables as propositions; 9). Evaluate and refine the ISM model as needed.

The research was carried out over a year and included numerous meetings with CCS/CCUS experts in Indonesia. Given that CCS/CCUS initiatives in Indonesia are in their nascent phase, the ISM approach is suitable for conducting research to achieve the study objectives. Ensuring the high-quality result is crucial, and enhancements may be necessary to achieve precise outcomes.

The structural analysis was performed using the ISM approach with the assistance of EXSIMPRO Software, a licensed proprietary tool specifically designed for ISM analysis. To enhance the modelling process, SmartISM (an open-source too for pairwise comparisons and SSIM formulation) was integrated. Furthermore, Miro, an online collaborative whiteboard platform, was utilized to visualize the final reachability graph and hierarchical structure. The use of Miro ensured more interactive and comprehensive graphical representations, aiding interpretation and discussion.

RESULT AND DISCUSSION

The following results were obtained the study data and surveys. The SSIM represents the initial phase in compiling the data collected from the questionnaire. The column and rows in the matrix denote the variables that may affect the implementation of CCS/CCUS in Indonesia. Subsequently, the normalization process was carried out through multiple steps, as shown in Table 1 and Table 2, respectively.

Table 1 represents a SSIM, which is a key tool for analyzing the relationships between various factors based on survey data. In this matrix, each factor (represented in rows and columns) is assessed for its interaction with other factors. The values "X" and "A" indicate the type of interaction, while "NA" signifies the absence of a relationship. The matrix provides a clear overview of the interdependencies between factors, which can be further analyzed to understand the structure and dynamics within the system. The SSIM plays a crucial role in identifying patterns and connections for decision-making and model development.

Table 2 is a final reachability matrix, also known as a conical matrix, employed in ISM. This matrix delineates the linkages and reachability among various factors (A1 to A12) inside a system. The binary numbers (1 or 0) signify the influence of one factor on another. The "Driver Power" column measures the effect of each factor, while the "Rank" and "Hierarchy" columns present a ranking and hierarchy of the factors, respectively. This matrix is vital for comprehending the structural dependencies and hierarchy in the system for subsequent analysis and decision-making.

Figure 1 shows a hierarchical system in which the lower levels denote higher-priority objectives for Indonesia's deployment of CCS/CCUS. As we progress through the levels, the emphasis transitions to actions and processes vital for attaining the overarching objective. These tasks are generally fundamental and must be prioritized to establish a robust basis for later actions. The focus on foundational aspects, such as "Analysis of Storage" and "Availability of Test Technology," underscores areas need prompt intervention to facilitate sustained success. This priority guarantees the prompt resolution of essential issues, facilitating a more effective execution of plans at elevated levels.

Meanwhile, Figure 2 is a scatter plot depicting the correlation between "Driving Power" and "Dependency Power" for various factors within a system. The plot is divided into four quadrants: Linkage Quadrant, Autonomous Quadrant, Dependent Quadrant, and Critical Quadrant. Factors situated in the Critical Quadrant possess substantial driving and dependence force, signifying their centrality to the system and the necessity for focused attention.

Table 1. Structural self-interaction matrix

	[, 1]	[, 2]	[, 3]	[, 4]	[, 5]	[, 6]	[, 7]	[, 8]	[, 9]	[, 10]	[, 11]	[, 12]
[1,]	NA	"X"	"X"	"X"	"V"	"V"	"X"	"X"	"A"	"A"	"X"	"V"
[2,]	NA	NA	"V"	"X"	"X"	"V"	"X"	"X"	"A"	"X"	"A"	"V"
[3,]	NA	NA	NA	"V"	"V"	"V"	"X"	"X"	"A"	"X"	"X"	"X"
[4,]	NA	NA	NA	NA	"V"	"A"	"X"	"X"	"A"	"A"	"A"	"A"
[5,]	NA	NA	NA	NA	NA	"A"	"A"	"A"	"A"	"A"	"X"	"A"
[6,]	NA	NA	NA	NA	NA	"V"	"A"	"A"	"A"	"A"	"X"	"A"
[7,]	NA	NA	NA	NA	NA	NA	NA	"A"	"A"	"A"	"A"	"A"
[8,]	NA	NA	NA	NA	NA	NA	NA	NA	"A"	"X"	"X"	"A"
[9,]	NA	NA	NA	NA	NA	NA	NA	NA	NA	"A"	"A"	"X"
[10,]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	"V"	"X"
[11,]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	"X"
[12,]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

The Autonomous Quadrant contains factors with strong driving power but low dependency, while the Dependent Quadrant includes factors with significant dependency but limited driving power, indicating their susceptibility to external influences. This analysis facilitates the prioritization of strategic actions according to the influence and dependence of each component.

Table 2. Final reachability matrix (Conical matrix)

	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	Driver Power	Rank	Dependence	Hierarchy
A1	1	1	1	1	1	1	1	1	1	1	1	1	11	2	9	4
A2	1	1	1	1	1	1	1	1	1	1	1	1	11	2	9	4
A3	1	0	1	1	1	1	1	1	1	1	1	1	10	3	9	4
A4	1	1	0	1	1	0	1	1	1	1	1	0	8	4	11	2
A5	0	1	0	0	1	0	0	0	0	0	1	1	4	7	12	1
A6	0	0	0	1	1	1	0	0	0	0	1	1	5	6	10	3
A7	1	1	1	1	1	1	1	0	0	0	0	0	7	5	10	3
A8	1	1	1	1	1	1	1	1	0	1	1	1	11	2	9	4
A9	1	1	1	1	1	1	1	1	1	0	0	1	10	3	4	6
A10	1	1	1	1	1	1	1	1	1	1	1	1	12	1	7	5
A11	1	1	1	1	1	1	1	1	1	0	1	1	11	2	10	3
A12	0	0	1	1	1	1	1	1	1	1	1	1	10	3	10	3

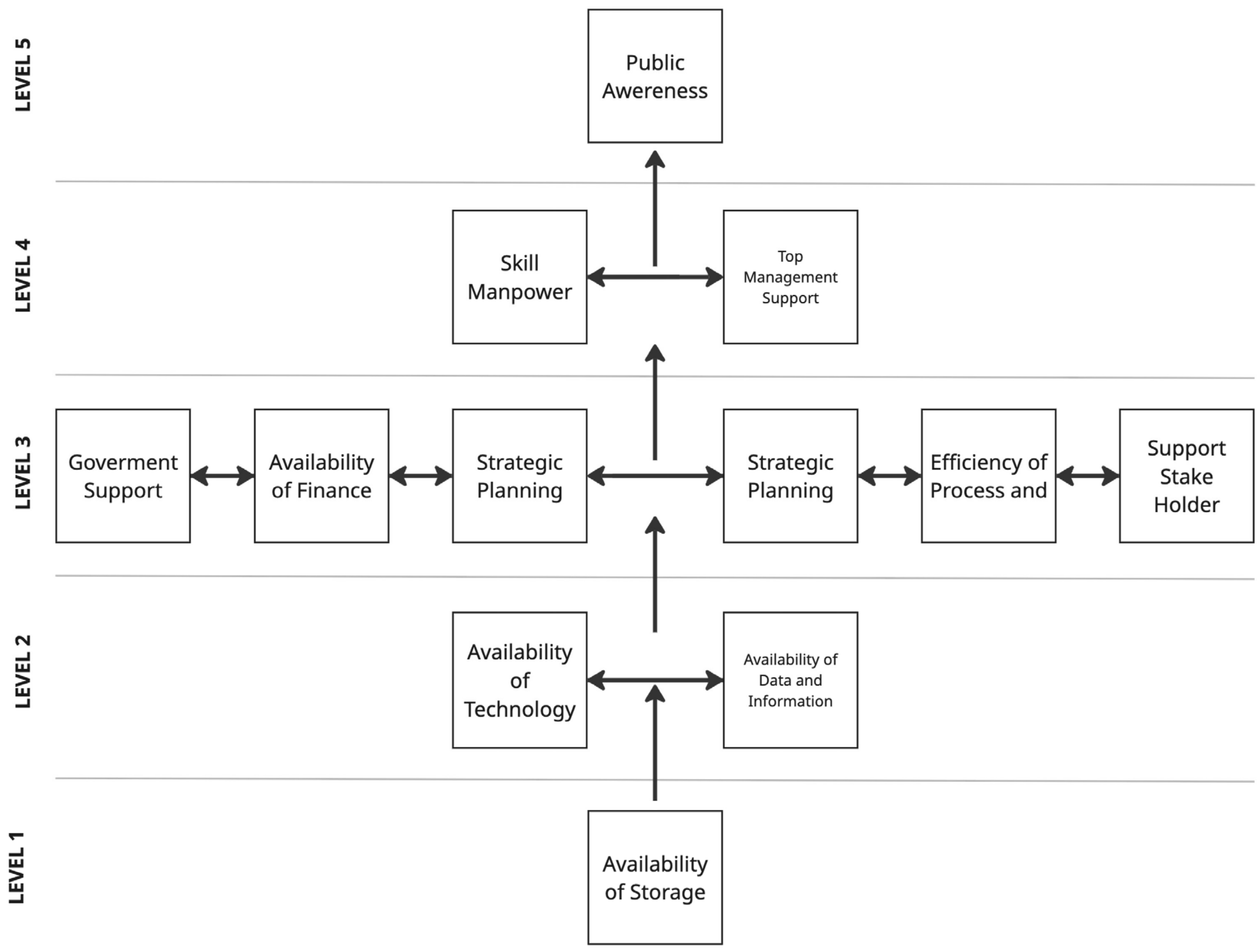

Figure 1. ISM level model scheme

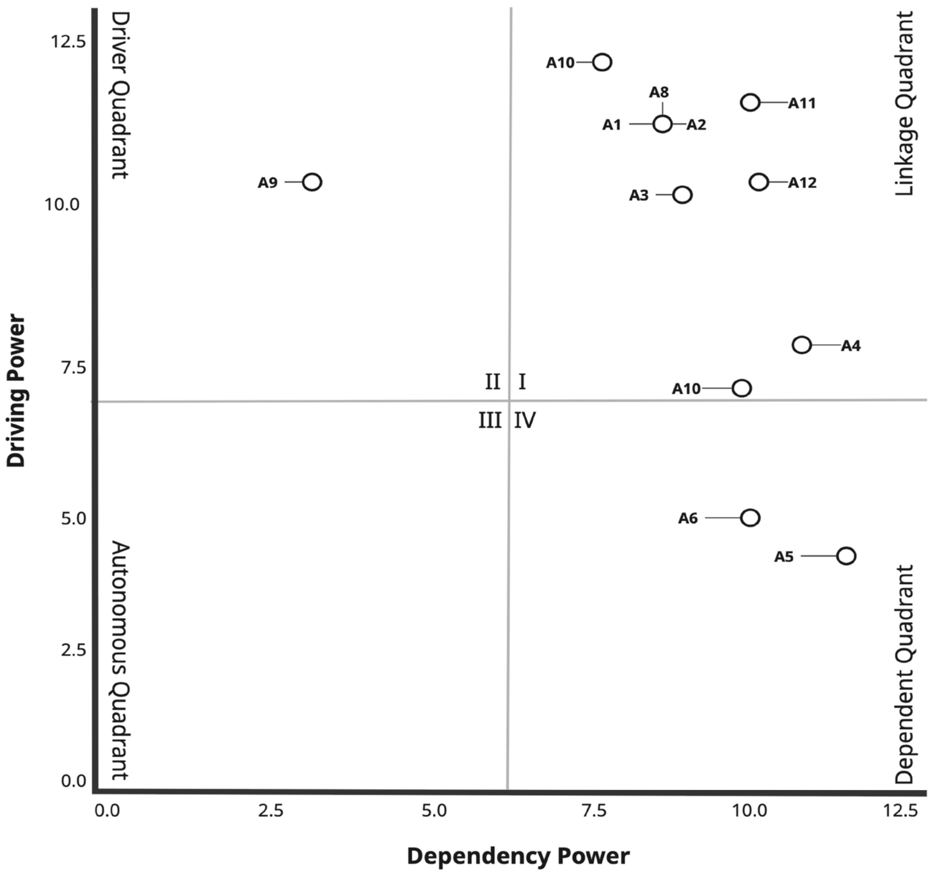

Figure 2. Direct influence map

Table 3. Classification of variables in CCS/CCUS deployment (2025)

No	Cluster	Characteristics	Key Factor
1	Driver Variable (II)	Important factors which need to be considered prior to other factors	9
2	Linkage Variable (I)	Factor which serves as a link between independent and dependent variables	1, 2, 3, 4, 7, 8, 10, 11, 12
3	Autonomous Variable (III)	Important Factors, but somewhat detached from other factors	None
4	Dependent Variable (IV)	Factors which serve to further develop CCS/CCUS management practices	5, 6

Table 3 is a categorizes factors into four categories according to their characteristics and key influences. The Driver Variable (II) includes important factors that must be considered before other factors in the system. These variables have a significant impact and are prioritized in decision-making. The Linkage Variable (I) serves as a connection between independent and dependent variables, highlighting factors that link different factors of the system. The Autonomous Variable (III) refers to factors that are somewhat detached from other variables, operating independently within the system without direct links to others. Finally, the Dependent Variable (IV) consists of factors that further develop the system, particularly in relation to CCS/CCUS management practices, indicating their crucial role in advancing the process.

CONCLUSION

This research delineates numerous critical factors influencing CCS/CCUS implementation in Indonesia and elucidates their interconnections through the ISM approach. The resultant model delineates a distinct hierarchy of measures that policymakers must undertake to improve the efficacy of the CCS/CCUS system in Indonesia.

Key variables like storage and technology availability, strategic planning, financial resources, government support, and stakeholder assistance, respectively, are recognized as essential for prompt consideration by policymakers.

The significance of these factors is dictated by the extent of their influence on policy and regulatory frameworks. The primary priority tier underscores the significance of Storage and Technology Availability for the effective implementation of CCS/CCUS. Given this, it is imperative that the Indonesian government ensure the availability of accurate and reliable storage information.

The suitability of a storage site depends on geological conditions, reservoir depth, rock structure, and sealing integrity factors crucial for the safe and efficient sequestration of CO_2. Proximity to CO_2 sources also reduces transportation costs and energy consumption. Typically, a CCS/CCUS storage assessment begins with identifying potential areas through national or regional evaluations and basin availability studies. This involves analyzing the regional setting, reservoir facies, reservoir characterization, and the integrity of seals and traps. Subsequently, the development of structural and stratigraphic models is necessary to refine potential site selection. To increase investment attractiveness and reduce risks, it is recommended that the government take the lead in conducting these models.

Once potential areas are identified, subsequent steps include screening CO_2 sinks, planning wells and infrastructure, estimating the costs, preparing management plans, and conducting the economic analysis. However, the effectiveness of CCS in reducing carbon emissions is significantly constrained by insufficient storage capacity. Consequently, establishing adequate storage facilities alongside investment in related infrastructure is crucial.

Similarly, the Availability of Suitable Technology is essential for CCS/CCUS adoption in Indonesia. The success of CCS depends on access to specified capture, transport, and storage technologies. As CCS/CCUS operates a value-chain business model, the ability to capture CO_2 to from multiple point sources is essential. Without these technological capabilities, the potential of CCS to mitigate emissions is severely compromised. Technological advancements must therefore align with the development and integration of these specialized systems.

Ultimately, the study highlights the importance of stakeholder engagement, emphasizing the need for investment and regulatory clarity. While public awareness of CCS may be higher in some other countries, the findings suggest that Indonesia should prioritize strong regulatory support and the provision of essential sources to ensure efficient and large-scale of CCS/CCUS implementation.

In order the regulation framework on CCS/CCUS, the Testing Center for Oil and Gas (LEMIGAS) as an agency under Indonesia's Ministry of Energy and Mineral Resources focusing on oil and gas research and laboratory certification reported in 2024 that the country's subsurface potential comprises 4.85 gigatons of CO_2 storage in hydrocarbon reservoirs and an addition 572.77 gigatons in saline aquifers. This assessment was based on subsurface data gathered from 20 active sedimentary basins in Indonesia. To attract potential CCS/CCUS investors, Lemigas is conducting further detailed studies.

Meanwhile, the Indonesian government has significantly improved the regulatory framework for CCS and CCUS technologies. A Presidential rule was passed in 2024, establishing a thorough legislative foundation to support CCS/CCUS implementation, following the issuance of a Ministerial Regulation by the Minister of Energy and Mineral Resources in 2023.

Applying interpretive structural modeling (ISM) to identify key variables with significant driving and dependence powers, this study examines these structural determinants. The analytical findings show that the availability of storage capacity and technological readiness are critical enablers for accelerating CCS/CCUS deployment. Accordingly, this study recommends that the Indonesian government formulate targeted policies that address these strategic factors, adopting a risk-managed approach. Strengthening governance and institutional support in these areas is essential to ensure the sustainable and scalable integration of CCS/CCUS into the national climate and energy agenda.

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GLOSSARY OF TERMS

Symbol	Definition	Unit
CCS	Carbon capture storage	
CCUS	Carbon capture utilization storage	
CO_2	Carbon dioxide	
EOR	Enhanced oil recovery	
EGR	Enhanced gas recovery	
GHG	Greenhouse gas	
ISM	Interpretive structural modeling	
NZE	Net zero emissions	
SSIM	Structural self-interaction matrix	
TRL	Technology readiness level	
MBOE	Million barrel of oil equivalent	MBOE
bscfd	Billion standard cubic feet per day	bscfd

REFERENCES

Abdullah, M.R.T.L., Siraj, S., & Ghazali, Z., 2021, An ism approach for managing critical stakeholder issues regarding carbon capture and storage (Ccs) deployment in developing asian countries. Sustainability (Switzerland), 13(12). https://doi.org/10.3390/su13126618.

Adisaputro, D., & Saputra, B., 2017, Carbon Capture and Storage and Carbon Capture and Utilization: What Do They Offer to Indonesia? Frontiers in Energy Research, 5. https://doi.org/10.3389/fenrg.2017.00006.

Aziz, P. A., Nurhandoko, B.E.B., Marhaendrajana, T., Siagian, U. W. R., & Ariadji, T., 2024, The Effect of CO2-Brine-Rock Interaction Towards Sand Onset Modeling in Dolomite-Rich Sandstone: A Case Study in Air Benakat Formation, South Sumatera, Indonesia. Scientific Contributions Oil and Gas, 47(3), 341–360. https://doi.org/10.29017/SCOG.47.3.1649.

Best, D., Mulyana, R., Jacobs, B., Iskandar, U. P., & Beck, B., 2011, Status of CCS development in Indonesia. Energy Procedia, 4(2011), 6152–6156. https://doi.org/10.1016/j.egypro.2011.02.624.

Budinis, S., Krevor, S., Dowell, N. Mac, Brandon, N., & Hawkes, A., 2018, An assessment of CCS costs, barriers and potential. Energy Strategy Reviews, 22(May), 61–81. https://doi.org/10.1016/j.esr.2018.08.003.

Chevet, P.-F., Kalaydjian, F., & Maisonnier, G., 2022, L'état de l'art du CCS et du CCUS : description, coût et contraintes. Annales Des Mines - Responsabilité et Environnement, N° 105(1), 15–20. https://doi.org/10.3917/re1.105.0015.

Dimabuyu, A., 2023, Upscaling CCUS in Asia Pacific – a look at upstream synergy projects and potential for multi-user hubs. The APPEA Journal, 63(2), S371–S374. https://doi.org/10.1071/aj22164.

Eswarlal, V. K., Kumar Dey, P., & Shankar, R., 2011, Enhanced Renewable Energy Adoption for Sustainable Development in India: Interpretive Structural Modeling Approach. Proceedings of the World Renewable Energy Congress – Sweden, 8–13 May, 2011, Linköping, Sweden, 57(November), 351–358. https://doi.org/10.3384/ecp11057351.

Gan, X., Chang, R., Zuo, J., Wen, T., & Zillante, G., 2018, Barriers to the transition towards off-site construction in China: An Interpretive structural modeling approach. Journal of Cleaner Production, 197, 8–18. https://doi.org/10.1016/j.jclepro.2018.06.184.

General, S., National, T.H.E., & Council, E., 2024, Indonesia Energy Outlook 2024.

Global CCS Institute. (2024). Collaborating for a Net-Zero Future.

Hsu, W.-L., & Liu, H.-L., 2018, Using Interpretive Structural Modeling to Analyse the Key Factors in Small-Scale Construction Project Management in Taiwan. 2018 IEEE International Conference on Advanced Manufacturing (ICAM), 346–349. https://doi.org/10.1109/AMCON.2018.8614800.

IEA, 2023, CO_2 Emission in 2022. In Encyclopedia of Sustainable Management (pp. 600–600). Springer International Publishing. https://doi.org/10.1007/978-3-031-25984-5_300288.

Janes, F.R., 1988, Interpretive structural modelling: a methodology for structuring complex issues. Transactions of the Institute of Measurement and Control, 10(3), 145–154. https://doi.org/10.1177/014233128801000306.

Kim, D.-R., 2022, A Study on the Current Status of CCUS-Related Legislation and Improvement Plan in Korea. Law Review, 22(4), 43–66. https://doi.org/10.57057/lawreview.2022.12.22.4.43.

Kristanto, D., Abdassah, D., Siregar, S., & Yusgiantoro, L.A., 2023, Implementation of Reservoir Management Approach in Improving Oil Recovery Processes. Journal of East China University of Science and Technology, 66(1), 20–33.

Kristanto, D., & Yusgiantoro, L.A., 2023, Minimum Miscibility Pressure and Swelling Factor Determinations of Carbondioxide Gas Injection Application in the KHL Oil Field. February. https://doi.org/10.20944/preprints202302.0385.v1.

Kumar, A., & Singh, D.V., 2019, Overview of Interpretive Structural Modeling. International Journal of Engineering Applied Sciences and Technology, 04(05), 536–540. https://doi.org/10.33564/IJEAST.2019.v04i05.078.

Li, Y. E., Wang, X., Jiao, J., Togaibekov, A., Nian, V., Zhong, S., Hoo, P. Y., Loh, W. L., Wissam, A. K. S., Tan, X. W., Usadi, A., Jones, S., Dasari, G., Lacasse, M., & Teletzke, G., 2022, Carbon Capture and Storage Prospects in ASEAN: transport and storage feasibility and cost study for ASEAN. https://doi.org/10.31223/X56Q1W.

Ma, G., Jia, J., Ding, J., Shang, S., & Jiang, S., 2019, Interpretive Structural Model Based Factor Analysis of BIM Adoption in Chinese Construction Organizations. Sustainability, 11(7), 1982. https://doi.org/10.3390/su11071982.

Melo, C., Cardoso, D. dos S., Thomassim Guimarães, T., Felippe, L., Zielinski, J. P., Andres, F., Santos, C., Vieira Genro, L., Gomes, P., & Martins, M., 2025, GIS CCUS Brazil Platform: A New Tool to Promote Carbon Capture, Utilization, and Storage in Brazil's Territory. SSRN Electronic Journal. https://doi.org/10.2139/ssrn.5066348.

Mualim, A., Huda, H., Altway, A., Sutikno, J. P., & Handogo, R., 2021, Evaluation of multiple time carbon capture and storage network with capital-carbon trade-off. Journal of Cleaner Production, 291, 125710. https://doi.org/10.1016/j.jclepro.2020.125710.

Pla López, R., Martínez de la Rosa, F., & Parra-Luna, F. (2019). The Catalonian Conflict: an Interpretive Structural Model. Revista Internacional de Sistemas, 23(1), 6–15. https://doi.org/10.7203/RIS.23.1.13766.

Prabowo, T. B., 2024, Indonesia's Green Future: The Important Role of Carbon Capture Technology. Modern Diplomacy. https://moderndiplomacy.eu/2024/05/17/indonesias-green-future-the-important-role-of-carbon-capture-technology/.

Prabowo, T.B., & Rozi, R.F., 2023, The Study of the Impact of Carbon Finance Effect on Carbon Emissions in Indonesia. INNOSCAPE, Conference and Exhibition on Business, Applied Science and Technology 14 February 2023, Jakarta.

Prabowo, T.B., & Sihaloho, R.A., 2023, Analisis Ketergantungan Indonesia Pada Teknologi Asing Dalam Sektor Energi dan Dampaknya Pada Keamanan Nasional. Jurnal Lemhannas RI, 11(1), 72–82. https://doi.org/10.55960/jlri.v11i1.426.

Prabowo, T.B., & Sihaloho, R.A.H., 2024, Impact of the Ukraine-Russia Conflict on the Stability of Energy Geopolitics in Southeast Asia. Journal of International Studies on Energy Affairs, 5(1), 35–56. https://doi.org/10.51413/jisea.Vol5.Iss1.2024.35-56.

Putra, A.A., Juwari, & Handogo, R., 2018, Multi Region Carbon Capture and Storage Network in Indonesia Using Pinch Design Method. Process Integration and Optimization for Sustainability, 2(4), 321–341. https://doi.org/10.1007/s41660-018-0050-5.

Rafiq, M., Naz, S., Martins, J.M., Mata, M.N., Mata, P.N., & Maqbool, S., 2021, A study on emerging management practices of renewable energy companies after the outbreak of covid-19: Using an interpretive structural modeling (ISM) approach. Sustainability (Switzerland), 13(6). https://doi.org/10.3390/su13063420.

Romanak, K., & Dixon, T. (2022). CO_2 storage guidelines and the science of monitoring: Achieving project success under the California Low Carbon Fuel Standard CCS Protocol and other global regulations. International Journal of Greenhouse Gas Control, 113(November 2021), 103523. https://doi.org/10.1016/j.ijggc.2021.103523.

Rubin, E. S., Davison, J.E., & Herzog, H.J., 2015, The cost of CO_2 capture and storage. International Journal of Greenhouse Gas Control, 40, 378–400. https://doi.org/10.1016/j.ijggc.2015.05.018.

Sandbhor, S.S., & Botre, R.P., 2014, Applying total interpretive structural modeling to study factors affecting construction labour productivity. Construction Economics and Building, 14(1), 20–31. https://doi.org/10.5130/AJCEB.v14i1.3753.

Scott, V., Gilfillan, S., Markusson, N., Chalmers, H., & Haszeldine, R.S., 2013, Last chance for carbon capture and storage. In Nature Climate Change (Vol. 3, Issue 2, pp. 105–111). Nature Publishing Group UK London. https://doi.org/10.1038/nclimate1695.

Simanjuntak, J.T., & Yusgiantoro, L.A., 2022), Evidence of Environmental Kuznets Curve of ASEAN Plan of Action for Energy Cooperation. Mapping the Energy Future-Voyage in Uncharted Territory-, 43rd IAEE International Conference, July 31-August 3, 2022.

Sitinjak, C., Ebennezer, S., & Ober, J., 2023, Exploring Public Attitudes and Acceptance of CCUS Technologies in Jabodetabek: A Cross-Sectional Study. Energies, 16(10), 4026. https://doi.org/10.3390/en16104026.

Sugihardjo, S., 2022, CCUS-Aksi Mitigasi Gas Rumah Kaca dan Peningkatan Pengurasan Minyak CO_2-EOR. Lembaran Publikasi Minyak dan Gas Bumi, 56(1), 21–35. https://doi.org/10.29017/lpmgb.56.1.916.

Sunaryo, T., Radyati, M.R.N., Utha, M.A., & Minarti, A., 2023, Research development on carbon capture, utilization and storage as a climate change mitigation technology. Environmental. https://www.erem.ktu.lt/index.php/erem/article/view/32424.

Sutrisno, Z.P., Attaya Artemis Meiritza, & Raksajati, A. (2021). Understanding the Potential of Bio-Carbon Capture and Storage from Biomass Power Plant in Indonesia. Indonesian Journal of Energy, 4(1), 36–56. https://doi.org/10.33116/ije.v4i1.99.

Syahrial, E., Pasarai, U., & Iskandar, U.P., 2022, Understanding Carbon Capture And Storage (Ccs) Potential In Indonesia. Scientific Contributions Oil and Gas, 33(2), 129–134. https://doi.org/10.29017/scog.33.2.816.

Tcvetkov, P., 2021, Climate Policy Imbalance in the Energy Sector: Time to Focus on the Value of CO_2 Utilization. Energies, 14(2). https://doi.org/10.3390/en14020411.

Wang, M.-T., 2015, Using Interpretive Structural Modeling to Make Decisions for Direction of Caring Design (pp. 132–142). https://doi.org/10.1007/978-3-319-20678-3_13.

Wowor, C., Yusgiantoro, L., & Bernardus, W., 2017, Investment Management of Petroleum Fund on Exploration and EIOR Activities in Indonesia. Meeting the Energy Demands of Emerging Economies, 40th IAEE International Conference, June 18-21, 2017.

Yusgiantoro, L.A., & Prabowo, T.B., 2023, Important Factors to Deploy Carbon Capture Storage/Carbon Capture Utilization Storage (CCS/CCUS) in Indonesia by Using an Interpretive Structural Model. 47th IPA Convention and Exhibition (IPA Convex), 24-26 May 2023 at the Jakarta Convention Center (JCC). https://archives.datapages.com/data/ipa_pdf/2023/ipa23-bc-29.htm.

Yusgiantoro, L., & Prabowo, T.B., 2022, Effective Indonesia's Government Policy to Reach Net Zero Carbon in Year 2060. Mapping the Energy Future-Voyage in Uncharted Territory-, 43rd IAEE International Conference, July 31-August 3, 2022.

Zhang, B., Liu, G., Ai, N., Shi, K., & Shu, C., 2008, Analysis of ecosystem degradation factors in Yuanmou arid-hot valleys based on interpretative structural model. Wuhan University Journal of

Natural Sciences, 13(3), 279–284. https://doi.org/10.1007/s11859-008-0304-0.

Zhang, Z. F., Wang, J. Z., Zhao, Z., Shao, Y. F., Zhu, Y. Bin, Zhou, X. Q., & Yu, S. T., 2024, Research and Practice on CCUS Process Supporting Technology for Heavy Oil Bottom Water Reservoirs. Springer Series in Geomechanics and Geoengineering, 558–573. https://doi.org/10.1007/978-981-97-0268-8_43.

Zhao, Z.Y., Chen, Y.L., & Li, H., 2019, What affects the development of renewable energy power generation projects in China: ISM analysis. Renewable Energy, 131, 506–517. https://doi.org/10.1016/j.renene.2018.07.063.