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Potential Development of Unconventional Oil and Gas Resources in Indonesia: Key Challenges and Future Prospects

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Abstract

The demand for energy is increasing along with the rise in population. Indonesian people rely on conventional resources such as coal, oil, and natural gas to meet their energy needs. It is estimated that coal can only be exploited for up to 61 years, natural gas for 34 years, and oil for 19 years. Meanwhile, Indonesia possesses unconventional oil and gas resources (e.g., coal bed methane (CBM), tight gas, shale gas and oil, and methane hydrate), estimated to reach 1,800 trillion cubic feet (TCF). These resources are in the exploration stage and have yet to be fully exploited due to technological limitations. Nevertheless, the Indonesian government continues to emphasize the development of this type of energy resource. Therefore, this study conducts a review of the potential of unconventional oil and gas resources in Indonesia, covering characteristics, potential occurrences in Indonesia, exploitation methods, utilization as a source of energy, and opportunities and challenges in their application. The method used is a narrative review based on secondary data by examining papers published in reputable national and international journals in the last ten years. Results show that unconventional oil and gas resources have different characteristics, including permeability, porosity, and depth. CBM can be found at the shallowest depth, followed by tight gas, methane hydrate, and the deepest is shale gas. Potential occurrences of these resources in Indonesia include gas hydrate (858.2 TCF), then shale gas (574.07 TCF), coal-bed methane (453.3 TCF), and shale oil 11.24 million tons. Exploitation can be done in various ways, such as dewatering for CBM, hydraulic fracking for tight and shale, and depressurization for methane hydrate. Once exploited, methane gas can be used for power plants, vehicle fuel, and industrial and household needs. Opportunities and challenges from various aspects, as well as applicable laws in Indonesia, are also discussed. In this light, the contribution of our study is to provide a comprehensive review of the characteristics, location, exploitation methods, opportunities, and challenges of utilizing unconventional oil and gas resources in Indonesia.

Keywords:
coal bed methane, methane hydrate, shale gas, tight gas, unconventional oil and gas

1. Introduction

In this modern era, the demand for energy is on the rise, in tandem with the growth in population. As of mid-2023, Indonesia boasts a population of 278.69 million people, indicating a 1.05% increase compared to the previous year (year-on-year), which stood at 275.77 million people (BPS, 2023). This surge in population has propelled energy consumption in Indonesia to reach 123 million TOE annually, with an anticipated yearly increase. Notably, the sector with the highest energy consumption is transportation (44.2%), followed by the industrial sector (33.5%) and households (16.3%) (Suharyati et al., 2023). Meanwhile, projections indicate a 40.2% increase in the world's primary energy until 2040 (IEA, 2023). Despite these trends, society still relies heavily on conventional resources such as coal, oil, and natural gas to fulfill energy needs. Ongoing exploration of conventional oil and gas resources is underway, but their availability is limited. Estimates suggest that coal can only be exploited for another 61 years, natural gas for another 34 years, and oil for another 19 years (BPS, 2022). In the event of domestic resource depletion, Indonesia may resort to expensive oil and gas imports, underscoring the urgent need for energy diversification.

Unconventional oil and gas resources, including shale oil, shale gas, tight sand gas, coal bed methane (CBM), and methane hydrate, represent promising sources for future energy supply. The availability of these resources surpasses that of conventional oil and gas. Globally, current reserves of tight gas stand at 15,100 TCF, CBM at 5,000 TFC, shale gas at 32,600 TCF, and methane hydrate boasts vast reserves exceeding 12 times that, totaling 300,000 TCF. In contrast, conventional oil and gas resources are notably smaller, totaling only 15,100 TCF (Aguilera, 2016). Indonesia also possesses unconventional oil and gas resources estimated at 1,800 TCF. These resources are still in exploration and have yet to be fully exploited due to inadequate technological limitations (Indonesian Ministry of Energy and Mineral Resources, 2022). However, through Minister of Energy and Mineral Resources Regulation Number 35 of 2021 concerning Procedures for Determining and Offering Oil and Gas Working Areas, the Indonesian government emphasizes the development of unconventional oil and gas for energy independence.

In-depth studies on the potential of unconventional oil and gas resources in Indonesia remain relatively limited. This gap in research serves as the foundation for the author's undertaking of this study, encompassing an exploration of the characteristics of unconventional oil and gas resources, their geographical distribution, methods of exploitation, and their application as an energy source. The study delves into the opportunities and challenges associated with the implementation of these resources in Indonesia. The findings of this research aim to serve as a valuable reference for researchers and industry professionals engaged in the development of unconventional oil and gas in Indonesia. Thus, the contribution of this study is to outline the opportunities and challenges of developing unconventional oil and gas resources in Indonesia by reviewing the characteristics, location, exploitation methods, and utilization of these energy resources.

2. Method

This study employed a narrative review approach, focusing on research articles that addressed (1) the characteristics of unconventional oil and gas, (2) the presence of unconventional oil and gas in Indonesia, (3) methods of unconventional oil and gas production from the source, and (4) the utilization of unconventional oil and gas after production. The literature search was delimited by specific keywords, including unconventional oil and gas production, physical and chemical properties of unconventional oil and gas rocks, unconventional oil and gas sources, and non-conventional oil and gas utilization, with an additional emphasis on Indonesian keywords.

Articles were curated from various reputable databases, including ScienceDirect, ProQuest, Springer, and Garuda Ristekdikti, ensuring that the selected journals were nationally (SINTA) and internationally (SCImago and Scopus) indexed. The publication range of the selected journals spanned from May 2013 to May 2023, ensuring the relevance of the research results. Additionally, the authors drew upon references from trustworthy government websites, reports, and proceedings. Following the meticulous selection of titles, abstracts, and discussions, a total of 42 articles were identified as the primary basis for composing this study. Subsequently, the gathered data was presented through a qualitative descriptive approach, complemented by tables to articulate quantitative information. Figure 1 illustrates the schematic representation of the literature selection process.

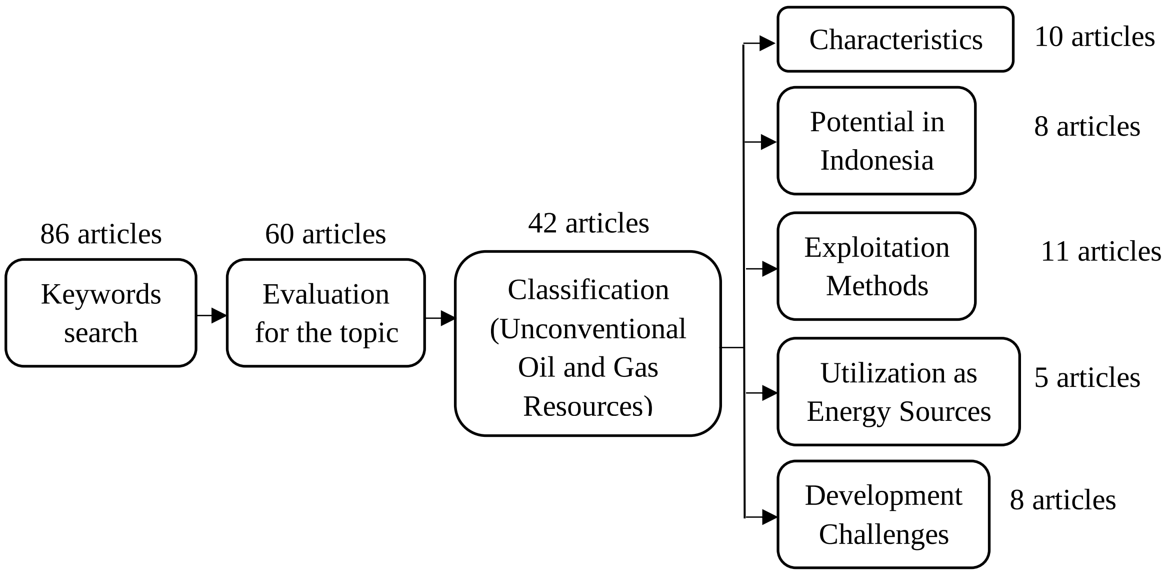


Figure 1. Schematic of the literature selection.

3. Results and Discussions

3.1 Characteristics of Unconventional Oil and Gas Resources

3.1.1 Characteristics of CBM

Several prior studies indicate that CBM is a coal deposit comprising 95% methane gas and 5% other gases with a heavier fraction. CBM formation occurs through thermogenic processes, involving increased heat and pressure converting organic matter into coal. This process initiates with biogenic processes, wherein organic matter decomposition by bacteria takes place. Biogenic processes occur when plant residues accumulate under anaerobic conditions, subsequently oxidized by bacteria to form peat. Over time, heat and pressure transform peat into light coal, commonly known as lignite (35% carbon). With prolonged exposure to heat and pressure, the coal quality improves; bitumen (86% carbon) forms and eventually transitions into anthracite (98% carbon).

Methane gas is absorbed on the kerogen surface and dissolves in the water trapped in coal fractures. The gas is trapped because the water thickness exceeds that of the coal bed (Colosimo et al., 2016). The depth at which CBM is found varies, contingent on the geological characteristics of the site. However, the majority of CBM is typically found at depths ranging from 400 to 1,000 meters (Zhang et al., 2022). The CBM source should have a depth of no more than 1,500 meters because it affects gas capacity. Greater depths result in less trapped gas due to a lower volume of water in the fractures and higher salinity (Hartiniati, 2011). Beyond depth, other factors influencing methane gas absorption capacity in CBM include coal quality (e.g., maturity and total organic content) and CBM pore size. Higher coal quality corresponds to greater absorbed gas capacity. Micropores within CBM play a vital role in methane gas absorption, with the ability to store 98% of the gas, while macropores and mesopores serve as gas transport channels (Colosimo et al., 2016).

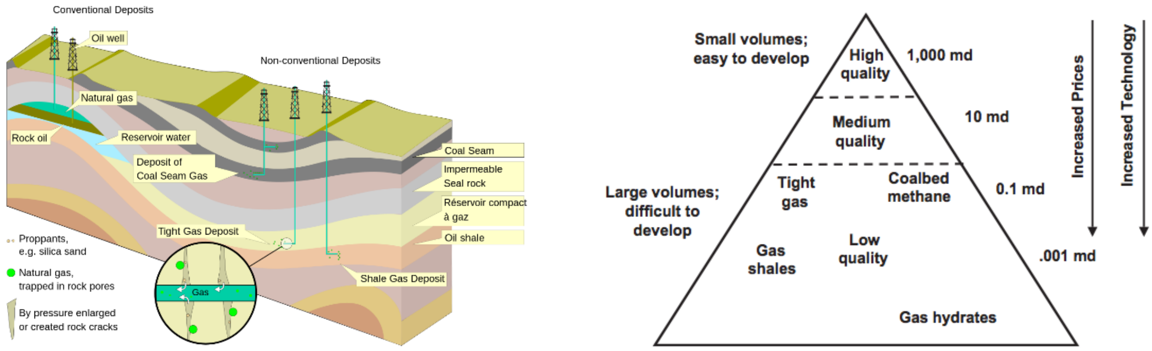
3.1.2 Characteristics of Tight Gas

Tight gas refers to a natural gas reservoir derived from rocks with low permeability, typically measured at 0.1 billion darcies (mD), and a matrix porosity of less than 10%. These values, though low, still surpass those found in shale gas. The diminished permeability in tight gas results from the delicate nature of the sediment, compaction, or the spaces between compacted sand and sediment from water (Wu et al., 2020). In the case of tight gas, the pores in rock formations are irregularly distributed or poorly connected in capillaries that are too narrow, thus diminishing the permeability and the ability of gases to traverse the rock. Tight, non-porous sandstones, and limestones are identified as suitable reservoirs for containing gas. Methane gas becomes trapped in these rocks through van der Waals attraction (adsorption) or dissolves in the fluid within the rock pores (absorption). Elevated temperature and pressure contribute to this process, leading to the long-term entrapment of gas in the rock (Akilu et al., 2021). Rocks housing tight gas can be found at shallower depths compared to shale gas and deeper than CBM, typically around 1,000 meters below the surface (Mao et al., 2020).

3.1.3 Characteristics of Shale Gas and Shale Oil

Shale is a fine-grained sedimentary rock composed of clay minerals, and shale gas is the natural gas formed and trapped within this type of rock. Functioning both as a source rock and a gas reservoir, shale has the capacity to store gas in the pore volume of the matrix as well as on the surface area of the pores. Similar to CBM, the pore size of shale rocks influences the gas absorption capacity, with micropores playing a crucial role in adsorbing gas into shale due to their significant contribution to the total surface area. Macropores and mesopores, on the other hand, serve as gas transport channels. Gas formation in shale can occur through anaerobic microbial activity and changes in temperature and pressure. Shale possesses three distinct pore systems: gas-wet organic porosity, primarily water-wet porosity, and natural fractures (Niu et al., 2023). Shale gas is found at greater depth than CBM: 1500-4000 meters from the ground. (Feng et al., 2023). Parameters that indicate shale gas quality include organic matter content (TOC), kerogen type, brittleness index, and maturity. TOC values are 1-4%, the kerogen type is quality III, brittleness index above 0.4, and maturity between early mature and oil zone indicates good-quality shale gas-containing rocks (Jumiati et al., 2020).

Figure 2 is a pyramid describing the characteristics of unconventional oil and gas resources, encompassing porosity and permeability, along with the depth at which these characteristics are typically found. Shale gas is commonly located at greater depths compared to CBM, typically ranging from 1500 to 4000 meters below the surface (Feng et al., 2023). Key parameters indicative of shale gas quality encompass TOC, kerogen type, brittleness index, and maturity. High-quality shale gas-containing rocks are characterized by TOC values of 1–4%, kerogen type quality III, a brittleness index exceeding 0.4, and maturity falling within the range of early mature to the oil zone (Jumiati et al., 2020).



(a) (b)

Figure 2. (a) Graph of locations of unconventional oil and gas existence (Green, 2014), (b) Characteristics of unconventional oil and gas (Tverberg, 2011).

Apart from shale gas, shale can also generate and store shale oil. Oil shale is a fine-grained sedimentary rock containing kerogen (a mixture of organic chemical compounds). Oil shale is typically found at relatively shallow depths, less than 900 meters. The locations where shale oil is prevalent are on ancient lands, lakes, and seas, as clay minerals and organic matter accumulate in these areas. Following deposition, compaction, and burial to a certain depth, the rock transforms into oil shale (Zhao et al., 2020). Oil shale can be classified based on its mineral content into carbonate-rich shale, siliceous shale, and cannel shale. The distinctions among these shale oil sources lie in the forming organisms and the nature of the shale support. Various factors determine the quality of oil shale, including organic matter content, moisture, hydrogen, and nitrogen content, the concentration of contaminants, and the volume of oil contained within the shale (Zhao et al., 2020).

3.1.4 Characteristics of Methane Hydrate

Methane hydrate is a compound resembling ice cubes formed when water molecules trap gas molecules under high-pressure and low-temperature conditions. Most of these rock formations are filled with methane gas, commonly referred to as methane hydrates (Malagar et al., 2019). There are three types of methane hydrate structures: s1, s2, and H. The s1 structure is pentagonal, comprising two small cavities and six large cavities, each containing 46 water molecules per unit cell. A single guest molecule, such as carbon dioxide, methane, or ethane, can enter the s1 structure. Another structure, s2, is also pentagonal, consisting of 16 small and eight large cavities with 136 water molecules. Hydrocarbon gases like propane and isobutane can enter the s2 structure. In contrast, the H structure is hexagonal, featuring three small cavities, two medium cavities, and one large cavity. The H structure requires two molecules to fill its formation—large organic guest molecules such as nanohexane and helper gases such as methane (Kondori et al., 2017).

Most methane hydrate is found on the seabed, comprising 98%, while in the Arctic permafrost, it constitutes only about 2%. Generally, specific conditions are required for the formation of gas hydrates: a temperature of <26.85 °C and a pressure of >0.6 MPa (Malagar et al., 2019). The seabed's gas hydrate stability zone (GHSZ) is found at a depth of 400-1500 meters above sea level and a temperature of 0 °C to 17 °C. The GHSZ on the seabed is located at a depth of 400–1500 meters above sea level and a temperature range of 0 °C to 17 °C. However, methane hydrate accumulates solely on the seafloor, specifically at a depth of 1500 meters, where methane gas is emitted. In contrast to seabed conditions, methane hydrate in permafrost is found along the GHSZ, specifically at depths of 200–1000 meters and temperatures ranging from -5 °C to 17 °C (Wirandoko et al., 2021).

3.2 Potential of Unconventional Oil and Gas Resources in Indonesia

3.2.1 Potential of Coal Bed Methane

Figure 3 displays CBM availability in Indonesia. The CBM potential in Indonesia is estimated at 453.3 trillion cubic feet (TCF), ranking Indonesia as the 6th largest CBM producer globally (Hartiniati, 2011). The primary CBM sources are concentrated in South Sumatra (183 TCF), followed by Barito (101.6 TCF), Kutai (80.4 TCF), Central Sumatra (52.5 TCF), and seven other basins (Stevens & Hadiyanto, 2004). The basin with the most substantial potential, South Sumatra, covers an area of 18,800 km^2 with a thickness of 36.6 m, coal density of 1,800 tons/acre-foot, ash content of 10%, moisture content of 7.5%, and CH_4 content of 7.0 m^3/t. This basin exhibits asymmetry, with the thickest sediments forming in the western to central areas and thinner sediments in the eastern areas near the Sunda Strait. The Jambi, Central Palembang, and South Palembang regions are identified as sub-basins with the thickest coal and optimal depth, making them the most prospective areas in the South Sumatra Basin (Stevens and Hadiyanto, 2004).

3.2.2 Potential of Tight Gas

Tight gas sources in Indonesia are currently in the exploration stage. Although tight gas is predicted to exist in East Kalimantan, Java, South Sumatra, and North Sumatra, the exact locations are yet to be determined (Indonesian Ministry of Energy and Mineral Resources, 2022). The quantity of tight gas is uncertain, necessitating further research in Indonesia.

3.2.3 Potential of Shale Gas and Shale Oil

The potential for shale gas in Indonesia is estimated at 574.07 TCF spread across 14 basins. The region with the highest shale gas content is Central Sumatra (86.90 TCF), followed by Kutai (80.59 TCF), Barito (74.59 TCF), North Sumatra (64.78 TCF), and ten other basins. In addition to shale gas, shale oil has also been discovered in smaller quantities, specifically 11.24 million tons (Jumiati et al., 2020). While significant shale oil resources are identified in Central Sumatra, the exact amounts in other areas have yet to be determined with certainty (Indonesian Ministry of Energy and Mineral Resources, 2022).

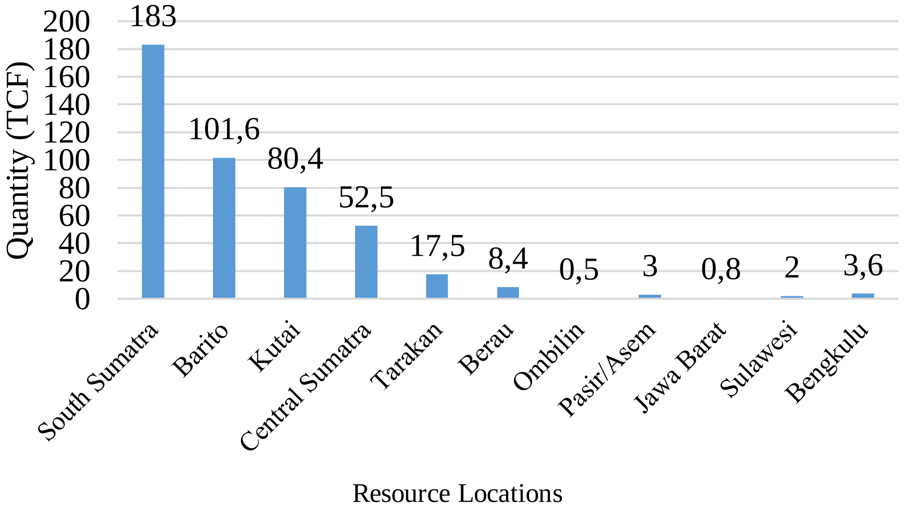


Figure 3. CBM availability in Indonesia (Stevens & Hadiyanto, 2004).

Several basins in Indonesia exhibit potential for shale gas. Figure 4 illustrates shale gas availability in Indonesia. Jumiati et al. (2020) assessed the quality of these formations based on Total Organic Carbon (TOC), kerogen, maturity, and brittleness index values. The Akimeugah Basin and the Bintuni Basin stand out as locations with the highest TOC values, ranging from 2–4%wt. Nevertheless, the Barito, Kutai, and Central Sumatra basins also display commendable TOC values, albeit slightly lower than those in the former two locations. The Pamaluan Formation in the Kutai Basin and the Batu Kelau Formation in the Melawi-Ketungau Basins possess the highest kerogen values (Quality III). The Brown Shale Formation in the Central Sumatra Basin, along with the Batu Kelau, Silau, and Ingar Formations in the Melawi-Ketungau Basins, demonstrate optimal maturity values, placing them in the early mature-oil zone. In terms of the brittleness index, the Kutai and Batu Kelau formations exhibit the most favorable values, ranging from 0.57 to 0.82. Considering all aspects, the basins with promising production prospects include the Kutai Basin with the Pamaluan Formation and the Melawi-Ketungau Basins with the Batu Kelau Formation.

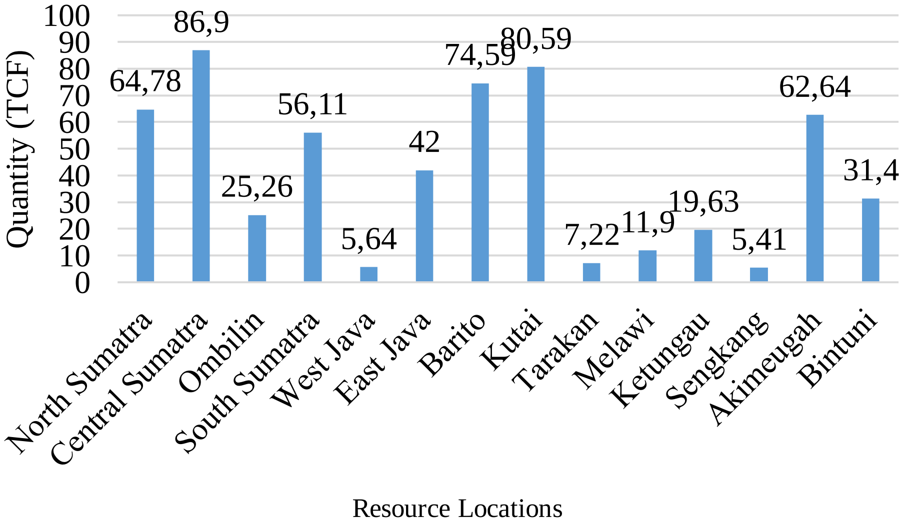


Figure 4. Shale gas availability in Indonesia (Jumiati et al., 2020).

3.2.4 Potential of Methane Hydrate

Figure 5 illustrates methane hydrate availability in Indonesia. The current sources of methane hydrate in Indonesia amount to 858.2 TCF and are distributed across two locations: the offshore area to the south of Sumatra and to the northwest of Java, known as the Sunda Strait (625 TCF), and the Makassar Strait (233.2 TCF). This quantity is equivalent to six times the current natural gas reserves in Indonesia, which stand at 41.62 TCF (Indonesian Ministry of Energy and Mineral Resources, 2021). In addition to these primary locations, methane hydrate is also present in the offshore areas of Simeuleu, Mentawai Trough, Java Forearc, North Lombok, Sulawesi Sea, Aru, Misool, Kumawa, Wigeo, Wokam, and Salawati. However, the exact amounts in these areas have yet to be determined with certainty (Wirandoko et al., 2021).

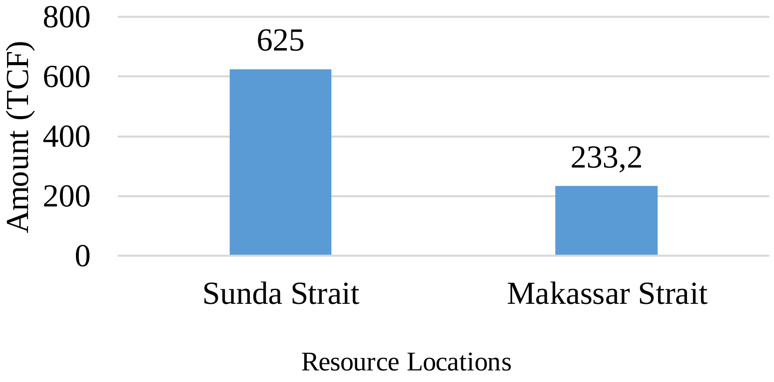


Figure 5. Methane hydrate availability in Indonesia (Indonesian Ministry of Energy and Mineral Resources, 2021).

The sediments present in the fold belt area of the western Makassar Strait originate from the late Pliocene Mahakam Delta. Tectonic events played a crucial role in the development of the west-verging fault propagation fold, ultimately giving rise to the fold belt. This belt comprises several thrust sheets, forming an extensive anticlinal structure that initiates the creation of mini-basins. The deposition process within these mini-basins involves a series of 'spill and fill' turbidite processes, leading to the accumulation of methane hydrates in the Makassar Strait (Bachrudin et al., 2015).

The formation of methane hydrate sediments in the western Sunda Strait is related to the bending of the Indo-Australian plate subduction zone. The Sunda Trench is formed along the west coast of Sumatra, starting from the Sunda Strait northward to the western part of northern Sumatra. The depth of the trough gradually shallowed from 6000 m to 5000 m. Apart from that, the trench axis extends to the bottom of the trench, and its size widens towards the north, which has the potential to become a zone for the formation of methane hydrate. The sediment that fills this basin has layers parallel to the sea floor, does not experience much disturbance, and is separated by several anticline structures (Triarso & Troar, 2017). The formation of methane hydrate sediments in the western Sunda Strait is associated with the bending of the Indo-Australian plate subduction zone. The Sunda Trench runs along the west coast of Sumatra, extending from the Sunda Strait northward to the western part of northern Sumatra. The trough's depth gradually decreases from 6000 m to 5000 m. Additionally, the trench axis extends to the trench's bottom, widening towards the north, presenting the potential to become a zone for methane hydrate formation. The sediment filling this basin maintains layers parallel to the sea floor, experiences minimal disturbance, and is separated by various anticline structures.

Generally, the formation of methane hydrates occurs when methane gas diffuses from gas-rich areas and subsequently mixes with water in the hydrate stability zone (GHSZ), leading to the formation of methane hydrate deposits. The fluid flow in this process adheres to Darcy's Law, which is the momentum balance relationship for slow fluid flow through sediment that can change shape. While tectonic events do not directly cause the formation of methane hydrates, they play a facilitating role because the basins generated by these events provide environmental conditions conducive to the GHSZ (You et al., 2019).

Cumulatively, the highest availability of unconventional oil and gas resources in Indonesia is in gas hydrate (858.2 TCF), followed by shale gas (574.07 TCF), and coal-bed methane (453.3 TCF). Additionally, shale oil has been identified with a total of 11.24 million tons, presenting potential for further exploration.

3.3 Exploitation Methods of Unconventional Oil and Gas Resources

3.3.1 CBM Exploitation Method

Table 1 compares the CBM production method. The exploitation or production of methane gas in coal can be achieved through dewatering and Enhanced Coal Bed Methane Recovery (ECBMR) processes or gas exchange. In the dewatering process, water in CBM is pumped out to reduce pressure. When the fracture system produces water, surpassing the coal's absorption capacity, the pressure decreases, leading to the desorption of gas trapped in the coal matrix. Methane gas then diffuses from the micropores into the fractures, is pumped, and flows through pipes to storage and production wells. However, this process can take up to several months to recover methane gas and may disrupt the natural balance underground (Hartiniati, 2011).

Methane gas production in CBM can also be achieved through ECBMR, involving the injection of other gases into the coal bed, such as CO_2 and N_2. Coal could store methane and other gases through gas adsorption on micropores. This process unfolds in two stages: CO_2 adsorption and CH_4 desorption from the pores. Adsorption induces swelling of the coal matrix, and eventually, gas flows through the fracture, contingent on the compressibility of the fracture (Mukherjee & Misra, 2018). The injection of a nitrogen and carbon dioxide mixture has the potential to increase CBM production rates and minimize adverse effects on the natural balance. However, this process operates on a micro-scale and is sensitive to factors such as temperature, pressure, moisture content, and the type of coal involved (Colosimo et al., 2016).

Table 1. Advantages and disadvantages of the CBM production method.

Method	Advantages	Disadvantages
Dewatering (Hartiniati, 2011)	- Utilizes water as the injector material, making it environmentally benign. - Cost-effective financing.	- Triggers a groundwater crisis. - Involves a prolonged duration, taking up to months.
Enhanced Coal Bed Methane Recovery (Colosimo et al., 2016)	- Captures CO_2 gas, a significant contributor to global warming. - Enables a considerably faster process.	- Poses dangers in the event of a large gas leakage.

3.3.2 Tight Gas Exploitation Method

Table 2 shows various methods for tight gas production. Tight gas can be extracted from rock formations through hydraulic fracturing, a process that involves opening rock fractures by injecting high-pressure liquid. Fracking materials, which include water, propane, and chemicals, are pressurized, and injected into the ground until they penetrate the tight rock, typically non-porous sandstone, or limestone, where the tight gas is present. The chemicals used serve various functions, such as adhesives, microorganism inhibitors, rock breakers, friction reducers, and proppant carriers (Wu et al., 2020). Vertical drilling is commonly employed for production holes as tight gas reservoirs generally exhibit more resistance to horizontal cracking. After breaking the rock with water pressure, sand is introduced to keep the fracture open, allowing gas to be pumped to the surface. Alternative methods, like explosive fracturing, pulsed fracturing, and thermal fracturing, can also be considered for tight gas production.

However, it's important to note that these methods are still in the early experimental stages and may be less feasible when applied in the field (Feng et al., 2023).

Table 2. Advantages and disadvantages of the tight gas production method.

Methods	Advantages	Disadvantages
Hydraulic Fracking (Wu et al., 2020)	- Endures fractures for extended periods and reaches deep gas sources. - Cost-effective financing.	- Risk of water contamination in case of a leak.
Explosive Fracturing (Feng et al., 2023)	- Acquires gas sources quickly. - -Cost-effective financing.	- Potential for earthquakes. - Significant damage to soil structure.
Pulsed Fracturing (Agarwal & Kudapa, 2023)	- Acquires gas sources quickly.	- Complex operation of the technology. - The operation of the technology is complicated
Thermal Fracturing (Xue et al., 2019)	- Acquires gas sources quickly.	- Slow gas source acquisition due to strengthening rock structure with increasing.

3.3.3 Shale Gas and Shale Oil Exploitation Methods

Shale gas production shares similarities with tight gas, but key differences lie in hydrofracturing strength, fracturing materials, and crack spreading. The pressure required to fracture shale gas is higher compared to tight gas due to its deeper location. Additionally, the composition of fracturing materials varies, considering the different hardness of shale rock. Shale gas cracks are initially drilled vertically to a certain depth and then continued horizontally, as shale gas reserves are more horizontally distributed than vertically (Aguilera, 2016).

Table 3 compares the shale gas production methods. The hydraulic fracking method is also employed in shale oil production. However, distinctions arise in the fracturing materials used for shale oil production (Hayes, 2022). Methods such as explosive fracturing, pulsed fracturing, and thermal fracturing are applied in both shale gas and tight gas production. Moreover, shale gas production may involve biological fracturing. However, biological fracturing is still in the early experimental stages and may be less feasible when applied in the field (Feng et al., 2023).

Table 3. Advantages and disadvantages of the shale gas production method,

Method	Advantages	Disadvantages
Hydraulic Fracking (Hayes, 2022)	- Endures fractures for extended periods and reaches deep gas sources. - Cost-effective financing.	- Risk of water contamination in case of a leak.
Biological Fracturing (Feng et al., 2023)	- Minimizes environmental pollution.	- Prolonged extraction time due to dependence on microbial activity.

3.3.4 Methane Hydrate Exploitation Method

Methane hydrate production methods are compared in Table 4. Depressurization is a method for recovering methane gas from methane hydrate by reducing the pressure in the wellbore through sediment-containing hydrate. When the pressure drops below the GHSZ, methane hydrate becomes thermodynamically unstable and decomposes due to geothermal inflow from the sediment (Kondori et al., 2017). Depressurization is an easily accessible and economically affordable method for methane gas recovery, making it potentially applicable on a commercial scale. In addition to laboratory testing, depressurization was the first method successfully tested in the field. Optimal conditions for this method include high temperature, high permeability, and high geothermal flux (Malagar et al., 2019). Recent studies suggest that heat transfer from the environment enhances depressurization performance.

Table 4. Advantages and disadvantages of methane hydrate production methods.

Method	Advantages	Disadvantages
Depressurization (Malagar et al., 2019)	- Requires no excess energy input. - Suitable for gas hydrate reservoirs with low hydrate saturation, high porosity, and low free gas.	- Leads to land subsidence and underwater landslides. - Hydrate reformation can occur due to endothermic depressurization.
Thermal Stimulation (Kondori et al., 2017)	- Production rate can be controlled by adjusting the heat injection rate.	- Slow production rate - High potential for heat loss. - Expensive financing.
Chemical Injection (Li et al., 2008)	- Enables increased production rates in a short time.	- Not suitable for use in gas hydrate reservoirs with low permeability. - May cause environmental damage if chemicals are released. - Expensive financing
Gas Exchange (Park et al., 2008)	- Captures CO_2 gas, addressing the cause of global warming.	- Not suitable for use in gas hydrate reservoirs with low permeability. - Slow production rate.

Thermal stimulation involves raising the temperature above the equilibrium hydration temperature. As the temperature increases, methane hydrate sediment gradually melts, releasing methane gas. Methane hydrate is highly responsive to heat and quickly reacts to heat sources. Additionally, the injected energy can be evenly distributed across the gas hydrate layer in the reservoir and extend to the surrounding zones. The energy used in thermal stimulation should not be greater than the energy recovered from the gas to keep this method economically affordable (Kondori et al., 2017).

Chemical injection works by injecting an inhibitor, such as methanol or brine, into the methane hydrate to separate the recoverable gas from the reservoir. Recent studies have found that the concentration and temperature of the injected hot brine affect the amount of gas recovered from methane hydrate. However, this research has yet to study porous rock with different porosity and permeability (Li et al., 2008).

Methane gas in methane hydrate sediments can be exchanged for other gases, such as CO_2. This process is advantageous because it can store CO_2, address emissions, and obtain CH_4 as an energy source. Combining CO_2 with other gases can also be injected as a guest gas (Kondori et al., 2017). Molecular simulation studies show that the region adjacent to the interface between the gas and hydrate phases is the most likely site for an exchange of CO_2 with CH_4. This gas exchange occurs rapidly, in as little as 20 ns, and the efficiency of this method can reach 60% when applied to large amounts of methane hydrate sediments. However, this method is not suitable for low permeability methane hydrate because it is difficult to spread, and the guest gas diffusion is hampered, so the reaction is slow (Park et al., 2008).

3.4 Utilization of Unconventional Oil and Gas Resources as Energy Sources

CBM, tight gas, shale gas, and methane hydrate primarily consist of CH4 (70–90%), making their potential utilization like natural gas. Natural gas finds applications in various sectors, including power plants, motor vehicle fuel, and as a raw material in industrial processes. Industries such as petrochemicals, fertilizers, and hydrogen production use natural gas. Moreover, natural gas is utilized in households (for cooking, heating, and as fuel for cooling equipment) and the commercial/business sector (U.S. Energy Information Administration, 2021).

The projected utilization of natural gas in Indonesia is illustrated in Figure 6. Most natural gas in Indonesia is allocated to the power generation sector (52%) and the industrial sector (47%), with the remaining 0.9% utilized in households and transportation. In the electricity generation sector, natural gas serves as fuel for Steam Gas Power Plants (PLTGU) as an intermediate load bearer and Gas Power Plants (PLTG) as a peak load bearer. Industries relying on natural gas include the metal industry, fertilizer industry (as a raw material), and ceramics industry (Suharyati et al., 2023).

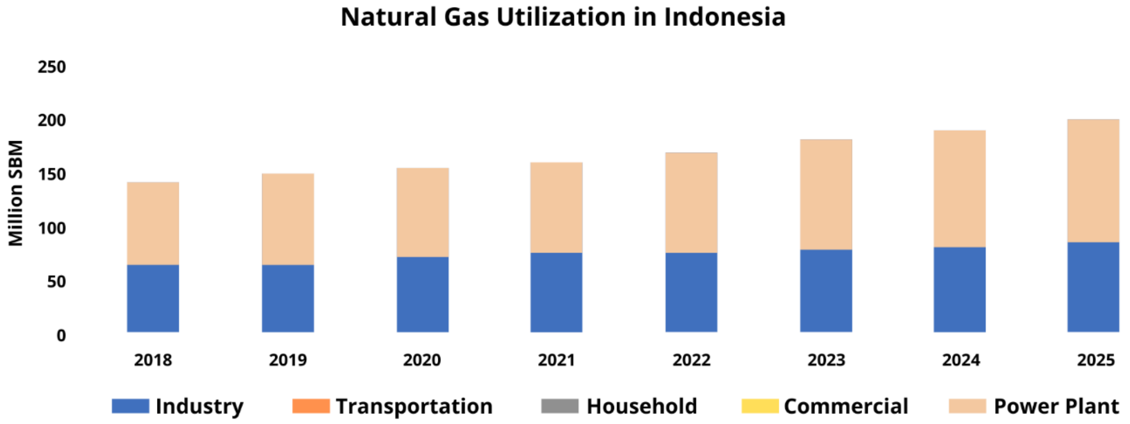


Figure 6. Projection of natural gas utilization from various sectors in Indonesia (Indonesian Technology Assessment and Application Agency, 2020).

Natural gas-fired power plants (PLTG) exhibit lower emissions compared to coal-fired ones, specifically Steam Power Plants (PLTU). According to data from the U.S. Energy Administration data (2021), the United States has achieved a significant reduction in carbon emissions through the implementation of PLTG. CO_2 emissions from PLTU are 2,257 pounds per Megawatt-hour (MWh), whereas CO_2 emissions from gas-fired power plants are less than half at 976 pounds per Megawatt-hour (MWh). In 2021, Indonesia successfully established 66 units of PLTG. Presently, the capacity of PLTG in Indonesia has reached 21.6 GW, indicating a 22% increase over the last five years, equivalent to 3.9 GW (BPS, 2022).

Shale oil is utilized similarly to conventional petroleum, serving as fuel, lubricants, petrochemical raw materials, asphalt, and in household products such as detergents, soaps, and other cleaning products (Suharyati et al., 2023). This shows that overall, CBM, tight gas, shale gas and oil, and methane hydrate serve as substitutes for conventional coal, oil, and natural gas, whose availability is depleting.

3.5 Challenges in Developing Unconventional Oil and Gas Resources in Indonesia

The development of unconventional oil and gas resources in Indonesia has several challenges from various aspects, including water resources and pollution, biodiversity, spatial and land management, air quality and noise, as well as social, economic, and cultural aspects.

3.5.1 Water Resources and Pollution

Water pollution is a difficult problem, considering that the production of shale gas, tight gas, and CBM from rocks involves the use of water. The dewatering process in CBM requires large amounts of water, obtained by pumping groundwater, causing a continuous decrease in groundwater quantity. Similarly, in shale gas and tight gas extraction, the hydraulic fracking process also demands significant water volumes, estimated at around 1 million liters per well. After gas production, the wastewater discharged

to the surface poses a significant risk if left untreated. The gas drilling process, situated deep below the ground surface, results in high water salinity (Hartiniati, 2011). Water can carry benzene, toluene, ethylene benzene, and other organic materials to the surface, especially when corrosion and leaks occur in fracking pipes, allowing hazardous chemicals to be transported along with the water. Upon interaction, these substances can lead to a decrease in soil fertility and the death of organisms.
In the production of methane hydrate, seawater pollution is also a concern. The production process, employing gas exchange and chemical injection methods, may lead to hazardous impacts in the event of leaks or technical errors. The predominant gas used for injection is CO_2, and if large quantities of CO_2 interact with water, it can result in the acidification of seawater. The consequences of seawater acidification directly affect organisms, including reduced growth rates of coral reefs, diminished survival of larval species, and a weakened ability of protective shells in marine organisms (Malagar et al., 2019).

Several recent cases of water pollution have been attributed to hydraulic fracturing gas drilling. In the Permian Basin (Western Texas), contamination has occurred due to Total Dissolved Solids (TDS), Chloride, Fluoride, Nitrate, and Arsenic (Nelson & Heo, 2020). In Wyoming (Pavillion), contamination has been reported from organic materials, including Benzene, Toluene, Ethylbenzene, Xylenes, and Methane (Folger et al., 2016). Additionally, the Appalachian Basin (Pennsylvania) has faced contamination from Total Dissolved Solids (TDS) and inorganic materials such as Ba, Ca, Na, and Sr (Skalak et al., 2014). All these contaminants pose significant risks if they surpass the maximum threshold. Companies intending to engage in gas production must adhere to the following laws and regulations:

- Law No. 7 of 2004 concerning Water Resources.
- Government Regulation no. 82 of 2001 concerning Water Quality Management and Water Pollution Control.
- Government Regulation no. 74 of 2004 concerning Management of Hazardous and Toxic Materials.
- Amendment to the Decree of the Minister of State for the Environment No. 42 of 1996 concerning Liquid Waste Quality Standards for Oil and Gas and Geothermal Activities.

3.5.2 Land Governance

The opening of production wells containing gas can lead to land-related issues. When land was previously utilized for agriculture, residential purposes, or designated as a conservation area, conflicts may arise between the company and the local community. These conflicts often stem from the company purchasing land at an inadequate price. The swift transformation of land geography, transitioning from green fields to oil and gas mining, can result in various disasters, including flash floods. Another significant hazard is the occurrence of earthquakes induced by the injection of high-pressure water into the ground to activate faults during the gas production process.

In the case of methane hydrate production, changes in pressure and temperature can disrupt the formation of underwater sediments, leading to underwater earthquakes. An incident in England in 2011 reported two minor earthquakes attributed to hydraulic fracturing. Although they did not cause significant damage, they resulted in economic losses, including a decrease in land prices around the drilling site by 3.9–4.7%, extending up to 25 km from gas drilling sites (Gibbons et al., 2021). Companies intending to engage in gas production must adhere to the following laws and regulations:

- Law of the Republic of Indonesia Number 24 of 1992 concerning Spatial Planning.
- Laws regarding regulation, utilization, and control of space starting from the national space up to the district/city area.

3.5.3 Air and Noise Pollution

Air and noise pollution are common occurrences in areas surrounding unconventional oil and gas production projects. This is primarily attributed to the emission of hazardous pollutants and loud noises from heavy drilling equipment. The operation of such machinery generates significant noise levels, disrupting various activities in the vicinity. In the event of a methane gas leak resulting from errors in the drilling process, it can pose a serious problem, given that the greenhouse gas methane has an impact 25 times stronger than carbon dioxide. Long-term exposure of these gases to humans can cause respiratory diseases for workers.

Several cases of air pollution linked to hydraulic fracturing gas drilling have occurred in various locations worldwide. In Pennsylvania (USA), more than 20,000 wells contributed to an increase in PM 2.5 concentrations ranging from 0.017 to 0.062 $\mu g/m^3$, resulting in approximately 20 deaths between 2010 and 2017 (Zhang et al., 2023). Texas (Mexico) experienced a 12% rise in nitrogen dioxide pollutants, equivalent to 71 tonnes per day, from 2009 to 2013 (Honeycutt, 2014). Wysin (Poland) witnessed pollutant increases of 108%, 21%, 18%, 12%, 7%, 4%, and 1% for nitrogen oxides, non-methane hydrocarbons, carbon monoxide, nitrogen dioxide, particulate matter, carbon dioxide, and methane during the period 2012–2017 (Jarosławski et al., 2022). In most cases, the rise in pollutants at these locations was primarily attributed to project vehicle activities, while drilling activities produced comparatively less significant pollutants. Companies seeking to engage in gas production must adhere to the following laws and regulations:

- Government Regulation Number 41 of 1999 concerning Air Pollution Control.
- Decree of the Minister for the Environment No. 129 of 2003 concerning Emission Quality Standards for Oil and Gas Businesses and or Activities.
- Decree of the Minister for the Environment No. 48/MENLH/11/1996 concerning Quality Standards for Noise Levels.
- Decree of the Minister for the Environment No. 13/MENLH/3/1995 concerning Quality Standards for Stationary Source Emissions.

3.5.4 Disturbance to Biodiversity

Biodiversity faces disruption through land clearing for unconventional resource drilling. As highlighted in the preceding sub-chapter, water pollution associated with gas production contributes to the mortality of both terrestrial and aquatic organisms. Furthermore, the acidification of seawater resulting from chemical injection leakage in methane hydrate drilling can lead to a decline in the diversity of marine life. The loss of the original habitat for animals and plants due to land clearing significantly heightens the potential for extinction. Companies aiming to engage in gas production are obligated to comply with the following laws and regulations:

- Law of the Republic of Indonesia No. 5 of 1990 concerning Conservation of Biological Natural Resources and Their Ecosystems.
- Government Regulation No. 28 of 1985 concerning Forest Protection.

3.5.5 Social, Economic, and Cultural Aspects

Land clearing for non-conventional oil and gas exploitation will create new jobs, thereby improving the economy of the community surrounding the drilling location. However, in practice, oil and gas companies often opt to hire workers from outside the local area. This is due to the specialized knowledge and expertise required for handling unconventional resources, necessitating the employment of experts. Since most residents lack educational backgrounds aligned with the offered positions, companies tend to absorb only a limited number of local workers, primarily in labor positions. Incidents like these can foster social jealousy between residents and migrant workers, potentially leading to conflicts. Therefore, it is crucial for companies and the government to implement policies regarding labor resources wisely and enforce them effectively.

4. Conclusions

The conventional oil and gas resources in Indonesia are limited and are expected to deplete soon. Consequently, efforts to develop unconventional oil and gas resources are ongoing, motivating the author to undertake this study. The study's findings reveal that unconventional oil and gas resources (i.e., CBM, tight gas, shale gas, and oil, methane hydrate) exhibit distinct characteristics, including permeability, porosity, and depth. The order of depth, from shallowest to deepest, is CBM, tight gas, methane hydrate, and shale gas. Indonesia possesses potential resources still in the exploration stage, with gas hydrate leading (858.2 TCF), followed by shale gas (574.07 TCF), coal-bed methane (453.3 TCF), and shale oil (11.24 million tons). Recovery methods for gas from these sources include dewatering (CBM), hydraulic fracking (tight and shale), and depressurization (methane hydrate). The gas extracted can be utilized for power plants, transportation, industrial processes, and household needs. Despite providing energy, the production process of gas has negative impacts, including water pollution, land management issues, damage to biodiversity, social jealousy, and air and noise pollution. Given the substantial potential for unconventional oil and gas in Indonesia, continuous research and development are imperative to achieve energy independence for the country in the future.

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