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Assessment of Unconventional Natural Gas Resources

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ABSTRACT

In the 21st century, the petrochemical industry has experienced a significant increase in oil and gas consumption due to the growing global population and energy demand. Among nonrenewable resources, natural gas stands out as the cleanest option, making it an essential resource for the energy industry in comparison to other hydrocarbons. Unconventional gas, including shale gas, tight gas, coalbed methane, and gas hydrate, has emerged as a substantial hydrocarbon resource. This study aims to explore the environmental impacts, geological features, obstacles, and technical challenges associated with the exploitation of unconventional gas reservoirs, encompassing aspects such as energy demand, consumption and production, water pollution, greenhouse gas emissions, and reservoir geology properties. The paper also reviews the various approaches to developing unconventional gas in different countries, with a particular focus on the United States. The findings indicate that the feasible development of unconventional gas is indeed possible in different countries. However, the future outlook for this resource will heavily rely on several factors, including addressing environmental concerns, investment in renewable energy, and the state of global gas markets.

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1. Introduction

The world has been concerned about global energy demand since World War II, when sharply rising oil prices led to global recessions and high inflation in the last quarter of the 20th century (Brown et al., 2013). In recent years, due to environmental pollution, climate change and rapid developments in technology, the energy industry tends to consume and fossil invest in low-carbon fuels (natural gas resources) and renewable energies. Although there has been significant development and investment in renewable energy in the last decade. But the fossil fuels play a fundamental role in the future. However, the world has seen rapid growth in energy demand and unconventional oil and gas are considered as indispensable bridge fuel that will allow society to continue to use new resources of fossil fuels instead of conventional oil and gas (Islam et al., 2020). There is large volume of unconventional gas resources in different countries and these have been known for a long time. Unconventional gas resources are contained large accumulations of gas with low production rates (20 Mcf/d to 500 Mcf/d), trapped in low permeability formations with diffuse boundaries and no well-defined hydrocarbon-water contacts (Conti et al., 2016; Sahraei et al., 2022).

The category of unconventional gas comprises of various types of gas, including shale gas, tight gas, coalbed methane (CBM), and hydrates. Shale gas is usually in shale, mudstone, siltstone, and fine-grained sandstone. Tight gas often has been stored in tight sandstone or sometimes limestone. Coalbed methane is typically adsorbed onto the surface of coal seams, while gas hydrates are commonly found in deep water and Arctic regions. Shale, is the main sources of gas all over the world, tight gas is just sandstone gas which cannot easily flow toward existing wells, Coal Bed Methane is a form of natural gas found in coal deposits with low permeability and gas hydrate is a solid clathrate that contains a significant amount of methane under seafloors. Their common characteristic is the very low permeability and the permeability mostly has been improved by artificial (hydraulic fracturing (HF)) or natural fractures (Jin et al., 2022; Su et al., 2020).

In the last decade, the production of unconventional gas reservoirs has enabled a new era of economic advantages (economically competitive over the past several years), moderate greenhouse gas emissions (fewer CO_2 emissions per generated energy unit than coal and oil) and altering geopolitics and energy policy at international levels (Hultman et al., 2011). Moreover, new technologies such as horizontal drilling technology, multistage HF, has led to production from shale gas, tight gas and coalbed methane reservoirs, but hydrate gas has not yet been produced commercially (Hancock et al., 2019; Wang et al., 2021). In the future, the extraction of gas hydrates in seafloors potentially lead to a significant increase in natural gas reserves. Economically recoverable gas hydrate deposits may contain an energy content comparable to that of the estimated total conventional gas resource (Wallmann et al., 2020). Unconventional gas resources already have been developed economically in some places. Economically unrecoverable resources may become recoverable, as soon as their production technology becomes less expensive or the characteristics of the market are such that companies guarantee the return of their investment. In order to economically exploit gas from such reservoirs, the development of HF in the heterogeneous porous media under such complicated conditions should be expanded (Tian et al., 2022).

Due to environmental concerns and the high production costs associated with unconventional natural gas (UNG), there are relatively low expectations for UNG production in Europe. In fact, France, Bulgaria, the Czech

Republic have been temporarily banned from unconventional gas development. These rules are related to environmental risks and energy market restriction. There is uncertainty about the export potential of European gas when the Middle East conventional resources are more quickly accessible (Janda et al., 2018; Holz et al., 2015).

Technological advancements and increasing gas prices are expected to rapid in the growth of unconventional gas production in the United States (US), and this trend is expected to expand worldwide. Sustainable development of shale gas resources is already underway in several regions of North America, such as Texas, Oklahoma, Louisiana, Pennsylvania, among others (Soeder, 2018; Mei et al., 2022). As gas demand increases and crude oil price rises, the substantial question for researchers is whether UNG can be developed with appropriate approach with minimal impact on groundwater and climate. After a background of unconventional gas resources, this review focuses on the technical and environmental assessment of unconventional gas development. We studied and briefly summarize various aspect of UNG development. The result indicates the increase in natural gas consumption can be compensated by UNG resources, but this market development will depend on the supply and demand, which will be influenced by environmental policies and renewable energy investment.

2. Definitional issues

2.1. Natural gas reservoirs

Natural gas is the cleanest burning fossil fuel and emits significantly less carbon dioxide, particle pollution, sulfur, and nitrogen oxide than other hydrocarbons. Natural gas resources are generally classified as conventional and unconventional reservoirs. The difference between conventional and unconventional natural gas is not only based on gas composition but also on the deposit geology characteristics, well drilling and well completion. In terms of geology structure, the main distinguishing feature of unconventional oil and gas rocks is their pore sizes and reservoir traps (Fangzheng, 2019; Nia et al., 2016). Conventional resources occur in a discrete reservoir with discrete traps by the cap rocks, in contrast, unconventional resources are distributed continuously in basin slopes or centers with no obvious trap boundary (Chengzao et al., 2021). The "continuous type hydrocarbon accumulation" theory proposed by Schmoker et al. in 1995 was a milestone of petroleum geology (Zou et al., 2018). Unconventional gas includes shale gas, tight gas, coalbed methane, and gas hydrates (Figure 1) (Capuano, 2018).

2.2. Coalbed methane

Coalbed methane is a type of unconventional natural gas that is typically found in coal mines. CBM resources are naturally fractured and contain a significant amount of methane as well as other hydrocarbons. Methane is primarily trapped within the micropores of the coal matrix and secondarily in fractures and cleats. Unlike conventional gas deposits where free gas is accumulated in the pores of the formation, CBM can contain significant amounts of methane that is adsorbed in nanoscale pores (Miao et al., 2018; Jia et al., 2021). CBM is typically stored in the pores, cleats, and fractures of the coal as follows:

- ✓ Micropores containing a large volume of methane in a dissolved state
- ✓ Macropores having free and dissolved gas in water.
- ✓ Cleats and open fractures having a fraction of water and gas volumes

Most of the coalbeds contain significant amounts of water. The pressure from this water keeps the methane in place. In order to produce methane from CBM, the water trapped in cleats and fractures of reservoir rock should be removed which can lower the pressure, and the methane easily flows up to the well. The process of dewatering of the formation from the coal surface may continue for several months before economic gas production can be achieved (Mohamed et al., 2020; Satter et al., 2015). In the case of US-based operations, each well is estimated to produce between 1.7 to 14.3 million liters of flowback and produced water. The majority of this water, ranging from 92% to 96%, consists of naturally occurring brines. The remaining 4% to 8% of the produced water is made up of the injected hydraulic fracturing fluids that are returned to the surface (Willems et al., 2022). in North America, flowback-produced waters can be introduced into surface water environments through authorized discharges permitted under the National Pollutant Discharge Elimination System (NPDES), as well as through accidental spills and leaks. On the other hand, in Australia, where coal bed methane production remains prevalent in the natural gas industry, approximately 80% of flowback-produced water from coal bed methane is effectively and beneficially reused within the agricultural sector or through reinjection into underground water reservoirs (Willems et al., 2023).

CBM resources is found in shallow depth of less than 1000 meters, while tight/shale gas is exploited at a depth of about 3500 meters. Both tight gas and shale gas are produced faster, while CBM is produced at lower speed. However, the reduction rate for shale/tight gas is faster, between 70-90% during first year exploitation (Dadwal, 2012).

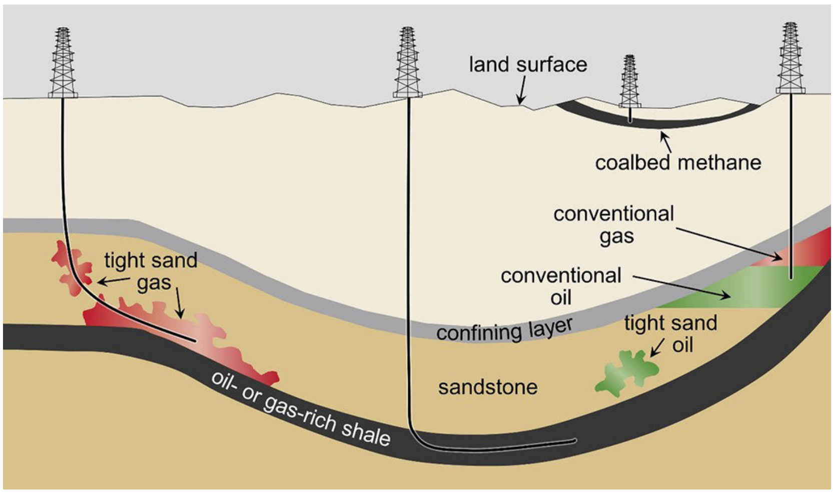

Figure1 schematic of onshore oil and gas resources (Capuano, 2018).

2.3. Shale and tight gas

Shale gas or tight gas refers to UNG trapped in fine grained low-permeability sedimentary rocks (usually below 0.1 mD), impermeable (tight) sandstone, siltstones, limestones or dolomite. Shale gas can be generated from the thermogenic or biogenic process. Biogenic natural gases are produced through the anaerobic biodegradation of organic matter, while thermogenic natural gases form as a result of the thermal decomposition of organic matter under high pressure and depth (Vinson et al., 2017; Milkov et al., 2020). Tight gas is a gas accumulated in relatively very low porosity and impermeable rock pores of limestone or sandstone, rather than shale formations. Shale gas is a type of natural gas that is trapped in fine-grained sedimentary rock formations. Its production typically requires HF technology. In contrast, tight gas sandstones act only as reservoirs. Coalbeds and shales, on the other hand, can serve both as a source rock and as a gas reservoir (McGlade et al., 2013; Rutter et al., 2022).

Effective porosity, permeability, pore size diameter, and the capillary pressure are some of the parameters controlling the fluid properties of a reservoir. (Table 1) shows reservoirs properties of unconventional and conventional gas resources. According to (table 1), the geological properties of conventional gas are more suitable, with porosity of 15%-30%, permeability of 10-1000 mD, pore size diameter higher than 2000 nm, and recovery efficiency of 50%-80%. In contrast, properties of unconventional reservoirs are poorer, especially in case of shale gas reservoirs. Typical coal porosity ranges from 0.5% to 5%, with 1-2% being the most common for current coals with commercial production. Shale and tight porosity are estimated to be under 10%. The hydrate gas sedimentary rock porosity is generally of < 30%, permeability of <100 mD and total organic carbon (TOC) of 0.5-2 wt. %. (Aminian et al., 2014). Permeability mainly controlled by pore-throat size. Pore-throat sizes are generally greater than 2000 nm in conventional reservoir rocks, range from about 20 to 700 nm in tight-gas, and range from 5 to 600 nm in shales, about 100 nm in hydrates and below 1000 nm in coalbed methane (Nelson et al., 2018). The porosity is directly associated with the TOC of the unconventional resources. The TOC content of reservoirs can range from as low as 0.5% in organic shale to as high as 90% in coal. Shales with TOC contents below 6% are the most common, accounting for roughly 74% of total resources (Mahmood et al., 2018; Wang et al., 2018).

The primary difference between unconventional and conventional gas resources lies in the forces that drive their accumulation. Conventional gas resources accumulate due to buoyancy, typically in structural or stratigraphic traps. There are abundant micro-nano pores in unconventional gas resources which caused strong capillary displacement forces in reservoirs. Therefore, buoyancy forces cannot dominate gas capillary pressure and thus cannot be the principal driving force for gas exploitation. In addition to the factors associated with the fluid properties, the rock parameters are also important. These are controlled by depositional environment of reservoir basin (Jiang et al., 2015; Song et al., 2015). (Table 2) indicate the most important field or basin in China and US. As mentioned before, unconventional gas has different lithology and reservoir condition compare to conventional reservoirs.

Table 1. Properties of unconventional gas reservoirs (Zou et al., 2018; Aminian et al., 2014; Wang et al., 2018; Yin et al., 2017)

	Gas storage	Porosity (%)	Permeability (mD)	Pore diameter (nm)	Geological rock	TOC (Wt. %)	Development technique	Ref.
Conventional	Free gas	15-30	10-1000	> 2000	Sandstone, limestone, dolomite	--	Vertical drilling, EOR	50-80
Coalbed	Mainly adsorbed gas	0.5-5	< 0.1	< 1000	Coal formation	Up to 90%	Horizontal drilling, HF	20-30
Methane	Mainly free gas	< 10	< 0.1	20-700	Sandstones Limestones	< 20	Horizontal drilling, HF	20-50
Tight gas	Free and absorbed gas	< 10	< 0.1	5-600	Sandstone, limestone	0.5-25	Horizontal drilling, HF	20-40
Shale gas	Crystalline compounds	< 30	< 100	~ 100	Sandstone, Siltstone	0.5-2	Horizontal drilling, In Situ thermal treatment	50-80

Table 2. Top unconventional gas resources (Jin et al., 2022; Satter et al., 2015; Wang et al., 2018; Jiang et al., 2018; Kamali et al., 2012; Liang et al., 2014; Hu et al., 2017; Yoon et al., 2018; Kamari et al., 2018; Karthikeyan et al., 2018))

Country	Field or Basin	Reservoir type	Lithology	Recoverable gas content (×10^8 m^3)	Formation properties			
					Area (km^2)	Depth (ft)	Average Porosity (%)	Average Permeability (nD)
U.S.	Barnett	Shale gas	Siliceous Mudstone	14100	7500	5000-8000	6	150
U.S.	Haynesville	Shale gas	Argillaceous Calcareous	71075	23300	10000-14500	6	658
U.S.	Horn River	Shale gas	Brittle Shale	13300	12950	6600-13000	3	230
U.S.	Eagle Ford	Shale gas	Bituminous Shales	2550	3500	4500-14000	11	1100
U.S.	Marcellus	Shale gas	Argillaceous Mudstone	74000	180000	5000-9000	10	600
U.S.	Bakken	Shale gas	Sandstone Siltstone Carbonite	27000	518000	5000-12000	5	20
U.S.	San Juan	Shale gas	Coal	3679	4144	2000-3000	8	200
U.S.	Uinta	Coalbed methane	Sandstone	4740	37500	1000-7000	8.7	95
China	Ordos	Shale and Tight gas	Sandstone Dolomite	30000	9167	6560-16400	6.7	604
China	Sichuan	Shale and Tight gas	Shale Dolomite	20000-30000	230000	6560-17000	5.7	351
China	Songliao	Shale and Tight gas	Sandstone	1046	285	7200-11500	5	224
China	Turpan-Hami	Shale and Tight gas	Sandstone	Not found	35000	9800-12000	9.1	106
China	Junggar	Shale and Tight gas	Dolomite Siltstone	8800-12100	130000	13800-15700	6.5	125

2.4. Gas hydrate

Gas hydrate is a compound including of a lattice of host molecules (water) that enclose various sized gas molecules such as methane, nitrogen, and carbon dioxide without chemical bonding. Methane is typically the most abundant guest molecule found in gas hydrate resources. Gas hydrates have a volumetric conversion factor that can vary between approximately 160 to 180, meaning that they can hold significantly more gas than an equivalent reservoir volume of free methane (Gabitto et al., 2010). Gas hydrate formation is controlled by factors such as temperature, pressure and reservoir rocks. Under low-temperature and high-pressure conditions, gas hydrate is not stable and these conditions are not available in most basins. These conditions predominantly occur in continental slope sediment roughly between 4000 to 6000 ft under surface (depending on local conditions) (Hancock et al., 2019). Gas hydrate can be either thermogenic or biogenic gas. Biogenic hydrates predominate in depths >1000 meters, while thermogenic hydrates have been located in the 400-to-800-meter depth range with only a few sites such as in the Gulf of Mexico, Cascadia, and in the Caspian Sea (Zhang et al., 2019; Koh et al., 2007).

The gas clathrate forms differently shaped lattice to accumulate gas molecules. Clathrate hydrates typically exhibit one of three distinct structures: the body-centered cubic lattice structure I (sI), the diamond lattice structure II (sII), and the hexagonal lattice structure (sH). In each structure, water molecules arrange in unique patterns to create cavities of varying diameters, which are held together by hydrogen bonds and Van der Waals forces between the gas and water molecules. Most gas hydrates adopt the sI structure and have been identified in various locations, including the Gulf of Mexico, Ulleung Basin, and the South China Sea. In contrast, thermogenic hydrate sediments that form sII and sH structures can exist under milder conditions and have been found in several deposits, such as those in the Gulf of Mexico and Caspian Sea (Chong et al., 2016; Bavoh et al., 2020).

3. Unconventional Gas around the World

According to recent assessments, the total proven unconventional oil and gas reservoirs (excluding hydrates) around the world are estimated to be 5833.5×10^{8} t, with unconventional oil resources accounting for 4209.4×10^{8} t. The assessment also estimates that the global recoverable unconventional gas resources are approximately $227\times10^{12}m^{3}$, with tight gas and shale gas accounting for $161\times10^{12}m^{3}$ and coalbed methane accounting for $49\times10^{12}m^{3}$ see (Figure 2). (Figure 2) shows the distribution of technically recoverable global gas resources around the world, with shale and tight gas primarily concentrated in North America, Central Asia, and the Asia-Pacific region, and coalbed methane mainly produced in Canada, the US, Australia, and China. Gas hydrate, on the other hand, is found in continental margins and polar regions and is estimated to be 300 times more abundant than the gas in the remaining recoverable conventional reserves in the United States (Tong et al., 2018; Jianchao et al., 2018).

The global unconventional oil and gas resources are distributed mainly in 363 basins in 60 countries. Recoverable unconventional gas reservoirs mainly concentrate in 106 basins in 37 countries, the top countries include the US, Iran, Canada, China, Russia, Australia, Saudi Arabia, Brazil, Argentina and Libya, with 76.8% of the global resources. While some countries are actively pursuing the production and exploitation of their unconventional gas reserves, others are still in the process of exploring and developing these resources. Some countries have yet to make a decision about developing their unconventional resources, either because their unconventional gas reserves are relatively small or because their conventional gas reservoirs are much larger (Tong et al., 2018; Cooper et al., 2016).

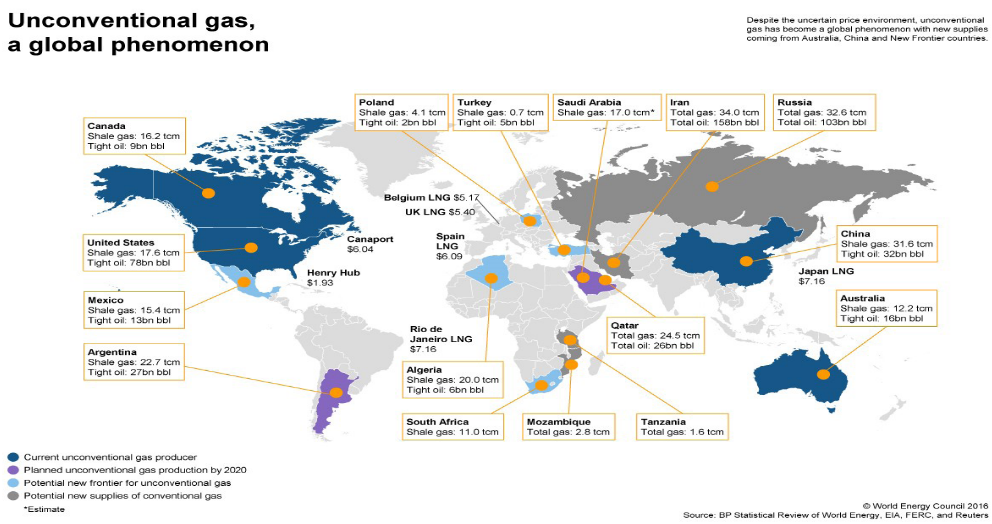

Figure 2. technically recoverable global conventional and unconventional gas resources (source: BP statistical review of world energy, EIA, FERC and Reuters)

According to estimates, the US has approximately $39\times10^{12}m^3$ of recoverable gas resources, accounting for 17.4% of the global total. The majority of these resources are shale gas. China has an estimated $31\times10^{12}m^3$ of recoverable gas resources, accounting for 13.9% of the global total. These resources are largely comprised of shale gas, coalbed methane, and tight gas. Russia has an estimated $29\times10^{12}m^3$ of recoverable gas resources, accounting for 12.6% of the global total, with shale gas and coalbed methane being the primary sources. Canada has an estimated $16\times10^{12}m^3$ of recoverable gas resources, accounting for 7% of the global total, with coalbed methane and shale gas being the primary sources (Hongjun et al., 2016). In the European Union, countries such as Poland and France have estimated technically recoverable shale resources of 4.19 billion and 3.87 billion, respectively. Other countries with predicted technically recoverable shale gas resources include Romania (1.44 $\times10^9$ m^3), Denmark (900 $\times10^6$ m^3), the United Kingdom and the Netherlands (730 $\times10^6$ m^3 each), as well as Germany and Bulgaria (481 $\times10^6$ m^3 each) (Reins, 2014).

4. World Production and Consumption

Over the past decade, advanced HF, directional drilling and related technologies significantly enable the production of oil and natural gas, particularly from unconventional oil and gas resources. Aguilera et al assessed the supply curves of CvNG and UNG (excluding gas hydrates) for the global gas markets. Based on their estimates, there is currently sufficient natural gas reserves to meet global energy demands for almost 400 years at current consumption rates. If production were to increase at a rate of 2% per year, these reserves would last for around 110 years (Aguilera et al., 2014).

Global unconventional gas production in 2015 reached 8227×10^8 m^3, accounting for 23% of total gas production. Tight gas was the first unconventional deposits that has been developed economically. The Cauthage field in the US produced daily gas of 340×10^4 m^3 in 1955 and became the US's largest tight gas reserves in 1976. The US tight gas production was more than 600×10^8 m^3 in 1998 and $1200\times10^8m^3$ in 2015 (Chengzao, 2017). According to a study by Jia et al., the unconventional gas industry has experienced rapid growth. Based on predictions, coalbed methane production is expected to remain at 136×10^9 m^3 in 2035, while unconventional natural gas production is projected to increase to 115×10^9 m^3. In addition, an estimated 9×10^9 m^3 of dissolved gas is expected to contribute to a total domestic natural gas production of 260×10^9 m^3 (Jia et al., 2021). In 2019, shale oil production in the United States represented a significant portion, accounting for 63.3% of the total oil production within the country. Looking at global reserves, in 2020, China had proved unconventional oil and gas reserves of 350 million tons, while the world's total proved unconventional reserves amounted to 5.45 billion tons of oil equivalent. These reserves contributed to more than 50% of the newly added global reserves during that period (Jia et al., 2023). Between 2009 and 2019, the United States saw a significant increase in the annual production of shale gas and tight oil (including shale oil). Specifically, shale gas production increased from 1.4×10^{11} to 7.2×10^{11} m^3, while tight oil production increased from 3.2×10^7 to 3.9×10^8 tons. Outside of North America, China has become a major player in the exploitation of unconventional petroleum resources. In 2020, China's annual production of shale gas exceeded 2×10^{10} m^3, while tight gas and tight oil production reached over 4.5×10^{10} m^3 and 3×10^6 tons, respectively (Zou et al., 2022).

(Table 3) shows natural gas consumption and projection of world in future. The results indicate that the US and Russia were the largest gas consumers in 2016 by using 75 Bcf/D and 38 Bcf/D respectively. In the future, global gas consumption by 33% between 2016 and 2040. It will reach 502 Bcf/D. All of the growth in energy consumption comes from developing economies and population growth. China, India and other emerging Asia are expected to consume half of the natural gas demand by 2040. Among the different countries, China will have the largest growth in global gas consumption. Chengzao et al. have developed a predictive model for estimating the potential of tight gas resources in China. According to their model, the geological resources of tight gas in China are estimated to range from 17.4×10^{12} to 25.1×10^{12} m^3, with an estimated extractable resource of 8.8×10^{12} to 12.1×10^{12} m^3 (Chengzao et al., 2012).

Table 3. World gas consumption and projection in future, 1990-2040 (Global BP, 2017).

Year / Billion Cubic feet per day	1990	1995	2000	2005	2010	2016	2020	2025	2030	2035	2040
North America	62	72	77	76	82	93	102	109	114	120	126
US	53	61	64	60	66	75	81	85	89	93	97
S. & Cent. America	6	7	9	12	15	17	18	20	23	26	29
Brazil	0	0	1	2	3	4	4	6	7	8	8
Europe	33	38	45	51	53	47	49	51	51	51	50
EU	32	36	43	48	48	41	43	44	44	44	42
CIS	61	51	50	54	55	53	55	56	55	55	53
Russia	39	35	35	38	40	38	41	41	40	40	38
Middle East	9	14	18	27	38	49	54	62	68	74	80
Africa	4	5	6	8	10	13	15	19	22	27	33
Asia Pacific	15	20	28	39	55	70	84	97	109	120	131
China	2	2	2	5	11	20	31	39	46	53	60
India	1	2	3	3	6	5	6	8	10	11	14
Other Asia	5	8	12	18	21	25	28	31	33	35	38
World	189	206	233	268	308	342	377	413	444	474	502
OECD	102	118	133	140	152	160	170	179	185	192	195
Non-OECD	87	88	101	128	157	182	207	234	259	282	307

(Figure 3) shows the global consumption of primary energy resources in terms of Million's toe and their ratio in percentage. As the results indicate different countries would have to invest more in renewable energy and natural gas by the year 2040. Renewable energy will account for 40% of energy consumption, while Natural gas grows much faster than oil or coal and the share of natural gas consumption will be 26%. Coal consumption will decrease in the next 10 years. However, China remains the world's largest coal market, accounting for 40% of global demand in 2040. The share of coal energy declining from about a third today to less than a quarter in 2040. In contrast, renewable energy, together with nuclear and hydro, account for more than 80% of China's energy demand by 2040 (Global BP, 2017).

The first economically CBM well was drilled in the Appalachian basin in the early 1980s. For over a decade, CBM has been extracted from various coal basins in North America, including the San Juan and Powder River basins. Currently, CBM accounts for approximately 10% of total US gas production, with the majority of production coming from the Black Warrior basin, San Juan in Colorado, and the Powder River basin. In 2016, CBM production in the US amounted to roughly 4% of the country's total natural gas consumption (Joshi et al., 2022).

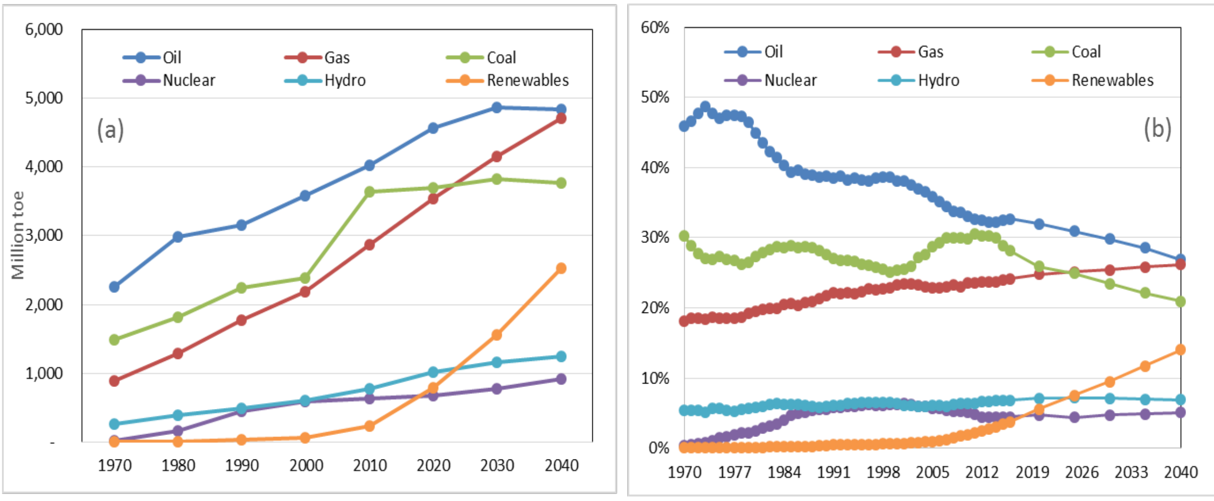

Figure 3. Estimate of global natural gas consumption, (a) Mtoe, (b) percent (Global BP, 2017).

The first economically CBM well was drilled in the Appalachian basin in the early 1980s. For over a decade, CBM has been extracted from various coal basins in North America, including the San Juan and Powder River basins. Currently, CBM accounts for approximately 10% of total US gas production, with the majority of production coming from the Black Warrior basin, San Juan in Colorado, and the Powder River basin. In 2016, CBM production in the US amounted to roughly 4% of the country's total natural gas consumption (Joshi et al., 2022).

According to projections, US energy production is expected to increase by approximately 31% from 2017 through 2050, due to increases in the production of renewables, natural gas, and crude oil. However, it should be noted that crude oil production is expected to increase only during the first 15 years of the projection period. Natural gas production accounts for nearly 39% of U.S. energy production. Unconventional resources play as a substantial share of total U.S. natural gas production because of the shale gas resources. However, by using more in transportation, electricity generation and petrochemical industry, the total growth in gas demand may be much faster than expected by EIA. It is expected that the global unconventional oil and gas yield reached more than 20% of the total production by 2030. While shale gas exploration is being conducted in many countries around the world, commercial production from shale reservoirs is currently limited to only four countries: the United States, Canada, China, and Argentina. Shale gas production in the US began in 2007 and has been ongoing since then (Solarin et al., 2020). (Figure 4(a)) shows several U.S. shales deposits have been developed in gas production. Over the past 10 years, Barnett is the most productive gas field in Texas due to annual production and is growing at an annual rate of more than 10 %. Exploitation of the Marcellus formation in the United States led to an increase in gas production starting in 2004. In 2011, further increases in gas production were observed due to exploitation of the Cretaceous Eagle Ford Formation and the Jurassic Haynesville Shale (Solarin et al., 2020; Kirat, 2021). According to a report by the Energy Information Administration (Capuano, 2018), the United States has been the leading global producer of natural gas since 2009, when its production surpassed that of Russia. The report states that the US currently produces approximately 20% of the world's total supply, with around 40% of this production coming from shale gas fields. Notably, the US is the only country in the world that has engaged in shale gas production (Figure 4(b)). The report also projects that shale gas exploitation will grow by over 113% by 2043, and is expected to make up 79% of US natural gas production.

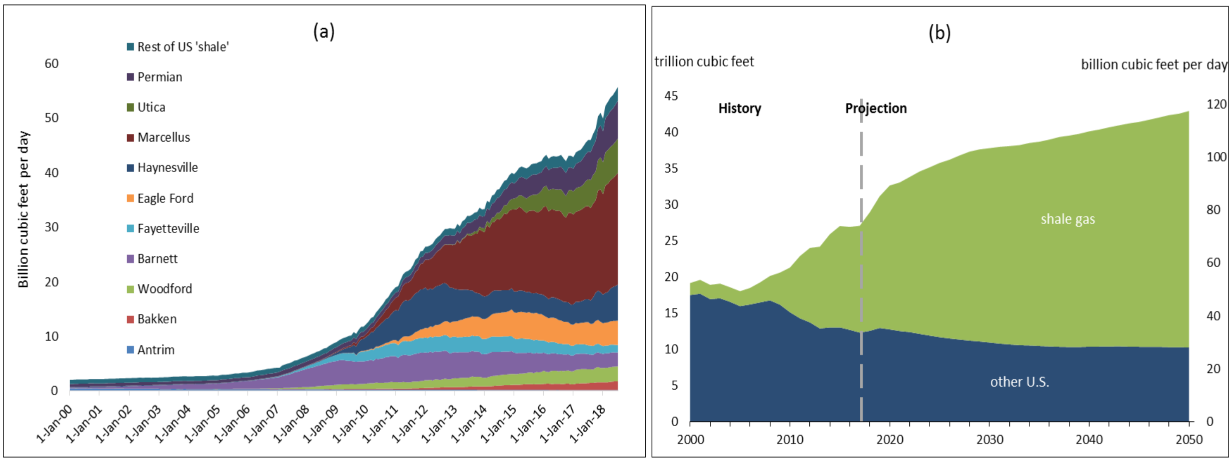

Figure 4. (a) U.S. dry natural gas production history and projection between 2000-2050 years (b) production of shale gas (Capuano, 2018).

The U.S. program has two plans, focusing on both the North Slope of Alaska and the Gulf of Mexico. Japan, India and the South Korean have expanded their gas hydrate program focusing on Nankai area, Ulleung Basin by using the drillship since 2010 respectively. The goal is to explore an appropriate site for a future production test. There are also gas hydrate development programs in Brazil, Colombia, Iran, Mexico, South Africa, and Uruguay. As U.S. achieves economical exploitation over the next years, it seems that other nations will begin programs to evaluate the gas hydrate resource potential (Yu et al., 2021; Chong et al., 2017).

5. Challenges Ahead

5.1. Potential risks to ecosystem health

UNG development includes several steps such as (1) well pad and infrastructure construction; (2) pipelines related to drilling and other facilities; (3) HF; (4) flow back of fracturing fluid which contains gas and fluid formation; (5) subsequent connection of production unit to the distribution system (Adgate et al., 2014). Each part of this process has potential of adverse effects, including significant sources of contamination for surface and ground water, producing more greenhouse gases, particulate air pollution, increased frequency of earthquakes, and harmful association with humans or livestock farming health (Deziel et al., 2022). In general, comprehensive environmental impact assessment and associated assumptions of unconventional gas production requires four steps. (1) Water resources, (2) air quality and climate change, (3) public health, (4) socioeconomic and community effects. Therefore, it could be argued that unconventional gas production poses public debate on the balance between the economic benefits of extraction of oil and gas and the associated environmental and health risks (Orak et al., 2021; Vengosh et al., 2017). However, unconventional gas development is controversial because of various sustainability problems related to its development and distribution.

Natural gas is predominantly composed of methane, which is a potential greenhouse gas. Methane has been estimated to have a climate impact that is 84-87 times greater than carbon dioxide over a 20-year period, making it a significant contributor to global warming. Consequently, methane emissions to the atmosphere from the development of unconventional gas (shale gas up to date) can have a large influence on the greenhouse footprints of UNG and related climate changes. The available data for estimating fugitive methane emissions from unconventional gas were poorly documented. Several recent studies by evaluating trends in downstream emissions (storing gas and delivering it to market) and upstream emissions (drilling and HF activity) for different shale regions (the Eagle Ford in Texas, the Bakken in North Dakota and Marcellus shale), estimated that the life cycle fugitive methane emissions of shale gas (considering from well to final consumer) were ~1.5 times higher than that of conventional natural gas (CvNG) (Deziel et al., 2022; Howarth et al., 2011; Schneising et al., 2014; Fernando et al., 2021). In the various researches, there is no obvious relationship between the methane in conventional and unconventional fields. The results demonstrate that the rate of emission depends on the well pad condition and natural gas production rate. Omara et al. have addressed methane emissions fluxes at the large scale in Pennsylvania and West Virginia in the Marcellus region. The total annual CH_4 emissions from 88,500 CvNG well pads were much greater than 3390 UNG well pads. The results show that CvNG well pads emissions 16% of total CvNG gas production. In contrast, UNG well pads emitted 0.64% of total production. The greater prevalence of avoidable process and operating conditions (e.g., unresolved equipment maintenance issues) have led to more methane emission in the CvNG well pads (Omara et al., 2016). McKenzie et al. evaluated the risks to human life's living near natural gas wells. They calculated cancer risks for residents living near wells compared to residents who live in remote areas during well completions. The results show that health effects resulting from gas emissions during development of unconventional gas resources are higher in residents close to the well pads (McKenzie et al., 2012). Benzene is the major factor of life-threatening cancer. Because of greater scale operations and above-ground infrastructure for economical producing rate, environmental impacts of unconventional gas exploitation are greater than for conventional gas deposits (Apergis et al., 2021). However, the emissions from this process could substantially increase the greenhouse gases in comparison to other renewable energy resources and many of the above-mentioned concerns have been further substantiated. Buchanan et al. evaluated the effects of water resources consumption in the development of Marcellus Shale which may have adverse effects on freshwater biological ecosystems. The results indicate that surface water discharge, can have significant environmental consequences and must be properly managed. Water resources withdrawals can significantly change natural flow regimes especially small drainage streams and the health of fish community (Buchanan et al., 2017).

As already mentioned, it is necessary to consider the influence of exploitation of unconventional resources on environment. Extraction unconventional gas reservoirs requires considerable amounts of water, that reduces the water levels, and it may affect human health. Another environmental constrains is the management of the fracturing flow-back. The flow-back should be restored and disposed. different disposal options are available: injection into used wells; treatment on site, then water can be reused for extraction of unconventional gas; or disposal an offsite treatment plant. each of these may cause significant damage to environmental or human health (Delgado et al., 2016). The high frequency of toxic chemicals used for HF including halides can persist in the environment and contaminated water (Vengosh et al., 2017).

Fracturing fluid primarily composed water as base fluid and sand (90 and 9% volume, respectively) and chemical additives (0.5-2% volume) used to hydraulic stimulate of unconventional gas resources. Some of the chemicals in (Table 4) are known to be toxic and carcinogenic. The amount of water and chemicals, including friction reducers, scale inhibitors, biocides, surfactants, corrosion inhibitors, clay stabilizers, iron control agents, gelling agents, cross-linkers, breakers, and pH adjustors, injected into a wellbore can vary depending on reservoir conditions, such as permeability, pressure, in-situ stress distribution, depth, and type of rock formation, as well as the number of stages in the well. Typically, between 3 and 50 million liters of water are injected along with varying amounts of chemicals at different application rates (McLaughlin et al., 2016; Yap, 2016; Khan et al., 2021). Each of these chemicals have distinct application. For instance, proppant form a thin layer between fracture faces to sustain the crack. The breakers (1-400 mg L^{-1}) reduces the viscosity of fluids and allows removal of residual polymers from fractures. 100-300 mg L^{-1} of Buffer agent are used to control pH of fluid and effectiveness of other chemical additives. The role of Crosslinker is to enhance fluid viscosity and elasticity as temperature changes. The higher viscosity increases the fracture width so that improves transport of proppant and reduces friction pressure. The most cross linkers used in fracturing fluid is quaternary Ammonium Chloride. The other chemicals and their application rates are shown in (Table 4) (Stringfellow et al., 2014; Barati et al., 2014). Flow back water contain injected hydraulic fracturing fluids and the fluids and chemicals within the formation. So, the waste water has different effects on environment around the well. Vengosh et al. studied the effect of shale gas development and HF on water resources in the US.

Studies suggest that the exploitation of shale gas can have a range of negative impacts, including: (1) pollution of shallow aquifers, which can potentially lead to the salinization of groundwater due to the underground leakage of fugitive gas; (2) contamination of surface water resources or shallow groundwater resulting from spills or improper disposal of hydraulic fracturing fluids; (3) the introduction of toxic chemicals into the soil, river basins, or lakes exposed to wastewater or fluids used in hydraulic fracturing operations; and (4) the excessive extraction of water resources for large-volume hydraulic fracturing fluids, which could exacerbate water shortages, particularly in water-scarce regions (Vengosh et al., 2014).

The UNG exploitation includes the equipment, labor, water, chemicals, and many other materials during production operation. Adgate et al (Adgate et al., 2014) evaluate the population health effects of UNG development in the US. The most important possible worker's health effects are damage caused by chemical stressors (e.g., H_2S and silica). Research has identified stressors that can negatively impact local workers involved in shale gas extraction. These stressors include exposure to hazardous chemicals, such as volatile organic compounds, diesel exhaust, and hydraulic fracturing wastes, which can migrate offsite through spills, leaks, or accidents. Patterson et al. investigated spill data from 2005 to 2014 at 31481 artificial fractured unconventional oil and gas wells in four states: Colorado, New Mexico, North Dakota, and Pennsylvania. During the first three years of well-life, 75 to 94% of spills occurred when wells were drilled and produce oil and gas in large volumes. In all four states, 50% of spills were due to storage and transmission of streams through the pipeline (Patterson et al., 2017). The HF can react with the formation and change the quality of flow-back water. For instance, Jackson et al. evaluated the flow-back fluids from gas wells in Fayetteville, Marcellus, and Barnett formations. The flow back fluids contain dissolved salts. In case of Marcellus, common salts are, Na 5363 mg/L; Ca 77 mg/L; SO_4 149 mg/L. The flow-back fluids usually require on-site storage followed by recycling, reinjection, or disposal into a saline aquifer (Jackson et al., 2013). The results of environmental effects of unconventional gas that have been above-mentioned are related to shale, tight gas and coal bed methane. The environmental impact of gas hydrates exploitation is still unknown. Therefore, further research is required to evaluate the effects of dissociation of hydrate sediments which may have impacts on sea-floor stability.

Table 4. Most ingredient used in HF fluid in gas production well (Cooper et al., 2016; Khan et al., 2021; Barati et al., 2014; Yap et al., 2016).

Additive		Application rates	Purpose
Clay Stabilizer	Choline Chloride Tetramethyl ammonium Chloride	500-2000 mg L^{-1}	Prevents clays from swelling
Proppant	Sand	~ 9% volume fraction	Form a thin layer between fracture faces to prop the fractures open
Crosslinker	Ammonium chloride Boric Acid Borate Salts Potassium hydroxide	0.5-250 mg L^{-1}	Maintains fluid viscosity, more elasticity and better proppant transport as temperature increases
Gelling Agent	Derivative of Guar Ethylene Glycol	10-1000 mg L^{-1}	Better proppant suspension and fluid stabilizer
Scale inhibitors	Phosphonic acid salts Sodium polycarboxylate Sodium acrylate,	75-400 mg L^{-1}	Protect piping and prevent from plugging
Corrosion inhibitor	Formic acid Acetaldehyde	10-7000 mg L^{-1}	Form protective layer and preventing corrosion
Iron Control	Citric Acid Acetic Acid ammonium chloride Sodium Erythorbate	50-200 mg L^{-1}	Prevents precipitation of metal oxides (control iron precipitation)
Biocide	Glutaraldehyde Quaternary Ammonium Chloride	10-800 mg L^{-1}	Control bacteria in the water that degrade fracturing chemicals and produces corrosive by-products
Friction reducer	Polyacrylamide	30-1200 mg L^{-1}	Reduce fluid surface tension and facilitate removal of fracturing fluid from the formation.
Breaker	Methanol Ethanol Sodium Chloride Isopropanol	1-400 mg L^{-1}	The breaker reduces the viscosity of fluids and allows removal of residual polymers from fractures
Buffer agent	Potassium Hydroxide Potassium Carbonate Acetic Acid Sodium hydroxide Sodium Carbonate Acetaldehyde Acetone	100-300 mg L^{-1}	Adjusts the pH of fluid to maintain the effectiveness of other chemical additives.
Surfactant	Sodium lauryl sulfate Isopropyl Alcohol 2-Butoxyethanol	500-1800 mg L^{-1}	Fluid stabilizer (control viscosity and surface tension)

5.2. Challenges of Production development

The extraction and production of unconventional gas reservoirs are still not fully understood, and for some reservoir types, we are still in the early stages of development. As a result, methods for evaluating hydraulic fracture properties are also in their early stages and are not yet fully developed. In recent times, there has been a growing utilization of nanomaterials and technologies in the hydraulic fracturing of unconventional oil and gas reservoirs, resulting in notable advancements. Nanomaterials can be customized in terms of their surface properties and activity to enhance the efficiency of fracturing fluid systems. This makes them particularly well-suited for application in challenging formation conditions, such as high temperatures and pressures (Mao et al., 2022; Marsden et al., 2022). Unconventional gas exploitation will face challenges in the following aspects: using significant amount of water in HF, deep water drilling hazard (in particular in gas hydrate accumulation). The depth of most shale gas basin in North America are usually more than one kilometer (e.g., the eastern extent of the Colorado ~300 m depth). Many coalbed gas formations are predominantly in shallow depths (less than 600 m) and horizontal fracturing is used in such cases. The empirical studies propose that horizontal fracturing predominates in shallower than 450 m depth, while vertical fracture being used in depth more than 600 m depth (Jackson et al., 2013; Tan et al., 2019).

Porosity, Permeability and pore size distribution are key parameters for developing an unconventional accumulation. Porosity of unconventional deposits is less than 10%, pore size of less than 1 μm and permeability values of less than 1×10^{-3} μm^2 which mean that the gas cannot flow easily within the rock under natural forces in the reservoir (Caineng et al., 2013).

Over the past decade, there has been significant growth in the use of horizontal drilling, hydraulic fracturing, and micro-seismic monitoring to exploit previously inaccessible or unprofitable hydrocarbon resources in shale gas reservoirs. HF is typically performed using a fracturing fluid made up of water, sand, and chemical additives. This extraction method involves injecting millions of gallons of water, sand, and chemicals under high pressure into the wellbore through horizontal or vertical drilling, which induces the unconventional gas reservoir and allows for the extraction of natural gas (Vengosh et al., 2017). The pumped fluid reaches the pressure of 8000 psi and may fracture a shale formation depth of 3000 feet in the lateral direction. The HF decomposes shale matrix and connects natural fractures to improve the reservoir permeability. The production of shale gas by HF compared to the conventional gas, consume large volume of water and chemicals with two orders of magnitude (Deziel et al., 2022). The amount of water required for HF is significant, ranging from 3000-21000 m^3, which constitutes 86% of the direct water needed to extract shale and 56% of the total consumption in the shale gas lifecycle. As production scales up, water consumption in a watershed is expected to increase. However, it can be difficult to accurately attribute changes in water levels solely to shale gas production, as other activities such as power plants and agricultural land use should also be taken into account when assessing water usage in a watershed (Cooper et al., 2016).

In 2013, Scanlon et al. compared the amount of water used in hydraulic fracturing for oil and gas production in the Eagle Ford shale and Bakken formations. They found that the average water use per well was similar for both oil and gas fields in the Eagle Ford, ranging from 4.7 to 4.9 million gallons per well. In contrast, the average water consumption in the Bakken formation was approximately half that of the Eagle Ford, at 2.0 million gallons per well. The Pennsylvania Department of Conservation and Natural Resources estimates that completion of a horizontal well in the Marcellus shale formation can require up to 3.0 million gallons of water (Scanlon et al., 2014; Conard et al., 2020; Kotsakis et al., 2012). In multiphase reservoirs containing gas and water, a threshold capillary pressure must be overcome to displace the wetting phase from the pores. Once this threshold pressure is exceeded, fluid flow is primarily controlled by capillary pressure and the pressure gradient. In cases where capillary pressure prevents viscous gas flow, molecular diffusion becomes more prominent. In shale deposits, the interaction of reservoir gases with the dispersed organic accumulation is one of the primary mechanisms that controls gas transport, according to studies by Bizhani et al. (2022) and Amann-Hildenbrand et al. (2012)).

6. Economic implications

The development of unconventional gas reservoirs can provide several potential opportunities and benefits. The need to drill large numbers of horizontal wells and perform hydraulic fracturing operations can support local businesses, making unconventional gas production more akin to a manufacturing process than traditional oil or gas production. Additionally, the replacement of coal with gas in the power sector can offer environmental benefits, such as reduced conventional pollution and greenhouse gas emissions. A study by Cronshaw et al. found that the US was able to reduce its greenhouse gas emissions by nearly 5% between 2010 and 2012 due to the increased use of natural gas in the power sector (Cronshaw et al., 2016). Unconventional gas development has many qualities that make it an efficient. The HF and directional drilling have the ability to drill multiple wells from a single well, which can be led to a considerable decline in surface footprint of the exploitation process. Unconventional gas resources reduce greenhouse gas emissions because natural gas has lower carbon and the combustion of natural gas emits 50% to 80% less CO_2 per unit of energy than that of coal (about 56% for gas and 79% for oil) (Schneising et al., 2014).

Bocora et al. conducted an assessment of the economic benefits of unconventional gas development in the US, where companies have discovered several large deposits of shale gas. The use of technologies such as horizontal drilling and hydraulic fracturing has enabled economically large-scale production. The development of unconventional gas reserves in the US could result in $3.2 trillion in investments and create 1.4 million new job opportunities (Bocora, 2012). Furthermore, the US has increased its natural gas production and is now looking to become a net exporter of natural gas to other markets such as the European Union or Japan, where the market price is higher. It can be seen that; unconventional gas exploitation is much lower in other countries due to economic and technologic backwardness (Shirazi et al., 2022; Le et al., 2017). Le et al. evaluated opportunities and challenges of Unconventional gas development in Vietnam. The gas consumption in Vietnam is projected to reach 17 billion cubic meters in 2025, and the estimates of Vietnam's gas demand will grow 188% between 2015 to 2040 years. The conventional gas resources may not be sufficient. So, unconventional gas could potentially provide the shortfall. The potential of unconventional gas in Vietnam remains at an initial stage of evaluation. In the recent years, CBM resources have been exploited and confined to the Red River Basin (Le et al., 2017).

7. Conclusions

The paper discusses the assessment of unconventional gas resources, as the future fossil fuel of the world. Low permeability is the Achilles heel for unconventional resources and horizontal wells with the option of the fluid fracturing process would facilitate the reservoir development. According to the research, the main challenges for the development of unconventional gas reservoirs are high production cost of unconventional gas, environmental restrictions, low production efficiency, undeveloped techniques for deep seafloors gas reservoirs and inadequate understanding of gas hydrate resources.

List of Acronyms

Bcf/D	Billion cubic feet per day
bcm	Billion cubic meters
CBM	Coalbed methane
CvNG	Conventional natural gas
EOR	Enhanced oil recovery
gal	Gallon
HF	Hydraulic fracturing
HFF	Hydraulic fracturing fluid
Mtoe	Million tonnes of oil equivalent
nD	Nano Darcy
NP-DES	National Pollutant Discharge Elimination System
TOC	Total organic carbon
UGR	Unconventional gas resources
UNG	Unconventional natural gas
Wt. %	weight percent
Mcf	1000 cubic feet

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ارزیابی مخازن گاز طبیعی غیرمتعارف

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چکیـــــده

در قرن بیست و یکم، حجم بزرگی از نفت و گاز در صنعت پتروشیمی مصرف می‌شود که با در نظر گرفتن جمعیت رو به رشد تقاضای انرژی جهانی رو به افزایش است. گاز طبیعی، پاک‌ترین منابع غیرقابل تجدید است که در مقایسه با دیگر هیدروکربن‌ها، به‌عنوان یک منبع انرژی مهم در نظر گرفته می‌شود. به‌طورکلی با توجه به حجم بزرگی از شیل گازی، ماسه‌ای متراکم گازی و بسترهای زغالی و هیدرات گازی، مخازن گاز غیرمتداول به‌عنوان یک منبع عظیم هیدروکربن شناخته شده است. دامنه این مطالعه شامل تأثیرات زیست‌محیطی، ویژگی‌های زمین‌شناسی، موانع و چالش‌های فنی استخراج از مخازن غیرمتعارف از جمله تقاضای انرژی، مصرف و تولید انرژی، آلودگی آب، انتشار گاز گلخانه‌ای و ویژگی‌های زمین‌شناسی مخزن است. این مقاله به بررسی روش‌های نوظهور در توسعه گاز غیرمتعارف در کشورهای مختلف با تمرکز بر ایالات‌متحده می‌پردازد. نتایج نشان می‌دهند که امکان توسعه گازی غیرمتعارف در کشورهای مختلف وجود دارد، اما آینده آن به مسائل زیست‌محیطی، سرمایه‌گذاری در انرژی‌های تجدیدپذیر و بازارهای جهانی گاز بستگی دارد.

واژگان کلیدی: گاز غیرمتعارف، شیل گازی، ماسه‌ای متراکم گازی، بسترهای زغالی متان، هیدرات گازی