Review Article

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Exploration and development of Shale gas in China: A review

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Abstract

This study presents a critical historical review of shale gas exploration and development in China from 2000 to 2020. It reviews achievements in theoretical and technological understandings by summarizing successful experiences in commercial development and prospects for future development. The analytical review implies that shale gas has become an emerging unconventional resource of energy, gaining much importance as a substitution over the past two decades with the use of cutting-edge technology. The developing proportion of natural gas in China's energy utilization system and the success of its commercial potential, along with significant progress in the prospective evaluation and pilot testing, indicates that shale gas is likely to be the most reliable future source of energy in China. The production of shale gas in the Sichuan Basin and its environs has relied on technological advancements in six areas: comprehensive geological evaluation; development optimization; fast drilling of horizontal wells; volume fracturing of horizontal wells; factory-like operation, and efficient and clean production. Further, the accomplishment of economic development of shale gas can be summarized from four key factors: (a) optimized horizontal section targets; (b) supporting technologies for effective and fast drilling and volume fracturing stimulation; (c) geological and engineering integration; (d) advanced organization and management. Lastly, with an anticipated 30 to 60 billion m^3 yearly commercial output in China indicates that shale gas has an immense usage potential to support future natural gas production growth. The given analytical, historical review is significantly helpful for stakeholders to formulate policies concerning the exploration industry.

Keywords: *Shale Gas, Unconventional Source, Production Technology Development, Annual Output, China*

1. Introduction

Shale gas is a rock resource and reservoir bed of shale gas, containing gases, mainly methane, and obtained from biogenic and thermogenic processes to classify the pores (Colosimo et al. 2016). It may contain biogenic, thermogenic, or biogenic gases (Kinnaman 2011). Thus, the study of the morphology, genesis, and distribution of the gas, the estimation of shale gas reserves, and shale pores understanding becomes an essential task for researchers and decision-makers (Niu et al. 2013). It is a renewable, relatively reliable, and alternative energy fuel, with approximately 1.4 times more efficiency than the other natural gas resources (Jenner et al. 2013). Its exploration and improvement have drawn attention from many nations and have experienced rapid growth.

From the innovation viewpoint, shale gas is a rising or sustainable breakthrough for mature and sustainable growth industry extremely profitable, the oil and gas sector (Basher et al. 2012). It is of great economic significance as it creates self-included reservoir-source networks with broad continuous (unconventional) extents. To achieve this goal and diversify the energy mix, shale gas can be one of the most valuable and compensating sources of modern energy fuels. It has low carbon emissions compared to other energy fuels such as coal, charcoal, and oil. Shale gas deposits can be found in the heterogeneous porous media and extracted as free gas (Jarvie et al. 2007). Further, the latest activities suggest that the world's largest energy demand supplier would be unconventional reservoirs (Umar et al. 2021; Mangi et al. 2020). Bearing all this in mind, this study aims to provide a brief account of exploration and China's developmental issues of shale gas in recent times and analyze its effects as an unconventional energy source. In China, unconventional gas provides the most contribution of the unconventional resources and accounts for 39.2% reserves and 24.6% annual production of the total natural gas (GhasemShirazi et al. 2014; Aqsa et al. 2022a; 2022b). After giving a brief analytical review, the study suggests some crucial steps to be taken by the government to excel in the development and make the environment more impactful. For this purpose, the government has to investigate and check the potential of shale gas as a cradle of energy in the coming times to make sure that it does not degrade the environment and resolve the energy crisis. With increased awareness and knowledge regarding shale gas reservoirs, it is possible to sort the crisis level to some reasonable extent. The

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analytical and critical historical review of this study is significantly helpful to formulate policies by the stakeholders accordingly.

2. Global Prospective of Shale Gas Development, Characteristics, and Production

Shale gas has dispersed usage as an energy source in power generation, heating, cooling, and transportation. Despite its wide potential utilization, its exploration is quite time-consuming, expensive, and requires advanced technology and knowledge to understand the composition of rocks, their permeability, and value, which is also vitally important (Hasan et al. 2015). In accordance with the 2013 EIA assessment, shale gas deposits were exceptionally abundant globally, with up to 206.56×10^{12} m^3 of technically viable shale gas resources (Kuuskraa et al. 2013). Significant shale gas deposits in North America provided a strongly integrated platform for the "shale gas revolution." However, shale gas extraction has only been commercialized in four nations. A growing number of countries are expected to join this booming industry in accordance with the advancements in technology. According to an EIA prediction from 2016 (Aloulou et al. 2016), worldwide daily natural gas production will grow from 98×10^8 m^3 in 2016 to about 159×10^8 m^3 in 2042, with shale gas production accounting for 33% of global natural gas production and China ranking second afterward the United States.

Apart from the four nations producing shale gas, Mexico and Algeria could collaborate with IOCs to commercialize shale gas in 2021 and 2031. Seventy percent of worldwide shale gas output will come from these six nations by 2041 (Conti et al. 2016). Undoubtedly, shale gas is the primary source of future natural gas production growth, and worldwide shale gas production growth is mostly dependent on China and the United States. Significant shale gas production and breakthroughs have been anticipated in China's southern marine shale basins (Caineng et al. 2016).

China began using marine shale from the Sichuan Basin in 2009, which quickly extended to marine, continental, and marine continental resources in southern China and throughout the country during the "12th Five-Year Plan" era (Fu 2014). Furthermore, shale gas exploration in China has been accelerated via the implementation of numerous government-approved shale gas policies, the contribution of numerous investors, and the involvement of non-oil enterprises, which has resulted in the quick expansion of the shale gas sector in the region (Fu 2014). The 44 shale gas exploration license blocks (containing 22 bidding blocks) covers an area of approximately 14.5×10^3 km^2, which were induced by the exploration appraisal in the "12th Five-Year Plan" era, have resulted in advancements in the fields of marine shale geologic assessment technique, drilling and fracturing techniques, as well as the strategic planning of shale gas reserves and processing (Caineng et al. 2016; Jehangir Khan et al. 2021; Yazdi et al. 2021). Table 1 presents shale gas properties such as its geological composition, developmental characteristics, production, and accumulation conditions. In terms of geology, the tight reservoir has adsorbed shale gas patterns in a non-dark liquid when it comes to its exploration.

Table 1. Synopsis of shale gas properties

Characteristics of geological	Characteristics of development	Condition of accumulation and high production in the core area
Tight reservoir, mainly nanopores; Natural gas has been deposited in adsorbed and free gas patterns	Mostly non-dark flow, water production, or feeble water output	For dynamic growth, the "artificial" retirement permeability requires a horizontal well, multi-stage fracking, micro-seismic, and other modern techniques.
The very same region as the useful gas-generation source rock not regulated by the structure, continuous and wide-area distribution	Lower recovery ratio	
The similar rock and reservoir source, constant accumulation, saturated accumulation; No obvious trap boundaries, sealing, and long production cycle or cap rock required.	Low individual well production	TOC > 2% (non-residual organic carbon and quartz) more than 40% of content: clay fewer than 30%; more than 1.1% of enriched organic maturity of shale; more than 2% of porosity and almost 30 to 50m thick organic shale
Wide potential resources, with the domestic “sweet spot” core areas		

Ultimately, it will require horizontal drilling of well or multi-stage fracking techniques. However, in the case of the non-regulated structure of gas, the generation source will have a lower recovery ratio. The natural resources are deployed log in nature, as can be seen in Figure 1. It enters the triangle of gas resources; the reduced grade of a reservoir is usually due to the reservoir's reduced permeability.

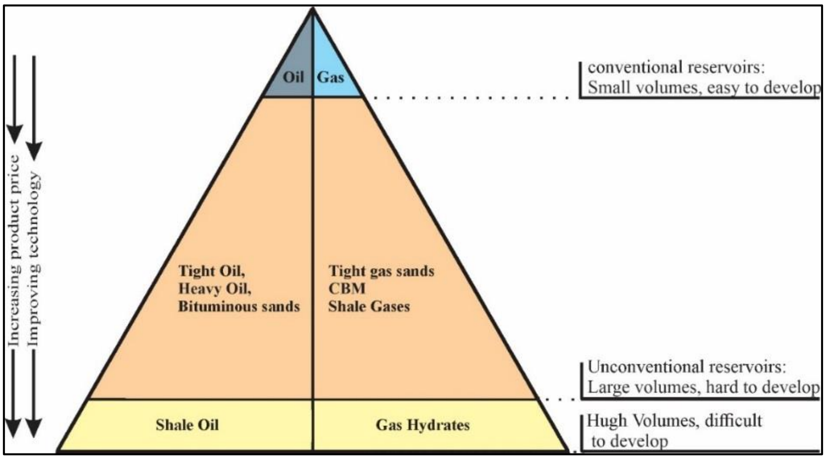

Fig 1. Visualisation of triangular resources of shale gas

Figure 2 presents the world shale gas resources that are technically recoverable (Rezaee 2015), representing that China has the largest recovered shale gas reserves globally with 1275 TCF and the USA being the second to have 751 TCF discovered deposits of shale gas so far. U.K, Colombia, Turkey, Venezuela, and Morocco are among the countries with the least recoverable shale gas reserves, less than 100 TCF.

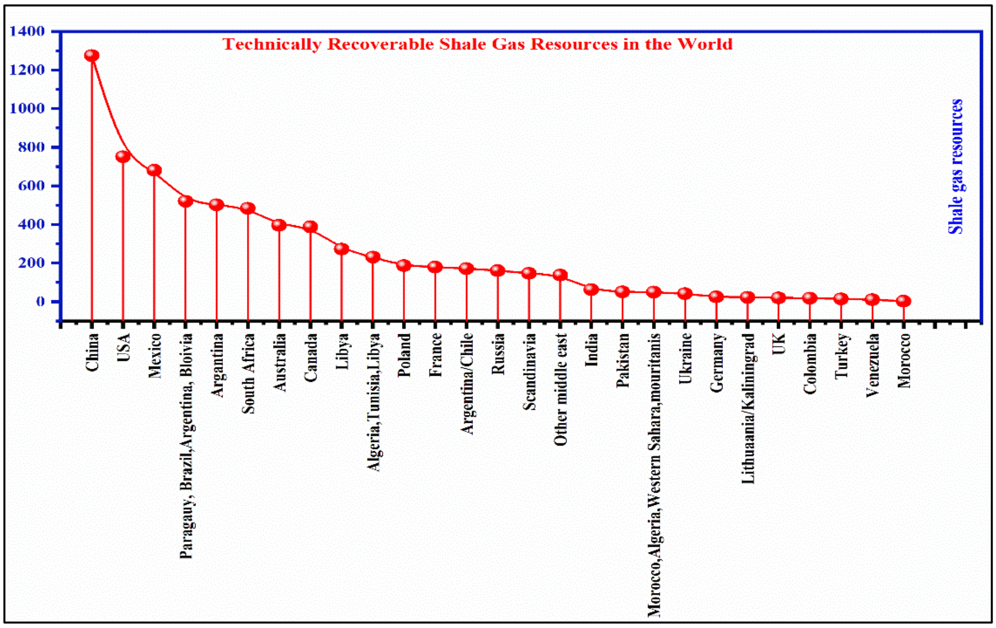

Fig 2. Distribution of worldwide deposits of shale gas (Rezaee 2015)

As the availability of standard hydrocarbons declines, shale gas reserves slowly become the primary hydrocarbon source combined with increasingly growing energy demands (Xu et al. 2015). The absorption ability of shale gas reservoirs is defined by various parameters, including the density, temperature, precise ground area, the extent of the pore, and adsorption affinity (Lei et al. 2018). Shale gas reservoirs are stereotypical self-production and self-storage gas reservoirs, where gas occurs as free gas and absorbed gas, and 20% to 80% of absorbed gas must first be desorbed before production (Jing et al. 2016). Shale gas storage has several varieties of gas content with self-production and self-storage properties. Pores influence the shale gas level, organic abundance, maturity, improved fracturing, temperatures and stress formation, composition, and mineral content (Sung et al. 2015). Based on shale gas reservoir properties, researchers have discovered multiple models that concentrate on output flow and output assessment (Deliang et al. 2015). The vertical and lateral determination of the gas in position (GIP) and the optimal method for producing the gas is necessary to comprehend and imagine an unconventional shale basin's feasibility using simulation techniques (Tan et al. 2014). Typically, awareness of the impact of shale gas reservoirs generation must still be explored.

The petroleum sector has dealt with shale, hydraulic fracturing, and horizontal wells over a long period. China, Canada, and the United States are now developing shale gas on a profitable basis(Chapman et al. 2016). The shale gas was discovered in the USA in 1821 and the first hydraulic fracture well in 1947. Sedimentary rock containing oil and natural gas deposits are naturally formed into shale formations. Because of horizontal drilling and hydraulic fracturing advancements, a domestic trend to boost shale formation has been developed. These methods have made shale gas resources available economically and commercially viable in these formations (Ethridge et al. 2015).

Two essential variables affect the rate of production of shale gas: Micro and macro flows. Macro flow is the movement of gas across the fracture network(Liu et al. 2016). Darcy or Non-Darcy Law may be described as comparable to conventional gas reservoirs(Xiong et al. 2012). The location and structure of the well are connected to macro-flow and trigger fractures. Microflows are the nonlinear diffusion between matrix and network fractures. Gas flushing through pores and the phenomenon of adsorption/desorption may play important microflow roles due to nanopore flow canals. Microflow is linked to pore space, the impact of Knudsen, slip flow, gas absorption, and subsequent permeability Hydraulic fracturing of water created by shale gas from the water and backflow (You et al. 2019). The elements of shale gas and the classification of shale gas have been formed by water (Shaffer et al. 2013). The illustration based on the categorization of shale gas is shown in Figure 3.

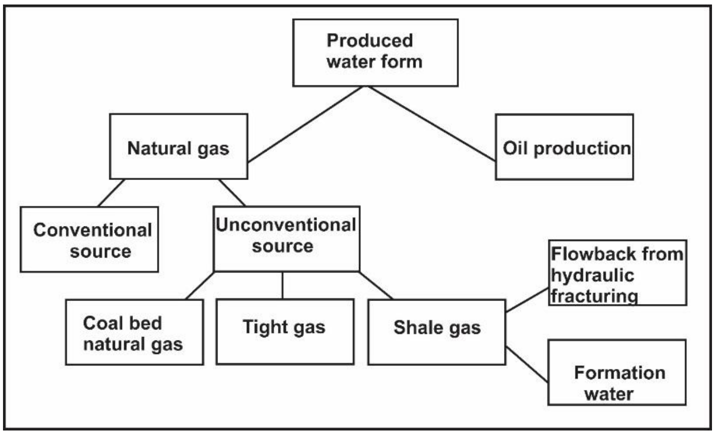

Fig 3. Scenario for shale gas classification

Developing new technologies that are consistent with environmental norms and crucial for energy security and prosperity hydrocarbon value chain is essential. TOC, porosity water and saturation of the matrix are the fundamental elements of any basin's shale gas potential. However, there are other shale gas enhancement assistant parameters (Figure 4) (Hasan et al. 2015).

Layers of shale gas need hydraulic fracturing stimulation due to excessively low shale layer permeability (Labani et al. 2015). Advances in technology for stimulating formation promote worldwide interest in hydrocarbon recovery from narrow reservoirs and shale gas. As regards the unconventional management of reservoirs and the fundamental complexities of these systems, numerical modelling should maintain a major influence in the evaluation, stimulating control, design as well as production procedures. (Jiang et al. 2015). The conventional extraction of gas by vertical wells is usually revised. Nevertheless, shale gas production involves horizontal drilling and hydraulic fracturing. Horizontal fracturing and hydraulic extraction of shale gas have enhanced U.S. gas supplies since the beginning of this century, affecting global energy marketplaces as well as causing a drop in the price of gas and oil. (Estrada et al. 2016).

2.1. Horizontal Drilling of Wells

Gas drilling is known as the drilling procedure of wells that contain air, natural gas and nitrogen. This is an ideal method for horizontal wellbore drilling in rough formations. The low cutting gas energy used in horizontal gas drilling ensures that the surface returned drill cuttings are dark and not only large cuttings cannot be discharged from the downhole in time, as shown in Figure 5. Subsequently, they are retained smoothly in the horizontal wellbores, leading to coincidences for instance pipe sticking as well as wellbore plugging. Lately, for the production of shale gas reserves, it was considered an efficient method.

It increases efficiency by almost 60% and mitigates the cost of drilling. (Chen et al. 2014). Nowadays, technology is crucial in eradicating the cutting accumulation, but during horizontal gas drilling, the diminishing of gas flow is necessarily required for the cleaning of a hole. The drill cuttings reverted to the surface in the gas drilling process is dust-like, with an average diameter of between 0.08 mm and 0.1 mm.

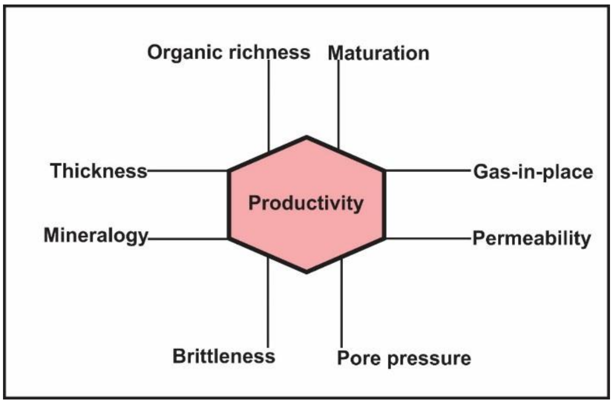

Fig 4. Elements for the development of successful shale gas

When the vertical well has the similar depth as the shale bed, horizontal drilling begins at the top of the vertical well.Horizontal drilling takes place over a long shale bed, often in numerous horizontal wells, with lengths of 1e2 km, in different directions so that the water drilling passes the maximum possible number of cracks. (Muresan et al. 2015). The bulk of horizontal wells are drained to reduce horizontal stress to allow several transverse hydraulic fractures (Yu et al. 2015). In order to increase the area of production, the horizontal section is drilled into shale rocks. The processing of casings and cementing are often used to stabilize the well situation and prevent gas from escaping afterwards horizontal drilling (Li et al. 2016).

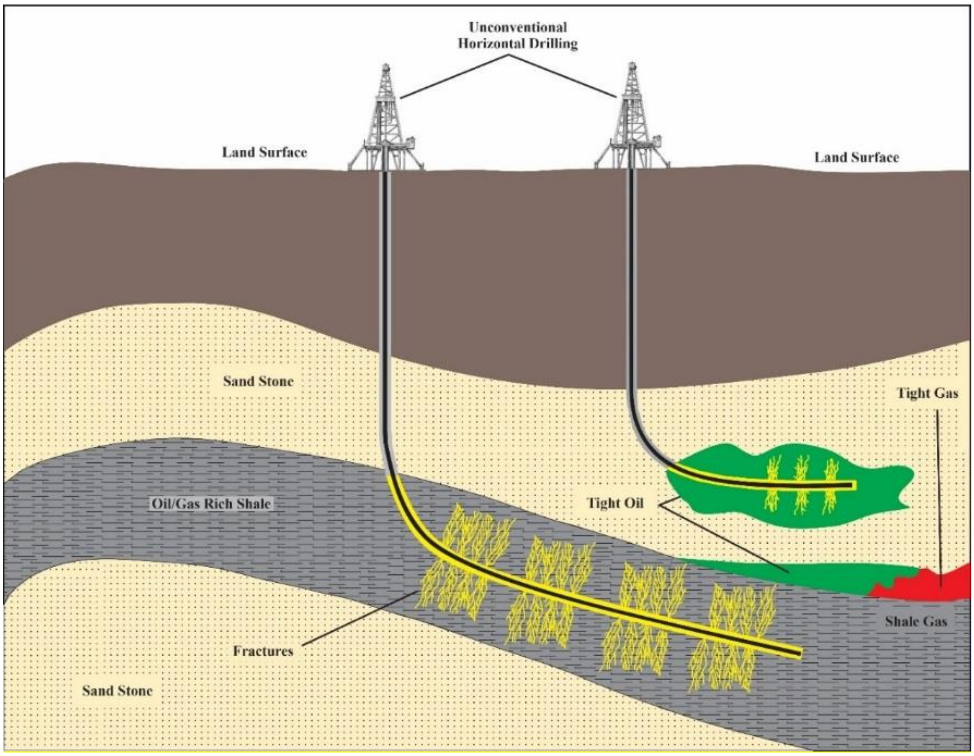

Fig 5. Horizontal drilling

2.2. Mechanism of Hydraulic Fracturing

The main method employed for shale gas extraction is hydraulic fracturing, as shown in Figure 6. The problem of swelling clay hydration cannot be avoided, and hydraulic fracturing can lead to massive fracture, which consumes large quantities of water (Li et al. 2016). Considering the vast shale gas reserves and the increasing hydraulic fracturing technique, shale gas produced by natural gas since the start of this century has risen quickly (Li et al. 2016). Hydraulic fracturing has dramatically boosted shale gas and oil production, leading to the recent and lower hydrocarbon prices of the indigenous energy boom. (Middleton et al. 2015). Hydraulic fracturing is a method employed in oil and gas development to boost the recovery of hydrocarbons from low - permeability formations. Throughout the hydraulic fracturing process, high-pressure fluid is pumped to an oil and gas well a procedure that breaks the rock of formation of hydrocarbons, increasing its hydraulic conductivity as well as the rates of formation of the bearing flow for oil and gas, increasing their hydraulic conductivity and the flow of oil and gas from formation to the well board (Burton et al. 2016).

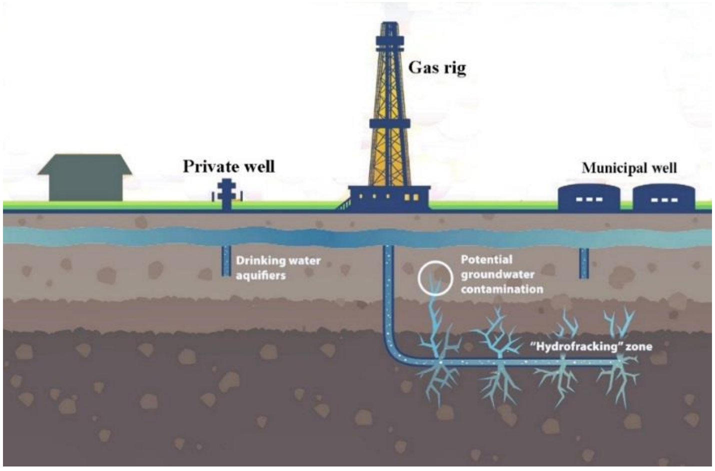

Fig 6. Hydraulic fracturing

Table 2. The adaptabilities and characteristics of hydraulic fracturing technology

Technology	Adaptability	Characteristics
Simultaneous fracturing	Offset or short distance wells	Simultaneousness, less cost, short operation time
Multi-stage fracturing	Wells with many layers of production	Maturity, universality, segment fracturing
Hydro jet fracturing	Wells of open-hole completion	Precise and quick position without packer
Re-fracturing	Old or declined production wells	Open cracks again
Water fracturing	Wells with several natural cracks	Low cost, low sand-carrying capability

Table 2 shows hydraulic shale gas drilling adaptability, properties and technologies. For hydraulic fracturing, high water consumption and the need to dispose of large numbers of backflow fluids is relevant. An average shale gas well takes approximately 10000e 20000m^3 of water. Water demand could be enormous, with a large grid well having an adverse impact on surface and groundwater supplies in the vicinity (Uliasz et al. 2014). The vertical component of a well is drilled from the surface to the shale layer during the first hydraulic fractures. After vertical drilling of wells, steel casing as well as cementing is required for freshwater preservation and steadiness (Li et al. 2016). The growing global demands for natural gas and more sophisticated production technologies are leading energy companies to produce shale gas by producing numerous hydraulic fractures from horizontal sources (Yin et al. 2015). Hydraulic fracturing technique has continuously advanced. This needs enormous quantities of water in order to shape the injecting fluid into the wells in order to discharge the gas. There are numerous concerns, and more focus is required. The fugitive methane emissions from shale gas and conventional gas formations are illustrated in Table 3. These include water problems linked to shale gas generation, like water supply for completion of the project, water collection, optimization of water supply designing and running equipment for waste-water processing and storage, optimization of wastewater disposal systems and at last optimization of transport tasks (Lira et al. 2016).

Table 3. Fugitive methane emissions from standard wells and shale formations (demonstrated as the proportion of methane generated during a well's lifecycle) connected with natural gas growth

	Shale gas	Conventional gas
Emissions from completed wells	1.9%	0.01%
Routine ventilation and leakage of materials on spot	0.3-1.9%	0.3-1.9%
Emissions while offloading liquids	0-0.26%	0-0.26%
Emissions during the processing of gas	0-0.19%	0-0.19%
Transportation, storage, and distribution emissions	1.4-3.6%	1.4-3.6%
Overall emissions	1.7-6.0%	3.6-7.9%

3. Shale Gas Exploration and Development in China

Since 2004, based on lessons learned from the U.S.'s experiences in shale-gas exploration and development, evaluation of the shale-gas resource potential and trials on shale-gas exploration and development has begun over China. Shale gas exploration and development have followed the path of "pioneering with scientific research resource evaluation-market" opens up-planning-construction of demonstration bases in China (Table.4). Exploration of shale gas and growth in China has followed the route of "opens up-planning-building demonstration bases with scientific research resource evaluation-market". During this trip, China had to face one failure after another while learning lessons from each failure that eventually resulted in a breakthrough and commercialized growth of Marine facies in the Silurian Longmaxi formation in the Sichuan Basin (Yongsheng et al. 2018). Subsequently, a few shale gas production bases were constructed in Jiaoshiba, Fuling, Chongqing, Weiyuan, Changning, Sichuan, Fushun-Yongchuan, Yunnan, and Zhaotong, etc. Lastly, the marine-facies shale-gas reservoir-formation, theoretical information enrichment, and the horizontal-well completion fracturing technology system in South China were developed (Yang et al. 2017). Among the different kinds of shale gas resources in China, apart from those in the Longmaxi Formation marine facies, shale gas exploration in the transition facies and the mainland facies has advanced slowly and has not made any commercial breakthroughs so far. Only the theoretical understanding of reservoir formation and the scheme of exploration and development technology on the continent have been accomplished (Fan et al. 2019).

Table 4. Yearly summary for exploration and development of shale gas in China (Zhai et al. 2018, Sun et al. 2021)

Year	Description of progress
2004	• Tracing research
2005-2008	• Features of shale gas were examined
2007	• First extensive geological assessment of shale gas by PetroChina
2009	• Funding for exploration and optimal potential. First shale gas survey well Yuye-1
2010	• The first vertical marine shale gas well Wei-201 • First pilot test • Targeted area evaluation was achieved by Sinopec • First continental shale gas well Jian-111
2011	• First marine shale gas horizontal well 201-H1 • First continental shale gas well Jianye-HF1
2012	• First horizontal production of industrial shale gas Ning 201-H1(over 10^4 m^3 / d • The first-time shale gas production was unveiled in China • First large-scale commercial exploitation of shale gas-Fulling field.
2013	• First factory operation test platform • Production of shale gas surpassed 10^8 m^3 • Shale gas production surged • First unprofitable, well Chaiye-1, of continental shale gas was explored • First shale gas well, Well-Jiaoye HF8-2, with a production capacity of 10^6 m^3 /day
2014	• Switching shale gas pipeline-Changning • The extraction of shale gas reached 1.5×10^9 m^3 • Field-filing of 1st large scale shale gas production • First non-profit marine shale gas scientific well Ciye-1
2015	• Shale gas production 6.5×10^9 m^3
2016	• Shale gas production 7.9×10^9 m^3
2017	• Shale gas production 9.1×10^9 m^3
2018	• Shale gas production 11.3×10^9 m^3
2019	• Shale gas production 10.3×10^9 m^3
2020	• Shale gas production 10.9×10^9 m^3

The regional geography of technically recoverable shale gas resources in China has shown in Figure 7, and the synthetic stratigraphic column is shown in Figure 8. Further studies are required to commercialize additional basinal marine shale gas growth due to numerous difficulties, including much older ages, intensive tectonic conversion, formations of normal pressure, incredibly profound reservoirs, and excessive heat evolution, etc.

The China Geological Survey (CGS) Survey Centre for Oil and Gas Resources (SCOGR) has performed various geological surveys and investigations into shale gas resources in various formations and structures in the latest years, such as Longmaxi Formation, Niutitang Formation, Doushantuo Formation, Dalong-Longtan Formation, and Devonian-Carboniferous System. It summarised the gaining of information on reservoir formation concepts and primary enrichment and high-yield control variables for the five shale gas kinds and, building on them, guiding the deployment of shale-gas parameter reservoirs and creating a sequence of breakthroughs (Yan et al. 2009).

Resources of shale gas in China are abundant, and their characteristics are shown in Table 5. According to an assessment carried out by resources and land ministry on shale gas energy, there are 134×10^{12} m^3 of shale gas resources, of which 25×10^{12} m^3 are technically mineable materials including a multitude of kinds such as those in marine, continental and transitional facies, and are dispersed in Palaeozoic, Mesozoic, and Cenozoic Erathems formations (Hao et al. 2017).

To date, breakthroughs in the exploration of shale gas have been produced by China, and production has an accumulated shale gas reserve of 7643 bcm as of 2017's end (Hao et al. 2013). The shale gas's average output is approximately 180×10^8 m^3. China has produced excellent breakthroughs and findings in marine, transitional, and continental production and exploration of shale gas that have created five primary shale gas areas: Fuling, Changning, Weiyuan, Zhaotong, and Yanchang (Dong et al. 2016). The distribution of technically recoverable shale gas resources in China is shown in Figure 9.

3.1 Technological Advancement's Role in Maturing Shale Gas Exploration in China

With recent years of exploration and production of shale gas in China, more and more key and critical technologies have been generated in China. With some later developed techniques globally to promote shale-gas oil engineering, China became the third nation to use its developed autonomous technologies and capacities (Xinhua et al. 2018). Innovations, addressing main challenges, and field applications have resulted in the provision of equipment for drilling horizontal shale-gas wells. Likewise, a series of tooling products, the development of packaged fracturing equipment and materials, and the production of well-developed leading equipment, tools, and materials for shale-gas exploration and production significantly lowered the production cost (Caineng et al. 2016).

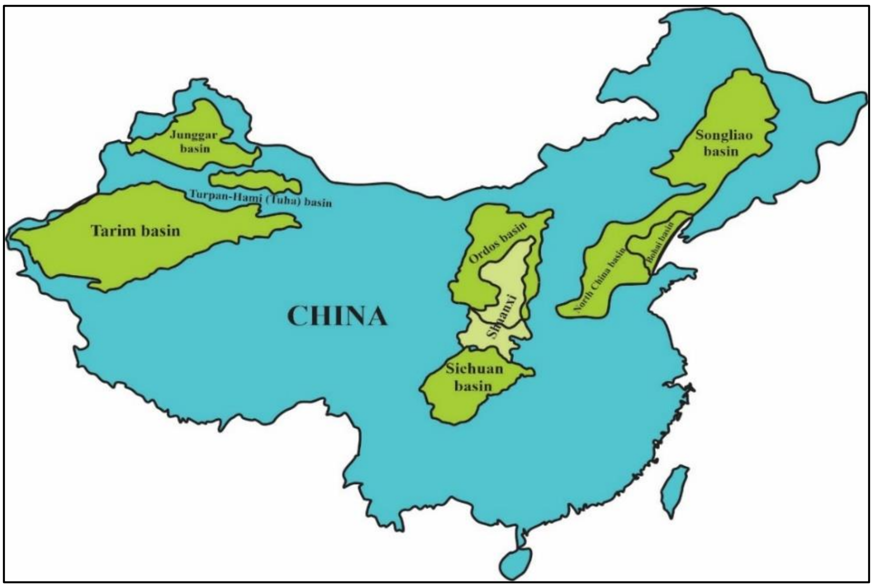

Fig 7. Regional geographical visualization of discovered shale gas reserves in China

Table 5. Geological properties of significant shale gas in China (Zou et al. 2010)

Deposit	Area (m^2)	Depth (ft)	Thickness (ft)	TOC %	Gas content (Sct/ton)
Songliao	108,000	3300–8200	500	4–5	45
Tarim	234,200	10,790–14,620	160–240	2–3	1.6–85
Yangtze platform	611,000	11,500–13,200	275-400	3.0–3.2	99.4–147.1
Sichuan	74500	9700–13200	251–400	3.0–4.0	109.8–162.6

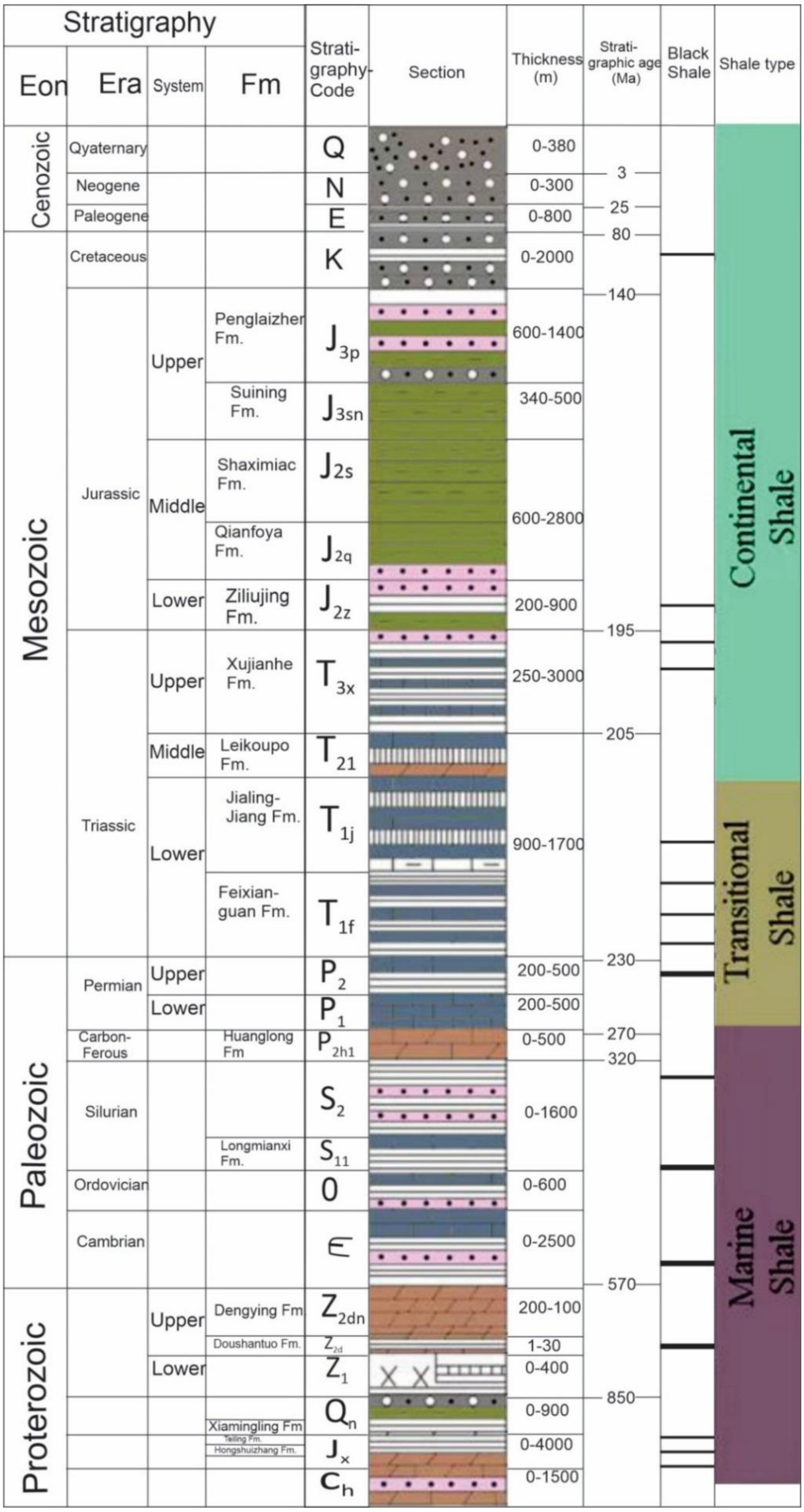

Fig 8. Synthetic stratigraphic shale in China modified after(Sun et al. 2021)

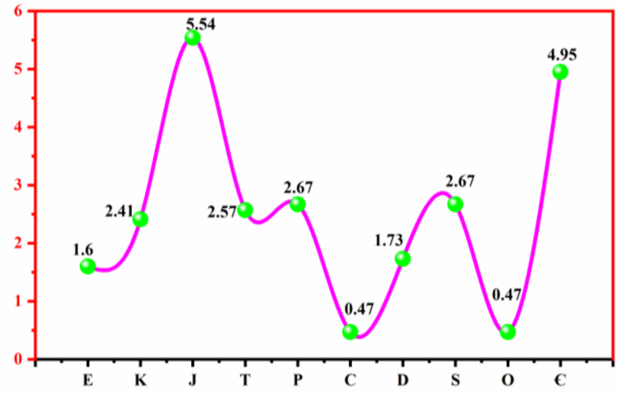

Fig 9. Distribution of deposits of shale gas in China. E= Tertiary, K= Cretaceous, J= Jurassic, T= Triassic, P= Permian, C= Carboniferous, D= Devonian, S= Silurian, O= Ordovician, and ϵ = Cambrian (Dong et al. 2016).

From adopting and studying sophisticated foreign technologies initially, China developed shale gas exploration and development technology and equipment systems through innovation with its intellectual property rights (Caineng et al. 2016). China has followed the below mentioned (see Table 6) historical courses to explore and produce shale gas on its journey to success.

Now, there are almost 21 autonomous proprietary developed systems of 5 main technology series in China that include sweet spot identification, reservoir evaluation, shale-reservoir fracturing conversion, horizontal good drilling and completion, well-fabricated manufacturing model, and environmental safety: seismic / logging-based reservoir identification and evaluation technology, home-made oil-based drilling fluid technology, mixed pumping bridge plug plus perforation technology, micro-seismic fracturing surveillance technology (Zou et al. 2019).

Table 6. History of technological development of shale gas in China (Zhai et al. 2018; Sun et al. 2021)

Year	Description of progress
2007	• Importing formation evaluation and resource evaluation techniques
2008	• Key technology laboratory for shale gas was founded
2009	• Hydraulic fracturing technology was firstly applied in vertical shale gas wells
	• Microseismic monitoring technology was used to analyze the content of shale gas in vertical wells
2010	• Vertical drilling was done the first time for shale gas
	• Fracturing and testing technology for the analysis of shale nanometer-micron pores
	• Special cutting-edge technologies such as trajectory control machinery were used during horizontal well drilling and formation element logging
2011	• First horizontal well-staged fracturing of shale gas
	• Geophysical technology for the identification of organic-rich shale in horizontal wells
2012	• Shale gas horizontal well completed
	• Fracturing truck model 2500 was designed successfully
	• The technology of geophysical identification was applied for Co_2 fracturing
2013	• Drilling of horizontal well cluster
	• Interactive fracturing technology was applied
	• Establishment of a fracturing fluid system
	• Deployment of drilling bridge plug for staged fracturing
	• A successful development of fracturing truck model
	• Successful application of technology to purify and dewater shale gas
	• Shale gas gathering and transportation technology was developed
2014	• The machinery of ultra-deep horizontal drilling of wells and staged fracturing
2015	• Three elements enrichment and accumulation
2016	• CO_2 water-free fracturing technology for continental shale gas
2017	• Fracturing and flow backtesting the technology in low-pressure shale gas reservoir
2018	• Three-dimensional seismic and logging data from shale in mountainous region were acquired, processed, and interpreted to define reservoir quality shale intervals and sweet spots in lateral distribution
2019	• The factory drilling model of “double-drilling rigs pattern, mass batched drilling, standardized operation” was implemented to accomplish optimal and rapid drilling techniques.
	• The outcome was a 50% reduction in single-well drilling cycle.
2020	• China has developed a robust technological system of volume fracturing based on foreign technology, including low-density proppant, zipper-style fracturing, high-displacement slick water, factory drilling pattern as well as soluble bridge plug.
	• As a result, fracturing proficiency and testing output was doubled.

China has placed excellent emphasis on environmental protection in shale gas's production and exploration process. Seeing that South China has karst developments on the surface (Jiang et al. 2021), action is taken to safeguard aquifers during drilling by using pneumatic and clean water exercises for the first and second "spud-in" (Zhai et al. 2018). Besides, the potential risk of harming the local ecosystem is minimized by using soil treatment technology, oil-based mud harmless treatment technology, and fracturing-flow-back fluid recycling technology (Shi et al. 2020).

3.2. Initial Identification and Assessment Technology of "Sweet Spot" Reservoir

Shale-gas sweet-spot identification and reservoir assessment technology systems for marine facies in South China are currently being created in shale-gas exploration blocks where development is marketed, including seismic reservoir identification/evaluation/ prediction technology, logging, and rapid information logging. The extensive seismic assessment scheme for marine-facies shale-gas was created to predict shale strata and parts of the "sweet-spot" by mixing seismic information and logging (Qiu et al. 2020). However, in the early phases of researching shale-gas geology and assessing resource potential, low-cost, green, and effective non-seismic shale-gas exploration technology was created using non-seismic (gravity, magnetic and electrical) shale-gas methods. It played a significant part in the early regional study, karst detection, and structural feature research. Technologies for predicting "sweet spot" such as acoustic-impedance (Umar et al. 2019; Umar et al. 2020), shale-thickness prediction technology, high-precision pre-stack density inversion TOC technology, and quality shale-distribution technology, all were developed using shale-gas seismic information prediction "Sweet Spot" technology to guide well deployment and boost the success rate of shale-gas exploratory wells (Xianzheng et al. 2017). The robust logging assessment technology also developed the marine shale gas rapid identification model (four highs and three lows) that interpreted key parameters for instance TOC (total organic content), porosity, and gas content (Ali et al. 2020 , 2021). The technical capacities for tracking micro-seismicity in fracturing wells under distinct geological and well circumstances were developed by creating micro-seismic processing and interpretation technologies and detection devices based on micro-seismic fracturing surveillance technology to guide real-time adjustment of the fracturing scheme (Zou et al. 2019; Umar et al. 2020; Ullah et al. 2022).

3.3. Setting up an Autonomous Horizontal Well Drilling and Completion Technology

The conventional and low-cost well-trajectory control technology, "MWD + Natural Gama" well-trajectory measurement technology, the 3D geological orientation software, the geological orientation technology for remote sensing, the extensive geological orientation technology, "logging curve + imaging technology + seismic," the horizontal-well optimal and quick drilling technology and the low-cost oil-based technology for drilling fluid was established in China currently (Lihong et al. 2020). Key drilling speed-up instruments such as new kinds of PDC drilling bits and long-life screws enabling instruments to be manufactured in China and enabling a continuous rise in drilling speeds at each "spud-in" were designed until 2016 (Wang et al. 2017). This new sort of oil-based mud made it possible to reduce the danger of well-borne instability and drilling fluid costs. The three-spud-in drilling spud-in speed-up technology "vertical section + directional section + horizontal section" was primarily created for building horizontal shale-gas wells, where the horizontal section is up to 2130 m, the drilling duration is at most 37 d and the duration for a single tap is up to 1530 m in the horizontal section-progressively improving the techniques and facilities that supported shale-gas drilling and completion (Xie 2018). The shale-gas-specific manufacturing casing was set up to satisfy the demands of the alternative load from staged fracturing on the tightness of the casing. The elastic and hard liquid cement scheme was established to increase the fixed cement's toughness by at least 40% to satisfy the requirement of simulated fracturing. The well cementation in Fulling, Chongqing is 100% skilled, meeting needs for the operation of staged fracturing at big discharge capability, so that the shale-gas well-cementing technology could be domestic, autonomous, and industrialized for its implementation (Yue et al. 2018). The effective drilling operation mode "well factory" used in complicated mountainous terrain was developed, and portable track rigs were altered to move rapidly between wells, boost operating effectiveness, reduce drilling expenses and save the used land. Currently, the Omni-directional whole self-moving equipment created separately and innovatively domestically can transfer a maximum weight of 1000t at an inter-well positioning precision of less than 10mm and shorten the relocation time form 72 hours to 4 hours retrospectively (Gao 2019).

3.4. Well-Staged Horizontal Fracturing Techniques

China currently possesses and masters leading technologies for horizontal shale gas fracturing and gas manufacturing testing, such as the differentiated stage fracturing process parameter optimization technology, the mixed pumping bridge plug + perforation technology, the continuous horizontal shale gas drilling, plugging technology, and the effective fracturing technology (Qun et al. 2018). The fluid system in China fits the geological properties of shale gas; thus, the micro-seismic surveillance technology and post-fracturing processing of backflow, etc., were also developed (Gao et al. 2014). Supporting machinery such as the world's first type 3000 and 4500 fracturing pump trucks, easy-to-drill composite bridge plug, soluble bridge plug, continuous oil-tube operating truck, and high-pressure manifold was created to satisfy the demands of high-pressure, high-pressure, and high-power shale-gas fracturing activities in China's mountainous regions efficiently, effectively and powerfully (Zhai et al. 2018). The composite fracturing fluid, the supporting agent, and the backflow fracturing are recycled and reused, leading to large-scale shale gas growth in China. Some techniques and machinery are developed globally and exported in large amounts.

3.5. Future Trends of Shale Gas Developments and its Related Problems

In the past few years, China has achieved success in the research and progression of shale gas resources, but the sector as a whole is still immature and faces numerous major challenges. However, only in the Sichuan Basin marine formations have significant innovations in shale gas exploration and exploitation been achieved; state-owned oil corporations have positively developed a modest quantity of shale gas but have suffered significant losses as a result of their efforts (Yongsheng 2014). The surface and geological characteristics of shale gas in China are much more complex than in other countries. Consequently, this raises the difficulty and costs of exploring for and developing shale gas. As a result, not only is shale gas exploration and production becoming more challenging, but it is also becoming more expensive to evaluate. Continental shale, as well as marine-continental transitional shale and, have also been introduced in China, in contrast to marine shale. Shale gas enrichment patterns in China are substantially more difficult because of the organic-rich shale deposit that has experienced extensive tectonic movements (Yongsheng et al. 2018).

Moreover, the burial depth of organic-rich shale in China is greater, with a previous estimate of about 3500 m in even more than 65 percent of shale rock. In Southern China, shale gas formations predominate mountains and hills. Substantial transportation and regular large-scale activities are hampered by the complicated surface situations(Yongsheng et al. 2018).

Shale gas resource evaluations have yet to be carried out in a systematic and comprehensive manner, and China's strategic study of shale gas resources is in its adolescence. Scholars and organizations have been forecasting China's shale gas resources since 2008. However, the estimates are very imprecise and vary dramatically, indicating a lack of sophistication about China's technically viable shale resources (Lu et al. 2018). As Lu points out, if China's proven deposits of shale gas are substantial, yet will not always be a huge number of sweet spots that are suitable for wide-scale exploitation (Lu et al. 2018). Finding the exact positions of these sweet spots can be a bit of a challenge. Just one Chinese shale gas field, Fuling, has made significant headway, proving this point. Finally, the peak and decline rates of shale gas wells are substantially faster than conventional wells (Yao et al. 2020).

As a result of a lack of shale gas technology and equipment in China, exploration and development costs are expensive. China has just recently standardized a batch of appropriate shale gas procedures and carried out a technical study. In contrast, Canada's shale gas technology is currently being promoted for sale on the world market. Several vital shale gas technologies (horizontal wellbore trajectory regulation, fracture identification, and so on), as well as essential equipment and instruments (bridge plugs, experimental analytic tools, and so on), must be bought (Liu et al. 2019). China's complicated geological and surface circumstances necessitate a significant deal of innovation and development in using foreign tools and devices.

Lagging environmental technologies are putting increasing strain on China's ecological environment. As a result, shale gas exploration and production may end up causing environmental damage in China. To begin with, most of China's surface water bodies have already been severely contaminated, and 90 percent of the country's groundwater has been damaged to varying degrees (Krupnick et al. 2014). The growth of shale gas could exacerbate the problem. Furthermore, despite the fact that shale gas is a comparatively clean energy source, its extraction method causes methane emission, which could exacerbate the greenhouse effect and affect China's climate. Although we ignore greenhouse gas emissions, Wigley estimates that replacing gas for coal will only be useful in minimizing the scale of future climate change if the leakage rate for new methane can be kept below 2% (Wigley 2011). Moreover, the Chinese government has almost no policies to address methane leaking in shale gas extraction (Qin et al. 2017). Ultimately, China's vast majority of shale gas reserves are found in heavily inhabited areas outside of the Tarim as well as Junggar Basins and the other major gas-producing regions (Stevens et al. 2013). Public health is threatened by water contamination and air pollution, especially noise pollution instigated by shale gas exploitation. Consequently, shale gas corporations will face hostility from society and communities if they fail to take adequate precautions to protect the environment and public health (Wang et al. 2014).

Tackling the challenge of shale gas research and innovation will be the responsibility of state-owned oil firms, which account for above 90% of oil-and-gas technical service companies and the majority of shale gas scientific research. In light of the massive expansion of shale gas production, the state-owned oil industry will contend with an increasingly diverse range of non-oil and gas firms. Even though national oil firms have mastered shale gas exploration and development procedures, they will limit the technology transfer in order to compete against non-oil-and-gas sectors (Sun et al. 2021).

China should concentrate its efforts in the next years on addressing a variety of short-term issues and making adequate preparations for substantial shale gas production. To that purpose, the following are the policy suggestions put forth in this paper: enhancing exploration and assessment efforts in China in order to acquire verifiable shale gas proved reserves; creating new policies and incentives for shale gas exploitation; The establishment of a national shale gas research and development zone; increasing scientific research in order to develop a technical system for exploration and extraction that is compatible with China's geologic features for shale gas; and building a shale gas regulatory framework that emphasizes the protection of the environment and oversight.

4. Discussion

The extraction and growth of shale gas in China have a promising future though in its original phase yet. While breakthroughs are currently being made in some strata and systems in certain areas, the potential and prospects for continental and transitional facies to explore and develop are still uncertain; future breakthroughs are anticipated because major findings have been acquired through surveys and evaluations of shale gas resources in more strata and structures in more areas. Based on the outcomes of the past first round of evaluations of the domestic shale gas resource potential, 81 favorable areas were further chosen for the evaluation of the shale gas resource potential of the Sinian System, Cambrian System, and Silurian System in South China for three sets of strata and structures. Accounting for current exploration data, it was found that the Lower Silurian Longmaxi Formation in and out of the Sichuan Basin is currently the best formation for shale gas extraction and production. The shale gas from Longmaxi Formation is widespread with high thickness, good gas-bearing potential, and high resource potential, representing 20% of total national shale gas resources, making it extremely promising in terms of exploration and development.

However, the key to future breakthroughs is to discover targeted regions with optimal preservation conditions and develop processes and technology for fracturing transformation and gas testing aimed at shale gas reservoirs with normal pressure(Yongsheng et al. 2018). Despite the fact that China has achieved significant strides in the extraction of shale gas, there is plenty more work to be done. Depending on relatively frequent development regulations for several other unconventional resources (which include tight gas). Quite extensive research and development methods must be enhanced with the help of strengthened geological research as well as technical growth in order to achieve inexpensive production at low gas prices, decrease investment prices per well, and raise economic advantages.

Applying valuable lessons from China's tight gas advancement, investigate low-cost shale gas development, including lowering initial investment on a single well while increasing economic advantages, as well as implementing sustainable advancements in drilling and completion in order to decrease the number of low-producing wells. Similarly, shale gas has been identified as an essential fuel to reduce short-term emissions of carbon as an alternative energy source that enables the transition from fossil fuels to clean, efficient, and environment-friendly. Over its lifecycle, GHG emissions from shale gas are 30% to 50% smaller as compared to those from coal. Because the size of a project rises, it becomes essential and economically viable to take steps to reduce environmental effects (Estrada and Bhamidimarri 2016). Critical to the effective growth of shale gas are environmental interests. In the latest years, an ongoing effort has been made to replace fewer damaging compounds for the most hazardous chemicals to enhance more eco-friendly shale gas. The involved agencies must not undermine the ecological intactness during the production of shale gas for the sake of wider political, social, and environmental services available to the production of shale gas resources. The policymakers, stakeholders, and regulators must access key knowledge to comprehend and minimize environmental issues on all economic and technical components of shale gas development. Précised plan can significantly decrease the harmful shale gas effects on the environment.

Lastly, the governments should ensure the transparent flow of information related to potential environmental issues. Meticulous planning will be significantly helpful in mitigating the adverse effects of shale gas production on biodiversity. Technology is another most important factor in establishing a competitive shale gas market. The techniques of mining shale gas influence not only extraction costs but also the production of shale gas. Ground-breaking advancements in hydraulic fracturing and horizontal drilling have done everything to produce trillions of cubic feet of shale gas potentially retrievable, if not once governments have assisted in creating well-organized and cost-efficient methods. Increasing national energy resource production usually leads to higher supplies and reduced prices. Additional jobs are also created by developing national shale gas resources.

Moreover, the shale gas supply improved taxes for federal stakeholders and the payment of royalties and bonuses to farmers. In recent years, the net output of electricity through power plants; running on natural gas – fire, has risen, coinciding with a continuous increase in shale gas supplies. Shale gas gives annual government revenue of billions of dollars through sales, income, excise, severance, and corporate taxes, federal royalties, assets, payroll, and usage of federal lands. Shale gas production and development have resulted in essential economic advantages, for example, mitigated prices of energy, foreign investment, benefits for the community, enhanced supply safety, a more sustainable base of manufacturing, and extra jobs (Cooper et al. 2016). The growth of shale gas is the revolution of energy that will be having a major effect on the energy landscape of the world. Shale gas would not solve energy security problems in the short term but will assist in lowering gas prices and compensating for energy crises. Extraction of shale gas on a local level can offset decreasing conventional gas manufacturing in Europe in the long and medium terms. Due to the established shale gas sector, the U.S has long been investigating the exploration of shale natural gas. Consequently, the rise in shale gas production in the U.S led to the reduction of its prices.

5. Conclusion

In conclusion, owing to the vital importance of shale gas, in an orderly and efficient way, it is necessary to build a healthy market. China has an enormous number of shale-gas reserves that are of different kinds and are widely distributed. Compared to the United States, where the geological circumstances for shale of marine facies are comparatively uniform, there are numerous unfavorable variables for resources of shale-gas in China, e.g., high depth, complex structure, and damaged conditions for conservation. Due to a number of issues, including high danger and low scale value, attempts must not be taken to "raise financing in shale gas exploration and speed sale gas prospecting" in the complex tectonic zones of South China. Two prerequisites must be met in order to reach the aim. As a first step, the developed shale gas blocks could either continue to produce at a high level or replace old wells by drilling new ones, and the production of the new wells is anticipated to duplicate that of the old ones. Secondly, and most importantly, a fresh group of shale gas replacement regions should be located and placed into commercial development. More than 65 percent of China's entire shale gas reserves are found under the depth of 3500 meters. Under 3500 meters, the Paleozoic marine shale gas resources in the southern Sichuan Basin are most abundant.

Shale gas production expansion under China's "13th Five-Year Plan" can only be achieved with the development of deep exploitation technologies. In terms of China's shale gas future, the concerns of danger and scale profitability must be considered cautiously and logically, and the lessons learned from exploration failure in several zones during the "12th Five-Year Plan" phase must be compiled. Furthermore, considerable work has to be done into the geological characterization of shale gas and creating engineering capabilities, fundamental shale gas exploration, as well as development processes, must be implemented, and a sensible industrial aim must be formed. In this manner, the domestic shale gas industry could grow steadily and efficiently over time.

Due to geological circumstances in China, the sweet-spot technical identification will be the basis for the future elevated output of shale gas. The horizontal-well orientation control technology is critical in determining whether the wells will move through the quality segments. At the same time, the final phase will be staged fracturing and gas testing, and the fracturing conversion method will determine the impact of fracturing. So, it is highly significant to tackle important challenges in the growth of these important technologies. The extraction and growth of shale gas in China are just in their original phase. Although some breakthroughs and findings have been accomplished in a few regions, in some tiny fields, they are only individual breakthroughs, and there are still a lot of issues to be resolved.

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