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Invited review

An assessment of methane gas production from natural gas hydrates: Challenges, technology and market outlook

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Abstract:
Natural gas hydrates are enormous energy resources occurring in the permafrost and under deep ocean sediments. However, the commercial or sustained production of this resource with currently available technology remains a technical, environmental, and economic challenge, albeit a few production tests have been conducted to date. One of the major challenges has been sand production due to the unconsolidated nature of hydrate bearing formations. This review presents progress in methane gas production from natural gas hydrate deposits, specifically addressing the technology, field production and simulation tests, challenges, and the market outlook. Amongst the production techniques, the depressurization method of dissociating natural gas hydrates is widely accepted as the most feasible option and it has been used the most in field test trials and simulation studies. The market for natural gas hydrates looks promising considering the increasing demand for energy globally, limited availability of conventional fossil fuels, and the low carbon footprint when using natural gas compared to liquid and solid fossil fuels. The major market setback currently is cheap gas from shale and conventional oil and gas reservoirs.

1. Introduction

The demand for energy across the world is expected to rise significantly in the near future to meet the world population growth. The United Nations population division has projected that global population will increase by 2 billion persons to 9.7 billion in 2050. This expected population growth will require more energy sources to drive global economy and to ensure energy sustainability. Conventional energy sources have been a major contributor to meeting the energy demand but recent decline trends have shifted focus to the unconventionals (Nair, 2018). Recent research has revealed that natural gas hydrate (NGH) deposits are enormous in nature and could be the potential source of energy for the future (Demirbas, 2010; Chong et al., 2016; Demirbas et al., 2016; Yang et al., 2017; Cui et al., 2018). Technically, natural gas hydrates are known as methane clathrate or methane hydrate. They are ice-like with methane molecules fixated in cages of water molecules (Cui et al., 2018; Zhao et al., 2018; Wang et al., 2020) (see Fig. 1). Methane hydrates generally consists of three principal crystal structure types: (1) sI (2) sII and (3) sH (Fig. 1). The hydrates can consist of a combination of these structures. Pure liquid water crystalizes with hexagonal symmetry when it freezes, but when it freezes with methane molecules it takes the shape of cubic symmetry for sI and sII, reverting to hexagonal symmetry for sH. NGHs occur in nature in two different geographic settings–in deep ocean sediments, and in the permafrost. The formation and stability of NGH in these environments require conditions of low temperature and high pressure conditions as illustrated in Fig. 2 (Boswell et al., 2014; Reagan et al., 2015; Dong et al., 2020; Dhakal and Gupta, 2021). When these settings are disturbed and depart out of the stable zone, the structure of NGH breaks and decomposes into water and gas (Koh et al., 2016; Dong et al., 2020; Dhakal and Gupta, 2021).

As has been previously reported in the literature, most prior investigations have emphasized the study of gas hydrates formation and inhibition in flow assurance perspective (Altamash et al., 2018; Chaudhari et al., 2018). However, with the discovery of NGH deposits in the late 1960s, NGH have attracted the interest of scientific community. As matter of

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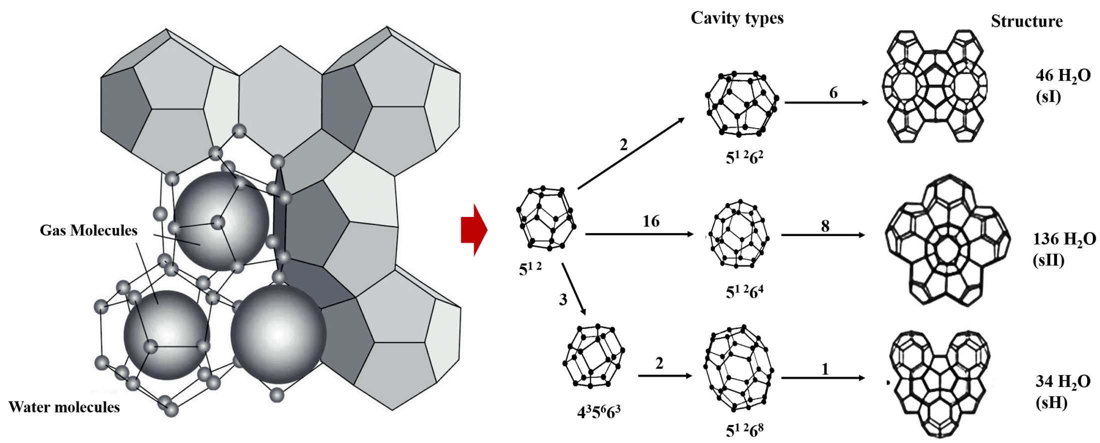

Fig. 1. Typical structure of gas hydrate (Siažik et al., 2017; Perrin et al., 2013).

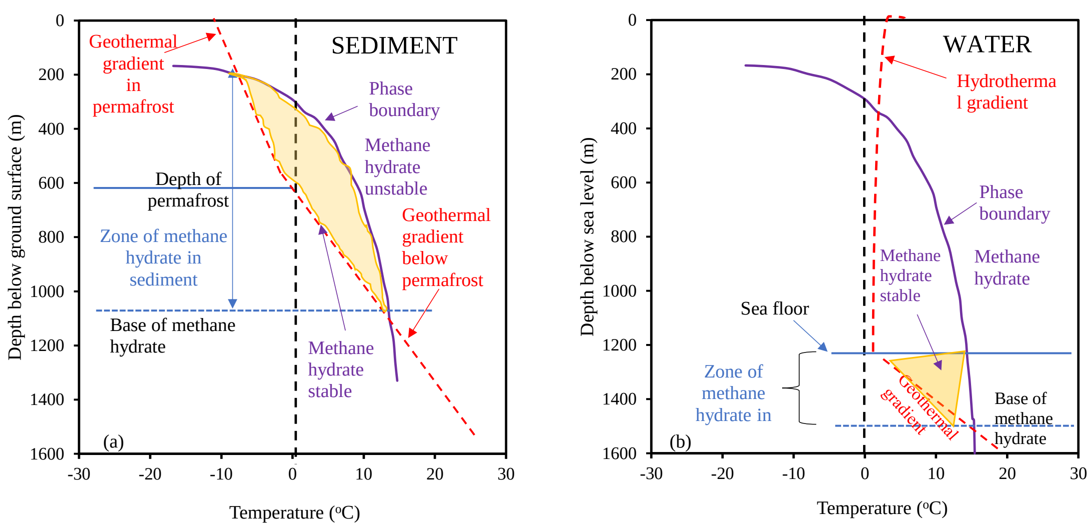

Fig. 2. Phase boundary diagram demonstrating gas hydrate stability zones (blue) for (a) permafrost and (b) oceanic environment (Sloan et al., 2010).

fact, NGH has become a research hotspot because of huge accumulation of methane in gas hydrate deposits and huge reserve of these deposits have been discovered all over the world (Cai et al., 2020). Data from the U.S. Geological Survey shows that global stocks of NGH deposits account for at least a ten-fold of the supply of conventional natural gas deposits. Estimates range from 100,000 to 300,000,000 trillion ft^3 of NGH (Collet, 2001; Hefner III, 2009) compared with 13,000 trillion ft^3 of conventional natural gas. One cubic meter of gas hydrate when brought to the earth's surface, releases 164 ft^3 of natural gas (Islam et al., 2018). The US has about 320,000 trillion ft^3 of NGH, but only 1,200 trillion ft^3 of conventional natural gas reserves (APS News, 2007). Globally, several exploration technologies suggest that NGH in the permafrost regions is two orders magnitude less than that found in the marine sediments (Klauda and Sandler, 2005; Chong et al., 2016).

Fig. 3 shows the gas hydrate resource pyramid as reproduced by Beaudoin et al. (2014) after Boswell and Collett (2006). The pyramid depicts gas hydrate resource quantity compared to conventional gas sources. Moving down the pyramid, in-place volumes increase, resource quality and concentration decrease, resource recoverability decrease, and there is increase in dependency on technology.

Despite the vast volumes of the resource, commercial scale exploitation is yet to be achieved. Although no commercial-scale extraction has yet occurred (Dong et al., 2020; Ma et al., 2020; Dhakal and Gupta, 2021), the development of the necessary tools, and production techniques is very likely because of advances in hydrocarbon production from deep shale formations (Beaudoin et al., 2014). Major efforts to explore the commercial development of NGH has been ongoing in a number of countries, with energy-resource-poor countries such as Japan and India contributing significantly to these efforts. (Demirbas, 2010; Konno et al., 2017; Yamamoto et al., 2017). A few fields scale experiments have been reported mainly in Canada, USA, Japan, and China with various degrees of recovery and associated problems (Kurihara et al., 2009; Hunter et al., 2011; Collett et al., 2013; Schoderbek et al., 2013; Li et al., 2018; Chen et al., 2020; Zhu et al., 2021). The reasons hindering commercial scale production bothers on economics, environmental, and as the pyramid in Fig. 3 illustrates,

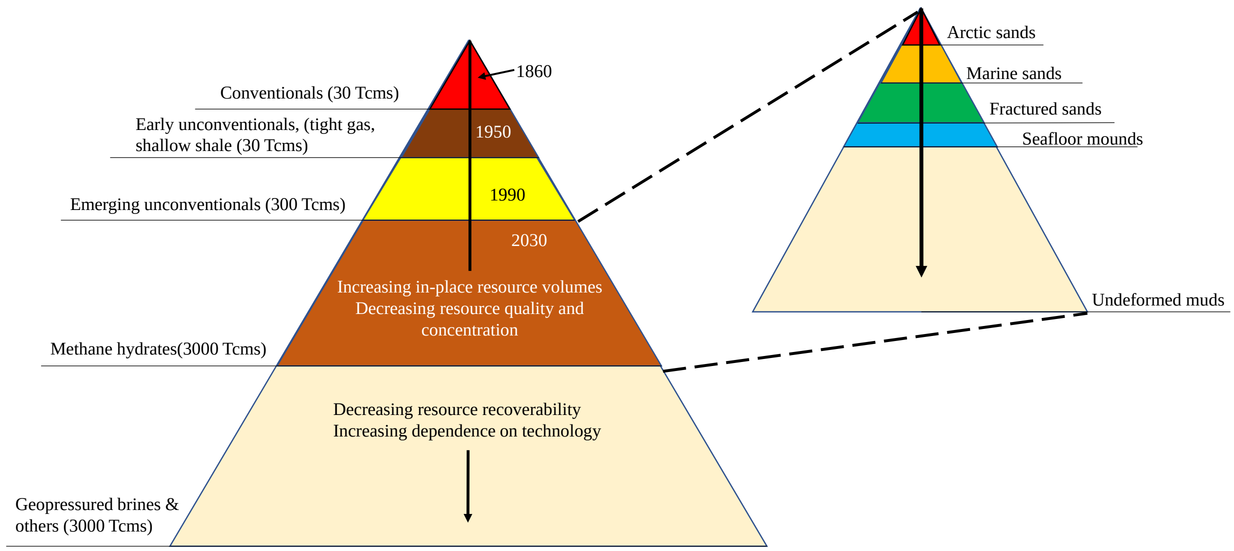

Fig. 3. Resource pyramid for gas hydrates (Modified and reproduced from Beaudoin et al., 2014).

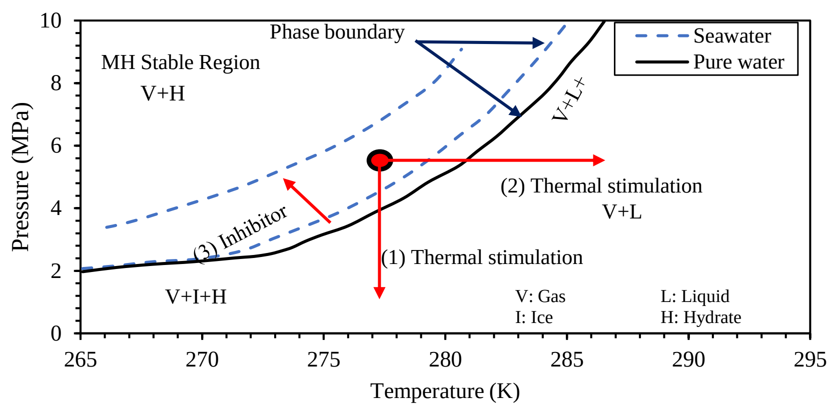

Fig. 4. Methods of gas hydrate production: 1) depressurization; 2) thermal stimulation; 3-4) chemicals injections (Reprinted from Chen et al., 2017).

technology–with technology being the major factor. Hence, this review attempts to evaluate the feasibility of available natural gas hydrates technologies. It also discusses how these technologies have been used for field test examples around the globe. The future technology development for producing gas hydrates should be able to produce the NGH efficiently and commercially in an environmentally safe manner with increased profit margins.

This review is sectioned into 4 parts,

1) **Gas hydrates dissociation methods**: This section summarizes and compares the methods currently being used for gas hydrate production.
2) **Field production tests and numerical simulations**: Conducted field and simulation tests on NGH production–the successes, failures, and duration of the tests are provided under this section.
3) **Gas hydrate production challenges**: The main challenges faced in both field and experimental studies are summarized and grouped under Technical, Environmental and Economic limitations in this section.
4) **Commercial outlook of NGH production**: The market viability of NGH is discussed.

2. Gas hydrate dissociation methods

Most of the theories on NGH recovery if not all are focused on NGH dissociation process. NGH is primarily dissociated using methods that depend on its phase state changes. This involves techniques for disturbing the temperature-pressure envelope within which the hydrates remain stable, and thermodynamically altering the hydrate structure by replacing methane with a different gas (Li et al., 2018) (Fig. 4). The dissociation could be achieved by reducing pressure at constant temperature (red line 1), increasing temperature at constant pressure (red line 2) or increasing or decreasing both temperature and pressure (red lines 3 and 4). The NGH dissociation methods can be classified into four groups: thermal stimulation, thermodynamic inhibitor injection, depressurization, and CO_2-methane exchange. These methods are limited to the production of methane from gas hydrates hosted in sand and clayey-silty reservoirs. The gas production process is based on the conventional well drilling as well as completion strategies. To date, the production of methane from gas hydrate hosted in other formations such as mounds or fractured clay systems have rarely been presented in the literature. This is because the production of gas hydrates in such deposits will require unavailable technologies at this moment (Moridis and Sloan, 2007; Moridis et al., 2009).

2.1 Depressurization (pressure reduction)

The depressurization method comprises decreasing the pressure in the gas stabilization zone (Fig. 5a), a procedure which causes the dissociation of methane hydrate (Collett and Ginsburg, 1998; Collett, and Kuuskraa, 1998; Koh et al., 2016). In hydrate deposits with an underlying free gas, production can be achieved using drilled wells (Demirbas, 2010). The option for a drilled well will be based on the formation strength and its ability to house production tubing. Under such circumstances, a pressure drop is created during conventional production of the free-gas leg. The resultant pressure decrease within the free-gas interval can be transmitted to the overlying gas-hydrate-bearing sediments. This causes instability of the hydrate and eventually it disassociates into free-gas and water. The gas is added to the underlying free-gas accumulation (Demirbas, 2010; Beaudoin et al., 2014; Koh et al., 2016). The dissociation of hydrate continues because of the sensible heat of the reservoir, and the heat transferred from the over-/underburden–it is an endothermic reaction (Demirbas, 2010; Beaudoin et al., 2014; Konno et al., 2017). Also, the depressurization technique could be carried out by pumping out formation water (Koh et al., 2016; Li et al., 2018; Ye et al., 2020). In cases where hydrate mining has been suggested, the depressurization process is achieved by exposing the hydrates to low-pressure environments such as lifting solid hydrates to atmospheric conditions.

The depressurization method is currently deemed the most practical and cost-effective way to dissociate gas hydrates (Beaudoin et al., 2014; Zhao et al., 2015; Koh et al., 2016; Konno et al., 2017). According to Koh et al. (2016), because of the low permeability for flow through hydrate formations, the propagation of the pressure perturbation can be limited. This

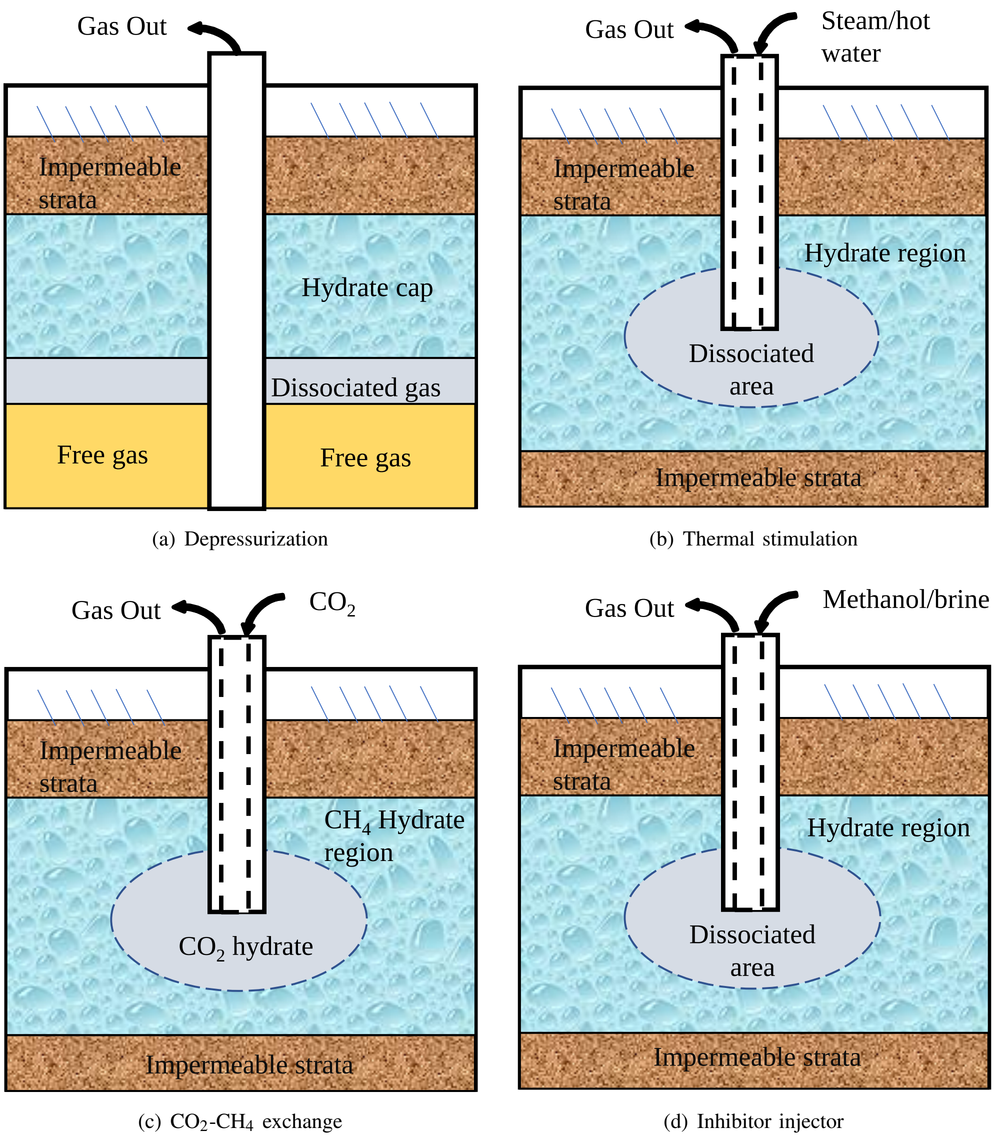

Fig. 5. Natural Gas Hydrate dissociation techniques (Modified and reprinted from Na et al., 2016).

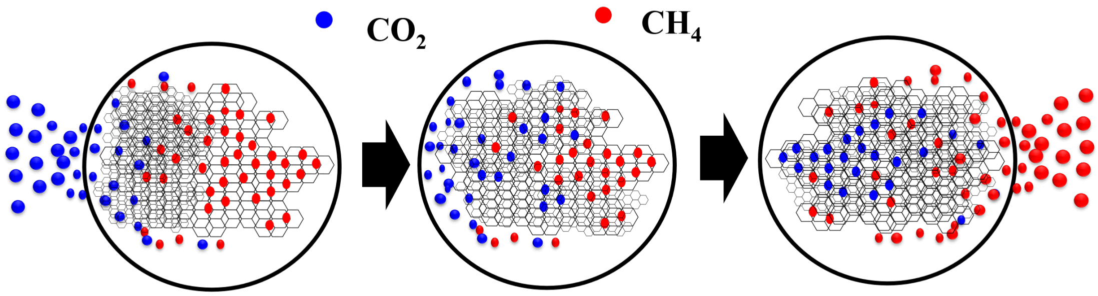

Fig. 6. Schematic illustration of the CO_2-CH_4 exchange reaction in three steps. A) Microscopic (partial) dissociation of CH_4 hydrate by CO_2 injection. B) CO_2 molecules penetrate the partially decomposed layer and reform the hydrate cage. C) Propagation of hydrate dissociation/reformation by heat and mass transfer (Koh et al., 2016).

limitation is also affected by the fact that the dissociation of NGH is an endothermic reaction and requires heat to progress the reaction.

The depressurization method was implementation in an offshore NGH production test in the South China Sea which lasted for 60 days of continuous production and the total production was 3.09×10^5 m^3. It was reported that the depressurization was achieved by formation fluid extraction (Li et al., 2018). Several tests with short production were conducted during the early Mallik tests. The results at least hinted that the idea of producing gas from gas hydrate with depressurization is promising (Hancock et al., 2005).

Another demonstration test was conducted in 2008 at Mallik site by the Japanese Canadian research group. This test took 6 days with stable and sustained production with depressurization method (Dallimore et al., 2012). The most surprising findings was that the results demonstration the test is likely to exceed the production predicted with available numerical models (Kurihara et al., 2012).

Although few short production tests have indicated the potential of depressurization method, several technical challenges need to be explored. These technical challenges include the stability of producing shallow reservoirs and deep reservoirs (Hancock et al., 2010; Boswell et al., 2014).

2.2 Thermal stimulation

This technique involves injecting a source of heat–either hot water or steam or another heated liquid directly into the hydrate stability zone. This could also be achieved indirectly via electric or sonic means, to raise temperature and cause the hydrate to decompose (Demirbas, 2010; Li et al., 2016) (see Fig. 5b). The direct method could be completed in either of two ways: 1) a frontal sweep akin to steam floods used in the production of heavy oil, and 2) pumping of hot liquid via a vertical fracture sandwiched between a production well and an injection well. Other approaches discussed in the literature include the use of pressure pulse stimulation, electromagnetic heating, microwave heating (Kantzas et al., 1994; Kamath, 1998). The thermal stimulation methods appear to be less attractive to many researchers because they require large amounts of heat. To put in perspective, it requires between 60 to 90 kJ to dissociate hydrates that contain 1 (one) mole of methane (Holder et al., 1984). Furthermore, this method has low energy efficiency–only a fraction of the supplied energy from the surface reaches the targeted hydrate-bearing sediments. The rest is lost in transport through the heating medium (Holder et al., 1984; Demirbas, 2010; Koh et al., 2016). Electrical heating, though complex can be used to avoid heat losses as the electrical heater is placed in the methane hydrates (Li et al., 2016). Several experiments were conducted at the Mallik site located in Canada in 2002. The results strongly suggests that the adoption of this method for commercial scale appears to be ineffective. It is also challenging to manage the flow paths of the released natural gas to reservoirs. Intermittent thermal stimulation does seem to improve the possibility for this technology (Moridis et al., 2009).

2.3 CO_2-methane exchange

Figs. 5c and 6 show the CO_2-CH_4 exchange procedure. The exchange of CH_4 in the NGH deposits with CO_2 is perceived as a win-win approach because of the simultaneous production of methane and storage of CO_2 (Na et al., 2016; Shaibu et al., 2018; Gharasoo et al., 2019). Koh et al. (2016) explained that pure CO_2 hydrates have better formation conditions than pure methane hydrates when gaseous CO_2 is present. Thus, for unfavorable pressure-temperature conditions for pure CH_4 hydrate formation, gaseous CO_2 can still react with water to produce pure CO_2 hydrates. The enthalpy of formation of CO_2 hydrate, which is about-57.98 kJ/mol, is smaller than the enthalpy of formation of CH_4 hydrate (about-54.49 kJ/mol). This implies that under the same conditions of temperature and pressure, CH_4 hydrate is less stable relative to CO_2 hydrate (Li et al., 2016; Gharasoo et al., 2019). Pure CO_2 does not exist in nature, as such gas mixtures containing mainly CO_2/N_2 can be used for CO_2-CH_4 replacement in hydrates. A major setback is that CO_2 hydrate formed also obstructs further contact between the CO_2 and CH_4 hydrate, thereby inhibiting the dissociation of NGH. Just as ocean storage of CO_2 though carbon capture and storage, this approach may face a lot of challenges–both legal and environmental, than the geological storage methods. Injecting CO_2 directly into hydrate bearing geologic structures below the ocean floor could cause leaks to the seabed if a poor seal exists, which may affect the chemistry of seawater. A typical effect is the reduction in pH of seawater which can lead to ocean acidification (Shaibu et al., 2018). This could

Table 1. Comparison of NGH dissociation method.

Factor	Dissociation method			
	Depressurization	Thermal stimulation	CO_2-CH_4 exchange	Inhibitor injection
Technique	-Pumping up ground water -Producing from underlying free gas zone -Excavating solid hydrates to surface conditions	-Hot water, steam injection -Electric heating	Displacement of CH_4 by either liquid or gaseous CO_2 or CO_2 $+N_2$ injection	Perturbation of hydrate stability region by chemical injection (methanol, MEG[1], DEG[2], brine)
Advantages	-No heat consumption or loss -Economical and Convenient (tr) -Preferred method	-Fast and controllable	-Low probability of Geo-stability related problems -No alteration in gas hydrate layer -CO_2 Sequestration	-Simple and convenient
Disadvantages	-Sand production -Geo-stability problems -Slow production rate	-Requires external heat source -Low thermal efficiency -High cost	-Possibility for Ocean acidification -Low gas diffusion -Technology could be expensive	-High cost of chemical -Inefficient dissolution of hydrates (Na et al., 2016) -Leakage of chemicals to ocean floor -Recovery and recycling costs
Field tests and production rate (Koh et al., 2016)	2013 Japan Nankai Trough (120,000 m^3/6 days)	2002 Canada Mallik (470 m^3/5 days)	2012 USA Alaska Ignik Sikumi (24,000 m^3/30 days)	Messoyakha hydrate gas field, Russia (Na et al., 2016)

[1]MEG = Mono Ethylene Glycol
[2]DEG = Di-Ethylene Glycol

cause catastrophic effects to the marine environment. The 1972 Convention on the Prevention of Marine Pollution by Dumping of Waters and Other Matters prohibits storage of CO_2 in the water column if it is considered an industrial waste. Whiles the CO_2 will not be injected directly into the water column, leakage could introduce CO_2 into the water.

2.4 Thermodynamic inhibitor injection

The injection of inhibitors is adopted to disturb the NGH equilibrium condition away from the thermodynamic conditions of the hydrate stability zone (Kvamme and Kuznetsova, 2004; Li et al., 2013; Li et al., 2016). Typical liquid chemicals used are brine, methanol, di-ethylene glycol (DEG), and mono ethylene glycol (MEG) (Li et al., 2013; Zhao et al., 2015; Koh et al., 2016; Na et al., 2016). The schematic diagram of the thermodynamic inhibitor injection is illustrated in Fig. 5d. Field experiments in Messoyakha hydrate gas field, and in the permafrost of Alaska using inhibitors proved the method can shift the phase boundary to obtain an obvious gas recovery (Na et al., 2016). Although the use of inhibitors has been demonstrated to be effective for the dissociation of gas hydrates, its applicability to field production is met with challenges due to chemical costs and anticipated environmental consequences (Sung and Kang, 2003; Li et al., 2007; Na et al., 2016). Chemical inhibitor injection into marine sediments can be harmful because the injected chemicals could leak to the ocean floor and damage plant and animal life (Zhao et al., 2015). Similar to thermal stimulation, the inhibitor injection tends to have a challenge such as questionable efficiency of dissociating agent when subjected to hydrates reservoir conditions (Cranganu, 2009).

Table 1 summarizes the different NGH dissociation methods.

3. Numerical simulation studies on gas hydrate production

For decades, researchers have conducted a series of field tests focused on gas production from different NGH reservoirs distributed around the world (Anderson et al., 2011; Chong et al., 2016; Li et al., 2016). However, these field tests are costly, risky, limited to short duration and vertical well configuration. One approach to solve these problems involves the use of reservoir simulation. Reservoir simulation can be used to predict the environmental changes and production rates from gas hydrates reservoirs. It can lead to an effective field development plan and better interpretation of the collected data.

Several reservoir simulators and codes have been reported in the literature to predict natural gas production behaviors in NGH reservoirs. These reservoir simulators (computer codes) have been developed by private and public sector. The most popular numerical codes include TOUGH+/HYDRATE, MH21, HYDRATE RES-SIM, STOMP-Hydrate, and CMG-STARS (Xu and Li, 2015; Li et al., 2016). Most of these simulators and computer codes solve the governing equations derived from complex coupled processes which include mass and heat transfer, gas hydrate dissociation, kinetic, and mechanical deformation, and multi-phase fluid flow physics. Researchers have been selecting these simulators/codes based on availability of specific requirement and other individual advantages.

Numerical simulation results of hydrate decomposition processes have been reported in the literature. Since there are no long duration field tests, several works have conducted

Table 2. Summary of numerical simulation studies on natural gas hydrates production.

Field locations	Site	Researcher	Simulators/code	Method	Well configuration
Shenhu Area of SCS (China)	SH7	Li et al., 2010	3D, TOUGH+HYDRATE	Depressurization with circulating hot water	Horizontal well
		Li et al., 2011	3D, TOUGH+HYDRATE	Huff and puff	
	SH3	Su et al., 2012	3D, TOUGH+HYDRATE	Depressurization	Vertical well
	SH2	Su et al., 2013	3D, TOUGH+HYDRATE	Thermal Stimulation	Vertical well
	SH2	Jin et al., 2016	3D, TOUGH+HYDRATE	Depressurization and	Horizontal well
		Jin et al., 2018a	3D, CMG-STARS	Thermal Stimulation	
Dongsha Island of SCS (China)	GMGS2	Feng et al., 2015	3D, TOUGH+HYDRATE	Depressurization (Single well) Depressurization, and warm brine stimulation (for dual wells)	Horizontal well
	GMGS3	Sun et al., 2017	3D, TOUGH+HYDRATE	Depressurization	Vertical well
Qilian Mountain permafrost of China	DK-3	Li et al., 2012a	3D, TOUGH+HYDRATE	Huff and Puff	Horizontal well
		Li et al., 2012b	3D, TOUGH+HYDRATE	Depressurization	Horizontal well
		Zhao et al., 2013	3D, TOUGH+HYDRATE	Depressurization	Vertical well
	DK-8*	Sun et al., 2014	3D, TOUGH+HYDRATE	Depressurization, Thermal stimulation	Vertical well
	DK-2	Li et al., 2014	3D, TOUGH+HYDRATE	Heat-Assisted Antigravity Drainage (HAAD)	Horizontal well
		Liang et al., 2015	3D, TOUGH+HYDRATE	Depressurization and thermal stimulation	Horizontal well (five-spot well)
Eastern Nankai Trough of Japan	AT-1	Sun et al., 2016	3D, TOUGH+HYDRATE	Depressurization	Vertical well
Mallik site, Mackenzie Delta, Canada	Mallik 2L-38 Zone #1	Moridis et al., 2004	EOSHYDR2	Depressurization with Thermal Stimulation	Horizontal, vertical, Multi-well system
	Mallik 2L-38 Zone #2	Moridis et al., 2004	EOSHYDR2	Depressurization	Vertical Well
	Mallik 2L-38 Zone #3-5	Moridis et al., 2004	EOSHYDR2	Thermal Stimulation	Vertical Well
Prudhoe Bay, Alaska	Kuparuk 7-11-12 Site	Myshakin et al., 2020	Tough+ and MH-21 (2D)	Depressurization	Vertical well
Black sea, Bulgaria	Danube Delta	Janicki et al., 2017	HyReS, COMSOL	Depressurization	Vertical well

parameter sensitivity analysis to investigate the impact of different parameters on gas production as well as hydrate gas dissociation during long duration production (Song et al., 2014).

The Table 2 summarizes the different numerical reservoir simulation methods used by researchers in different field locations for NGHs exploitation.

Notable fields around world where numerical simulation has been used for NGH exploitation includes the Shenhu Area of South China Sea (SCS), Dongsha Island in SCS, Eastern Nankai Trough of Japan, Mallik site, Mackenzie Delta of Canada, Qilian Mountain permafrost of China, Prudhoe Bay, Alaska and Black Sea, Bulgaria etc.

Numerical studies were used to investigate the gas production form Hydrates using the depressurization method combined with circulating hot water using 3D, TOUGH+HYDRATE simulators on SH7 site of the Shenhu Area of South China Sea (SCS) (Li et al., 2010). Simulation results also showed that horizontal wells perform better than vertical wells with regards to gas production behavior for Class 3 hydrates reservoirs and in preventing the formation of secondary hydrates (Li et al., 2011). Simulation work done by Chen et al. (2017), studied the effect of fracturing on gas production using depressurization method on the SH7 site. There was significant increase in the cumulative gas volume, and gas production rate by about 43.5% and 25.6% respectively.

Also, numerical simulation was employed to assess gas production from a thin Hydrate-Bearing Layer by depressurization using vertical wells at drilling site SH3 in the Shenhu area (Su et al., 2012). The results were not promising due to the low hydraulic diffusing of the deposits. There was a decline in the gas production rate which later averaged at $211 m^3$/d.

Su et al. (2013) applied numerical simulation (3D, TOUGH + HYDRATE) to study gas production potential from hydrate deposit of the SH2 drilling site in the Shenhu area using thermal stimulation method through vertical wells. Similarly, Jin et al. (2016), studied gas production from unconfined hydrate-bearing sediments screened with a permeable layer using combined depressurization and thermal stimulation to extract the gas in the SH2 site. The results showed that gas recovery can be improved by placing vertically the injection well at the center of hydrate-bearing sediment. Jin et al. (2018b) used the 3D CMG-STARS simulator to study the effect of geomechanical responses caused by the depressurization with horizontal well during gas production from hydrate bearing formation located at SH2.

The Dongsha Area of SCS was also studied by researchers such as Feng et al. (2015) and Su et al. (2017) for NGH opportunities. Feng et al. (2015) using 3D, TOUGH + HYDRATE was able to study the gas production from hydrate-bearing deposits in site (GMGS2-16). They used the depressurization method first with single horizontal well and then with dual horizontal wells. The results show that the average gas production rate due to depressurization using dual horizontal well was more than twice that with single well. Also, joint depressurization and warn brine stimulation with dual horizontal wells was tested as well. Sun et al. (2017) carried out a simulation study using TOUGH+HYDRATE and FLAC3D simulators and results show that it was not economical to produce the Hydrate reservoir of GMGS3-19 site owing to low reservoir permeability and permeable burdens.

The Qilian Mountain Permafrost was also studied by researchers such as Li et al. (2012a, 2012b), Zhao et al. (2013), Sun et al. (2014) and Liang et al. (2015). Li et al. (2021a) numerically examined the production potential of methane gas from hydrates at the DK-3 site of the Qilian Mountain permafrost China. They applied the huff and puff procedure with a single horizontal well. The simulation helped evaluate gas-to-water ratio, gas/water production, and energy efficiencies. Sensitivities on gas production performances were analyzed.

Zhao et al. (2013) used 3D Tough+Hydrate simulator to simulate the production potential of gas from a hydrate bearing formation by the depressurization method. The average gas production rate was approximately 188 STm^3/d. Only a 2.3% of the total NGH was recoverable. This suggests a single vertical well, which was used in the simulation, is not optimal for the development of gas hydrate deposits in the DK-3 site. Li et al. (2012b) concluded that carrying out the depressurization method using a single horizontal well was not economically viable as well. The DK-8 site in the Qilian Mountain permafrost was studied for gas production potential from its hydrate bearing deposits. Numerical results using 3D, TOUGH + HYDRATE showed that recovering gas by joint depressurization and thermal stimulation method were not economically viable (Li et al., 2012b).

Using the Heat-Assisted Antigravity Drainage (HAAD) method on a horizontal well, Li et al. (2014) simulated the production of gas for DK-2 site in the Qilian Mountain permafrost. Five-spot horizontal well system was used to recover gas from NGHS at site DK-2 from simulation studies conducted by Liang et al. (2015).

The Eastern Nankai trough of Japan was also studied by researchers such as Sun et al. (2016). Using 3D, TOUGH + HYDRATE simulator they were able to simulate the gas production from hydrate-bearing deposits in AT-1 site by the depressurization method with single vertical well.

Numerical simulation studies of gas production using EOSHYDR2 model for several hydrate bearing zones at the Mallik site (Mallik 2L-38 Zone #1-5), Mackenzie Delta, Canada was carried out by Moridis et al. (2004). Their work shows that in Zone #1, when using the depressurization method, some gases were produced. Horizontal wells were found to be slightly preferable to vertical wells, while multiwell systems using joint depressurization and thermal stimulation method increased gas productivity. Zone #2 produced more gas with high water cut. Thermal stimulation method was applied to Zones #3, #4 and #5.

Myshakin et al. (2020) carried out numerical simulation of gas production from gas hydrate formations at the Kuparuk 7-11-12 Site, Prudhoe Bay, North Slope, Alaska using the 2D Tough+ and MH-21 simulator. The depressurization method was applied to a reservoir unit at constant bottom hole pressure. The results have been used to forecast reservoir performance using up to 1 year of depressurization using vertical wells. Also, the result of the numerical simulations support field development planning.

Janicki et al. (2017) applied numerical simulation to investigate the gas hydrate potential from Submarine Gas Hydrate Reservoirs located in the Danube delta, Black Sea which is within Bulgaria. The HyReS simulator which was implemented in COMSOL Multiphysics was used to describe the gas (methane) production from subsea hydrate deposits. Gas production occurred using simple depressurization method but at low production rates. It was found out that the gas production strongly depends on the reservoir geo physical and geothermal properties.

4. Field production tests

The literature shows a handful of field production tests that have been performed in some part of the world as shown in Table 3. The conclusions drawn from these tests continue to be debated considering most of the tests are of short duration. The long-term production has rarely been analyzed in the literature. As matter of fact, as of today no prior studies have investigated the long duration production tests.

In 1969-1970, field production of gas tests using depressurization method was carried out in the Messoyakha gas hydrate resources located in eastern border of West Siberia, Russia for the first time. (Makogon et al., 2013). The gas hydrate reserve prior to field development in the Messoyakha field was estimated at $9-12\times10^9$ m^3. The cumulative gas produced due to hydrate decomposition was about 5.4×10^9 m^3 at the end of 2011. Significant cumulative volume of water has been produced from the reservoir and it has also maintained

Table 3. Field production test of hydrates around the world (Li et al., 2018).

Year	Location	Production method	Duration	Total yield (m^3)
2020	Shenhu area of SCS, China	Depressurization	30 days	861,400
2017	Shenhu area of SCS, China	Depressurization	60 days	309,000
2017	Nankai trough, Japan	Depressurization	12 days	35,000
2017	Nankai trough, Japan	Depressurization	24 days	200,000
2016	Permafrost area of the Qilian, Mountains, Qinghai, China	Depressurization	23 days	1078
2013	Nankai trough, Japan	Depressurization	6 days	119,000
2012	North slope of Alaska, USA	CO_2 replacement and depressurization	30 days	24,000
2011	Permafrost area of the Qilian, Mountains, Qinghai, China	Depressurization and heating	101 hrs	95
2008	Mackenzie Delta, Canada	Depressurization	6 days	13,000
2007	Mackenzie Delta, Canada	Depressurization	60 hrs	830
2002	Mackenzie Delta, Canada	Heating	5 days	516

almost constant pressure for more than 25 years. There have been concerns raised by researchers such Collett and Ginsburg (1998) to consider the possibilities that the gas produced from Messoyakha reservoir might have been released from a free gas zone rather than hydrate dissociation. Thus, negating the facts that Messoyakha should be seen as the only sample of commercially successful methane hydrate reservoir in history. (Moridis et al., 2009).

In the year 2007, depressurization was applied to a methane hydrate reservoir zone at Mallik site in Canada. An estimated cumulative gas production of 830 m^3 was recorded for a 60 hr production test period. The test was short lived due to excessive sand production. A longer test period was carried out in 2008, where depressurization was carried out in 3 stages and more measures were put in place to combat the excessive sand production. A total estimated cumulative gas production of 13,000 m^3 and water production of 70 m^3 were recorded for a 6-day production test period.

Between the years 2011 and 2012, a pilot test which involved the huff and puff method of CO_2/N_2 injection into the Eileen gas hydrate reservoir in the Ignik Sikumi site, of the Alaska North slope was carried out by team of researchers from the industry and academia. A total 24 MSm^3 of methane gas was produced, 40% injected CO_2 and 70% injected N_2 were recovered. Large volume water and sand were produced.

The first deepwater hydrate production was undertaken in Japan in early 2013 in the Daini Atsumi Knoll, Eastern Nankai Trough. A well was drilled through a kilometer of water and a few hundred meters of mud to reach a target of a 60-meter-thick layer of hydrate-rich formation in the Nankai trough. Water was pumped out to lower pressure which resulted in gas flowing at 20,000 m^3/day. This production test took 6 days and the total amount of gas that was recovered from this test was 119,500 m^3. It could simply mean that the average production rate was 19,917 m^3/day (Konno et al., 2017; Yamamoto et al., 2017).

Most recently in 2017, Japan conducted another gas production test. This second production test produced 41,000 m^3 of gas in a period of 12 days, meaning that the daily average production rate was 3,417 m^3/day for the well AT1-P3 and another well which was identified as well AT2-P2 produced a total of 222,500 m^3 within a period of 24 days. This could simply mean that the average production rate for well AT2-P2 was 9,271 m^3/day.

In 2017, China conducted its first offshore NGH production test in the Shenhu Sea. This production test produced 309,000 m^3 of gas for a period of 60 days (2 months). This implies that the average gas production rate was 5,150 m^3/day (Li et al., 2018). In these tests, a single vertical well was used, and the reservoir depressurization method of production was adopted. Following success with some related operations challenges from the 2017 production from the Shenhu sea, a second offshore NGH production test was conducted in the same Shenhu sea using horizontal wells, from October 2019 to April 2020 (Ye et al., 2020). Due to various operational challenges encountered, including sand production, 30 days of continuous gas production was recorded (Ye et al., 2020). The cumulative yield was 861,400 m^3 with an average daily gas production of 28,700 m^3. From a close look at the production data, it can be seen that the test produced relatively high volumes of gas from NGH reservoirs than in the 2017 test. It is however important to note that the reported production rates were far below the acceptable commercial production rate which is generally around 300,000 m^3/day.

Several technical questions have arisen regarding the production of methane from NGH based on these tests. These questions include how to handle the problem of high-water production as well as the issue of sand production. These problems can hinder the long-term gas production from the NGH formations (Uchida et al., 2016; Yin et al., 2019). It would be special interest for the scientific community to provide answers to these questions so that effective and commercial gas production will be achieved in the future. One approach to solve this problem involves the use of existing technology namely, horizontal well technology can be very promising method. The horizontal well has longer length passing through producing layer which in turns increase the surface between the reservoir and well. This seems to lead to high gas production in short period of time.

5. Gas hydrates production challenges

Several short duration field tests on gas recovery from NGH reservoirs have been explored in the literature in various locations including in Canada, Alaska, Japan, and China. The main conclusion that can be drawn from these field tests is that reservoir depressurization is likely to be the dominant method to produce natural gas from NGH reservoirs. At this stage of understanding, the consensus is that other production methods do not seem to lead to the significant production of gas. The optimization of gas production could be achieved through combining reservoir depressurization with other methods such as heating and chemical injection. Although field tests and reservoir simulation results from the literature have demonstrated the potential of producing natural gas from NGH reservoirs, the feasibility of gas recovery from NGH reservoirs requires overcoming technical, environmental, and economical challenges. Also, improving NGH production capacity will require expansions of NGH dissociation front, improvements on the dissociation rate, and enhancements in fluid flow through sediments (Li et al., 2021).

5.1 Technical limitations

The occurrence of gas hydrates differs geographically. Various variables and location-specific parameters influence the nature and development potential of gas hydrate deposits (Cui et al., 2018). These include the presence and size of the zone with favorable conditions of pressure-temperature for gas hydrate formation, the characteristics of the host strata and their capacity to hold rich accumulations, and the local supply of methane gas, (Beaudoin et al., 2014). The geological locations of gas hydrates deposits vary significantly–they occur in the permafrost, which is much shallower than ocean deposits. In the ocean deposits, there are those on the sea floor and those beneath. These presents technical challenges in technology developments for exploiting NGH.

In most field tests one major challenge encountered is sand production (Kurihara et al., 2012; Schoderbek et al., 2013; Yu et al., 2018). Because methane hydrates usually exist in shallow and unconsolidated formation, high degree of pressure change, and subsequent effective stress change happen during production. The dissociation of hydrates may cause deformation and failure of the formation and lead to sand production (Yang et al., 2016, 2017; Liu et al., 2017). The worlds' first methane hydrate production attempt was undertaken in the early 2013 in the Daini Atsumi Knoll, Eastern Nankai Trough, Japan. It came to an unexpected end due to massive sand production (Yamamoto et al., 2017). Lu et al. (2018) observed sand production in lab scale experiments of NGH production. These events endanger the safety of hydrate exploitation. Chong et al. (2016) noted that technology for exploiting methane hydrates will be subject to the effective management of sand production. One technical concern also reported is a flow assurance and blockage of the flow lines due to gas hydrate re-association during flow to the surface (Yamamoto et al., 2017). Hydrate dissociation during drilling can also be induced by the drilling activity. Gas hydrates exist in a thermodynamic equilibrium within a pressure and temperature envelope. However, multiphase flow and heat transfer in the sediments does occur during drilling which could disturb the stability of the hydrate deposit, causing it to decompose and leak gas. This reduces the resource in place (Liu et al., 2019, 2020).

Wu et al. (2017) estimates that over 90% NGH reserves are found in marine clayey-silt sediments. The two field production tests in the Shenhu area of the South China sea (Li et al., 2018; Ye et al., 2020) were from these sediments. However, marine clayey-silt sediments are characterized by low formation permeability, weak consolidation, and shallow burial depths. These characteristics presents major challenges for NGH exploitation. These sediments are prone to geohazards during drilling, and production due to the shallow burial depth and poor consolidation (Ye et al., 2020; Li et al., 2021). Other challenges faced with marine clayey-silt sediments include hydrocarbon estimation, development of appropriate production technique, and deposit parameter refinement (Li et al., 2021).

Wan et al. (2019) presented a feasibility study on the use of horizontal snake wells to produce natural gas from offshore gas hydrate deposits. They demonstrated the use of coiled tubing string to drill coiled wells in a spiral manner inside a hydrate-bearing layer. The technique addresses problems pertaining to well productivity and wellbore stability. Similarly other authors have sort to address other issues facing gas hydrate development. The use of frac-pack to address sand production and well stability have been studied by Shan et al. (2020) and Guo et al. (2021).

Even if we can situate a rig safely, methane hydrate becomes very unstable when removed from the deep sea and it begins to escape when being transported to the surface. Unless there's a means to avoid the gas leakage, extraction won't be effective. It will be a bit like drawing up water from a well with a perforated pail (Koh et al., 2016). When drilling through the hydrate-bearing zones, temperature of the drilling fluid could also cause hydrate dissociation. Sun et al. (2018) showed that gas diffusion in from pore water to the drilling fluid could also cause hydrate diffusion even in cases where temperature and pressure effects are controlled.

5.2 Environmental limitations

Besides developing methods for efficient gas production from hydrates, it is of great importance to assess the potential environmental effect of hydrate production given the distinctive nature of this resource. The major environmental concerns from methane hydrate development are the release of produced water into the oceans, gas leakage from the seafloor upon dissociation, seafloor submarine landslides and subsidence (Chong et al., 2016). Methane is a powerful greenhouse gas. Extraction of the gas and gathering activities for ocean deposits could lead to heating/warming of the oceans. This could cause extensive decomposition of hydrate deposits causing the release of large amounts of methane gas into the atmosphere, increasing the amount of greenhouse gases in the atmosphere (Beaudoin et al., 2014). Jones (2017) is of the view that escaped methane gas from the seafloor may never reach the surface. It is most likely to get trapped in sediments, get gobbled up by microbes or dissolves into the water (Ruppel, 2017). The seepage of gas in the oceans is common globally, it is a continuing natural phenomenon within zones of likely gas hydrate existence and in shallow water zones where gas hydrates do not occur. However anthropogenic large-scale leakage of methane gas could present a totally different picture, one that could contribute significantly to global warming and destruction of the marine ecosystem.

Drilling and extraction activities could also disrupt the sea floor and cause geohazards.

5.3 Economic limitations

The world is awash with gas from existing unconventional sources (shale gas, tight gas) and gas from conventional sources–with well-established markets, to worry so much about hydrates. A typical deep-water natural gas well produces over 1 million m^3 /day of methane, thus 50 times more than the rates achieved with hydrates so far (Jones, 2017). For countries such as India and Japan who import more than a third of their energy resources, hydrates might look a lot more attractive and could make economic sense to invest substantially in its exploitation (Jones, 2017).

While the field tests and associated modeling undertaken to date have proven the technical practicality of production, realizing economic viability–even in the most promising reservoirs–would necessitate overcoming a range of multifaceted technical and operational challenges (Walsh et al., 2008). Economic feasibility will also be strongly influenced by the nature of local energy markets and global energy supply issues.

6. Commercial outlook of ngh production

Understanding the economic effect of gas hydrates includes evaluating a wide range of variables (Beaudoin et al., 2014). Natural gas in general has long been known as a comparatively clean-burning fuel, and its importance is projected to grow because the world's energy portfolio and infrastructure are changing into a gas-based economy. The global market for energy is huge and ever increasing (10-year average of 2.5%) (British Petroleum, 2015). This means the energy market in the future will offer opportunities for alternative energy sources and natural gas will play an important role as the cleanest of the fossil fuels in the transition period for more than 50 years (Koh et al., 2016). The global estimates of methane gas present in hydrate reservoirs range from 2×10^{14} to 3.053×10^{18} m^3 at standard conditions (Silva and Dawe, 2011). Even if the conservative estimates are considered, the unanimity is that the global amount of methane hydrates are huge and spread widely in marine and permafrost regions around the globe, including in those regions with the highest anticipated growth in energy demand (Japan, China, India, USA) (Silva and Dawe, 2011). This interest is augmented by: (i) the growing demand for energy, (ii) the limited availability of conventional fossil fuels and (iii) the environmental friendliness of natural gas relative to liquid fossil fuels.

The potential direct market paybacks of hydrate resources derive essentially from the sale of the produced natural gas. Additional natural gas from hydrate deposits could translate into expanded economic activities, tax and royalty payments, and employment. Other benefits include mitigation of energy prices, decreased price volatility, and energy security (Beaudoin et al., 2014).

7. Conclusions

This work reviewed the progress made so far in the exploitation of natural gas hydrates. The main themes covered were production technology methods, production challenges, and market outlook. The production challenges were discussed in the context of technology, environment, and economy. From the literature, sand production has been identified as one of the major challenges which needs to be addressed through technology development. The sand problem has led to most pilot projects grinding to a halt. The use of fac-packing to address the problem as has been investigated by some researchers, but it still requires further research on its feasibility.

Currently, there is no commercial scale production of methane from NGH. The highest yield ever recorded is 861,400 m^3 in 2020 in the Shenhu area of the South China Sea. Continuous production was recorded for 30 days. An earlier production expedition in the Shenhu area resulted in a cumulative gas production on 309,000 m^3 for a period of 60 days in. The Shenhu area is characterized by clayey-silt sediments which are known to contain over 90% NGH reserves. The use of numerical models has shown that the introduction of multiple horizontal wells could increase the production rates and improve hydrocarbon production.

A commercial assessment shows that methane from NGH has high market prospects and will provide a perfect energy mix as the world transition towards clean energy whilst at the same time global energy demand is on the rise. The market viability is however clouded with some uncertainty due to cheap shale and conventional gas. The success of NGH in the energy market will depend on economic conditions in the future. As a way of progress, the development of technology and methodology to reduce the overall cost of natural gas hydrate development needs to be encouraged.

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Conflict of interest

The authors declare no competing interest.

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