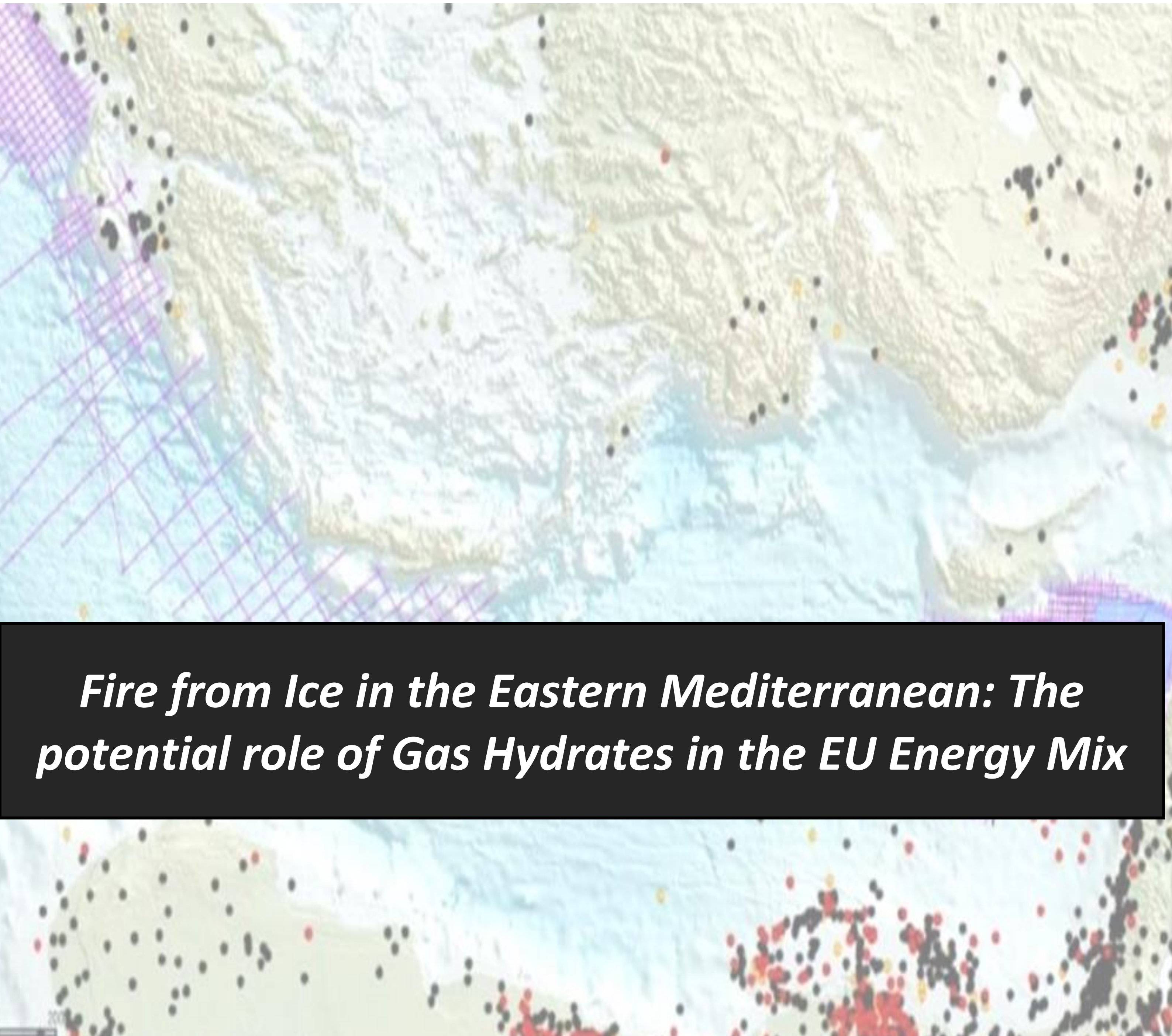

Fire from Ice in the Eastern Mediterranean: The potential role of Gas Hydrates in the EU Energy Mix

Konstantinos Michalopoulos

Athens, 2021

“Science is built up of facts, as a house is with stones. But a collection of facts is no more a science than a heap of stones is a house.”

Henri Poincare

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Konstantinos Michalopoulos

Athens, 2021

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Abstract

To meet its expanding needs, Europe is heavily reliant on Russian natural gas. In recent decades, there have been efforts to reduce this reliance by investing extensively in renewable energy sources. Natural gas is expected to play a significant role among renewables and in the future energy mix. Methane hydrates is a source of methane gas in crystalline formation that looks like ice and can be found in permafrost regions or under the sea in outer continental margins.

Methane hydrates have the potential to revolutionize future gas production. Several countries including the United States of America, Japan, and Canada have invested heavily in research programs in order to find viable ways to extract natural gas from hydrates. These countries have successfully achieved small-scale production, demonstrating that natural gas extraction from hydrates is technically feasible. In the Eastern Mediterranean Sea, under the EU-funded "Anaximander Project," significant methane hydrate samples have also been recovered (2003-2004). However, there has been no additional progress in carrying out exploration and production test programs since then.

The purpose of this study is to demonstrate the significance of the methane hydrates as a potential resource and reserve for natural gas. The projected scenario of domestic conventional gas production combined with gas produced from hydrates may help diversify Europe's gas resources and reduce the EU's reliance on external sources of natural gas. Under this prism, the EU should continue to investigate methane hydrate deposits by making the necessary investments and executing production test programs as well as continue funding all relevant research programs.

Introduction

The era of hydrocarbons does not seem to be over, however there might be some indications in the horizon. They will still account for a significant portion of the global energy mix by 2050, despite significant breakthroughs in renewables. Many new players come in the energy market with the elusive promise of additional and cheaper resources and the will to disrupt the game – and eventually make money out of it.

Gas is believed to gradually replace coal, which is a source of distress for some existing players. The world is facing a proliferation of Liquefied Natural Gas (LNG) supplies that are already impacting gas markets and competing with pipeline gas.

There is a constant call for further investments in renewables, but lower oil, gas and coal prices and increased efficiency might slow this down. The global players do take into consideration the call for renewables (like solar and wind energy), either for publicity purposes or even because they do believe that this could be the future.

The European Union seems determined to proceed with all legislative acts regrading renewables and the energy mix. A unified European energy market will allow Europe to increase its security of supply by allowing energy to flow freely across borders, therefore avoiding unforeseen complications or imbalance between union members. But the union members do seem to have some conflicting interests which they subtly but firmly pursue.

Russian perceptions of energy security are apparently very different than those of the EU (not the whole EU – also apparently) and primarily about predictability and stability of energy prices because they heavily rely on hydrocarbon revenues. Russia does not want to be vulnerable to Ukraine transit problems, so it will accelerate the development of alternative routes. Just to set a clear example on Europe's complicated interests: Germany and the Baltics are supporting Nord Stream while other members (and the ever-present US partner) definitely see it as a Russian manipulation gambit.

With the existing global turmoil within the energy market there has been a hope for a new 'gamechanger': gas- or methane- hydrates. The supporters of this new potential energy source evangelize that gas hydrates should be seen as a fuel for future and can meet energy requirements of future generations. Gas hydrates is a source of methane gas which is found in crystalline formation and can be found in permafrost regions or under the sea in outer continental margins. It is estimated that the total amount of carbon in the form of methane hydrates could be almost double the carbon content in all the fossil fuel reserves put together.

Enormous amounts of methane hydrate have been found beneath Arctic permafrost, beneath Antarctic ice, and in sedimentary deposits along continental margins worldwide. In some parts of the world they are much closer to high-population areas than any natural gas field. These nearby deposits might allow countries that currently import natural gas to become self-sufficient. The current challenge is to inventory this resource and find safe, economical ways to develop it.

In 1930's it was found that solid gas hydrate formed in the oil and gas transmission pipelines in the U.S. were accountable for the clogging of pipelines. After this, gas hydrate was seen as a curiosity and definitely not positive. The first such example responsible for blocking the pipes due to gas hydrate was provided by Hammerschmidt in 1934 who invented the first algorithm for calculating the amount of methanol to inhibit the formation of natural gas hydrates.

More than half a century ago, natural gas hydrates were located for the first time as gas hydrate deposit in the vast wasteland of Siberia. Since then there has been always a discussion about its potential to become the alternative energy solution. It was also discovered that the low temperature and high-pressure conditions is the necessity for the hydrate formation which should present extensively around the globe, under the deep oceans and in permafrost regions. The occurrence of gas hydrates in oceanic sedimental layers was first observed through seismic observations before the Ocean Drilling Program started intentionally identifying hydrate deposits, bringing samples to the surface. The last decade the efforts of research and development in the field of gas hydrates has resulted into the discovery of occurrence of gas hydrates in the continental margin areas.

Despite this promise, future production volumes are speculative because methane production from hydrate has not been documented beyond small-scale field experiments. Large-scale commercial operations to develop gas-hydrate deposits are still further away in the horizon. There are many challenges in exploiting gas hydrates. Drilling operations that aim to extract methane from hydrates have to cope with the most crucial challenge, that of the volatile nature of the gas and its subsequent expansion as it rises to the surface from a high-pressure to low-pressure environment.

Additionally, there is criticism for methane as is it is indeed a potent greenhouse gas and the impact to climate change as a result of hydrate exploitation is an important concern. A given volume of methane causes 15 to 20 times more greenhouse gas warming than carbon dioxide, so the release of large quantities of methane to the atmosphere could exacerbate atmospheric warming and cause more gas hydrates to destabilize in a destructive spiral.

Some research suggest that this may have happened in the past. This is the case of the Paleocene-Eocene Thermal Maximum, around55 million years ago, when global warming may have been related to a large-scale release of global methane hydrates. Some scientists have also advanced the Clathrate Gun Hypothesis to explain observations that may be consistent with repeated, catastrophic dissociation of gas hydrates and triggering of submarine landslides during the Late Quaternary (400,000 to 10,000 years ago).

Chapter 1: Basic Facts about Gas Hydrates

A clathrate is a chemical compound in which molecules of one material form a solid lattice that encloses molecules of another material. Methane hydrate is a naturally-occurring clathrate in which a host lattice of water-ice encloses guest molecules of methane. Methane, made of one carbon atom and four hydrogen atoms, is the simplest hydrocarbon molecule and the primary component of natural gas. In methane hydrate, the gas molecules are not chemically bound to the water molecules but they are trapped within their crystalline lattice. The substance from this reaction looks exactly like ice but it does not behave like ice. When the hydrate is dissociated the methane molecules are released and they can be ignited. Methane hydrates are very closely tied to their environment and they form in very specific conditions of temperature and pressure.

They form in quite large quantities here on Earth. Approximately 85 per cent of a gas hydrate is water molecules which form a crystalline lattice. Other guest molecules like methane stabilize this lattice , enclosed in its cavities. In the gas hydrates case, stability requires at least 70 per cent of the cavities to be occupied by methane molecules. The occupancy rate usually is more than 95 per cent.

Figure 1: Different manifestations of gas hydrates. Photo (A) originates from the 2002 Mallik Gas Hydrate Production Testing Program; (B) is courtesy of Ian MacDonald and (C) courtesy NGHP Expedition-01.

1.1 Formation of Gas Hydrates

Gas hydrates form where sufficient supplies of methane and water can combine in a location with relatively low temperature and high pressure. Methane is formed by the decomposition of organic carbon, which migrates upward through water-laden sediment. In the right conditions, gas hydrates are formed. The Gas Hydrate Stability Zone (GHSZ) is the location in the range of depths at which pressure and temperature are suitable for gas hydrates. The local conditions define exactly where the GHSZ is found and how far it can be extended.

In the Arctic, where temperatures are low and there are thick zones of permanently frozen soil the the top of the GHSZ lies about 300 to 400 metres below the land surface. In regions of relatively thick permafrost, the GHSZ often extends 500 metres or more below the base of the permafrost.

When we refer to oceans or deep inland lakes, high pressures are generated by 300 to 500 metres or more of overlying water. Then the top of the GHSZ occurs within the water column, and the base is some distance below the sea floor.

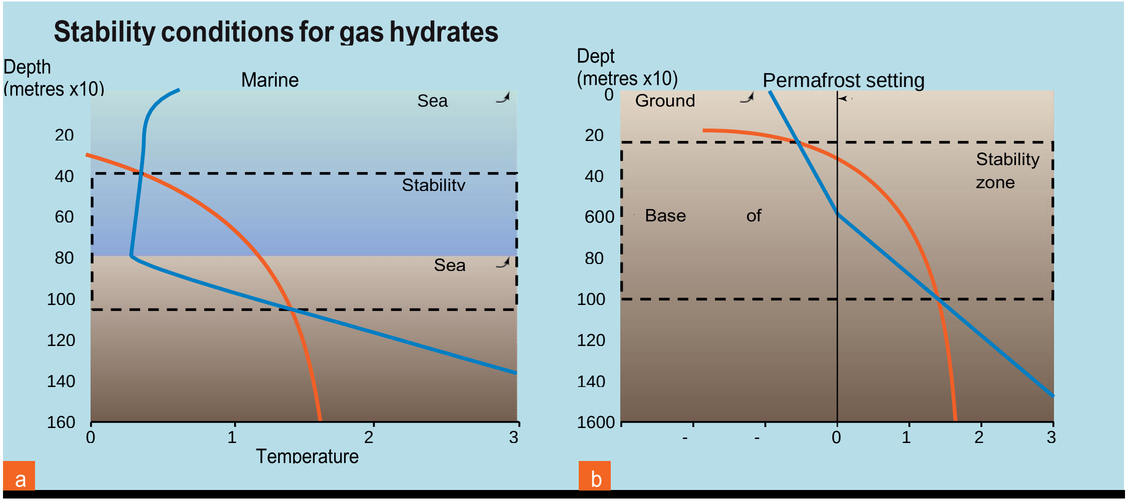


Figure 2: Phase diagrams illustrating the stability zones of Gas Hydrates in Marine (a) and Permafrost environments (b). Blue Curve is the temperature and Orange Curve is the Hydrate Stability Curve. (Beaudoin Y. C., 2014)

As we can see in Figure 2 above, temperature and pressure both increase with depth in Earth, and while in higher depths hydrates can exist in warmer temperatures when there are high temperature conditions because of the high pressure it gets too hot for them to be stable. This fact limits the hydrate stability zone to the upper 1000 meters or less of the sediment.

Because methane hydrates can only remain solid at low temperatures and high pressures, it is difficult to recover methane hydrate samples intact. When the recovered samples from marine sediments reach Earth's surface they tend to dissociate. Gas hydrate is a very concentrated form of natural gas. When dissociated at surface temperature and pressure, one cubic foot of solid methane hydrate will be equal to about 164 cubic feet of methane gas. (Beaudoin Y. C., 2013)

1.2 Gas Hydrates in Nature

Methane hydrates are a solid part of the global carbon cycle. Methane is the third most common greenhouse gas in the atmosphere, following water and carbon dioxide. Although it comes in relatively small concentrations, methane's role is of high importance due to its efficiency in absorbing and trapping the heat emitted off Earth's surface.

Additionally, methane molecules in the atmosphere eventually break down to form the other two most common greenhouse gases: carbon dioxide and water. Current estimates indicate that gas hydrates contain the majority of the world's methane and almost a third of the world's mobile organic carbon.

Gas hydrates are dynamic and not static nor a permanent methane trap. Methane migrates into hydrate formations and seeps out of them, but very little of that methane will come out to the atmosphere. Microbes in the sediment are consuming most of the available methane, and the escaping methane is widely dissolved in the ocean and metabolized by microbes before it can reach the atmosphere.

In some locations, such as offshore Vancouver Island, Barkley Canyon and the Gulf of Mexico, methane seeps have formed massive mounds of gas hydrate, many meters across. These mounds can change shape or vanish completely in the space of a few years, but they can also host unique biological communities that include methane-consuming bacteria and a variety of invertebrates, including large "ice worms" that graze on bacteria. These ecosystems are relatively common features along the continental margins and in tectonically active areas of the sea floor. Although their scientific investigation is still in early stages, fossil evidence suggests that such ecosystems have been oases for sea-floor life for millions of years.

Figure 3: Example from the methane seep ecosystem. 3, 4, 5 are chemosymbiotic animals whose energy source is hydrogen sulphide produced by methane-degrading microorganisms in the sediment. 1: Lithodid crab embracing tube cores placed in a field of vesicomyid clams and bacterial mat. 2: Yeti crabs Kiwa puravita. The “fur” on their claws is filamentous symbiotic bacteria, which they garden by waving in sulphide-rich fluids and then consume. E: Snail – Neptunea amianta and their egg towers attached to rock. F: Thyasiridae, Quespos Seep, 400 m, Costa Rica margin. Photos are of Greg Rouse and Lisa Levin.

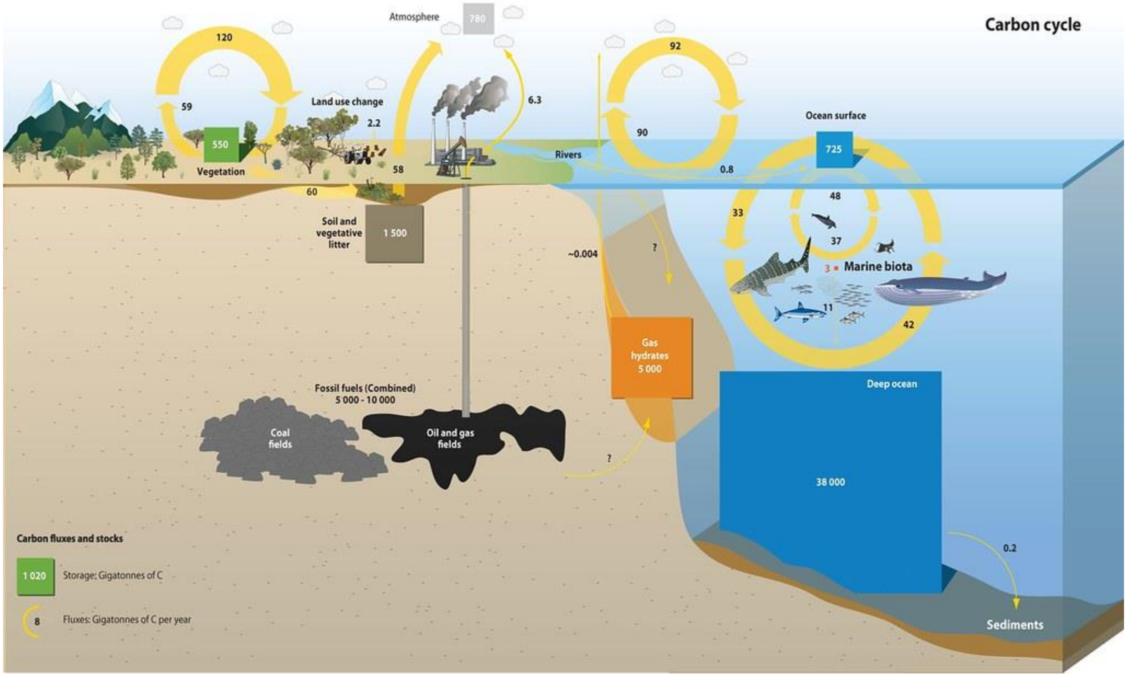


Figure 4: Global carbon cycle. Carbon moves through the atmosphere, biosphere, geosphere, and hydrosphere. as hydrates (orange) are shown in marine sediments, but are also buried beneath permafrost sediment in Arctic regions. The 5000 GtC cited for gas hydrates is a midrange estimate from recent global assessments, and the ~.004 GtC/year carbon flux from hydrates is taken from the Intergovernmental Panel on Climate Change (IPCC, 2007). All other values are compiled from Houghton (2004).

Chapter 2: The Global Energy System & Gas Hydrates

Throughout all of modern history, the energy system has played a crucial role in the advancement of economic and social development. Furthermore, the energy system is now recognized as a significant contributor to humanity's impact on the global environment, particularly when considering climate change. It is also essential for the promotion of sustainable economic growth. In many parts of the world, the demand for energy is increasing at an alarming rate. With the advent of the coal age and the development of steam power, the global energy system transitioned away from a reliance on traditional energy sources, such as firewood, and toward a reliance on fossil fuels. The annual increase in global energy demand has increased from an increase of approximately 2.2 percent per year. Throughout history, the composition of the world's fuel mix has become significantly more diverse. Although oil, coal, and biomass consumption are declining as a percentage of total energy consumption, their absolute consumption continues to rise as a result of the energy demands of an expanding population and a growing global economy, despite their declining share of total energy consumption.

The evolution of the global energy system is a slow process. The introduction of new and advanced energy technologies, as well as their market deployment, take a very long time. Any new resource, regardless of its attractiveness, could take anywhere from 30 to 50 years to replace 80 percent of the world's energy capital stock, according to some estimates. For example, it took roughly half a century for crude oil to displace coal as the world's dominant energy source from the United States. Energy conversion changed fundamentally with each new technology: internal combustion engines, electricity generation, steam and gas turbines, and chemical and thermal energy conversion, to name a few examples. Internal combustion engines were the first. On a global scale, the time constant for fundamental energy transitions has been approximately 50 years in the past century.

During the period 1910 to 1920, coal achieved its maximum market share of the world's energy supply, and it continued to hold a dominant position until 1965. Oil fields were first discovered in the late nineteenth century, but it was not until the 1960s and early 1970s that oil began to take over as the primary energy source of choice for the world. Oil has dominated the energy mix since 1965, as the automotive, petrochemical, and other industries have grown in sophistication. The increase in natural gas consumption has been less rapid, but it has been consistent. Since the mid-1950s, natural gas has more than doubled its share of the world's primary energy mix. (WEF, 2013)

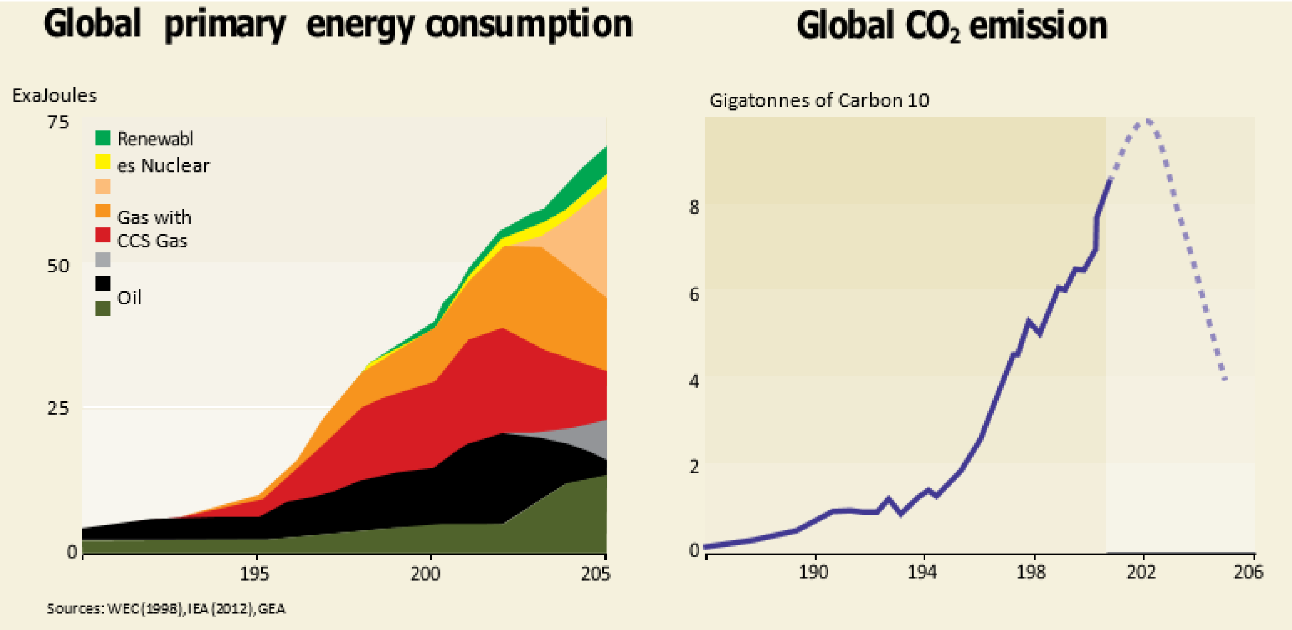


Figure 5: Global primary energy consumption by sources: 1860- 2009. Sources: WEC (1998), IEA (2012).

According to many energy analysts, this trend points to a future in which natural gas will be increasingly used as a fuel, which could serve as a bridge to a low- to zero-carbon long-term energy outlook. That is consistent with the dynamics of primary energy substitution, as well as with the steadily decreasing carbon intensity of primary energy and the steadily increasing hydrogen to carbon ratio over the last several decades. With the incorporation of non-fossil energy sources into the primary energy mix, new energy conversion systems will be required to provide low- to no-carbon energy carriers, in addition to the increasing share of generated electricity. Carbon capture and storage technologies, combined with conversion systems, are considered as the best bet. It is anticipated that the implementation of such technologies will result in a greater role for energy gases and, over time, hydrogen in the methane economic system. The potential for natural gas to overtake coal as the dominant energy source and for the methane economy to serve as a bridge to a carbon-free future has been suggested by an analysis of primary energy substitution and market penetration.

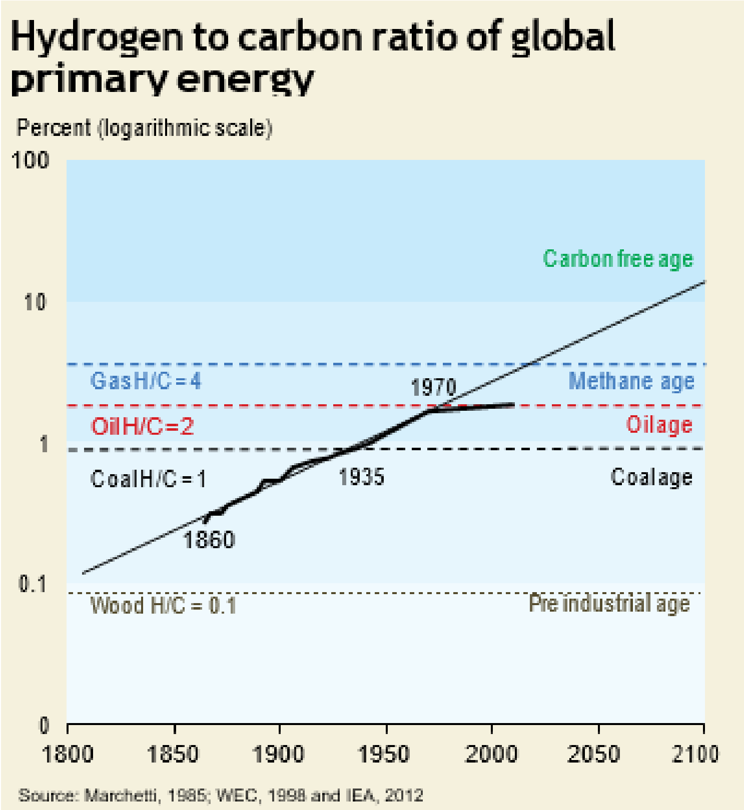


Figure 6: Hydrogen to carbon ratio of global primary energy, 1860-2009. The ratio is expressed in fractional shares of hydrogen and carbon in average primary energy consumed. Source: Marchetti (1985), WEC (1998), IEA (2012).

Most global energy scenarios predict that global energy demand will have increased significantly by 2050. According to long-term energy system projections based on business-as-usual assumptions, such as those conducted by the International Energy Agency, the use of fossil fuels, including natural gas, is expected to increase steadily over the next decades. The BLUE Map 2050 scenario, is intended to depict one possible least-cost path to reducing global carbon dioxide emissions by half by 2050. The BLUE Map 2050 scenario demonstrates that energy demands can still be met by reducing coal and oil consumption, maintaining natural gas production, and expanding nuclear, renewable, energy efficiency, and carbon capture and storage technologies, among other solutions.

The partial displacement of coal or oil use accounts for the majority of the greenhouse gas reduction associated with increased gas use. However, it is necessary to take into account the additional potential displacement caused by nuclear and renewable energy. However, while this interaction may result in a net reduction in greenhouse gas emissions, these reductions are considered insufficient to achieve the desired total carbon emissions levels. The resolution of cumulative environmental impacts, which include other land, air, and water impacts in addition to greenhouse gas emissions, is significantly more difficult.

However, even if commercial feasibility of gas hydrate extraction is demonstrated, technology alone will not determine the direction of the energy future. The decision will be influenced by a number of factors, including economic, social, and environmental considerations. The projections by Germany and Japan to gradually phase out nuclear power as a source of energy are examples of this. As a result, the time horizon of 2050 provides an opportunity to consider alternative future pathways for the external factors that could have a significant impact on how the gas hydrate option shall be utilized over the long term.

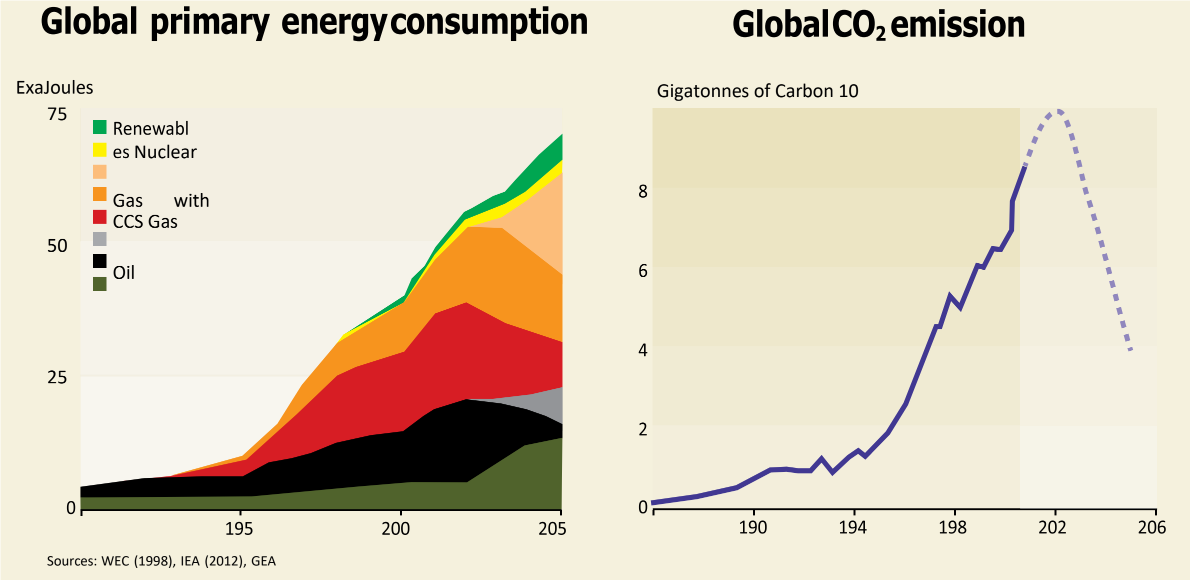


Figure 7: Global primary energy consumption by source. The figure on the left shows historical consumption from 1900 to 2009 and the GEA scenario's projections for the period 2010 to 2050. The figure on the right shows global carbon dioxide emissions, both historical since 1860 and projected. The projections are based on one of three illustrative GEA pathways that were interpreted by two different modelling frameworks: IMAGE and MESSAGE. This figure shows IMAGE modelling results (IMAGE - GEA_MED_450). Sources: WEC (1998), IEA (2012), GEA (2012).

2.1 Global Energy Resources and Gas Hydrates

When it comes to resource occurrences and energy potential, quantification is a challenging task. Energy resource estimations and assessments consist of three basic interrelated components: geological knowledge, economics and technology. Increased prices often leads in an increase of technology improvements and geological knowledge. Resources such as gas hydrates and ultra deep hydrocarbon resources that were once considered unrecoverable or unknown are now an attractive field of study.

When referring to hydrocarbons there are some basic terms that we have to take into consideration. The total volume of a resource includes all hydrocarbons present within a given geographic area. Practically producible resources with the existing technology are called the technically recoverable resources. (TRR). The resources that can be practically produced with a profit are the economically recoverable resources. (ERR). Economically recoverable hydrocarbon resources which are confirmed and quantified are called reserves.

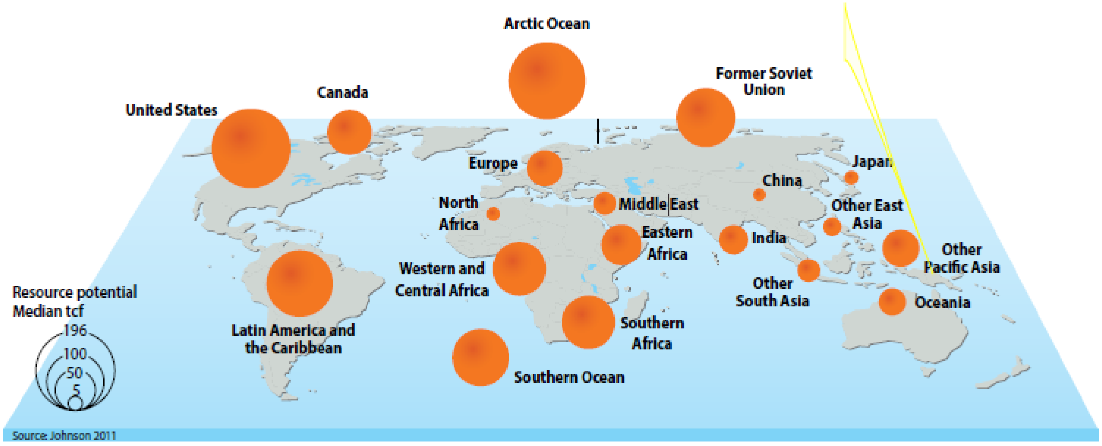


Figure 8: Gas hydrates resource potential by global regions. The figure includes only the most likely targets for development, the in-place gas hydrates that appear to occur at high concentrations in sand-rich reservoirs. Source: Johnson 2011

Definition of Resources

To have a better understanding of the resource potential of gas hydrates, it is important to know the various sub-categories of resource definitions in common usage in the energy industry. These are the following:

• **In-place resource:** The estimated total volume of a resource present. An estimate of in-place resource attempts to account for the entire amount of hydrocarbons (in the case of gas hydrates, almost exclusively methane) present within a given geologic unit or geographic area, without consideration of their recovery potential.

• **Recovery factor**: The percentage of the in-place resource that is technically recoverable. In the case of conventional oil and gas, the recovery factor can sometimes exceed 80-85 per cent. However, recovery factors may be very low for many unconventional resources such as shales. As a consequence, estimation of total in-place resources is of limited relevance to the discussion of energy supply potential.

• **Technically recoverable resource (TRR):** That subset of the in-place resource that is practically producible. Although the definition of TRR is not precise, it generally refers to just those accumulations from which recovery is possible at non-trivial rates, given the expected capacity of industry to apply known or evolving technologies over a specific time frame, such as 30 years. Assessments of TRR are, however, only snapshots in time. Technological advances have a long history of providing access to resources that were previously considered unobtainable .

• **Economically recoverable resource (ERR):** That subset of the TRR that can be produced at a profit. ERR describes only those volumes that are economically viable under prevailing regulatory and market conditions, including the costs of re- covering and delivering the gas and its market value. Key to assessing ERR are data on how wells will produce, both in terms of total volumes and in the time profile of production rate. At present, little of this information is available for gas hydrates, and economic evaluations conducted thus far are highly speculative (Masuda et al. 2010; Walsh et al. 2009). Equally important to understanding ERR are regional markets and societal and national drivers for gas production, which vary substantially around the globe. Resources that are not ERR in one region may be viable somewhere else.

• **Reserve:** A gas volume that has been confirmed by drilling and is available for production from existing wells or through development drilling projects. At present, as the long-term production potential of gas hydrates has not yet been demonstrated, there are no documented gas hydrate reserves anywhere in the world.

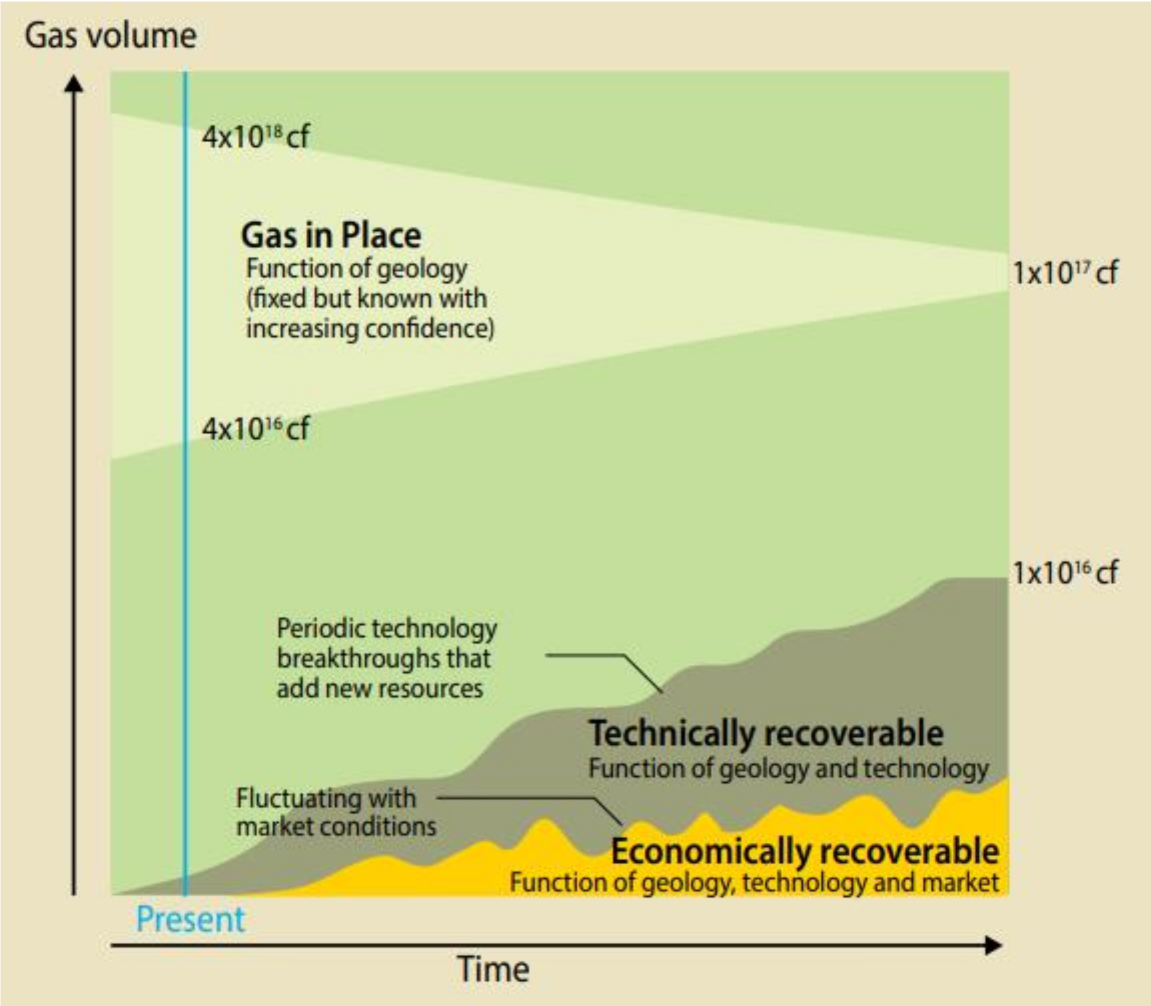


Figure 9: Example of the classification of a gas hydrate resource. Estimates of the total resource of gas associated with gas hydrates currently range over several orders of magnitude, but this volume is likely to become better known with time. More significant in assessing gas hydrate resource potential, however, are the volumes that are technically recoverable (green) and economically recoverable (orange). (Figure from Boswell and Collett 2011).

	Consumption				**Reserves**	**Resources**
	1860–2009 (cumulative)		**2009**			
	ZJ	**GtC**	**ZJ**	**GtC**	**ZJ**	**ZJ**
	Oil					
Conventional	6.58	131	0.17	3.3	4.0–7.6	4.2–6.2
	Natural gas					
Conventional	3.45	50	0.11	1.5	5.0–7.1	7.2–8.9

Unconventional	NA	NA	NA	NA	20.1–67.1	40.2–122
	Coal					
All	**7.21**	**183**	**0.14**	**3.7**	**17.3–21.0**	**291–435**
	All fossil fuels					
Total occurrences	17.2	355	0.42	8.5	50–108.4	354–587

	Renewable Energy Sources	
	Deployment potential in 2050 (ZJ/year)	**Technical potential (ZJ/year)**
Bioenergy	**0.145–0.170**	**0.160–0.270**
Hydro	**0.0187–0.028**	**0.0050–0.0060**
Wind	**0.170–0.344**	**1.250–2.250**
Solar	**1.650–1.741**	**62–280**
Geothermal	**0.023**	**8.10–1.40**

Table 1: Sources: GEA(2012), WEC(1998), IEA (2012)

Top: Energy consumption versus reserves and estimated resources of oil, natural gas, and coal. Consumption is given in ZJ (zettajoules; 1 ZJ = 1000 exajoules, EJ) and GtC (gigatonnes of carbon released to the atmosphere). Conventional sources of oil and gas are those exploited to date. Unconventional are potential sources not currently exploited.

Bottom: Potential energy from renewable sources with current technology, including approximations of the degree to which each might feasibly be implemented by 2050**.**

Note: Numbers shown as ranges indicate the lowest and highest published estimates.

When estimating oil and gas resources the main difference is between conventional and unconventional hydrocarbons. The term unconventional refers to resources that require special recovery processes and technologies in order for their extraction to be economically viable. In the case of shale oil and gas there is fracture stimulation. Also , there are different environmental challenges. The rapid developments in technology combined with variations in prices and demand means that there is a dynamic balance between economically recoverable and uneconomical unconventional resources. The global estimates of natural gas reserves and resources are continuously revised because technology, information and economics change. (Beaudoin Y. C., 2014) (Johnson, 2011).

The global estimates of natural gas resources and reserves are revised continuously and in a rapid pace amidst the progress of technology and information. Different regions lack the infrastructure for distribution at the moment or are too remote to make natural gas extraction economically viable. In this respect, exploration has often been limited in certain parts of the world.

A large amount of gas currently identified as unconventional or not economically recoverable will need to be transferred into the reserves category to meet future demand. The GEA (2012 data) estimates conventional gas reserves at 130 to 190 Tcm, or 5000 to 7000 EJ. According to the GEA, unconventional gas types include coal bed methane, tight formation gas, and gas hydrates. The total global reserves and resources of this category are estimated to be in the range of 1600 to 5040 Tcm or 60 000 to 90 000 EJ. This represents, potentially, one of the largest reserves of all fossil fuels, exceeding even known coal reserves. Gas hydrates appear to be widely distributed around the world in many marine and permafrost environments. This makes them very attractive to countries that are not naturally endowed with conventional domestic energy resources, as well as to the world's largest and most-rapidly growing economies.

In some locations around the globe there are places that further research is restricted at the moment. There is, however, still the possibility of discovering new resources in these locations in the future. In order to satisfy future demand, a significant proportion of gas that is presently classified as unconventional or not economically recoverable will need to be shifted into the reserves classification. According to the GEA (2012), conventional gas reserves are between 130 and 190 Tcm, or 5000 and 7000 EJ. Unconventional gas types include coal bed methane, tight formation gas, and gas hydrates, according to the Gas Exploration and Production Association. The overall worldwide reserves and resources in this category are projected to be in the range of 1600 to 5040 Tcm, or 60 000 to 90 000 EJ, according to current estimates. This indicates, potentially, one of the greatest fossil fuel deposits on the planet, surpassing even known coal reserves in terms of size.

Reviews of the literature reveal that gas hydrate occurrences are extremely common throughout the world. For example, the World Energy Assessment (WEA) (2000) estimates that the worldwide in-place resource potential for gas hydrates is approximately 350 000 EJ (9 400 Tcm). Gas hydrates, on the other hand, appear to be widely spread throughout the earth in a variety of marine and permafrost habitats. As a result, they are particularly appealing to countries that are not naturally endowed with conventional domestic energy resources, as well as to the world's largest and fastest-growing economies, as well as to developing countries. (Johnson, 2011)

2.2 Development of Methane Hydrates Resources

The global benefits of producing gas hydrate resources in an economically and environmentally responsible manner have the potential to be significant and far-reaching. In comparison to other fossil fuels, natural gas emits significantly fewer greenhouse gases – up to 40% fewer than coal and oil, for example (IEA 2013). For this reason, it has been recognized by a large number of countries as an important source of energy in the future. Natural gas hydrates are thought to exist in relative (in terms of the size and scope of the resource) but selective (in terms of location) abundance throughout the world, in both marine and permafrost environments where methane gas and water co-exist at pressures and temperatures conducive to the formation and stability of gas hydrates. Gas hydrates are a global resource that has the potential to be made available to many countries that do not currently have access to other significant domestic energy sources.

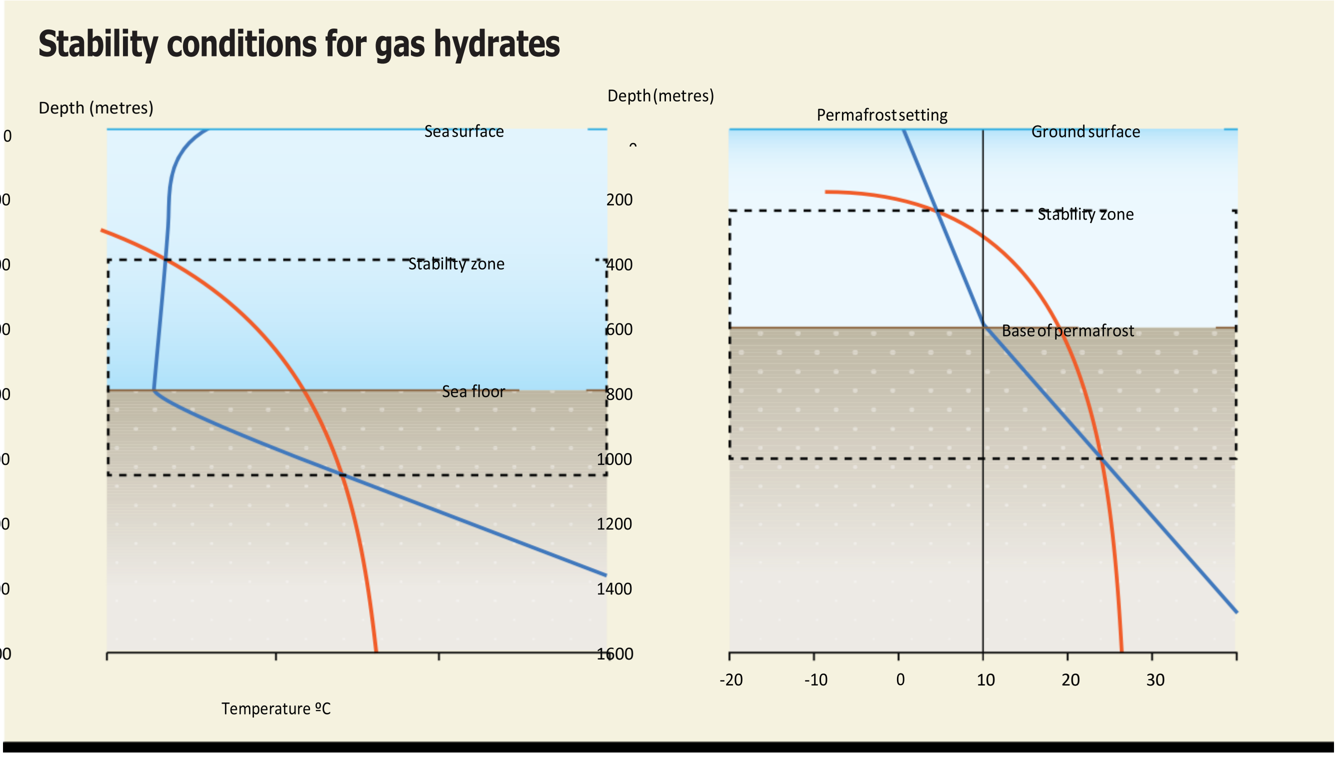


Figure 10: Phase diagrams illustrating where methane hydrate is stable in marine (left frame) and permafrost settings (right frame). Hydrate can exist at depths where the temperature (blue curve) is less than the maximum stability temperature for gas hydrate (given by the hydrate stability curve in orange). Pressure and temperature both increase with depth in the Earth, and though hydrates can exist at warmer temperatures when the pressure is high (orange curve), the temperature in the Earth (blue curve) gets too hot for hydrate to be stable, limiting hydrate stability to the upper ~1km or less of sediment. (Beaudoin Y. C., 2013)

Numerous field studies conducted around the world have confirmed that concentrated deposits of gas hydrates can occur in reservoir settings that are similar to those of conventional hydrocarbon deposits (Collett T. S., 2009). Production targets with the greatest potential are those characterized by the presence of gas hydrates in the pore spaces of discrete, permeable to highly permeable, laterally continuous sandbodies that are laterally continuous. It appears that conventional hydrocarbon drilling and production methods can be used to safely and efficiently exploit these deposits, based on the evidence available at this time . In order to accomplish this, it would be necessary to gain access to the reservoir, manipulate local pressure-temperature conditions in order to force crystals to dissociate into water and gas components, and then transfer released gas to the surface.

A major advantage of using traditional oil and gas production technologies is that there is a wealth of worldwide experience in the field, spanning the entire spectrum from exploratory drilling to commercial production. Based on our previous experience, we believe that the following critical requirements will be required for safe gas hydrate production in marine or permafrost environments in the future:

Establishment of safe foundation conditions for the well infrastructure through detailed preproduction study of the well-site geology in order to recognize and avoid potential hazards and provide a full understanding of the potential impact of production on the ground supporting the well infrastructure

- Installation and cementing of casing strings to maintain well stability while drilling into the target gas hydrate production interval

- Installation of production casing and downhole completion equipment to enable testing and production of hydro- carbon-bearing intervals

- Effective well control and zonal isolation during production; the solid hydrate

- Minimization of the impact of gas extraction on the sur- face and subsurface environment; and monitoring of the response of the gas hydrate field to production.

Below follows a brief presentation of some methods of gas hydrate production that have been proposed after harvesting the knowledge from experimental production sites around the globe.

2.3: Production Well of Methane Hydrates

Drilling through gas-hydrate-bearing strata presents a number of challenges. Examples include shallow gas flows and borehole stability issues, such as abnormal hole erosion and/or tight hole conditions, that occurred in some early exploration wells in the Arctic, among other things (Collett T. a., 2002). It was determined that the problems were primarily caused by the widely accepted drilling practices in the 1970s and 1980s, which were capable of causing significant thermal and/or mechanical disturbance of the gas-hydrate-containing strata. This has the potential to result in the release of free gas as well as a significant reduction in the strength of the sediment. It has been reported that similar issues have occurred in other settings (Borowski, 1997), (Nimblett, 2005).

The drilling industry has largely overcome these issues through the introduction of modifications to drilling procedures and equipment, such as:

- Chilling the drill mud to reduce thermal disturbance of the formation

- Controlling drilling rates to penetrate and case the hydrate-bearing strata quickly in order to stabilize the gas hydrate interval, while allowing sufficient time to remove the gas hydrate or the free gas contained in mud returns

- Controlling the weight of the drill mud to achieve sufficient downhole pressure to stabilize the gas hydrates in situ while maintaining gas hydrate stability in the formation while remaining below the pressures that could fracture downhole formations

- Using cements with low heat of hydration for casings in order to establish a good bond between the casing and the surrounding formation, while minimizing thermal heating and local gas hydrate dissociation

- Using chemical additives (or avoiding dissociation-inducing inhibitors such as salts and alcohols) in the drill mud in order to prevent gas hydrate dissociation in the drill cuttings

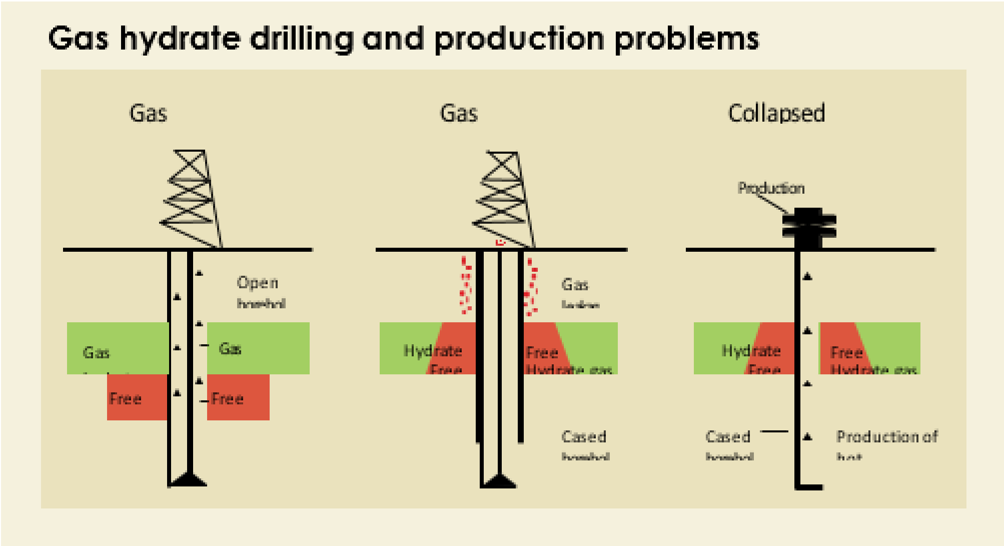


Figure 11: Drilling and production issues: The figure depicts typical gas-hydrate-related drilling and production issues that have been encountered during drilling programs in the Arctic during the past several years (from Collett and Dallimore 2002). A gas release scenario (on the left) occurs when an unexpectedly high-pressured free gas is encountered beneath a gas hydrate layer. Drilling-induced gas leakage scenario (centre): drilling-induced gas hydrate disturbance that has dissociated gas hydrate and caused free gas migration outside of the drill casing. The collapsed casing scenario (right) represents the possibility of gas hydrate disturbance caused by conventional deep-water production of warm hydrocarbon**.**

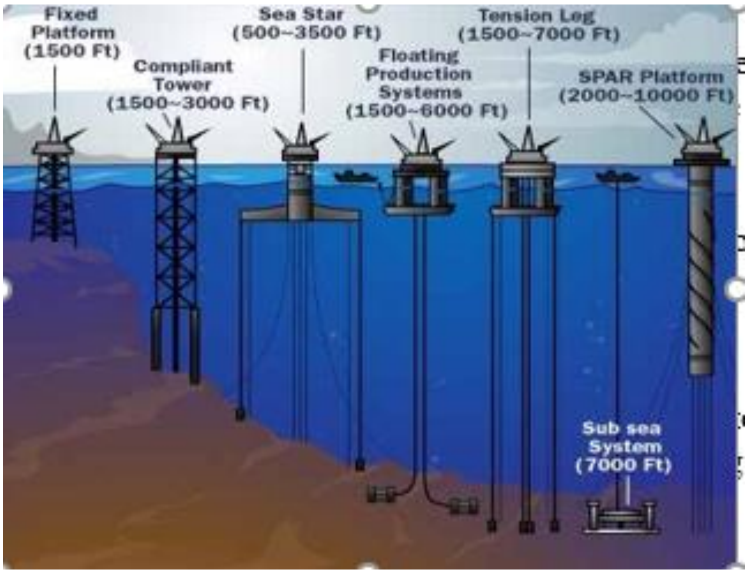


Figure 12: Marine drilling platforms. The platform designs are currently used in various deepwater settings around the world. The tension-leg system is founded on the bottom, whereas the other systems are floating structures (Figure from Lamb, Robert. "How Offshore Drilling Works" 10 September 2008. HowStuffWorks.com).

Field programs dedicated specifically to the study of gas hydrates have made significant contributions to our understanding of the drilling behavior of in situ gas hydrates. Over the past several decades, significant resources have been devoted to gas hydrate research and development (Collett T. S., 2009) with more than 100 dedicated gas hydrate wells successfully been drilled. In the recent past, several Integrated Ocean Drilling Program (IODP) expeditions have investigated the presence of gas hydrates along active and passive continental margins. National gas hydrate research programs in Canada, China, India, Japan, Korea, and the United States have conducted multi-well exploration campaigns. Additionally, there are dedicated research and development programs.

The effectiveness of gas hydrate drilling, coring, and cementing technologies has been tested in offshore Japan, as well as in permafrost environments in Canada and Alaska. A short horizontal well in gas-hydrate-bearing strata 350 metres below the sea floor was part of the Japanese program (Takahashi, 2005). In 2002, a full-scale thermal production test at the Mallik site in the Canadian Arctic was successfully completed (Collett T. a., 2002). During successive winter programs in 2007 and 2008, the reservoir's ability to produce gas hydrates through depressurization was tested. In Alaska, a high-tech production test program involving carbon dioxide injection and pressure drawdown was also successfully completed in 2012. (Schoderbek D. a., 2011)

2.4: Methane Hydrates Production

Up to this point, three primary gas hydrate production concepts have been proposed, all of which are based on the concept of in situ dissociation of gas hydrates to release free gas that can then be delivered to the surface of the earth. Local formation pressures are reduced in the depressurization technique, while the heating technique increases the formation temperature, and the chemical stimulation technique changes the chemical equilibrium conditions in the formation. (Makogon, 1981)

Despite the fact that no commercial gas hydrate production has yet taken place in the Arctic, several scientific field tests have been conducted there. In 2002, a five-country consortium conducted a full-scale thermal stimulation test at the Mallik gas hydrate field in the Mackenzie Delta, which was the first of its kind. (Dallimore S. a., 2005) Depressurization testing was carried out at the same location by a Canada-Japan research program in 2007 and 2008 (Dallimore S. Y., 2008-2012). The short-term drill-stem tests conducted by industry in the 1970s (Bily and Dick 1974) and small-scale formation tests conducted as part of the 2002 Mallik program provide additional information useful for evaluating gas hydrate production potential. Bily and Dick 1974 published a paper describing the short-term drill-stem tests.

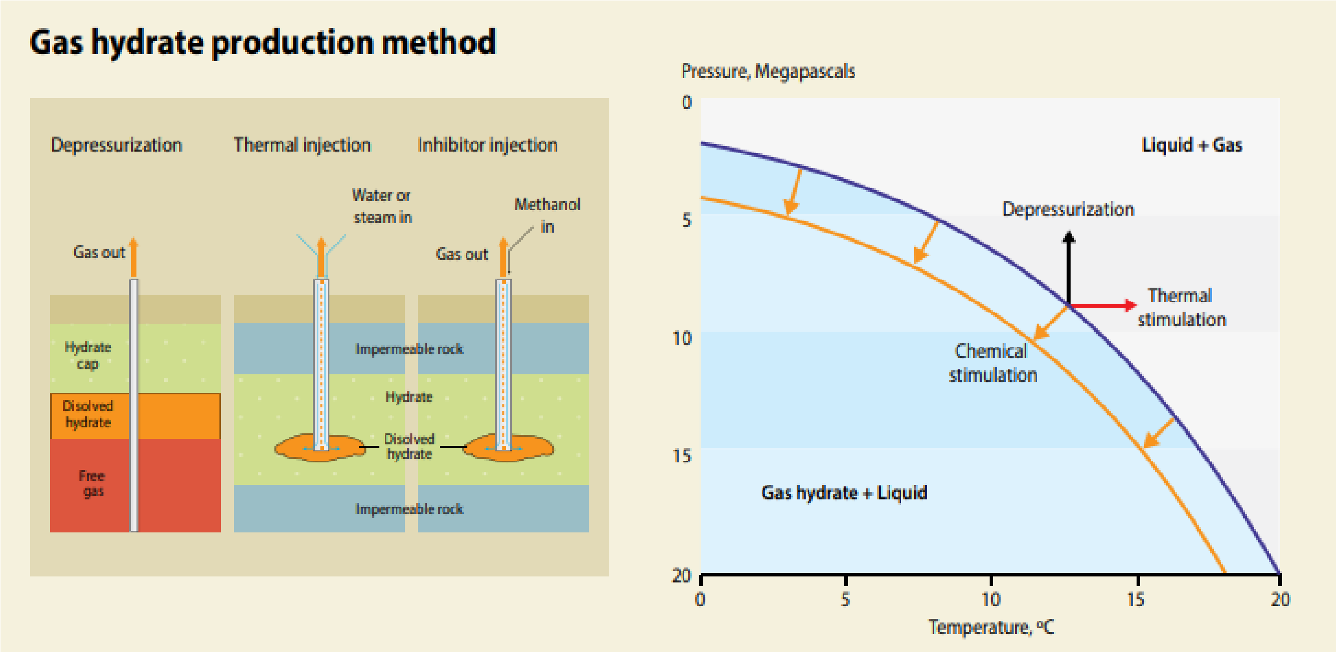


Figure 13: Production practices and gas hydrate stability. The left frame shows proposed gas hydrate production methods, while the right frame shows the resulting changes in gas hydrate stability. Depressurization: lowering the equilibrium formation pressure. Thermal stimulation: lowering the equilibrium formation pressure. Inhibitor injection causes changes in gas hydrate equilibrium conditions.

Depressurization of the Reservoir

At the moment, depressurization is regarded as the most cost-effective and practical method of dissociating gas hydrates (Moridis G. T., 2009). The primary method entails mechanically reducing reservoir pressure. This can be accomplished directly by lowering the reservoir pressure – typically by pumping pore fluids – or indirectly by lowering the pressure in the overlying or underlying sediments in contact with the gas hydrate reservoir and allowing the pressure change to naturally transfer to the reservoir. Initially, it was assumed that the formation of gas hydrates consumed all available water in the sediment pores, resulting in the formation of a relatively contiguous solid hydrate phase that effectively prevented the transmission of a pressure change into the formation. However, field studies (Kleinberg, 2005) and laboratory studies have demonstrated that even the richest gas hydrate accumulations retain small but detectable amounts of mobile liquid water, sufficient to support the propagation of a pressure field into the formation.

Depressurization can be accomplished using conventional oilfield technology by perforating the production well casing at the desired interval and reducing the weight of the fluid contained within the well. Normally, a well is filled from top to bottom with fluid. The weight of the fluid is balanced against the reservoir's pressure to prevent the reservoir's contents from overflowing.

By pumping a portion of the fluid out of the well casing, the pressure exerted on the bottom of the well (and thus on the reservoir in contact with the well bore via the perforations) can be controlled. When the pressure in a gas hydrate reservoir is reduced below the gas hydrate stability condition, dissociation of gas hydrates occurs near the perforations, releasing gas and water into the well. The efficiency of this technique is determined by the number and connectivity of pores containing liquid water that allow the pressure change to be transmitted into the formation.

A free-gas interval may directly underlie a gas hydrate deposit in certain reservoir settings, particularly those near the base of the gas hydrate stability zone (Makogon, 1981) (Moridis G. T., 2009). In these instances, the well could be perforated in the free-gas zone, allowing the free gas to be produced. As Makogon predicted and Grover et al. (2008) demonstrated for the Messoyakha gas field, the resulting pressure reduction within the free-gas interval can be transmitted to the overlying gas-hydrate-bearing sediments, thereby causing their gas hydrate content to dissipate. Although no significant deposits of this type have been verified to date, such settings should theoretically yield high productivity.

One practical advantage of the depressurization technique is that gas hydrate dissociation is an endothermic (heat-absorbing) process that cools the local formation. Gas hydrate dissociation can be slowed down if the magnitude of the temperature reduction is sufficiently large. If the dissociation-induced depressurization results in pressures lower than those at the hydrate's quadruple point (the point at which free gas, liquid water, ice, and hydrate all coexist), the liquid pore water can actually freeze. According to preliminary reservoir simulation modeling, this process is dependent on the initial reservoir conditions and the production rate (or the constant bottom hole pressure at which the well may be operated), with heat transfer caused by pore-water movement being particularly significant.

Heating the Reservoir

A similar factor to consider, which is frequently encountered with conventional gas wells, is the temperature regime of the free gas as it flows to and up the production tubing. In this case, the free gas cooled by the endothermy of gas hydrate dissociation and by the effects of pressure reduction and high gas velocities in the vicinity of the well (the Joule-Thompson effect) has the potential to reform gas hydrate in the well bore or production tubing, posing serious operational problems. Unwanted hydrate formation plugging pipelines or processing streams is a well-known occurrence in the oil and gas industry, resulting in costly shutdowns, sometimes lasting months. Flow assurance refers to the technologies that are routinely used to address this issue. They include injecting low-dose gas hydrate inhibitors, heating the system, or generating a flushable gas hydrate slurry.

The reservoir-heating technique's objective is to raise the temperature within the reservoir above the localized pressure-temperature threshold for the formation of gas hydrates. The only full-scale field production test utilizing this technique occurred at the Mallik site in 2002 as part of the program's gas hydrate production testing (Dallimore S. a., 2005)

The examination lasted about five days. A 13-metre perforated test interval was circulated with hot brine (70°C at the surface / 50°C at the formation depth). The bottomhole flowing pressure was kept slightly higher than the formation pressure. Thus, the test enabled evaluation of the heat conduction efficiency of the formation (that is, with no direct heat transfer by formation fluids). The 2002 Mallik test was not particularly productive, producing only 500 cubic metres of gas over the course of the testing period. However, the test's objective was to demonstrate the feasibility of producing gas indisputably derived from hydrate deposits, not to maximize such production. It concluded that thermal heating alone is likely to be an inefficient and costly method of producing gas hydrates in the long run. Moridis et al. (2009) demonstrated via numerical simulations that thermal stimulation is thousands of times less effective than depressurization at inducing dissociation in hydrates.

The research on developing downhole heating techniques that require less direct energy input and heat the formation more effectively continues. Downhole heating may be advantageous in certain reservoir configurations to overcome endothermic cooling of the formation caused by gas hydrate dissociation and/or to manage the temperature regime of the gas stream to prevent re-formation of gas hydrates near the wellbore and inside the tubing. For certain reservoir conditions, a combination of reservoir depressurization and supplemental in situ heating may be optimal for long-term gas hydrate production (Moridis G. a., 2007) (Moridis G. T., 2009).

Chemical Stimulation

Chemical stimulation of gas hydrate production requires manipulating the phase-equilibrium conditions of the gas hydrates in the reservoir by injecting dissociation-inducing chemicals such as salts and alcohols. These chemicals cause dissociation of water when it comes into contact with the solid gas hydrate phase. This approach has been used for decades to ensure gas well flow assurance and to avoid pipeline blockages caused by the formation of gas hydrates. While chemical injection remains a viable option for resolving flow assurance issues, its utility for large-scale gas hydrate production appears to be limited. Operational concerns and the associated costs of injecting large volumes of chemicals into the reservoir are significant, as are the inhibitors' rapidly declining effectiveness (due to continued dilution by the large amounts of water released during the dissociation process) and potentially overriding environmental concerns.

Laboratory and computational studies have been conducted on a novel concept based on molecular chemical processes (McGrail, 2007). The objective is to release methane by injecting another gas, such as carbon dioxide, into the reservoir, thereby altering the chemical conditions and displacing the native methane hydrate with carbon dioxide or another mixed gas hydrate. This process could alleviate some of the geomechanical concerns associated with alternative production methods and allow for synergistic carbon dioxide storage. However, numerous technical obstacles remain, the most significant of which is the ability to inject carbon dioxide into water-bearing, low-permeability formations. A field trial of this concept was successfully conducted in Alaska in 2012, using a mixture of nitrogen and carbon dioxide gas to enable injection (Schoderbek D. M., 2012).

Well Completion

The final stage of well construction prior to production is well completion. Completed wells include the design and installation of the production casing, measures to gain access to the formation and control near-wellbore interactions, the placement of downhole production equipment (production tubing, downhole pumps, etc.), and the installation of equipment to allow for intervention during production in the event of unexpected operational issues or if additional stimulation is desired. Advances in completion technologies have significantly increased oil and gas recovery efficiency and enabled cost-effective production in reservoirs that would not have been considered economically viable even a few years ago.

It is likely that the following methods will be considered during the completion phase of gas hydrate production:

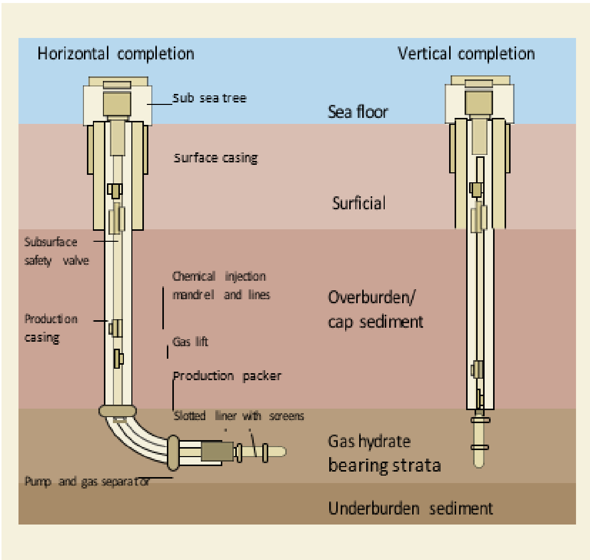
- The use of sand screens or gravel packs to control sand inflow into the wellbore as a result of sediment strength being lost as a result of dissociation of in situ gas hydrates in unconsolidated media.

- Downhole pumps, downhole heaters, and/or chemical flow lines that are specifically designed for the gas hydrate production method being used.
- Equipment for bringing produced gas and water to the surface via lift or pumping
- The inclusion of provisions for smart completions, which allow for real-time monitoring of the formation response, as well as manipulation of downhole pressure and temperature to optimize gas hydrate production

Production operations for a typical gas hydrate field would most likely last for a decade or more, depending on the field. Current experience suggests that the technologies used for sand-dominated reservoirs will be similar to those used in conventional oil and gas fields, with the exception of some minor modifications. Given the fact that commercial production of gas hydrate is still some years away, it is difficult to establish a reliable basis for predicting the long-term production response of a gas hydrate reservoir. Typically, such predictions are made for a conventional gas field using sophisticated numerical reservoir simulations that allow the estimation of flow responses and evolving changes in critical reservoir properties over the field's anticipated production life.

A recent drill campaign carried out in the Indian Ocean off the coast of Collett et al. (2008) and in the Korean Sea off the coast of Park (2008), however, discovered thick sedimentary sections that contained a variety of macroscopic gas hydrate forms, including fracture fillings and nodules. In these marine environments, gas hydrate concentrations can range from 20 to 40 percent of bulk sediment pore space, indicating that they could be viable production candidates if significant geomechanical challenges can be overcome (Moridis G. T.-D., 2011). Consequently, new technologies and approaches are likely to be required for the economically viable production of gas hydrates in fine-grained, unconsolidated marine sediments in the near future.

Figure 14: Completion of a well for the production of gas hydrates. The well schematics illustrate possible horizontal and vertical well completions for a depressurized gas hydrate production well. Modified from Hancock et al (2010).



2.5: Methane Hydrates as a Resource for Natural Gas

For many years, gas hydrate resources were characterized by extremely large numbers, with 700 000 trillion cubic feet being perhaps the most frequently cited value (roughly 20 000 trillion cubic meters). While these figures are useful for understanding the role of gas hydrates in carbon cycling and other global processes, they tended to grossly overstate the practical resource potential of gas hydrates by lumping together all possible gas hydrate occurrences. Earlier attempts to segment resources of all types according to their potential productivity revealed a distinctive pyramid shape, with the most advantageous elements (at the top) occurring in relatively small quantities, while those posing greater technical difficulties (at the bottom) frequently occur in far greater abundance. (Collett T. S., 2009)

As with all resource pyramids, the gas hydrate pyramid merely indicates the expected order of production, with resources at the top of the pyramid likely to be produced first. At the moment, the global energy industry has made significant progress down the total gas resource pyramid, initially concentrating on shallow onshore deposits and only recently – after more than a century of exploration – beginning to seriously exploit larger elements at the base, such as shale gas. Gas hydrates should follow a similar path. The time intervals, however, could be shorter, given the growing global demand for energy and, in particular, the growing use of environmentally friendly natural gas.

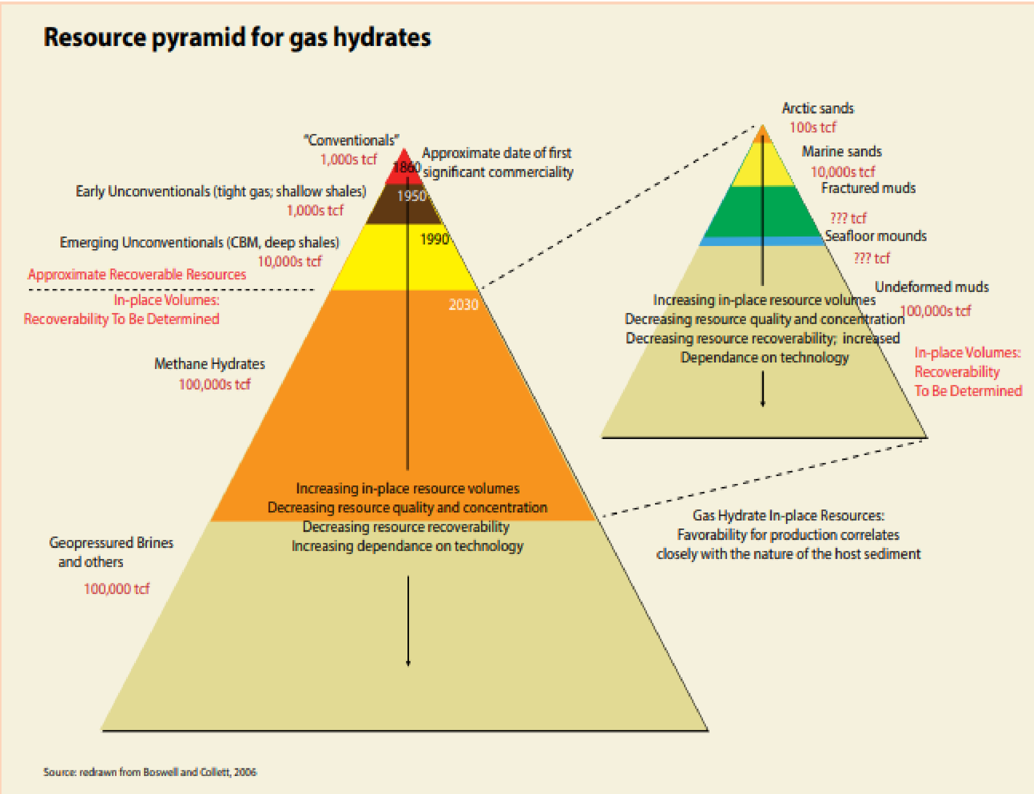


Figure 15: The generalized resource pyramid for gas hydrates (right) compared to all gas resources (left). As society progresses down the global gas pyramid (left), technological breakthroughs allow significant access to previously unrecoverable resources. Gas hydrates (right) may follow a similar path, with initial production occurring in marine or Arctic sands. In spite of this, the potential volumes at the apex of the hydrate pyramid are significant. Boswell and Collett, 2006. "Gas Hydrates Resource Pyramid".

Chapter 3: Case Studies for Methane Hydrate Occurrences

3.1: Cases of Pore Filling Gas Hydrates in Sand Reservoirs

The sand reservoirs type of deposit has been observed widely throughout the world in terms of production potential. Gas hydrate-bearing sands have been discovered offshore Korea and are currently being evaluated as future production test sites (Moridis G. J.-J., 2013) as well as in the Cascadia margin (Riedel M. N., 2006) Siberian permafrost (Makogon, 1981) and elsewhere. The best-studied occurrences are permafrost-associated sands on Alaska's North Slope (Boswell R. H., 2008) and the Mackenzie Delta of Arctic Canada (Dallimore S. a., 2005) extensive deep-water turbidites in the Nankai Trough, and deeply buried sands in the northern Gulf of Mexico.

Oil and gas exploration on Alaska's North Slope has a long history. In 1972, during the initial exploration of the Prudhoe Bay oil field, gas hydrates were discovered for the first time. Drilling data from over 1,000 wells in the area indicate that gas hydrates are most likely present on the Alaska North Slope. They have been spotted throughout a broad area known as the Eileen Trend within a thick sequence of sand reservoirs beneath the permafrost base (Collett T. , 1993). The Tarn Trend, which runs parallel to the Kuparuk River oil field, was discovered in the early 1990s Gas-hydrate-bearing sands are found primarily in the lowest permafrost-bearing section in this case. Inks et al. (2009) interpreted over a dozen distinct gas hydrate prospects within the Milne Point unit at the northern end of the Eileen Trend using standard industry seismic data. The Mount Elbert Prospect, the most promising of these, was drilled, logged, and cored in February 2007 (Hunter et al. 2011), confirming the presence of a sand reservoir with gas hydrate saturations ranging from 50 to nearly 80 percent. In 2011, the Ignik Sikumi n.1 research team confirmed without doubts the presence of gas hydrates in four distinct sand reservoirs in the western Prudhoe Bay unit (Schoderbek D. a., 2011).

The geology of the Alaskan North Slope's shallow sediments, as well as many other Arctic regions with gas hydrates, is dominated by sediments deposited in shallow-water marine, coastal, and terrestrial environments. These continental deposits typically contain significantly more sand-sized sediments than those found in deep-water settings. Almost every known occurrence of gas hydrates in the Arctic is associated with sands. Prudhoe Bay gas hydrates are charged primarily by the upward migration of gas from the deeper Prudhoe Bay oil and gas fields (aided by numerous faults). Gaseous methane is likely to have begun charging sand reservoirs prior to the development of gas hydrate stability conditions approximately 1.6 million years ago (Collett T. , 1993). Collett estimated the in-place gas sources from gas hydrates on Alaska's North Slope at 16.7 trillion cubic metres. Collett et al. (2008) then provided the first assessment of technically recoverable gas hydrates, estimating a mean of 2.4 trillion cubic metres from Alaska North Slope sand reservoirs using existingtechnologies, based on data from the 2007 Mount Elbert well and recent advances in numerical modeling (Anderson, 2010).

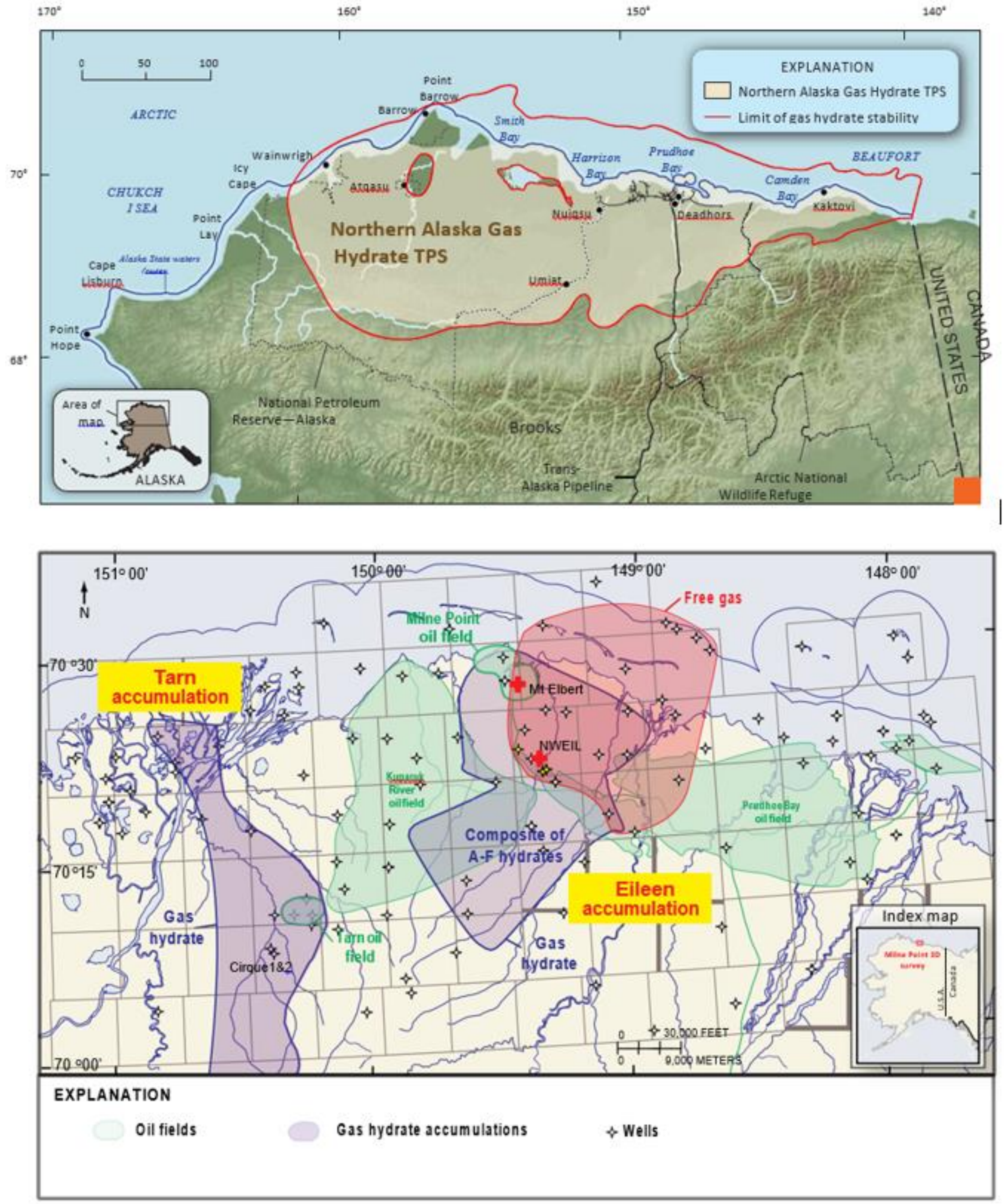


Figure 16: The Northern Alaska Gas Hydrate Total Petroleum System. There are two distinct trends of gas hydrate accumulations in sand reservoirs, the Eileen accumulation and the Tarn accumulation (Collett et al. 2008 & Collett, 1993).

The amount of information available about permafrost gas hydrates on the Alaska North Slope and the Mackenzie Delta is limited when compared to the amount of information available about gas hydrates in the vast deep-water basins of the world. The eastern Nankai Trough, off the southeastern coast of Japan, contains some of the best-studied occurrences in sand reservoirs, with those in the Nankai Trough being the most well-known. Nankai Trough is a subduction zone where the Philippines Sea Plate to the east is overridden by the Eurasian Plate to the west, resulting in the formation of the Philippines Sea Plate. A thick section of sediment eroded from the Japanese Islands has been collected in this deep basin, including extensive turbidite channel complexes and other sand-rich strata, as well as other types of sediment. Extensive gas-hydrate-bearing sand reservoirs were discovered in 1999 during exploration drilling in the eastern Nankai Trough, marking the first time such reservoirs had been discovered in a deep-water setting (Tsuji et al. 2004). Increased drilling in 2004 was guided by a variety of advanced geophysical studies, which resulted in the identification of more than ten distinct accumulations of gas hydrate in deep-water sandstone reservoirs (Takahashi, 2005). In the Nankai Trough, the reservoirs are characterized by thick sections of interbedded deep-water sands and muds, with individual gas-hydrate-bearing sand layers typically less than a metre thick.

Takahashi and Tsuji (2005) conducted an analysis of data collected during the 2004 drilling and coring programs, as well as associated geophysical programs, to demonstrate that conventional oil and gas data sets and concepts could be applied to the problem of deep-water gas hydrate detection and characterization. (Fujii, 2008). An assessment took place regarding gas hydrate resources in the most extensively studied area in the eastern Nankai Trough, an area estimated to represent perhaps ten percent of the total prospective area for gas hydrates in waters around Japan. They concluded that the area was rich in gas hydrate resources. Within a region covering 7 000 square kilometers, the assessment revealed a mean estimate of gas-in-place of approximately 1.1 trillion cubic meters. Of this, 550 billion cubic meters were found at high concentrations in sand reservoirs.

The numerical simulations of production potential (Kurihara, 2010) determined that the technically recoverable portion of this resource is likely large, constituting 50 percent or more of in-place resources, depending on production method and location-specific geology. In 2012, Japan restarted drilling and sampling activities in the Nankai Trough in preparation for the first field trials of gas hydrate production from a deep-water sand reservoir, which began in 2013 and are expected to last for several years. The planned testing program will include a thorough review of baseline environmental conditions as well as monitoring of any environmental impacts that may be associated with gas hydrate extraction and production. (Arata, 2011).

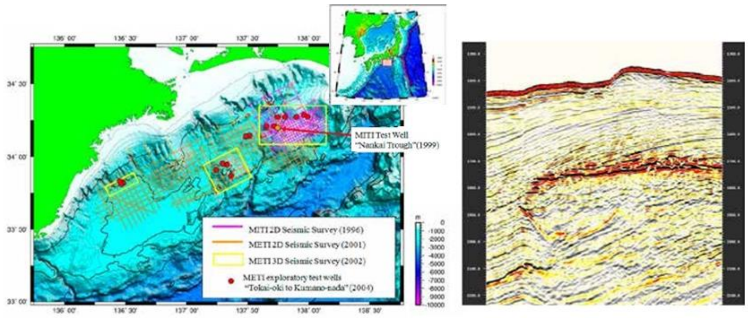


Figure 17: Exploratory drilling and geophysical surveys from the Nankai Trough. Surveys in the Nankai Trough have revealed thick sequences of gas hydrate in sand-rich sediments. The gas hydrate strengthens the sediment, resulting in seismic reflections where the sand-

rich units extend into the gas hydrate stability zone (right). These reservoirs are the subject of the world's first deep-water gas hydrate production tests, which began in Japan in early 2013 (JOGMEC).

3.2: Occurences in muddy sediments that are grain-displacing and fracture dominated

Japanese coring programs (Fujii, 2008) and Malaysian coring programs (Hadley, 2008). have discovered gas hydrates in the form of grain-displacing veins and nodules in fine-grained sediments, suggesting that gas hydrates are likely to be widespread throughout the world. The particularly thick and rich occurrences discovered offshore India in 2006 and offshore Korea in 2007 are among the most well-studied sites.

NGHP Expedition 01 in India discovered gas hydrates at Site 10 in the Krishna-Godovari Basin, where drilling revealed a widespread network of fracture-filling veins and lenses in the mud-rich sediments. The 150-metre-thick unit was buried beneath approximately 20 metres of mud-rich sediments that were devoid of gas hydrates and did not show any obvious sea-floor expression. At the top of the gas hydrate deposit, core samples revealed the fossilized remains of an earlier sea-floor chemosynthetic community (Mazumdar, 2009) indicating that a relatively recent sea-floor slump had buried a once-active cold seep, promoting the accumulation of sub-sea-floor gas hydrates at the site. Standard analyses of geophysical data do not reveal the presence of gas hydrates, but advanced techniques have delineated a 1.5-square-kilometer area that is believed to represent the zone of increased gas hydrate occurrence, according to the researchers (Riedel M. C., 2010A). It also provided an opportunity for scientists to cross-calibrate core-based and log-based analyses, allowing them to significantly refine the models used to estimate gas hydrate saturation from log data in fracture-dominated systems. (Collett T. S., 2009) The core data confirmed that gas hydrate concentrations are approximately 25% of the pore space on average throughout the gas hydrate deposit, which is consistent with previous findings. A common belief among geologists prior to the drilling at Site 10 was that gas hydrates could not accumulate to concentrations much greater than 10 to 15 percent in muddy sediments, and that any gas hydrates that did occur in such settings would be dispersed within the sediment pore space. These unexpected findings at Site 10 have fundamentally altered the way we think about fine-grained gas hydrate systems. Despite the fact that fracture-filling gas hydrate deposits are likely to contain significant in-place resources globally, no promising production strategies have yet been proposed for these deposits. Production difficulties (many of which are related to the geomechanical stability of the formation and of the wellbore assembly) and the potential environmental impact that shallow extraction may have are the main obstacles that need to be faced.

A gas hydrate drilling expedition in the South China Sea's Shenhu region (Expedition GMGS-1) added to our understanding of gas hydrate occurrences in mud-rich systems **(** (Yang, 2008) At five of the eight sites drilled, log data indicated the presence of potential gas hydrates at the base of the gas hydrate stability zone (GHSZ).

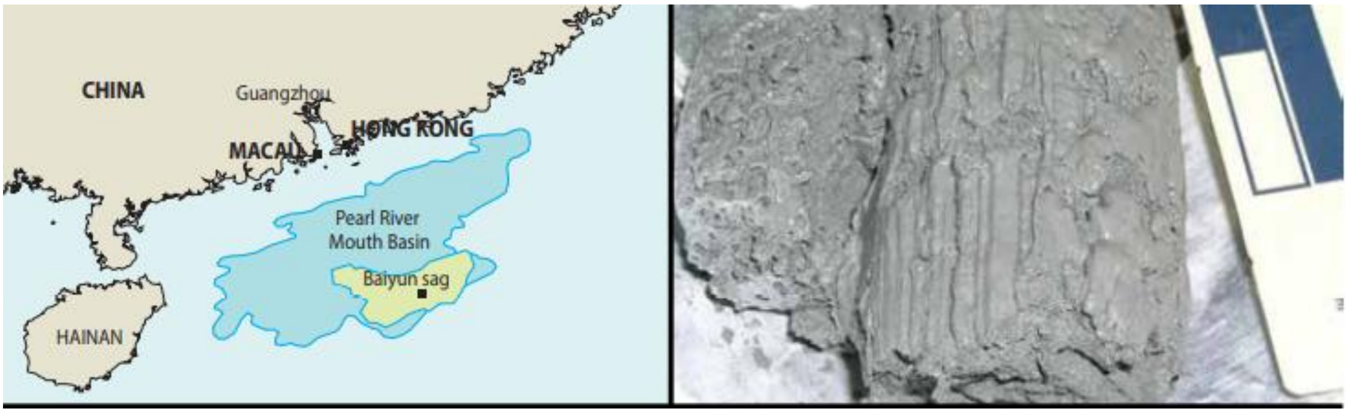


Figure 18: Gas hydrates in South China Sea. Mud-rich silt was collected from the Shenhu region, South China Sea, in 2007. After sampling and recovery, the sediment has a frothy texture due to the dissociation of gas hydrates and the release of gas (GMGS-01 Science Party).

Three of the five locations where cores were taken revealed significant gas hydrates near the base of the GHSZ. Degassing of pressurized core samples from each well revealed gas hydrate saturations of 20 percent on average, with local increases to more than 40 percent in thin zones (Wu et al. 2010). X-ray radiographs from Shenhu, for example, revealed that the gas hydrates were mostly disseminated and pore-filling. Only minor macroscopic lenses, nodules, or fracture-fills were found, which are typical of rich, fine-grained occurrences. Such high saturations are unprecedented in fine-grained gas-hydrate systems without macro-scale fractures, and could reflect locally high concentrations of silt-sized particles, particularly biologic fragments which could boost permeability above normally expected levels in predominantly fine-grained sediments (Wu, 2010).

In conclusion, over two decades of coring and drilling have proved that gas hydrates are quite abundant in nature. However, the form that these resources occur is heavily influenced by the surrounding sediment. Because of these different occurrences – including, burial depth, concentration and other parameters – only a portion of this resource may be technically recoverable and economically viable for extraction. This portion contains mostly sand-rich gas hydrates. The total resource volume in sand reservoirs remains unconstrained, but may range from 285 to over 1400 trillion cubic meters of gas (Boswell R. C., 2011). Large volumes are likely present also in muddy systems, particularly near chimney structures, but due to the lack of a viable production method these deposits cannot be considered recoverable yet.

Chapter 4: Project Anaximander- Recovered Gas Hydrate Samples In the Eastern Mediterranean Sea

Mud volcanoes (MVs) are the most important route for degassing of deeply buried sediments, and they are generally located along subduction zones and orogenic belts where lateral tectonic compressional stress is strong. Mud volcanoes are common in the Eastern Mediterranean and may contain substantial quantities of solid gas hydrates of economic significance (Woodside J. M., 1999), (Woodside J. I., 1998). When overpressured fluid muds originating in the décollement zone rise through the deformed strata of the Mediterranean Ridge and reach the seafloor, mud volcanism is triggered (Robertson, 1998). Mud volcanoes, mud diapirism, and fluid seeps have been discovered in a variety of habitats in the Eastern Mediterranean. The majority have been discovered on the accretionary prism of the Hellenic arc

(Mediterranean Ridge) and within the Anaximander Mountains (Woodside J. I., 1998) however, they have been discovered off the coast of Sicily (Holland, 2003) along the Florence Rise (Zitter T. , 2004), (Perissoratis, 1998). Gas hydrates were discovered in 1996 at the Kula mud volcano in the Anaximander Mountains. Mud volcanoes were discovered in the Anaximander Mountains as a consequence of a multibeam survey conducted in 1995 as part of the Dutch ANAXIPROBE project, as well as a follow-up survey in 1996 that included seafloor samples and deep-tow side-scans imaging (Woodside J. I., 1998) (Woodside J. M., 1999).

4.1 Geological Setting

Between the Cyprus and Hellenic arcs are the Anaximander Mountains, which consist of three primary seamounts. The westerly migrating Anatolian Plate and the African Plate are currently undergoing neotectonic deformation characterized by strike slip faulting (Zitter T. W., 2003); (Ten Veen, 2004). The Anaximander Mountains are massive fractured and inclined chunks that were once geologically connected to southwest Turkey. In its neotectonic development, the entire area has been undergoing extensive multiphase deformation (Ten Veen et al., 2004). The beginnings of differential subsidence that resulted in the construction of the Anaximander Mountains was marked by a kinematic change in the late Miocene, which was linked to the onset of Anatolia's westward movement.

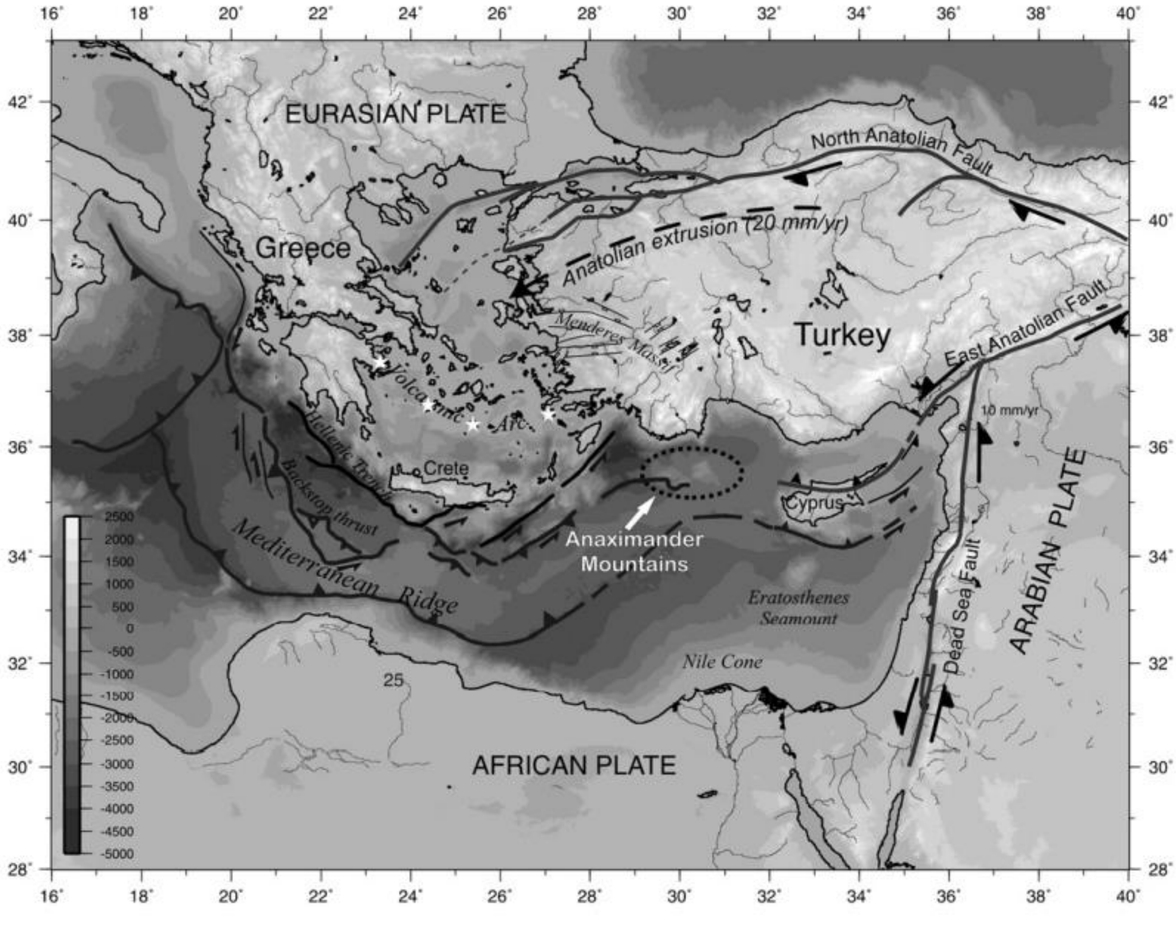


Figure 19: Geotectonic and bathymetric map of the Eastern Mediterranean with indication of the relative location of the Anaximander Mountains (Ten Veen, 2004).

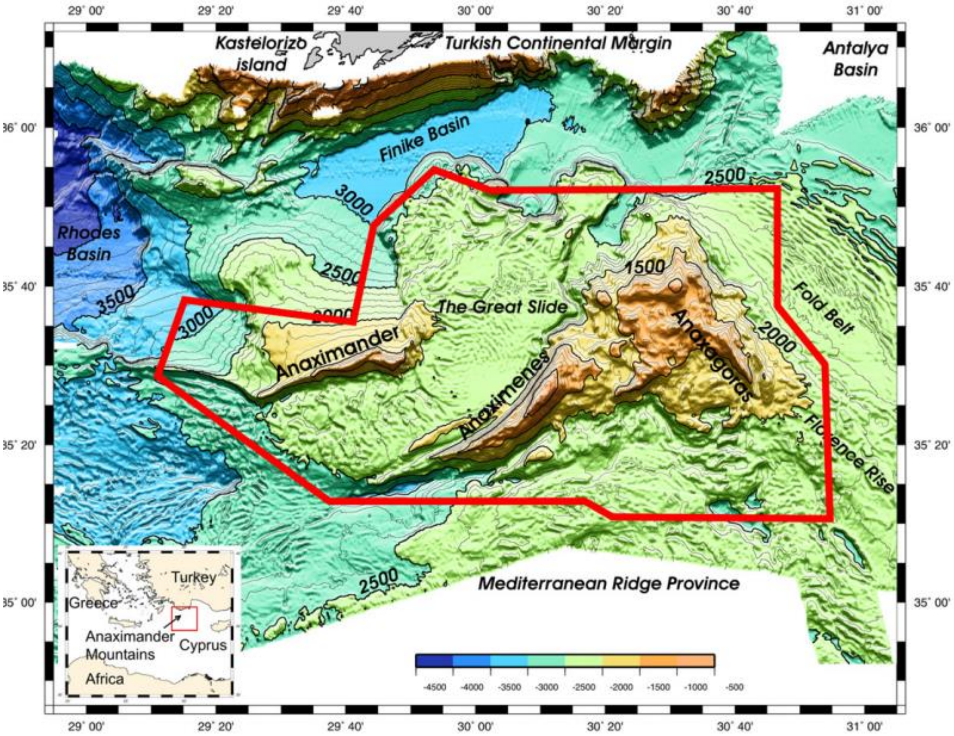


Figure 20: Bathymetric map and morphological features of the Anaximander Mountains and the surrounding basins (Woodside et al., 1997, 1998).

The Anaximander region's current structure reveals extensive rifting, yet their neotectonic form is the product of plate convergence (Woodside J. M., 1999). Thus, a complicated array of crosscutting faults affects the Anaximander area, interpreted to reflect the interference of vast wrench zones accommodating relative plate motions between Africa and Eurasia (Ten Veen, 2004) (Zitter T. W., 2003).

During a multibeam bathymetric survey aboard the French research vessel 'L'Atalante' in the scope of the Dutch ANAXIPROBE project in 1995, the mud volcanoes of the Anaximander Mountains were unexpectedly discovered. The ANAXIPROBE project and the International Training Through Research programme (TTR6) with the Russian research vessel R/V 'Gelendzhik' in 1996 verified the presence of the mud volcanoes, and sampled the first gas hydrates in the Mediterranean, from the Kula mud volcano (Woodside J. I., 1998), (Woodside J. M., 1999). In addition, in 1998, the French–Dutch MEDINAUT program used the submersible Nautile, to conduct a closer examination and collect site-specific samples; (Foucher, 1999).

Several mound-like features, expressed as high reflectivity patches on Simrad EM-12D backscatter intensity maps, were examined, but only a few were proven by sampling to be mud volcanoes. Gas hydrates, first sampled from Kula mud volcano during the 1996 ANAXIPROBE/TTR-6, were sampled again at Kula during the 1999 MEDINAUT/MEDINETH expedition (MEDINAUT/MEDINETH Shipboard Scientific Parties, 2000), as well as at Amsterdam mud volcano.

4.2 Mud Volcanoes and Gas Hydrates in the Anaximander Mountains

The Anaximander Mountains' mud volcanoes erupt a poorly sorted matrix-supported breccia containing rock clasts plucked from formations beneath the seafloor. The further studying of these clasts can reveal a lot about the rock sequences beneath the seamounts. The morphology, petrography, and biostratigraphy of mud breccia clasts from the Amsterdam, Kazan, and Kula MVs thus assisted in determining the deep stratigraphy and thus provided a better understanding of the formation and geological evolution of the mud volcanoes and the Anaximander Mountains' greater region. Microfacies investigations (using forams) carried out in thin sections by microscope and X-ray diffraction (XRD) examinations also resulted in a more exact calculation of the relative age of the source rock formations and a subsequent evaluation of the depositional environment during rock formation. (Lykousis, 2008)

The gas hydrates discovered in the Anaximander Mountains were classified to active mud volcanoes and related mud flows (Anaximander MV), but no associated Bottom Simulating Reflector (BSR) was detected in the adjacent slopes' sediment layers. In compressive settings such as the Eastern Mediterranean, Gulf of Cadiz (except locally below the "crater" of Mercator MV), Alboran Sea, and Calabrian and Cyprus arcs, where the MVs are the "seabed windows" of deeply overpressured methane-rich fluids ascending through major-fault systems, the absence of a BSR, or difficulty in observing one, is fairly common. Gas hydrates were sampled from MVs in the central basin, the Sorokin trough, and along the south (Turkish), southwestern (Bulgarian), and southeastern (Ukranian) borders, where protracted BSRs were also discovered in seismic profiles. (Limonov, 1997) (Klaucke, 2005). Extensive BSRs and GHs were located also in the mid-Norwegian margin (e.g.). (Bouriak, 2000.)

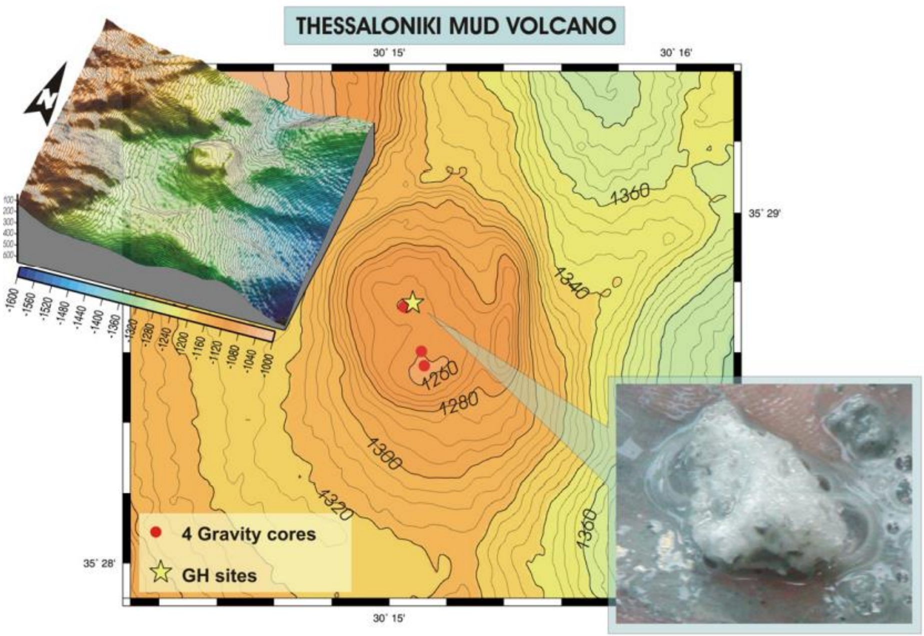


Figure 21: . Regional 3-D and microtopographic map of the Thessaloniki MV summit with sediment core sampling and the sites where gas hydrates were recovered. Image of active gas hydrate dissociation. (Lykousis et al., 2008)

Figure 22: Gas hydrate lump (8 _ 5 _ 4 cm) (center) and broken into pieces (lower) that was recovered from one of the cores from Amsterdam mud volcano . (Lykousis et al., 2008) .

During the two research cruises of R/V Aegaeo in May 2003 and October–November 2004, a large part of the Anaximander Mountains was surveyed by sea beam bathymetry and detailed seabed backscatter imagery, extensive seabed sampling, and (locally over the mud volcanoes) by high resolution seismic profiling. The multibeam topography/imagery accurately delineated not only new morphological features of the Anaximander Mountains but also detailed morphological and acoustic characteristics of each individual mud volcano studied. The study of seafloor backscattering revealed the possibility of new mud volcanoes, which were validated by sediment gravity coring (Athina and Thessaloniki MVs). In compared to the Amsterdam mud volcano, the Kazan, Kula, Thessaloniki, and Athina MVs have more mound-like conical mud volcanoes, indicating lower intensities of activity, shorter reactivation periods, narrower feeder pathways, or mud extrusion with higher shear strength. In terms of the volume and breadth of erupted mud breccias and gas hydrate occurrences, the Amsterdam MV is the most active mud volcano in the Anaximander Mountains. The large mud flow to the south, which contains gas hydrates, is a noteworthy feature. This suggests that a mostly methane gas supply from deeper formations can be found not only in the center active area, but also on the slope south of the Amsterdam MV.

The presence of gas hydrates in Thessaloniki MV sediment samples indicates recent activity. It is Mediterranean's shallowest mud volcano containing gas hydrates (1260 m) located on the boundary of the stability zone, which is characterized by depth and bottom temperature. As a result, the gas hydrates at Thessaloniki MV are sensitive to changes in temperature and sea level, making it an ideal location for research into mud volcanic activity, environmental effects, and gas hydrate stability. The potential aerial extent of gas hydrates on the Anaximander MVs is anticipated to be up to 46 km^2 based on core samples and multibeam backscatter imaging, the majority of which is located in the "crater" and mud flows of Amsterdam MV. Total methane volume in the upper 2 m of the Amsterdam MV is around 0.064 km^3, while total methane gas volume in the Anaximander MVs is estimated to be 2.56–6.40 km^3 (Lykousis, 2008). Gas hydrates were also sampled, for the first time, at Kazan and Thessaloniki MVs, while gas hydrate dissociation structures were found within the sediment cores from Kula and Athina MVs. Gas hydrates were observed and sampled at various depths within the sediment cores but were present usually deeper than 0.4 m from the seabed surface (Lykousis, 2008).

Chapter 5: Possible Geopolitical Consequences of the Gas Hydrates Findings in Eastern Mediterranean

As described in the previous chapter, not only were mud volcanoes (such as Amsterdam, Kazan, Athena, and Thessaloniki) discovered during the EU-funded project Anaximander, but also seven cores containing gas hydrates from five new locations were collected from Amsterdam Mud Volcano. With many new sites where gas hydrates were sampled, it was proved that active mud volcanism and the existence of gas hydrates in this area of the Eastern Mediterranean are far more widespread than previously anticipated. These samples show that there are gas hydrates present, as well as significant indicators of conventional hydrocarbon resources.

We can easily conclude from the foregoing facts that the sector in question will be of great commercial and scientific significance in the not-too-distant future. There are strong indications that conventional hydrocarbons, as well as methane hydrates, exist in large quantities. This means that places with conventional natural gas sources may also have the ability to produce natural gas from methane hydrates present in the same area. This might be a game changer in terms of economics, significantly increasing the area's overall natural gas production.

5.1 Eastern Mediterranean: a Region of Hydrocarbon Exploration & Conflict

In the last few years, the East Mediterranean has seen something that can be described as a gas revolution. Due to minimal exploration effort in the past, the region is now considered a "new frontier" for offshore gas development in the Middle East and North Africa, with low proved hydrocarbon resources (MENA). The discovery of huge gas resources by Israel and Cyprus in 2009, estimated to hold a total of 980 Bcm (35 Tcf), has sparked a flurry of exploratory activity, prompting some to conclude that the finds are so significant that the region's economic map is already being redrawn. The idea of an additional rich supply of energy will pique interest in the region, prompting the oil and gas industry to look into the possibilities of producing natural gas from methane hydrate formations in the Eastern Mediterranean.

This ‘game changing' discovery appears to have a geopolitical as well as climatic impact. The recent rise of the Eastern Mediterranean as a new energy hotspot has turned it into a potential zone of great conflict.

The gas reserves identified in Israel, Cyprus, and Egypt's territorial seas already contribute to their energy potential and security. As an example, the large Mediterranean gas reserves might help the EU diversify its energy providers, aided by the US. Recent discoveries in Israel (Tamar 2009; Leviathan 2010), Cyprus

(Aphrodite 2011) and Egypt (Zohr 2015) have boosted the East Mediterranean's potential as a future gas exporter.

The main cause of geopolitical unrest in the region is Turkey's aggressive energy claims. Using the occupied part of Cyprus as a platform for geopolitical arguments, Turkey openly challenges Cyprus and its dominance over its Exclusive Economic Zone (EEZ). This prevents the development of a gas pipeline from the Leviathan field to Ceyhan in Turkey. Short-term export of Israeli and Cypriot gas to the EU market via pipelines linking in Greece is improbable due to high development costs against estimated supplies.

Due to the recent discovery of the Zohr field, Egypt's total gas reserves now exceed those of Israel and Cyprus combined, making it the key regional gas player and possible catalyst of the Eastern Mediterranean gas hub. Unlike Egypt, Cyprus has no hydrocarbon industry experience and limited local gas demand, hence the country's energy sector is under virtually entirely external pressure. Potential new finds, tensions with Turkey and the Turkish Republic of Northern Cyprus (TRNC), the need to strengthen energy partnerships with regional countries, and to end its isolation via LNG and a gas pipeline have all been major concerns for the tiny European state. The goal is clear: safeguard it against Turkish aggression, which threatens the country's energy future and ambitions as a hub.

After the discovery of the Aphrodite gas field in block 12, the southernmost section of the Cypriot offshore concession area, in 2011, Cyprus had proven oil and gas resources. As a result of the uncertain delineation of EEZs between Cyprus and its neighbors, the volume identified is substantially smaller than Zohr.

In July 2016, ExxonMobil and Qatar Petroleum joined ExxonMobil in bidding for the last license round. Less known firms like Delek and Eni join Noble, Total, and Shell in securing Cyprus resources. However, while being distant from Central Asian gas reserves, Cyprus is closer to Southern Mediterranean gas fields and hence has a potential advantage over Turkey in becoming a new gas hub since its modest local market with limited development potential does not burden exports (as in the case of Turkey and Egypt). Finally, Cyprus' EU membership gives it preferential access to the EU gas market.

With Piraeus (Greece) and Haifa (Israel) as gateways, China's new global Silk Road aims to dominate shipping and logistics along the Mediterranean coast (Israel). The Chinese naval presence in Djibouti on the Red Sea may reflect this pattern of connecting the Silk Road to the Mediterranean. Meanwhile, US think tanks and the administration can see Russia and China consolidating their positions in the Eastern Mediterranean and cannot remain idly by. Washington ignores Erdogan's protests and supports the relaxation of limits on arms sales to Cyprus. Those efforts reflect Washington's rising interest in the Eastern Mediterranean's security and energy, as well as Turkey's continued isolation from the US. The Eastern Mediterranean energy roadmap may also help Europe overcome its reliance on Russian energy.

Under this prism, we have 3 distinct geopolitical levels, emerging from the situation in the Eastern Mediterranean:

- The immediate: Concerning the monetization potential and the distribution of wealth between Cyprus, Israel, Egypt, Turkey (and potentially Lebanon, the Palestinian Authority and Syria);
- The intermediate: Concerning the European Union (with all the conflicting interests within it) and its energy security and diversification from Russia;

- The global: that includes the geopolitical powerplays between the US, Russia and China, followed by the interested spectators like Iran and the OPEC countries.

  The emergence of a new sustainable energy source, located in the region, could spark even bigger tensions, focusing the global attention in a few square kilometres of sea.

5.2 Gas Hydrates Economics – Estimation of Price and Cost

Amidst this area of conflict, finding a cost-effective approach to harvest natural gas from methane hydrates concentrated zones is critical. Until now, three countries, namely Japan, USA, and Canada, have evaluated the most technically and economically viable extraction of natural gas from methane hydrates. Currently, Japan is conducting production tests, while the USA aims to follow the same example (Institute, 2015).

Because existing systems are capable of supporting methane hydrate development systems, methane hydrate production can be carried out in a manner similar to oil and natural gas development once the hydrate is dissociated in the layers. In many ways, however, the formation of methane hydrate varies from that of oil and natural gas.

- When a well is drilled, oil and natural gas easily flow out; however, methane hydrate requires an additional phase of dissociation, which must be included in the development system.
- Oil and natural gas can be found 2,000 to 4,000 meters beneath the ground or at sea level. Methane hydrate, on the other hand, can be found up to 500 meters beneath the surface of the seafloor.
- As a result, whereas oil and natural gas are often found in already consolidated strata, numerous methane hydrate layers are found in unconsolidated levels. Unconsolidated layers might result in production losses that are specific to certain layers. (MH21)

Once the most efficient method of dissociating methane hydrates in the layers has been determined, the extraction process and costs will be comparable to those of traditional natural gas. "The cost of producing deep-water gas hydrates is $3.40 to $3.90 per MMBtu more than typical gas deposits." Methane hydrates are expected to be produced at a cost of $4.70 to $8.60 per MMBtu by 2025, according to the International Energy Agency" (Kiani, 2017).

Furthermore, certain fundamental requirements must be met in order to harvest natural gas from concentrated zones of methane hydrates in a competitive manner. To make technical and economic sense of the extraction, the cost of production should be equivalent to or lower than the cost of traditional gas reserves. Natural gas produced from methane hydrates should cost the same as (or less than) conventional gas resources (or unconventional gas resources, such as shale gas).

In order for the investment to have a reasonable rate of return, the quantities available for extraction must be sufficient to ensure a constant supply of gas. After determining the costs of production, the costs of transportation in order for the gas to reach the European market must be determined. Of course, estimating such expenses will be easier because there is a lot of experience in the construction of offshore pipelines around the world, and there are studies available on the transportation of conventional natural gas from fields in the Eastern Mediterranean area. If the aforementioned conditions are met, investing in natural gas has a lower opportunity cost than investing in methane hydrates.

Conclusion and Comments

Considering all the recent developments in the energy sector - including the rapid introduction of hydrogen - the sector is undeniably changing in a very rapid pace, following the development of our nature as a species: technology, politics, wars and interests keep challenging and shifting the status quo in every known field. Therefore, all new potential “gamechangers”, including methane hydrates, should always be handled as solutions in order to cover our very human need for “more”.

Regarding the harvesting of natural gas from methane hydrates, the technology is still under development, and the road towards commercialization is still long but we are much closer than a decade ago. As research and production programs are being developed, we are discovering more about the nature of the resource with new fields and it is gradually proved that tremendous amounts of gas may be included in areas where gas hydrates are present, like the ones in Eastern Mediterranean near and around Cyprus.

Under this prism, we can conclude the following:

- It is estimated that producing gas from methane hydrates may become feasible globally approximately by 2025
- Up to date, no significant investments have been made by EU for extracting natural gas from methane hydrates
- Recovered and verified samples of Gas Hydrates in EU territory (project Anaximander) make the need for a solid research and active production test program most urgent
- The potential scenario of natural gas production from hydrates combined with future gas production from EU’s conventional reserves, located in the Eastern Mediterranean Sea, will limit effectively gas imports from external suppliers (mainly Russia) and result to enhanced Energy Security for Europe

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