

# FROZEN HEAT

## A GLOBAL OUTLOOK ON METHANE GAS HYDRATES

**EXECUTIVE SUMMARY**

UNEP

GRID ARENDAL

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### EXECUTIVE SUMMARY

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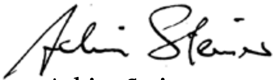
# FOREWORD

Growing energy demands, uncertainty about supplies, and the urgent need to reduce emissions of greenhouse gases mean that the world faces an uncertain energy future. Many countries have begun to explore alternative energy sources, including so-called unconventional fossil fuels such as natural gas hydrates.

Gas hydrates generally occur in relatively inaccessible polar and marine environments, which is why they have not been extensively studied until recently. Research about naturally occurring gas hydrates has increased markedly over the past two decades, however, and understanding about where hydrates occur and how they might be exploited is growing rapidly. Japan has recently tested offshore production of natural gas from a hydrate reservoir located more than 1,300 metres below the sea's surface and other countries are also actively exploring production potentials.

Continuing a tradition of identifying emerging issues, the Global Outlook on Methane Gas Hydrates is the result of a rigorous assessment process designed to ensure the availability of scientifically credible and policy-relevant information. This assessment format brings together diverse strands of knowledge and is a key mechanism through which science informs decision-making.

This report provides a basis for understanding how gas hydrates occur and the emerging science and knowledge as to their potential environmental, economic, and social consequences of their use. The intention of this publication is to enable sound policy discourse and choices that take into account a number of important perspectives.



**Achim Steiner**
UN Under-Secretary General
and Executive Director of UNEP

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THEME #1

# The Science and History of Gas Hydrates

# WHAT ARE GAS HYDRATES?

Gas hydrates are ice-like combinations of gas and water that form naturally and in great quantities here on Earth. Water molecules, which make up approximately 85 per cent of a gas hydrate, form a crystalline lattice. The lattice is stabilized by guest molecules, usually methane, that are enclosed in the lattice cavities. In the case of methane hydrates, stability requires that at least 70 per cent of the cavities are occupied by methane molecules, but the occupancy rate is usually greater than 95 per cent.

Methane gas hydrates are stable at the high pressures and low temperatures found in sediment beneath the sea or buried in polar regions. Few people have seen solid gas hydrates. Not only are they usually located in harsh and inaccessible polar and marine settings, but when they are brought to the surface, they quickly dissociate – or come apart – into their two major components, liquid water and methane gas.

A

In sands and other coarse-grained sediment, gas hydrate (white) can form between the sediment grains (dark grains) as shown in this example from the Canadian Arctic.

B

Near the seafloor above active methane seeps, gas hydrate can form mounds such as that pictured above in the Gulf of Mexico. The gas hydrate mound is tinted orange by small amounts of oil, and is partially covered by a thin sediment drape (grey material).

C

In fine-grained sediment (dark material), gas hydrate (white) can form as large chunks or nodules like the pictured specimen from offshore India.

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

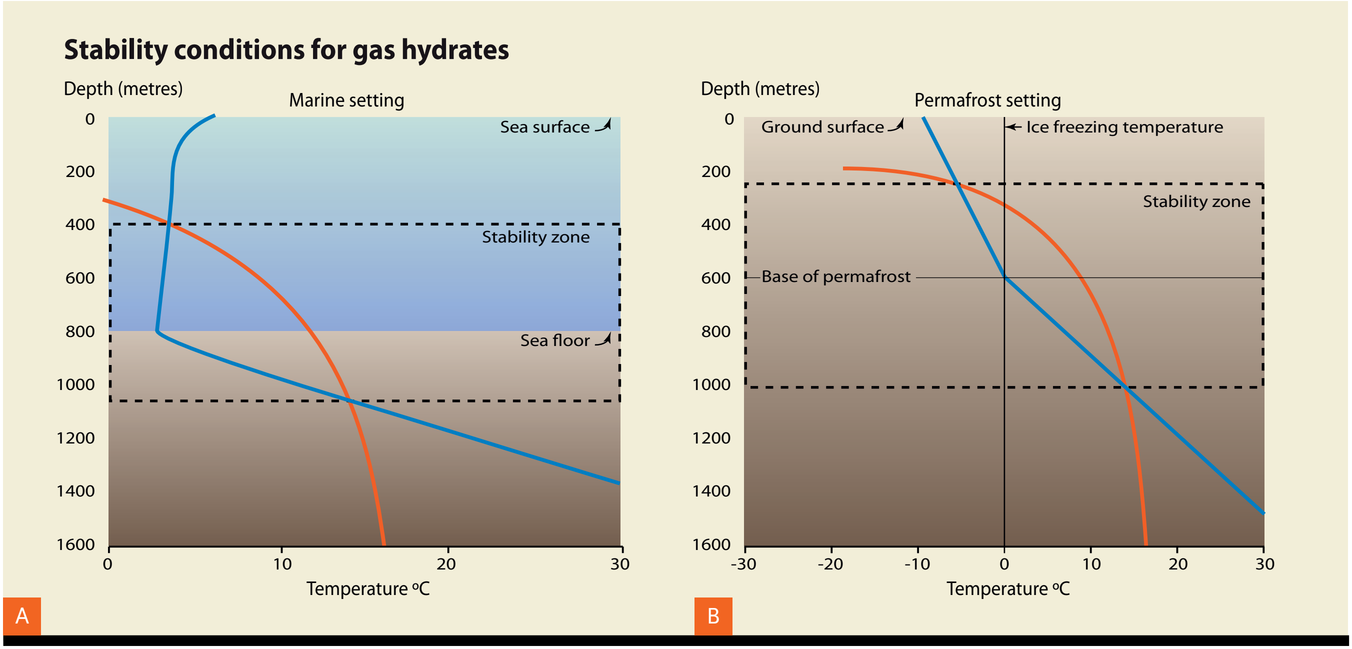
# HOW ARE GAS HYDRATES FORMED?

Methane gas hydrates form naturally where adequate supplies of methane and water can combine in a location with both high pressure and relatively low temperature. The methane itself is created by the decomposition of organic carbon, which generally migrates upward through water-laden sediment. In the right conditions, this triggers the formation of gas hydrates.

Gas hydrates can form naturally in the Gas Hydrate Stability Zone (GHSZ), the depths at which pressure and temperature are suitable for gas hydrates. Exactly where the GHSZ is found and how far it extends depend on local conditions.

In the Arctic, where cold air temperatures create thick zones of permanently frozen soils (permafrost), the top of the GHSZ typically lies about 300 to 400 metres below the land surface, often in the midst of the permafrost. In regions of relatively thick permafrost, the GHSZ often extends 500 metres or more below the base of the permafrost.

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




**Summary Graphic 2:** Phase diagrams illustrating where methane hydrate is stable in marine (A) and permafrost settings (B). 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.

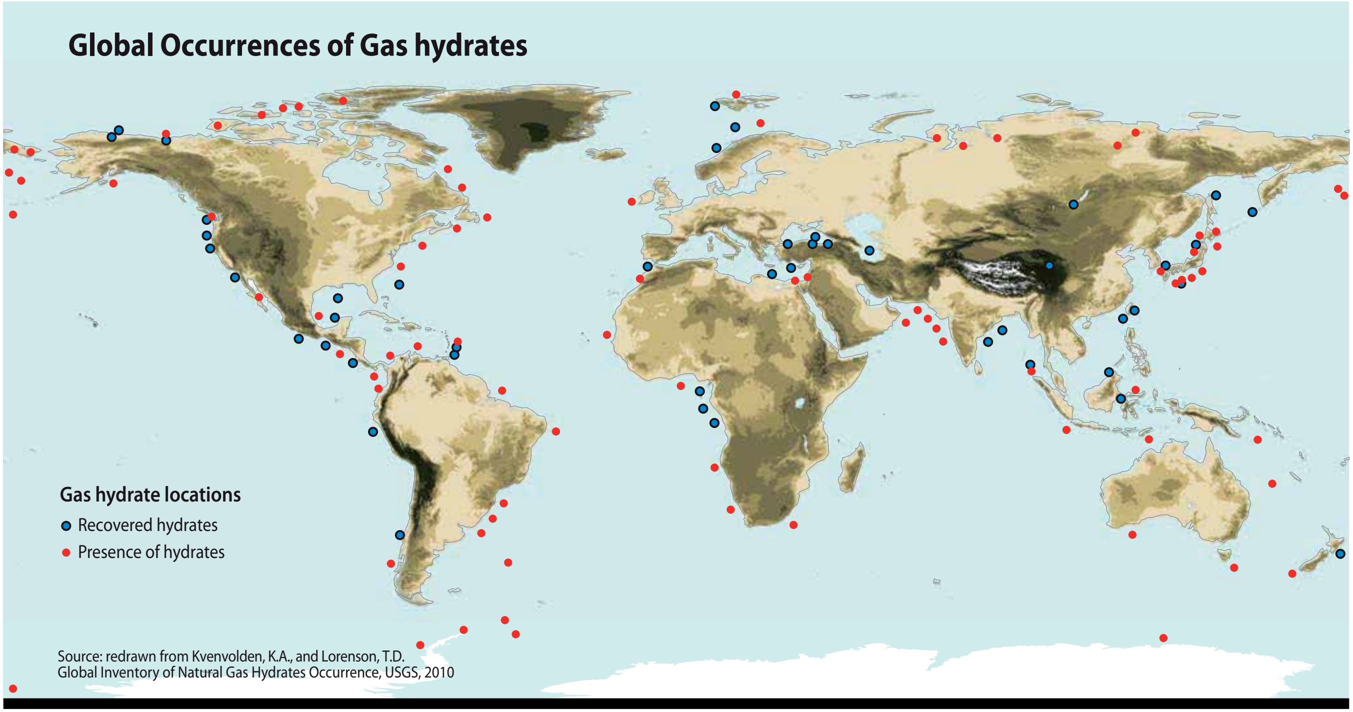
## Where methane comes from

The methane in gas hydrates comes from the breakdown of organic matter, the remains of dead plants and animals. Biogenic methane results when microbes consume the organic matter and expel methane as a waste product. Thermogenic methane comes from far below Earth's surface, where high pressures and temperatures cook ancient, buried organic matter, producing methane, as well as oil and other hydrocarbons.

# WHERE ARE GAS HYDRATES FOUND?

Even where a given location satisfies the pressure and temperature requirements for gas hydrate stability, there is no guarantee methane gas hydrates are present. The availability of organic carbon is vital for producing methane, and organic carbon is distributed unevenly around the globe.

In marine environments, for example, relatively little organic carbon is buried in the sediments beneath the open ocean, where life is sparse, so gas hydrates are generally absent from those areas, even where the temperature and pressure conditions are favourable. Approximately 90 per cent of the organic carbon buried in ocean sediment is currently found beneath relatively shallow water near the continents. In periods of much lower sea levels, organic carbon was deposited farther from today's continental margins, on what is now the continental slope. Thus, most marine gas hydrate deposits found so far have been in continental margin and slope sediments, often in association with deposits of other hydrocarbons, such as oil and natural gas.




**Summary Graphic 3:** Map of the locations at which gas hydrates have been recovered and or confirmed. It is important to note that hydrates likely have a much broader distribution. Based on seismic and other remote-sensing techniques, it has also been inferred that gas hydrates exist extensively in sub-permafrost, continental-slope, and continental-rise sediments, but the lack of inferred or recovered gas hydrates in the abyssal plains indicates that gas-hydrate formation is restricted not just by pressure and temperature requirements, but by the need for the elevated methane concentrations available near the continents.

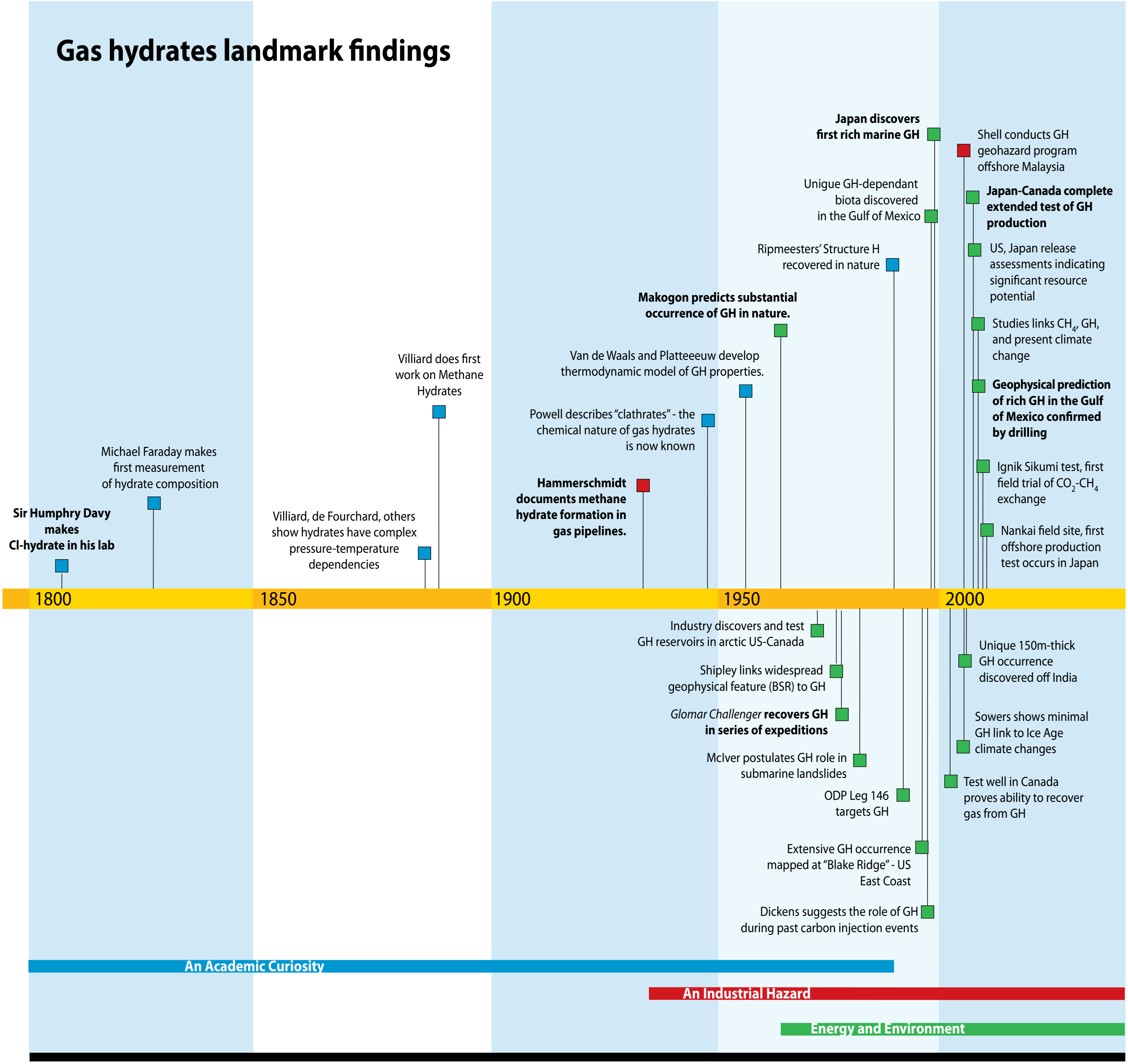
# HOW AND WHEN DID WE LEARN ABOUT GAS HYDRATES?

Gas hydrates are difficult to study because they dissociate at the conditions found at Earth's surface. Scientists who first created gas hydrates in the laboratory in the early 1800s thought they were were unlikely to exist in nature.

In the 1930s, however, gas hydrates were identified as an industrial hazard. Natural gas was beginning to be used widely as fuel and transported through pipelines. Some pipelines became plugged by what appeared to be ice, but turned out to be gas hydrates. For several decades after that discovery, research concentrated on preventing gas hydrate formation in pipelines and associated equipment, a practice called flow assurance in the oil and gas industry.

The research focus began to shift again in the 1960s when Russian scientists saw compelling evidence for naturally-occurring gas hydrates in the behaviour of shallow gas reservoirs in Siberia. They realized that the pressure and temperature conditions suitable for gas hydrate formation exist broadly in nature. A series of expeditions conducted by the Deep Sea Drilling Program in the late 1970s and early 1980s confirmed that gas hydrates exist in nature – and in substantial quantities.

Growing energy demands and climate concerns have increased interest in the potentially immense quantity of methane held in gas hydrates. Japan launched the first major national research effort in 1995, and several other countries have developed sustained and coordinated national programs since then.




**Summary Graphic 4:** Timeline of major milestones in gas hydrate (GH) research.

# WHAT ROLE DO GAS HYDRATES PLAY IN NATURE?

Gas hydrates are part of the global carbon cycle. Methane is the third most abundant greenhouse gas in the atmosphere, after water and carbon dioxide. Although it is found in relatively small concentrations, methane's impact is significant due to its efficiency in absorbing and trapping heat radiating off Earth's surface. In addition, methane molecules in the atmosphere eventually break down to form the other two major greenhouse gases: water and carbon dioxide.

Current estimates suggest gas hydrates contain most of the world's methane and roughly a third of the world's mobile organic carbon.

Gas hydrates are neither static nor a permanent methane trap. Methane migrates into hydrate formations and seeps out of them, but very little of that methane reaches the atmosphere. Microbes in the sediment itself consume most of the available methane, and methane escaping the sediment is largely dissolved in the ocean and consumed by microbes before it can reach the atmosphere.

In some locations, such as Barkley Canyon offshore Vancouver Island and the Gulf of Mexico, methane seeps have formed massive mounds of gas hydrate, many metres across, that lie exposed on the sea floor, often covered by thin drapes of sediment. 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 its infancy, fossil evidence suggests that such ecosystems have been oases for sea-floor life for millions of years.


**Summary Graphic 5:** Example from the methane seep ecosystem. C, D, F are chemosymbiotic animals whose energy source is hydrogen sulphide produced by methane-degrading microorganisms in the sediment. A: Alvinocarid shrimp, Mound 12, Costa Rica margin (1000 m). B: Lithodid crab embracing tube cores placed in a field of vesicomyid clams and bacterial mat. C: Vestimentiferan tubeworm – *Lamellibrachia barhami*. D: 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 courtesy of Greg Rouse and Lisa Levin (see Volume 1, Chapter 2).

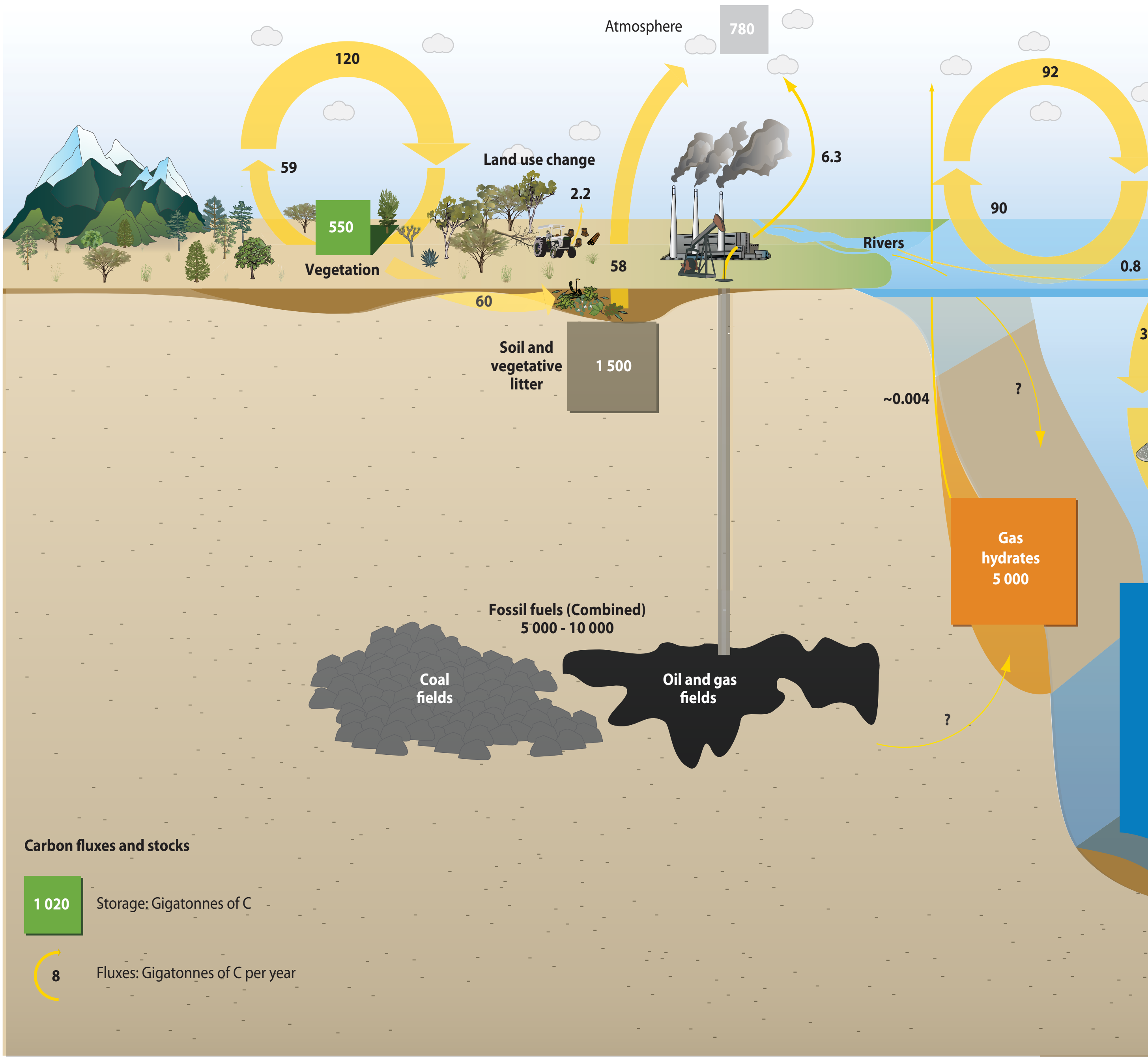

B

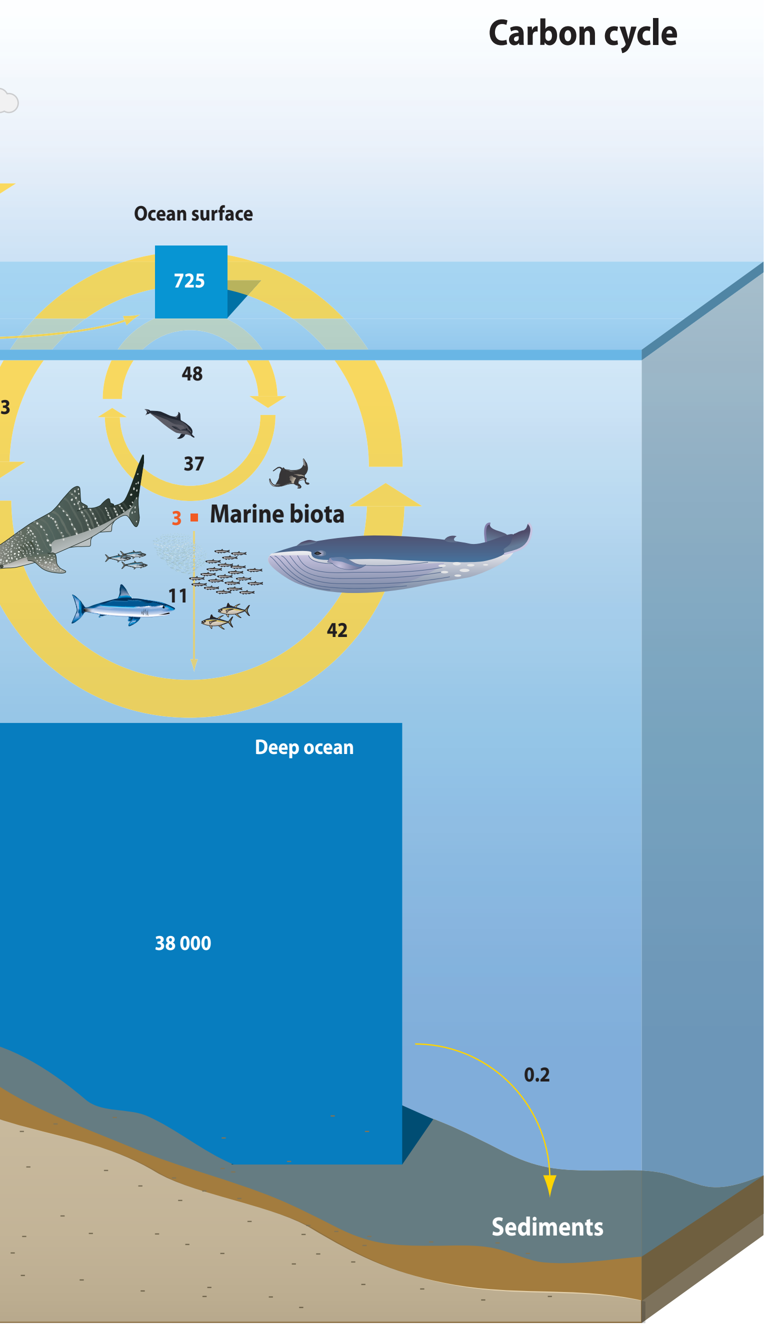

D


C


E


F


Atmosphere
780
120
59
550
Vegetation
Land use change
2.2
58
6.3
60
Soil and vegetative litter
1 500
92
90
Rivers
0.8
~0.004
?
Gas hydrates 5 000
Fossil fuels (Combined) 5 000 - 10 000
Coal fields
Oil and gas fields
?
Carbon fluxes and stocks
1 020
Storage: Gigatonnes of C
8
Fluxes: Gigatonnes of C per year




**Summary Graphic 6: Global carbon cycle.** Carbon moves through the atmosphere, biosphere, geosphere, and hydrosphere. Gas hydrates (orange) are shown in marine sediments, but are also buried beneath permafrost sediment in Arctic regions. The 5 000 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). Although gas hydrates are a significant global carbon pool, the precise amount of carbon, the amount of carbon released from gas hydrates to the atmosphere, and the extent to which that release could increase as the global climate changes are all under active debate. Improving upon the values for gas hydrates used in this figure will require extensive mapping and research efforts around the world.

THEME #2

# Gas Hydrates as a Potential Energy Resource

# ARE GAS HYDRATES A POTENTIAL ENERGY SOURCE?

In nature, methane is the dominant gas species making up gas hydrates and the dominant constituent in natural gas. The gas hydrate structure can hold substantial amounts of methane. In fact, when ignited at atmospheric conditions, the methane can sustain a flame, appearing as burning ice surrounded by a growing pool of water released from the hydrate structure.

The existence of methane in gas hydrate form does not necessarily make it a viable energy source. Solid gas hydrates occur in remote permafrost and deep-water marine settings. Their energy-resource potential depends on many factors, including how concentrated a deposit is and whether recovery can occur safely. Other considerations include the availability and cost of the infrastructure necessary to gather and distribute the natural gas. Evaluation of future gas hydrate development will be influenced by social, economic, environmental, and political considerations, not just scientific and technical issues. Prominent among these considerations is the need to reduce emissions of greenhouse gases.

# HOW BIG IS THE RESOURCE?

The global inventory of gas hydrates appears to be very large. Recent estimates of the total amount of methane contained in the world's gas hydrates range from 1500 to 15,000 gigatonnes of carbon. At standard temperature and pressure, this represents 3000 to 30,000 Tcm (trillion cubic meters) or 0.1 to 1 million Tcf (trillion cubic feet), and has an energy equivalent of 0.1 to 1.1 million exajoules.

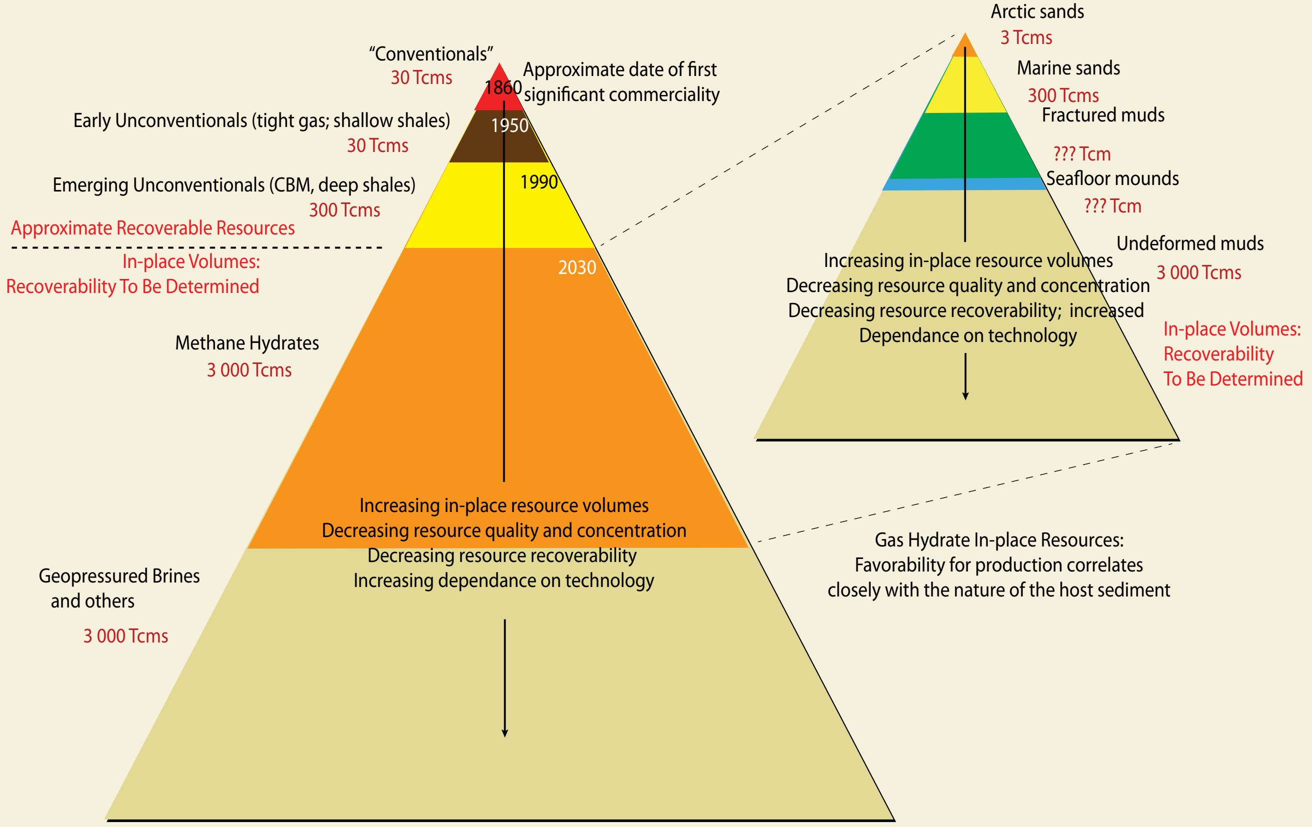
Within that global inventory, there is thought to be a smaller subset that is technically recoverable or suitable for production using existing extraction technologies. At present, the widespread but low concentrations of gas hydrates in fine-grained marine sediments are not seen as candidates for economic development. However, concentrated gas hydrates occur in marine and permafrost sands in some locations, particularly the Alaska North Slope, northwestern Canada, the Gulf of Mexico, and offshore Japan. These deposits have physical properties and reservoir settings that appear conducive to production using adaptations of conventional hydrocarbon recovery methods.

A global review (Johnson 2011) estimates that the portion of global gas hydrates located in sand reservoirs could contain more than 1 217 trillion cubic metres of gas. That is roughly 5 per cent of the typical mid-range estimate for global gas hydrate in-place resources. The review also suggests there is significant potential for technically recoverable resources of gas hydrates in every region of the globe. This view is supported by regional assessments conducted by the governments of Japan and the United States. However, in all cases, these estimates are highly speculative and require additional field confirmation.

## Resource terminology

*In-place resource:* All hydrocarbons present within a given geologic unit or geographic area.
*Technically recoverable resource (TRR):* The subset of in-place resources that is practically producible.

## Resource pyramid for gas hydrates



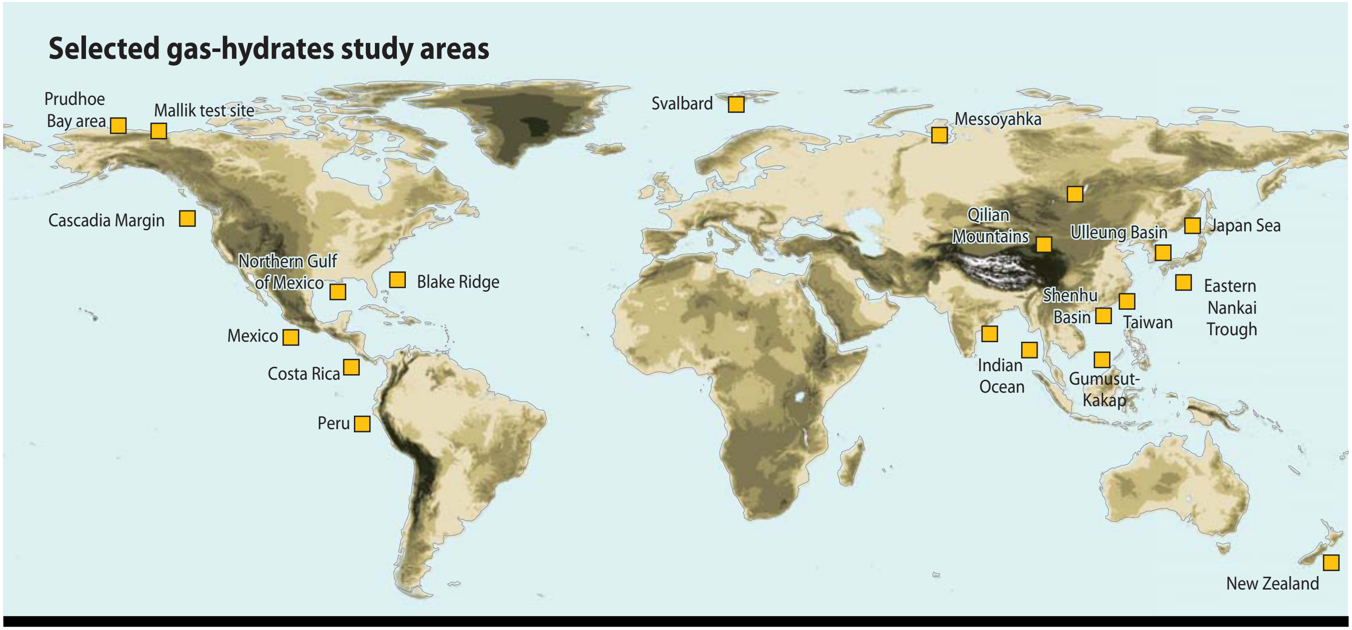

Source: redrawn from Boswell and Collett, 2006

**Summary Graphic 7:** While total in-place natural gas resources represented globally by methane hydrates are enormous, those resources are not all created equal. Instead they occur in a wide range of accumulation types. As with other petroleum resources, the accumulation types that are the most favorable for production are the least abundant, while the most challenging are the most abundant. This common attribute of natural resources creates a pyramidal distribution. A generalized resource pyramid for gas hydrates (right) is shown in relation to resource pyramid for all gas resources (left). Society continues to progress down through the global gas pyramid (left), aided by occasional technological breakthroughs that enable significant access to previously unrecoverable resources. Gas hydrates (right) may experience a similar progression with initial production most likely to occur within marine or arctic sands. Substantial new technological breakthroughs will be needed to access the large resources at the base of the hydrate pyramid. However, given the vast scale of hydrate resources, potential volumes even at the apex of the hydrate pyramid are significant. Figure after Boswell, R. and T.S. Collett, 2006. "The Gas Hydrates Resource · Pyramid." U.S. DOE-NETL Fire in the. Ice Newsletter, Vol. 6, Iss. 3, p. 5-7.

# DO WE HAVE THE TECHNOLOGY TO EXTRACT METHANE FROM GAS HYDRATES?

The types of gas hydrate deposits considered most suitable for natural gas production are buried hundreds of metres beneath the sea floor or ground surface. They are not amenable to mining techniques, due mainly to the depth of the deposits and the unstable nature of gas hydrates. The current consensus among researchers is that methane could be recovered from gas hydrates using conventional hydrocarbon recovery techniques. The proposed recovery strategy would be to drill hydrocarbon production wells to access the gas hydrate. The pressure and temperature conditions of the gas hydrate in the formation would be changed to break down the solid gas hydrate, releasing methane gas and water. The free gas would then flow up the well, to be collected at the surface using conventional equipment.

To date, more than a hundred dedicated gas hydrate research and exploration wells have been drilled to quantify gas hydrate occurrences. In addition, dedicated research wells offshore Japan and in permafrost settings in Canada and Alaska have field-tested production technologies. At the Mallik site in the Canadian Arctic, a full-scale thermal production test was completed in 2002, and gas hydrate production by depressurization of the reservoir was tested in the winters of 2007 and 2008. In 2012, an advanced production test programme involving carbon dioxide injection and pressure draw-down was completed in Alaska, and in early 2013, Japan conducted the first production test, using depressurization, offshore that country's southeastern coast.




**Summary Graphic 8:** This is a general representation of notable hydrate field programmes that have been or are taking place around the world. The compilation is indicative and does not depict all hydrate field programs.

# CAN METHANE BE EXTRACTED FROM GAS HYDRATES ECONOMICALLY?

While experimental programmes have shown that gas hydrates can be produced in the short term using conventional hydrocarbon recovery methods, it is still too soon to say whether large-scale methane production from gas hydrates would be economic. Because gas hydrates occur in remote frontier marine and permafrost settings, there would also be important economic considerations related to developing the infrastructure to collect and distribute the gas.

If meaningful production of methane from gas hydrates were to occur, it is probably still a decade or more away and would likely take place in association with existing production areas where natural gas infrastructure is already in place. Stand-alone development of offshore gas hydrate fields could also take place in areas of the world where access to conventional domestic energy resources is limited.

# WHAT ARE THE SPECIFIC ENVIRONMENTAL CONCERNS RELATED TO EXTRACTING METHANE FROM GAS HYDRATES?

Production research and development studies suggest that sand-hosted gas hydrate deposits in both marine and permafrost settings could be produced using techniques already employed by the hydrocarbon industry. The environmental considerations related to gas hydrate production from such deposits would likely be similar to those of conventional projects. Currently known gas hydrate fields with concentrated deposits are between 10 to 100 square kilometres in extent, with estimated operating lives of less than 25 years. The principal issues would likely include potential ground subsidence, disposal of produced water, disruption of sensitive ecosystems, and the cumulative impacts of development.

Since Earth's combined gas hydrate reservoirs represent a significant global supply of methane, there is considerable research interest regarding their role in the climate, particularly the response of gas hydrate occurrences to sea level change and atmospheric/ocean warming. Of particular interest is the global climate system response should large quantities of methane be released from marine or permafrost gas hydrate reservoirs. Research on the impact of gas hydrates on the climate system is ongoing and can inform decisions on gas hydrate extraction.

# DO WE WANT TO EXTRACT METHANE FROM GAS HYDRATES?

We live in an era of increasing energy scarcity, and many governments are considering a diverse energy mix that includes a growing proportion of renewable energy sources and natural gas. Proponents of this approach suggest that methane could play a role as a “bridge fuel” in allowing more rapid decarbonization of the world energy system.

So-called unconventional gas from such sources as gas hydrates is attractive to some governments that seek near-term energy independence while maintaining their commitment to reducing emission of greenhouse gases. For others, the attraction comes from possible new revenue streams that could be used to alleviate poverty and increase investment in green technologies.

Whether the development and use of natural gas from gas hydrates might become technically possible and commercially profitable is not the sole issue. At least as important is achieving a better understanding of how natural gas derived from gas hydrates might affect society and environmental stewardship at national and global scales

# WHERE DOES THE RESEARCH STAND?

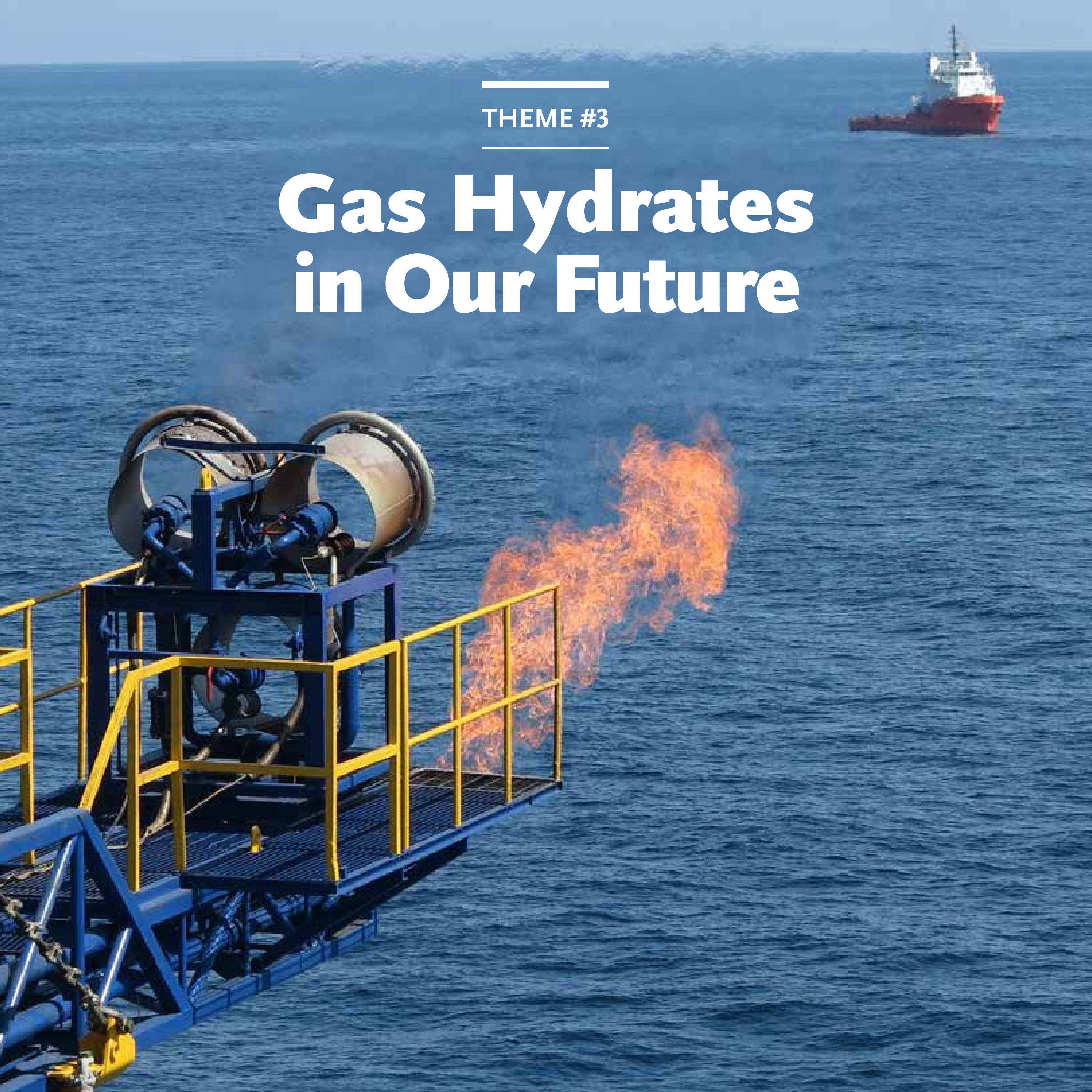
A substantial amount of investment in technical research and development would be required before commercial production of methane from gas hydrates could be contemplated. The next milestone in the field would likely be extended-duration production tests to assess the behaviour of a gas hydrate reservoir and the physical impacts of sustained production. These projects would be complex, expensive, and technically challenging.

Terrestrial sites in the Arctic, close to areas of ongoing industry activity, have generally been the primary focus of production-related research to date. However, in 2013, Japan’s national gas hydrate research program initiated a two-year field program to conduct the first full-scale depressurization testing of a marine gas-hydrate occurrence. A number of other sand-dominated reservoirs in other settings are also being considered as candidates for production.

Given the high costs involved, gas hydrate production research would likely continue to be facilitated primarily by government funding, with industry participation.

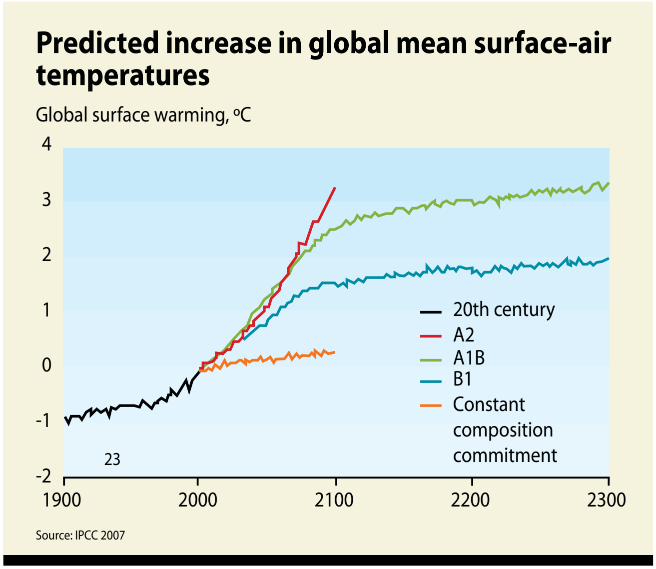
THEME #3

# Gas Hydrates in Our Future

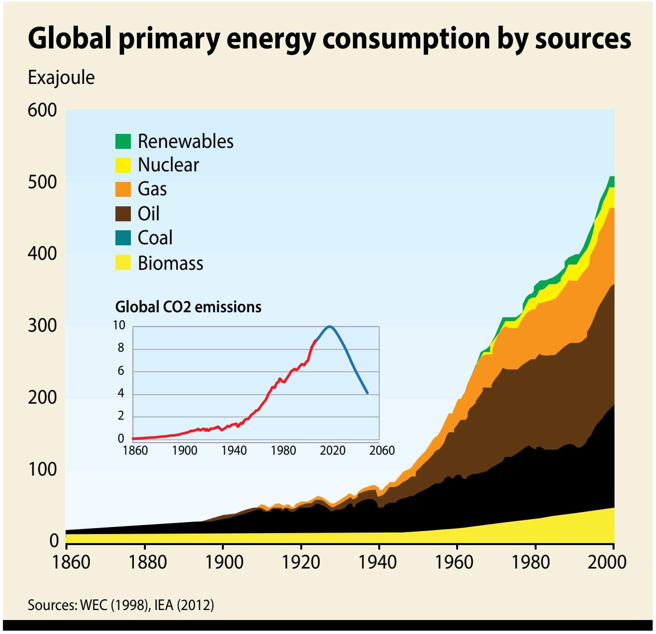


# WHY MUST THE WORLD'S ENERGY MIX CHANGE?

For most of modern history, access to inexpensive and reliable energy has been central to economic development and social progress. However, the world is increasingly characterized by unsustainable economic growth, resource scarcity, and climate change driven by growing fossil fuel use. All of these forces will have profound impacts on the environment, as well as on human societies and security. Although fossil fuels may well remain part of the world's energy mix for some time, changing the balance of fuels within the mix could reduce pressure on the global climate system and the world's ecosystems and buy more time to make the transition to a less damaging energy future.




**Summary Graphic 9:** Predicted increase in global mean surface-air temperatures. Increases are relative to 1980–1999 for different emission scenarios (IPCC 2007). The partial pressure of carbon dioxide in the atmosphere ($pCO_2$) is assumed to attain a value of 800 to 1 000 parts per million (ppm) at the end of this century for scenario A2. It increases to about 700 ppm in scenario A1B and reaches approximately 500 ppm in scenario B1. The current $pCO_2$ value of about 390 ppm is maintained until the end of the century in the constant composition scenario. (See IPCC (2007) for further information.)




**Summary Graphic 10:** Global primary energy consumption by source. The main diagram shows the historical consumption from 1860 to 2009 and the Global Energy Assessment's scenario projections for the period 2010 to 2050. The inset curve shows global carbon dioxide emissions, both historical and projected. The projections are based on one of three illustrative Global Energy Assessment pathways that were interpreted by two different modeling frameworks: IMAGE and MESSAGE.

# WHAT ARE THE POTENTIAL BENEFITS AND DRAWBACKS OF DERIVING GAS HYDRATES IN THE FUTURE ENERGY MIX?

Gas hydrates offer a potentially huge non-traditional source of natural gas. There is now substantial evidence that gas hydrates are widespread, both in terrestrial deposits in the Arctic and in marine deposits beneath the continental shelves and slopes of the world's oceans. Many of these deposits are located in parts of the world that lack more conventional sources of energy.

When methane derived from gas hydrates is combusted, it produces carbon dioxide, just like any other fossil fuel. However, the amount of carbon dioxide produced during methane combustion is up to 40 per cent lower than that produced by coal and about 20 per cent lower than oil for the same amount of energy produced. This means that a net displacement of higher greenhouse-gas-emitting fuels by natural gas could result in a net reduction of global greenhouse gas emissions. If, however, the potential energy source represented by gas hydrates is exploited chiefly to fulfil additional energy demand, it could perpetuate the world's dependence on fossil fuel energy.

## The Hydrogen to Carbon Ratio

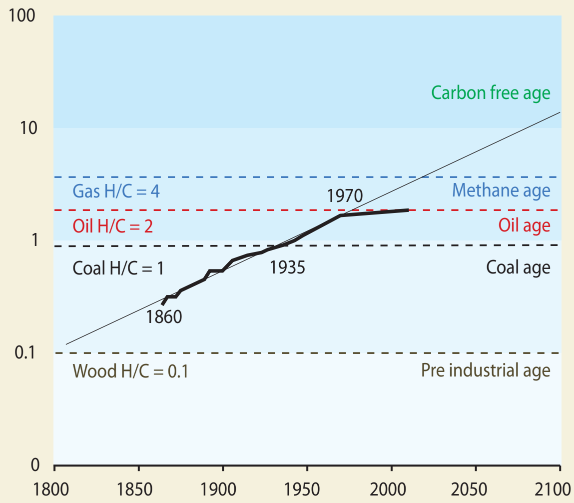
The hydrogen to carbon ratio (H/C) is an indicator of the environmental impact of a fuel (Marchetti 1985; Ausubel 1998). Fuelwood has the highest carbon content, with about one hydrogen atom per ten carbon atoms. Coal has roughly one hydrogen atom to one carbon atom. Oil has, on average, two hydrogen atoms to one carbon atom. Natural gas, or methane, has four hydrogen atoms to one carbon atom. These factors are used in the figure below to determine the H/C ratio of global energy.

References:


Ausubel, J., Marchetti, C. and Meyer, P. (1998). *Toward green mobility: the evolution of transport.* European Review 6(2), 143–162.

Marcetti, C. (1985). *Nuclear plants and nuclear niches: On the generation of nuclear energy during the last twenty years.* Nuclear Science and Engineering 90, 521–526.


**Hydrogen to carbon ratio of global primary energy**



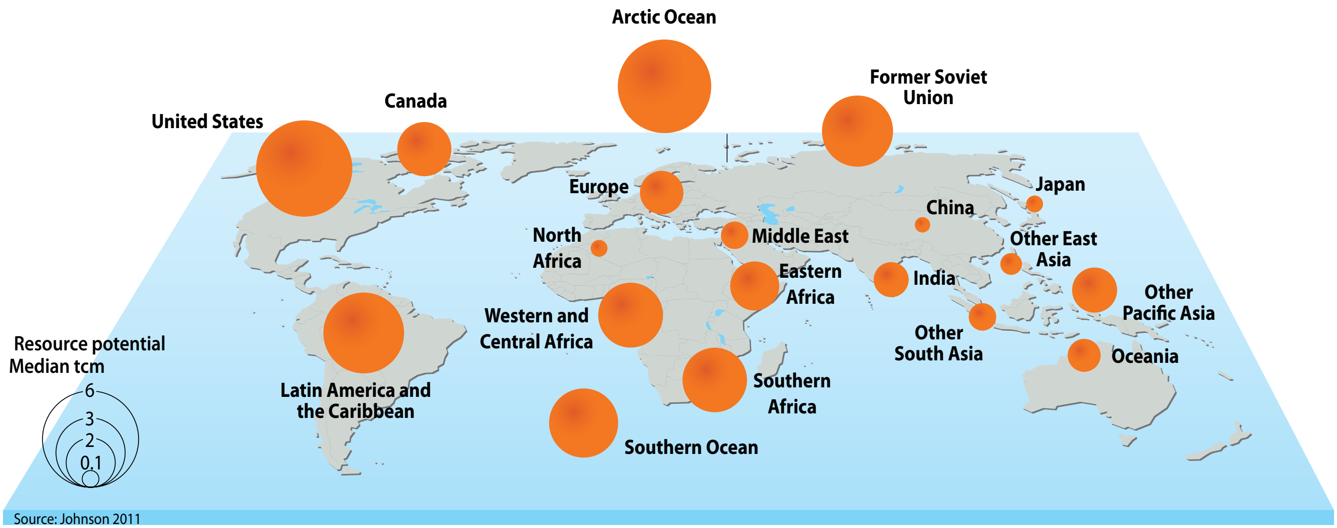

Source: Marchetti, 1985; WEC, 1998 and IEA, 2012

**Text box figure 1:** H/C ratios through fuels and time.

# COULD GAS HYDRATES JOIN THE GLOBAL ENERGY MIX?

Substantial investment will be required to realise significant worldwide gas hydrate production, and efficient as it is, methane is still a fossil fuel that emits greenhouse gases. Will it happen? The contribution of gas hydrates to social and development goals will depend on a region's, a nation's, or a community's state of development, its gas hydrate endowment, and other living, non-living, and human capital endowments. The key for each geographic region is to determine where gas hydrates fit in a larger development framework and whether the extraction, processing, and marketing of natural gas from gas hydrates provides a net advance in achieving its goals. With commercial production of methane from gas hydrates still years away, there is time for regions and nations to make those determinations.

## Gas hydrates resource potential by global regions




**Summary Graphic 11:** Gas hydrates resource potential by global regions. This figure includes only that subset of global in-place gas hydrates that appear to occur at high concentrations in sand-rich reservoirs. Source: Johnson, A. (2011). Global resource potential of gas hydrate – a new calculation. Proceedings of the 7th International Conference on Gas Hydrates (ICGH 2011), Edinburgh, Scotland, United Kingdom, July 17–21, 2011.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