

FROZEN HEAT

A GLOBAL OUTLOOK ON METHANE GAS HYDRATES

EXECUTIVE SUMMARY

UNEP

GRID ARENDAL

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FOREWORD

Growing energy demands, uncertain future supplies and concerns about climate change mean that the world needs to explore alternative energy sources and unconventional fossil fuel sources – such as the potentially immense methane stores held in natural gas hydrates. Gas hydrates generally occur in relatively inaccessible polar and marine environments – which is why they have not been extensively studied – till recently.

The result has been an increase in research over the past two decades and the pace of scientific discovery about naturally occurring gas hydrates continues to increase.

This report reviews hydrate occurrences that some countries intend to exploit to produce natural gas as a potential for energy security. For instance, Japan tested offshore production earlier this year in which they successfully drilled to the hydrate reservoir (1000 meters of water and about 300 meters sub-seafloor) using a depressurization technique to separate the natural gas from the frozen water. Much of this offshore effort was based on previous extensive onshore research and development as part of the Canada-Japan Mallik project in the Mackenzie Delta (Northwest Territories, Canada). USA onshore R&D on the Alaska Slope has also provided extensive data and knowledge and this research continues today.

The report highlights some interesting implications for sustainable development.

Environmentally, methane hydrates could be used to displace significantly, and in some cases completely, the use of coal and oil. By matching de-carbonization policies with increased investment in green technology, natural gas from hydrates could be a transitional or bridge fuel in the transition to a low carbon, resource efficient Green Economy. Socially, the global geographic distribution of hydrates can be an opportunity to ensure more equitable distribution of revenues from natural gas production. More importantly, it can, through sound policies, lead to local consumption in areas that traditionally pay high prices to import fuel – such as in Arctic communities and countries in West Africa.

This report should be used as a basis for understanding how gas hydrates occur and evolve in nature and their potential within future energy options. It reviews trends in energy supply, shows where there may potentially be gas hydrate resources; technologies that can be used; and the potential environmental, economic, and social implications of gas hydrate production.

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

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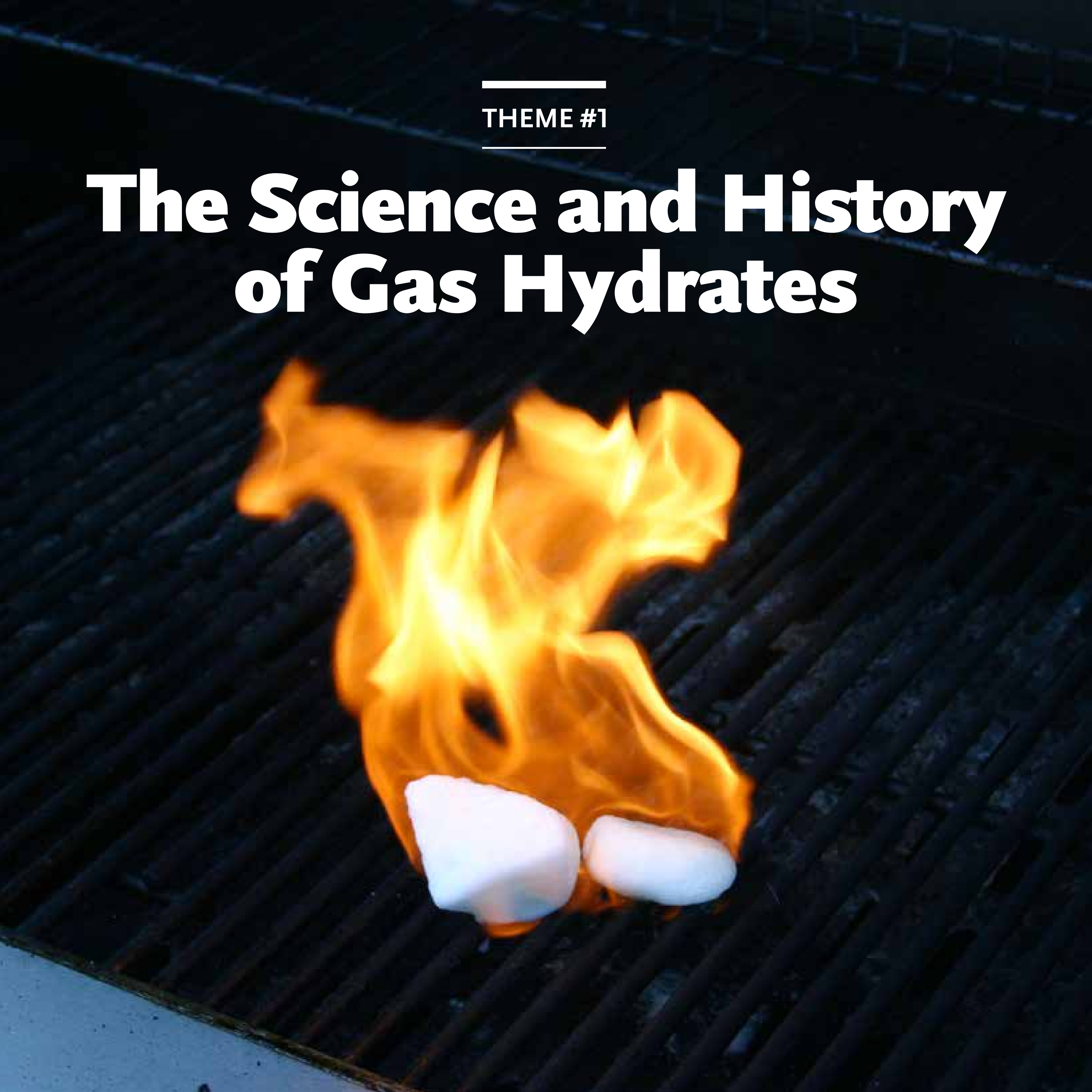
THEME #1

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. Where there are low temperatures and relatively high pressures, such as in polar or sea floor sediments, water can form a crystalline lattice. This lattice is stable only if "guest" molecules are available to fill the natural cavities in the lattice, and methane is the primary guest molecule here on Earth. Few people have seen gas hydrates in person. Not only are they limited to remote locations, but as they are brought to the surface, they begin coming apart, or dissociating, into water and methane gas. They must be photographed quickly, or in their natural setting, to be seen in solid form.

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).

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.

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

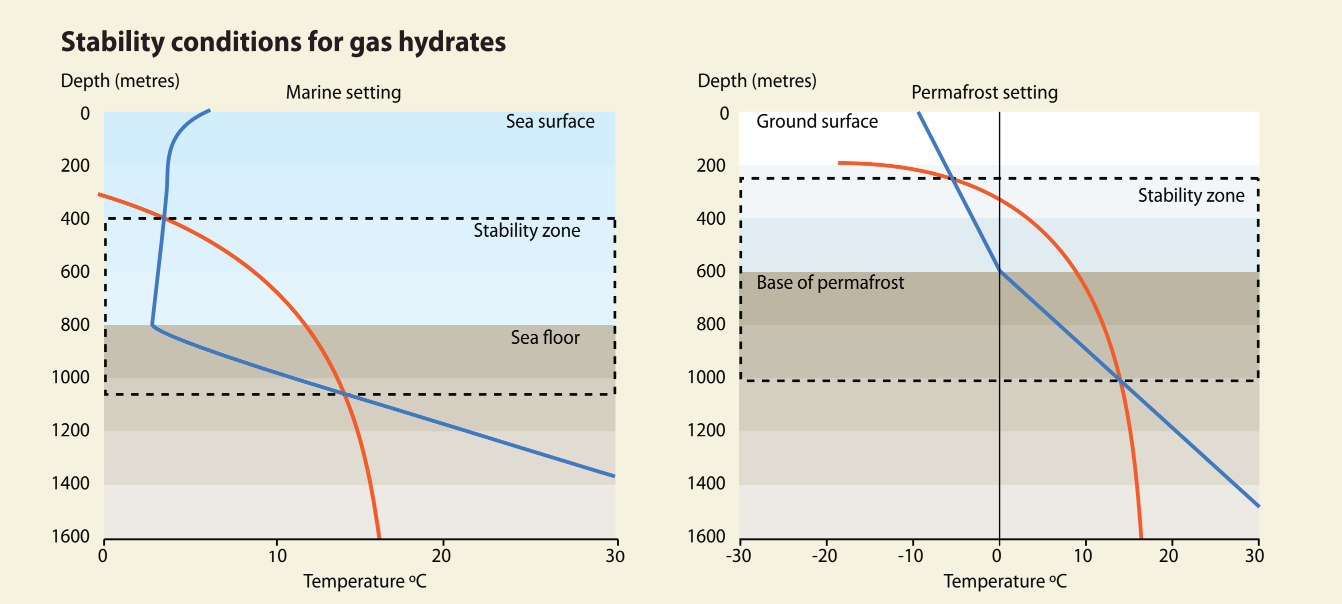
WHERE ARE GAS HYDRATES FOUND?

If adequate supplies of methane and water are available, gas hydrates can form naturally in the Gas Hydrate Stability Zone (GHSZ). The GHSZ refers to the depths for which pressure and temperature are suitable for gas hydrates, so the extent of this zone differs in cold polar regions compared to warmer marine regions.

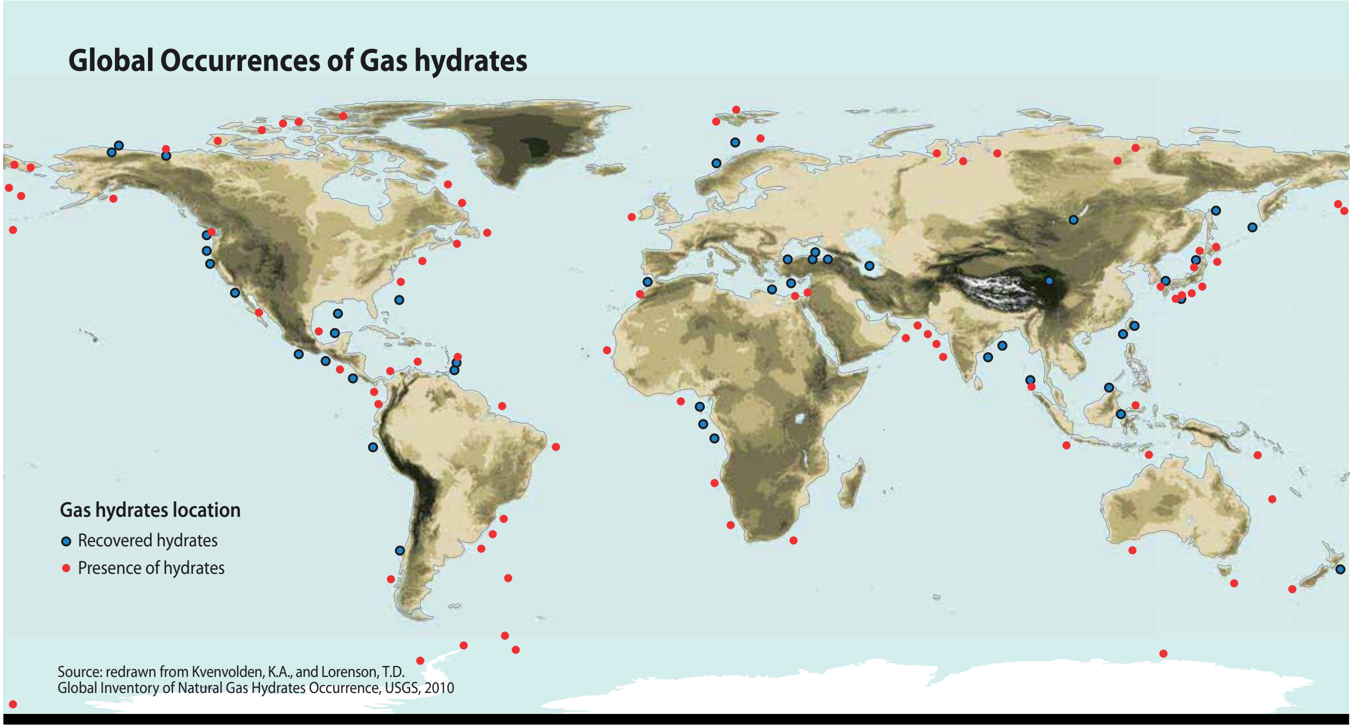
In the Arctic, where cold air temperatures create thick zones of permanently frozen soils (permafrost), the top of the GHSZ typically lies about 200 to 300 metres below the land surface, often in the midst of the permafrost. In regions of relatively thick permafrost, the GHSZ often extends 500 metres 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 depth below the sea floor.

Even where a given location satisfies the pressure and temperature requirements for gas hydrate stability, a supply of methane must be present for methane gas hydrates to form. The methane itself comes from either the microbial- or thermogenic-breakdown of organic matter, and must sometimes migrate up through the sediment to reach the GHSZ. Because organic matter is derived from living



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.



Summary Graphic 3: Map of the locations at which gas hydrates have been recovered and or inferred. 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.

organisms and distributed unevenly around the globe, gas hydrates are distributed unevenly as well.

For example, approximately 90 per cent of the organic carbon buried in ocean sediment was deposited beneath relatively shallow water near the continents. Organic carbon has also been deposited on what is now the continental slope during periods of lower sea-level or by river outflows and other transport mechanisms when sea-levels are high (as they are today). Thus, most marine gas hydrate deposits found so far have been in sediments near Earth's continents, sometimes in association with deposits of other hydrocarbons, such as oil and natural gas.

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.

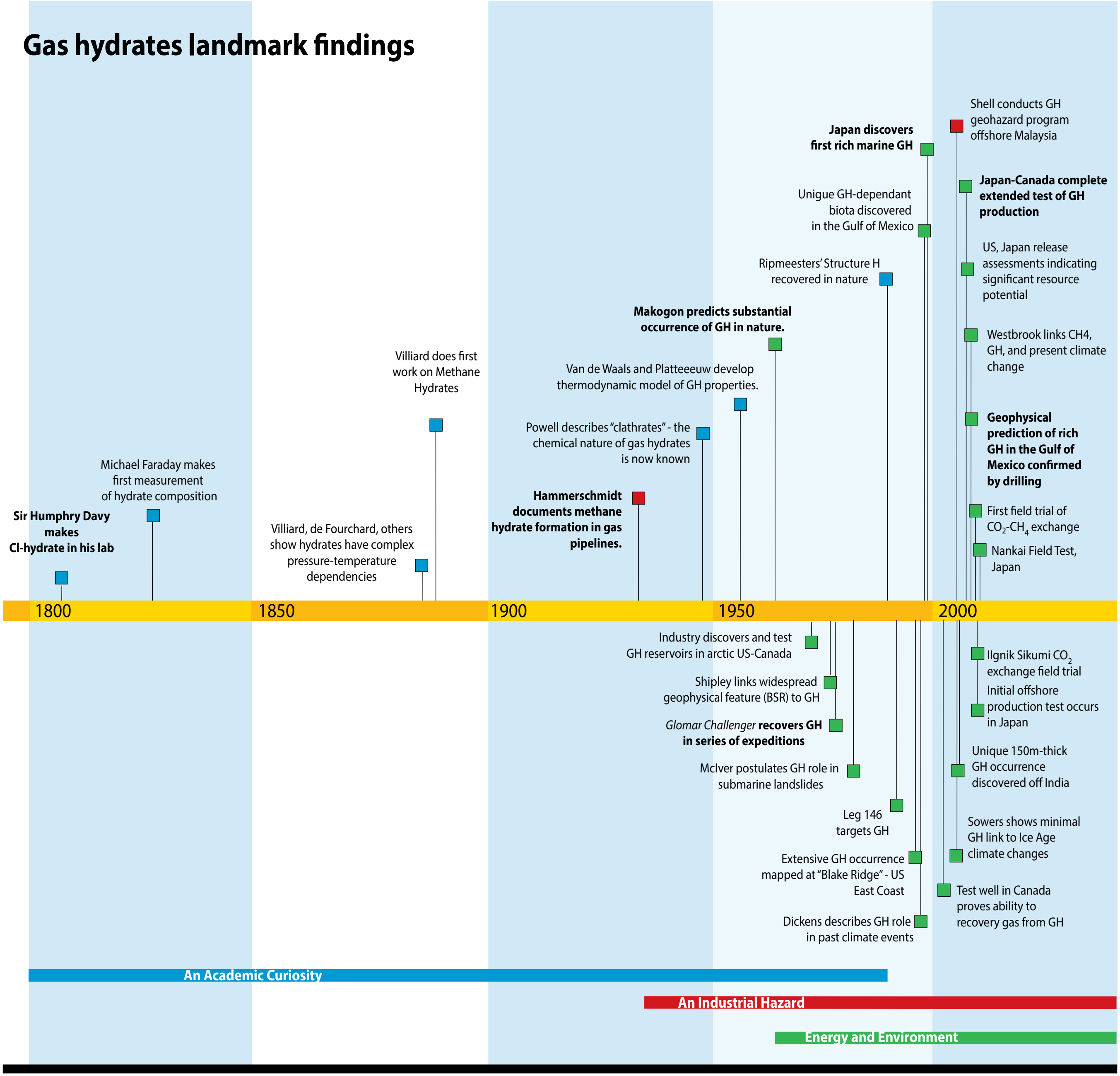
HOW AND WHEN DID WE LEARN ABOUT GAS HYDRATES?

Gas hydrates are difficult to study because they dissociate at the conditions found at Earth's surface. In fact, laboratory scientists who first created gas hydrates in the early 1800s considered them an academic curiosity that was 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 were, in fact, 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 gas hydrate research focus shifted again in the 1960s when Russian scientists saw compelling evidence for naturally-occurring gas hydrates in the behaviour of shallow gas reservoirs in Siberia and noted that the pressure and temperature conditions suitable for gas hydrate formation exist broadly in nature. A series of deep-ocean scientific drilling 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 the interest in the potentially immense quantity of methane held in gas hydrates. Over the past two decades, energy-based research has accelerated. 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 research.

WHAT ROLE DO GAS HYDRATES PLAY IN NATURE?

Gas hydrates are part of the global carbon cycle. Carbon close to Earth's surface cycles among four reservoirs: the atmosphere, hydrosphere (oceans and other water bodies), geosphere (rocks and soil), and biosphere (living things). Deeply buried carbon can be added to the near-surface cycle by volcanism – and by human actions, such as digging up and burning fossil fuels. Carbon can also be removed from the near-surface cycle via burial.

Methane is one form in which carbon moves through this cycle. In the atmosphere, it is the third most abundant greenhouse gas, after water vapor and carbon dioxide. Although methane is found in much smaller concentrations than carbon dioxide, methane's impact is significant due to its greater ability to absorb and trap heat radiating off Earth's surface. In addition, methane molecules in the atmosphere eventually break down to form the other two most abundant greenhouse gases: water vapor and carbon dioxide.

Evaluating the role gas hydrates play in modulating past and future climate change has become a research focus because current estimates suggest gas hydrates contain most of the world's methane and account for roughly a third of the world's mobile organic carbon. Of primary interest is the response of gas hydrate occurrences to sea-level change and atmospheric/ocean warming, because gas hydrates are neither static nor a permanent methane trap. Methane migrates into hydrate formations and seeps out of them as well, but very little of that methane reaches the atmosphere. Microbes in or on the sediment itself consume most of the available methane. 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 – many metres across – that lie exposed on the sea floor, often covered only 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. Even in the absence of gas hydrate mounds, methane seeps can host complex biological communities These communities were discovered fewer than 30 years ago and their investigation is still in its infancy, but fossil evidence suggests that such ecosystems have been oases for sea-floor life for millions of years.

Summary Graphic 5: Examples from the methane seep ecosystem. C, D and F are chemosymbiotic animals whose energy source is hydrogen sulfide produced by methane-degrading microorganisms in the sediment. A: Alvinocarid shrimp, Mound 12, Costa Rica margin (1000 m water depth), 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 nourish 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 water depth), Costa Rica margin. Photos courtesy of Greg Rouse and Lisa Levin (see Volume 1, Chapter 2).

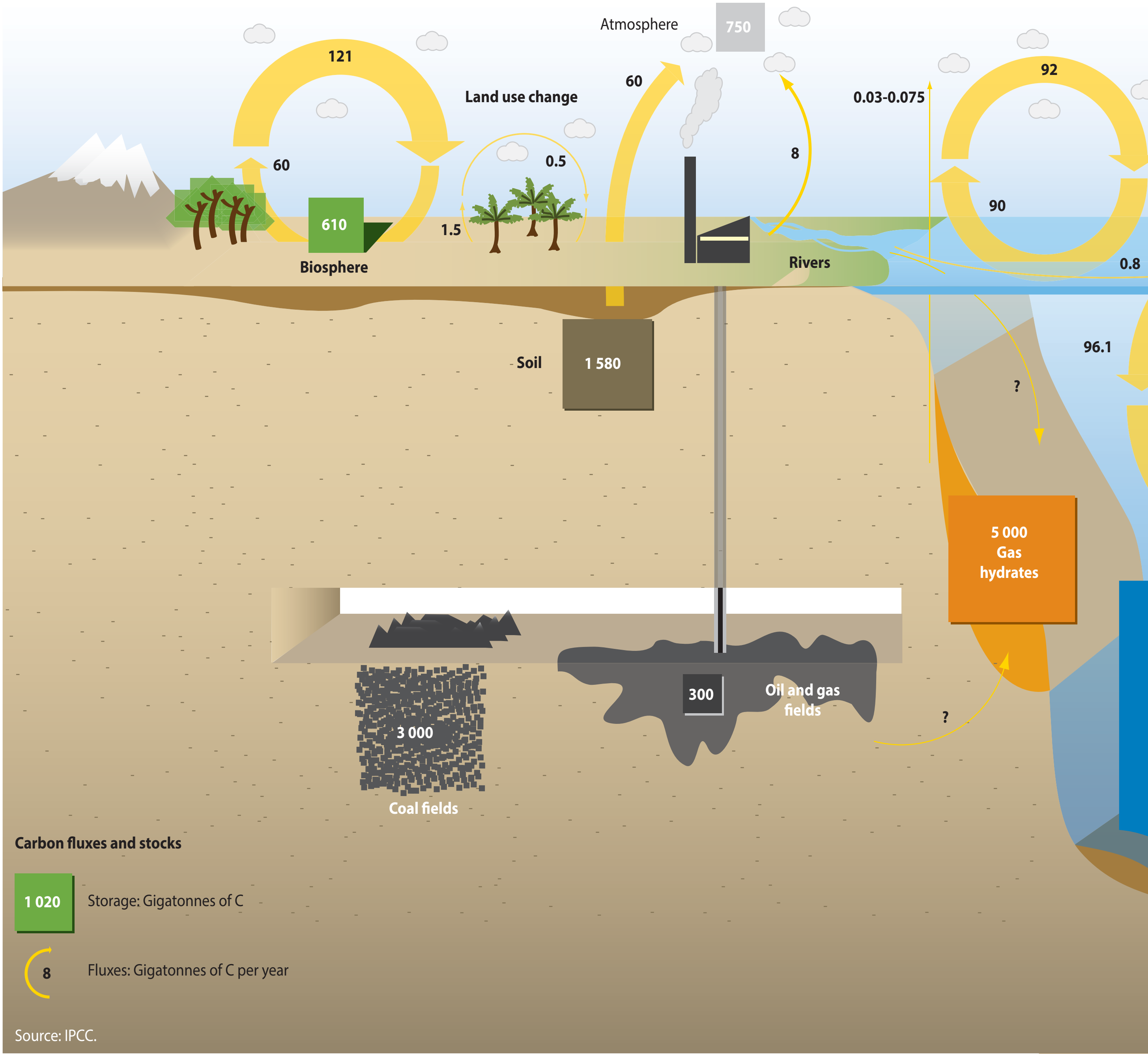

B


C

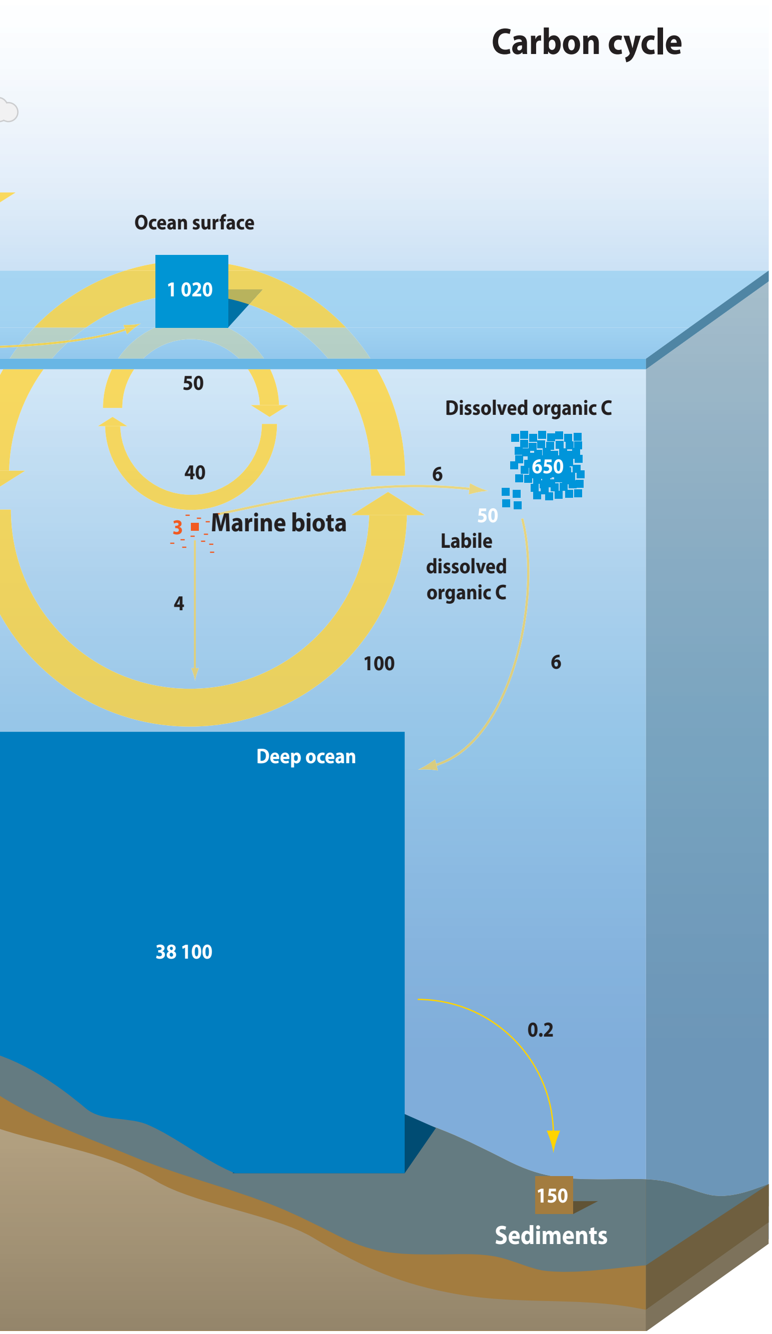

D


E


F



Atmosphere
750
121
60
610
Biosphere
Land use change
0.5
1.5
60
8
Rivers
0.03-0.075
92
90
0.8
96.1
Soil
1 580
?
5 000
Gas
hydrates
3 000
Coal fields
300
Oil and gas
fields
?
Carbon fluxes and stocks
1 020
Storage: Gigatonnes of C
8
Fluxes: Gigatonnes of C per year
Source: IPCC.



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 polar regions. The value cited for gas hydrates is a midrange estimate from recent global assessments (see full UNEP report for details). All other values are compiled from IPCC Working group assessments. Though 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 actively debated. Improving upon the Intergovernmental Panel on Climate Change (IPCC) values used in this figure for gas hydrate will require extensive mapping and research efforts around the world. (see Volume 1, Chapter 2).

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. In gas hydrates, methane is so highly concentrated that gas hydrates can sustain a flame if lit at atmospheric conditions. Methane is also the dominant constituent in domestic natural gas supplies, which already provide a significant part of the world's energy supply. The existence of methane in gas hydrate form in the sediment does not necessarily make it a viable energy source. Their energy-resource potential depends on many factors, including how concentrated a given deposit is and whether recovery from that deposit is economical. Economic 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, and political considerations, not just scientific and technical issues.

HOW BIG IS THE RESOURCE?

While field studies to quantify gas hydrate occurrences are still somewhat limited, 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 200 to 2 200 times the current annual global energy consumption from all sources.

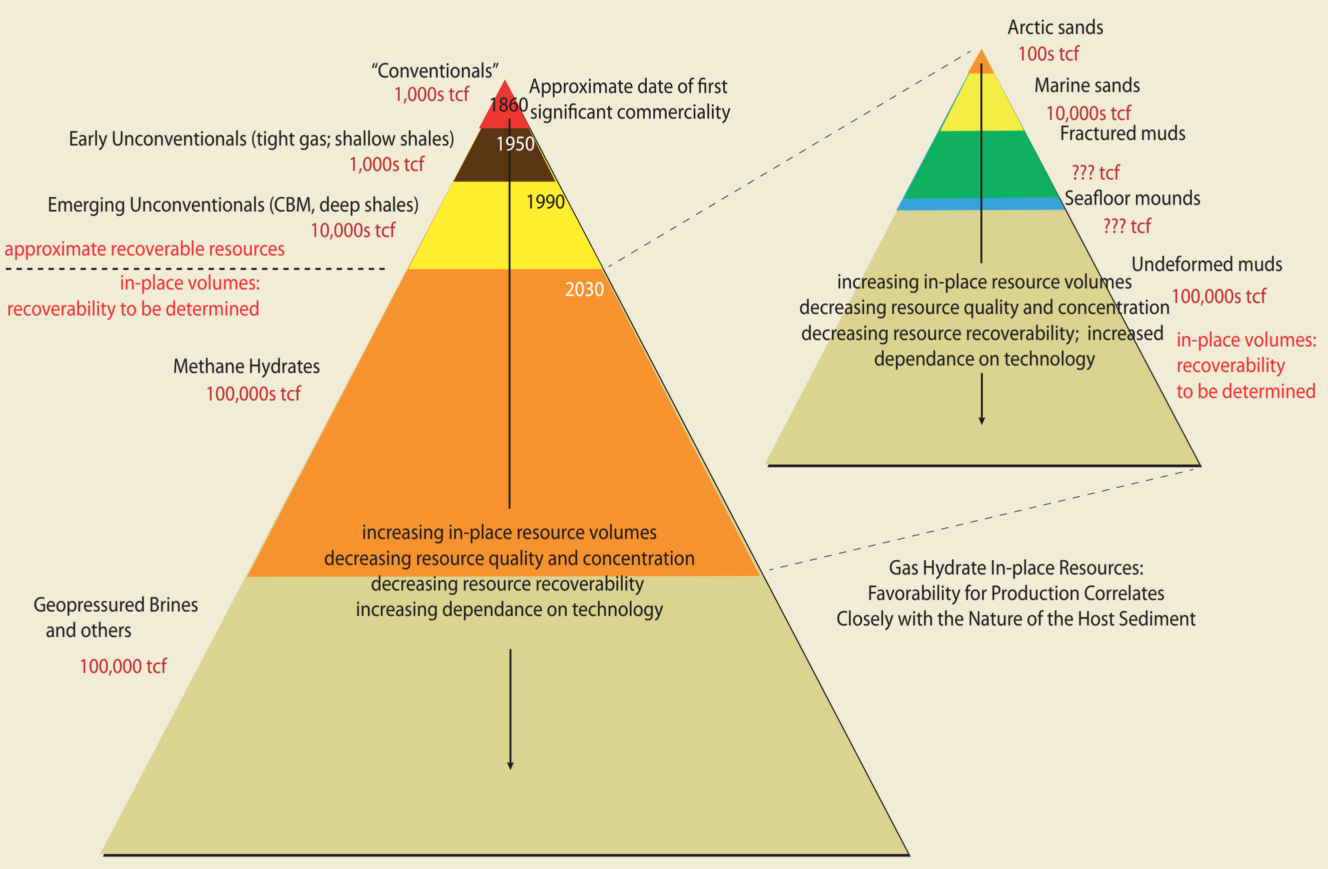
Within the global inventory of in-place gas hydrates, there is thought to be a reduced subset that is technically recoverable or suitable for production, given existing extraction technologies. At present, the widespread but low concentrations of gas hydrates occurring in fine-grained marine sediments are not seen as candidates for economic development. While more limited in occurrence, a number of localities have been identified where concentrated gas hydrates are found in marine and permafrost sands. Principal among these are the Alaska North Slope, northwestern Canada, the Gulf of Mexico, and offshore Japan. These deposits have physical properties and reservoir settings that are conducive to production using conventional hydrocarbon recovery methods. Thermal and/or pressure changes can be delivered into these reservoirs from a drilled production well, and released gas can flow to the well to be gathered and transported to the surface.

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.

A global review (Johnson 2011) estimates that the portion of global gas hydrates located in sand reservoirs could contain more than 1 217 trillion (10^{12}) 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 of gas hydrate resources conducted by the governments of Japan and the United States. However, in all cases, these estimates remain speculative and require additional field confirmation

Resource pyramid for gas hydrates



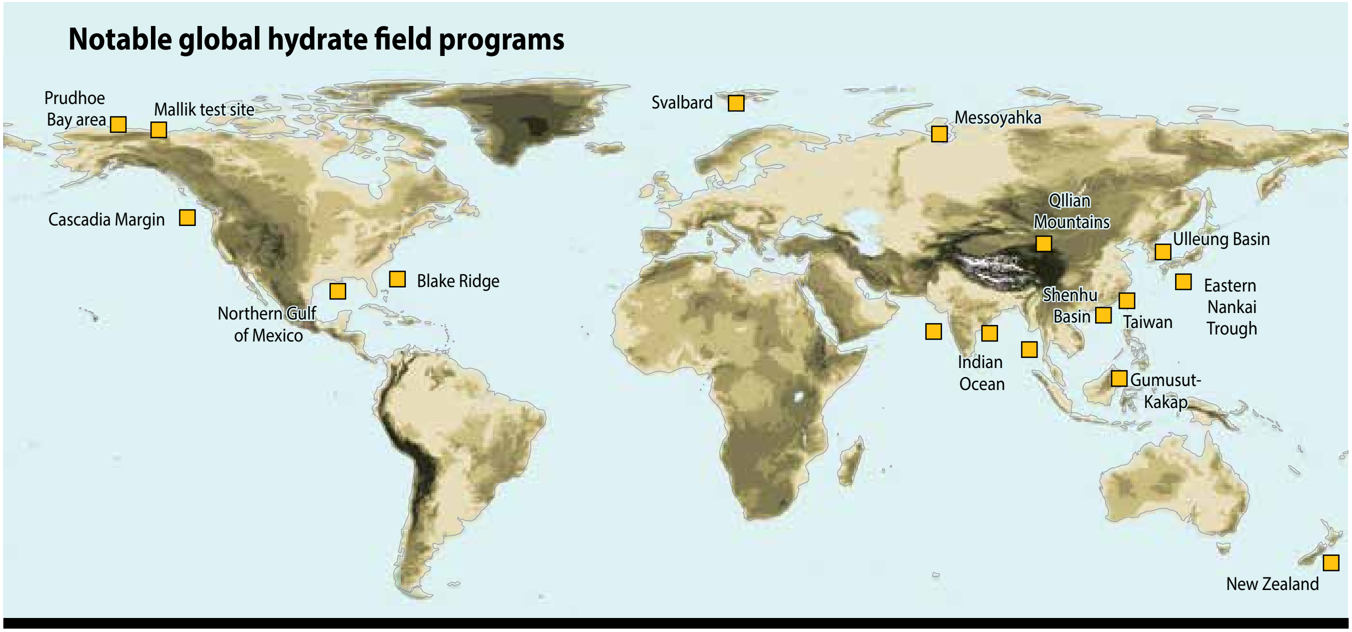
Source: redrawn from Boswell and Collett, 2006

Summary Graphic 7: The total in-place natural gas resources represented globally by methane hydrates are enormous, but they occur in a wide range of accumulation types. As with other petroleum resources, the accumulation types most favorable for production are the least abundant, creating a pyramidal resource 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. Given the vast scale of hydrate resources, however, 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?

Gas hydrates in both marine and permafrost settings 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 under changing pressure and temperature. The current consensus among researchers is that methane will be recovered from gas hydrates using conventional hydrocarbon recovery techniques. The recovery strategy would be to drill hydrocarbon production wells to access the in-place gas hydrate occurrence. Currently, the most effective and practical option is depressurization, in which the pressure in the gas-hydrate bearing formation would be decreased to break down the solid gas hydrate, releasing methane gas and water. The free gas would then flow up the well for collection 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. Many of these projects have been carried out by national research programs in Canada, China, India, Japan, Korea, and the United States. 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 2007 and 2008. In 2012, an advanced production test program involving carbon dioxide injection and depressurization 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: Notable gas hydrate field program locations (not all hydrate fieldwork is depicted).

CAN METHANE BE EXTRACTED FROM GAS HYDRATES ECONOMICALLY?

While technical advances 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 will be economic in various regions. More research is needed to assess long-term production response at a field-scale. Because gas hydrates occur in remote frontier marine and permafrost settings, there are also important economic considerations related to developing the infrastructure to collect and distribute the gas once it is produced.

Meaningful production of gas from gas hydrates is probably about a decade away. Development of offshore gas hydrate fields might also take place in areas of the world where access to domestic energy resources is limited

ARE THERE 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 can be produced using techniques and methods already employed by the hydrocarbon industry worldwide. The environmental considerations related to gas hydrate production from such deposits will therefore be similar. The principal issues are likely to include potential ground subsidence, disposal of produced water, disruption of sensitive ecosystems, and the cumulative impacts of development. While the impacts of local-scale exploitation of gas hydrates on natural processes must be addressed, they will probably be similar to those related to conventional oil and gas production.

WHERE DOES THE RESEARCH STAND?

A substantial amount of investment in research and development is required before commercial production of methane from gas hydrates can be contemplated. The next milestone in the field will likely be extended-duration production tests to assess the long-term production behaviour of a gas hydrate reservoir and the associated physical impacts of sustained production. These projects will be complex, expensive, and technically challenging. The lessons learned will contribute to the design of specific production strategies tailored to particular geological settings around the world.

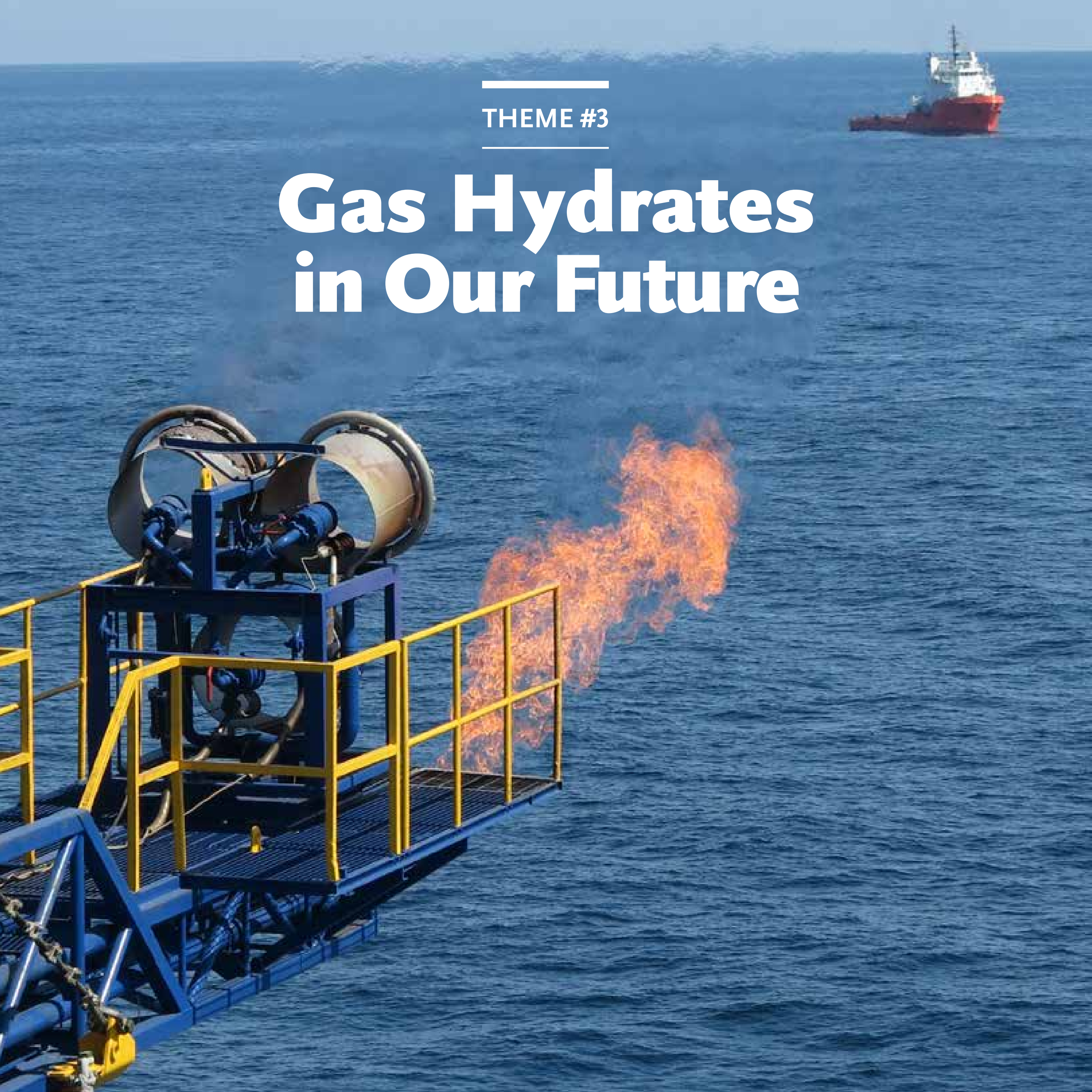
Terrestrial sites in the Arctic, close to areas of ongoing industry activity, have generally been the primary focus of production-related research to date. However, in 2013, Japan's national gas hydrate research program is initiating a two-year field program to conduct the first full-scale depressurization 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 will likely continue to be facilitated primarily by government funding, with industry participation.

Summary Graphic 9: Produced methane gas flared during the Ignik Sikumi gas hydrate field trial, Alaska North Slope, March, 2012.

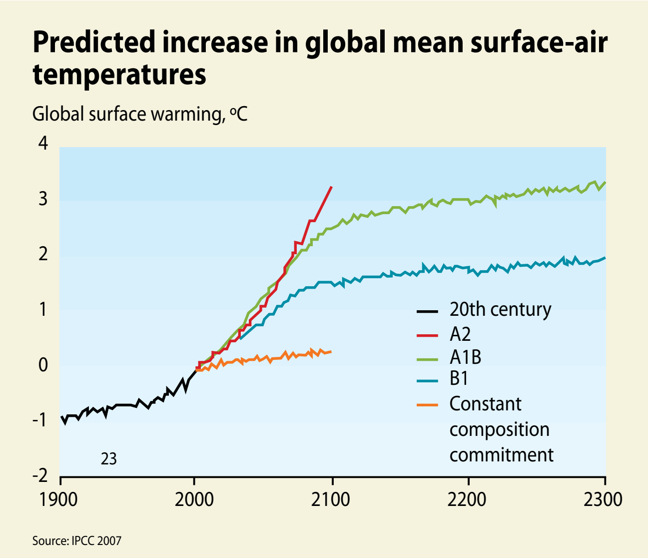
THEME #3

Gas Hydrates in Our Future

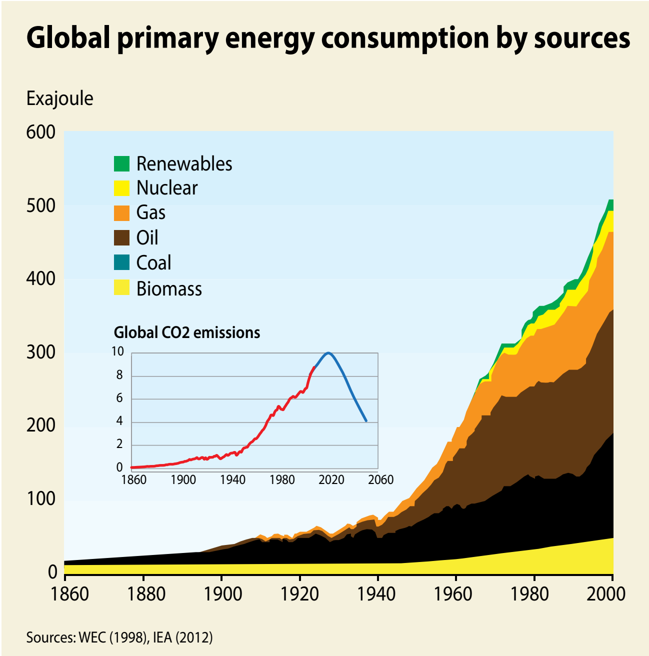


WHY MUST THE WORLD'S ENERGY MIX CHANGE?

For most of modern history, access to inexpensive and reliable energy has been central to economic development and social progress. However, continued economic growth, coupled with regional resource scarcity is having a profound impact on the global environment, as well as on human societies and security. While fossil fuels will likely 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 provide more time to make the transition to a sustainable energy future.



Summary Graphic 10: Projected increase in global mean surface-air temperatures in °C with respect to century.



Summary Graphic 11: 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 OF INCLUDING GAS HYDRATES IN THE FUTURE ENERGY MIX?

Adding methane from gas hydrates to the global energy mix can enable reduction in carbon and pollutant emissions while broadening global accessibility to energy resources.

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. Due to this efficiency, any net displacement of higher greenhouse-gas-emitting fuels by methane will result in a net mitigation of global greenhouse gas emissions. Methane from gas hydrates is also quite pure. Relative to other fossil fuels, burning methane from hydrates produces less particulate matter, smaller amounts of sulphur and nitrogen products, and no waste products that require management.

Methane from gas hydrates is also an energy source that is widely distributed around the planet, both where conventional hydrocarbon production is already underway and also where local hydrocarbon supplies are much more limited.

The Hydrogen to Carbon Ratio

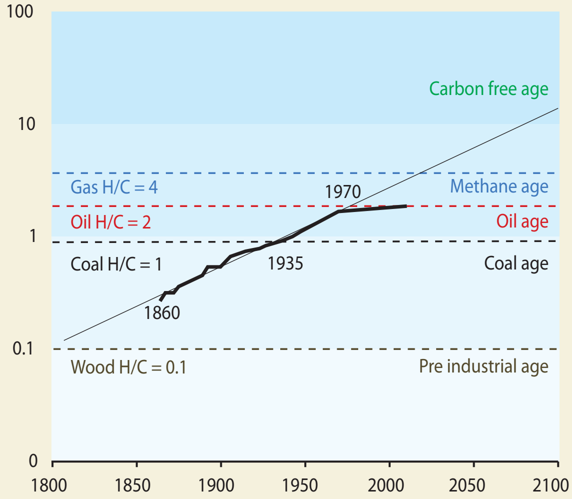
The hydrogen to carbon ratio (H/C) is an indicator of the environmental impact of a fuel (Marchetti 1985; Ausubel 1998). Fuel wood has the highest carbon content, with about one hydrogen atom per ten carbon atoms. Coal has roughly one hydrogen atom to one carbon atom. Oil has, on average, two hydrogen 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



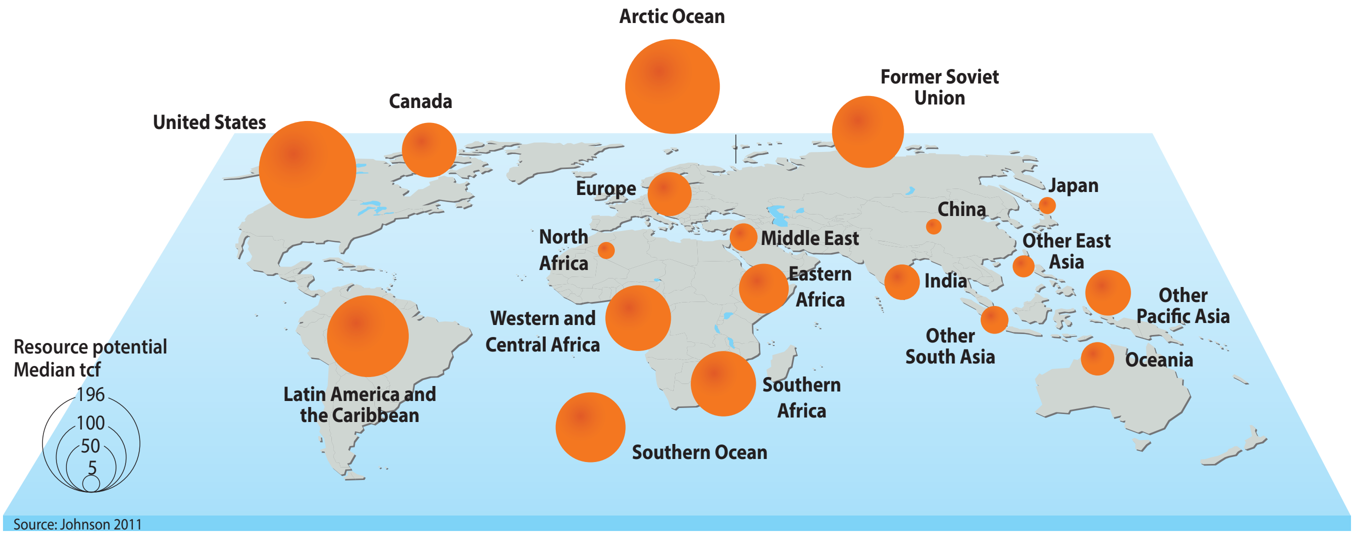
Source: Marchetti, 1985; WEC, 1998 and IEA, 2012

Summary Graphic 12: H/C ratios through fuels and time.

CHALLENGES IN ADDING GAS HYDRATES TO 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 13: 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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