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Avoiding Epimetheus: Planning Ahead for the Commercial Development of Offshore Methane Hydrates

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by Roy Andrew Partain[*]

Introduction

Methane from methane hydrates is a novel alternative source of energy. Its extraction and production would enable new energy supplies, revenues, water supplies and other green solutions. However, its risks include damage to oceanic biota, global climate stability, and inundation of coastal communities. Additionally, there are substantial international and transboundary social and political concerns to address. This study attempts to identify key concerns and hazards so that the development of offshore methane hydrates might be undertaken in a sustainable character.

Globally, methane hydrates are expected to dwarf the global supplies of traditional crude oil and conventional natural gas. Ninety-nine percent of that global supply is expected to be stored in offshore methane hydrates and much of those inventories will belong to countries that have never been energy producers.

The potential for methane hydrates to provide the world with a large source of methane supplies is countered with the potential for those same volumes of methane to accidentally escape and cause harm and injury.[1] Additionally, methane hydrate deposits can serve as sinks to store carbon dioxide; but that too provides opportunity for risk and harm.

Those offshore volumes are located offshore in almost every coastal state in the world. As diversely located as offshore methane hydrates are, so too would be the potentially impacted communities around the globe. This geographical diversity means that offshore methane hydrates will be located within a variety of legal settings, including both developed and developing countries.

The challenges of ensuring the sustainable character of the impeding commercial development of offshore methane hydrates will be difficult. Yet, unless those legal and policy challenges are met head-on, the identifiable risks might ripen into harms that exceed the benefits ultimately received from those developments.

This study attempts to identify central environmental and social concerns related to the commercial development of offshore methane hydrates so that these concerns can be squarely researched and addressed in anticipation of those developments. Sustainability begins with planning ahead; now is the time to begin planning for offshore methane hydrates.

Primer on Methane Hydrates

The Rapid Development of Methane Hydrates as an Energy Resource

Despite the vast potential of offshore methane hydrates, they remained largely unknown as an energy resource until recently. It was not until the 1990s that methane hydrates were broadly recognized as a potentially feasible energy source and respondent research and development programs were initiated.[2] The first international conference on methane hydrate extraction was held in 1991.[3] The first offshore methane hydrate well was drilled in 1999.[4] The first continuously flowing methane hydrate well was tested in 2013.[5] Thus, while hydrates are not recent discoveries, it is not until very recent times that their potential as an energy resource was identified.[6]

The engineering required to model and build safe and reliable methane hydrate extraction technologies has become quite advanced.[7] Soviet-era Russian scientists were the first to identify naturally formed methane hydrates in permafrost areas[8] and offshore subsea.[9] Due to those experiences and more recent well testing, certain hydrate fields are known to be safely producible with existing technology over long periods, if other conditions are in place.[10]

The development of coal bed methane production technologies took approximately three decades to progress from discovery of potential to commercial feasibility and investment.[11] It has been suggested that the arc of development for methane hydrate production technologies will follow a similar three decade progression.[12] Furthermore, due to the strategic needs of countries like Japan and South Korea to obtain local secure energy supplies, researchers in the Global Carbon Project forecast that commercial methane hydrate investments would begin by 2020 and spread to fields globally by 2030.[13] The head of methane hydrate research for the United States Department of Energy ("DOE") stated that the production of methane from a narrow class of methane hydrate deposits was already technically feasible back in 2005, and that the tailored application of existing off-the-shelf technologies would enable commercial feasibility for a broader range of deposits in the very near term.[14] Given

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that the comment was made seven years ago, it is no surprise that such feasibility is now in range.

Basic Science of Offshore Methane Hydrates

Methane hydrate deposits present a dense form of methane. The scientific literature refers to methane hydrates by several names, including natural gas hydrates, clathrates, and gas clathrates.[15]

In terms of energy content, methane hydrates as fully occupied hydrates contain 184,000 British thermal unit ("Btu") per cubic foot, in-between conventional natural gas at 1,150 Btu per cubic foot and liquefied natural gas ("LNG") at 430, 000 Btu per cubic foot.[16] The disassociation of 1 m3 of methane hydrates produces 170 m3 of methane at standard temperature and pressure.[17]

There is an effective envelop for offshore methane hydrates; low temperatures and high pressures favor their formation.[18] Despite their icy or slushy appearance, methane hydrates are stable in temperature ranges from negative five Celsius ("C") to positive thirty-four C, or twenty-three Fahrenheit ("F") to ninety-three F.[19] The top of offshore methane hydrate formations are commonly found at approximately 150m to 500m below the seabed, although in equatorial waters that depth has been found lower at 1000m.[20] The envelope is generally limited to no deeper than 1500m from the ocean's surface, as ambient temperatures rise with depth.[21]

Methane hydrate deposits can be characterized by their production profiles. Simple fields contain almost exclusively methane, with less than one percent of ethane and propane and even more faint levels of butane and pentane.[22] There are a few complex fields, so far only in the Gulf of Mexico, that display only about seventy percent methane, with large volumes of ethane and propane, and presenting trace amounts of butane, pentane, carbon dioxide and nitrogen.[23]

Hydrate deposits exhibit complex geometries with major perturbations due to water flow, pressure and temperature changes, and other factors.[24] In subsea deposits, the most stable methane hydrates are those highest in the reservoir with the most unstable, and gaseous, at the bottom of the reservoir.[25]

Scale of the resource

There are only two sure things known about the global volumes of methane hydrates: there are a lot of methane hydrates and there is a lot of uncertainty about exactly how much. Most researchers simply state that the energy stored in methane hydrates is at least as much as double the world's conventional fossil fuels.[26]

A quick review of global conventional natural gas is needed to compare against offshore methane hydrate estimates. The BP Statistical Review of World Energy estimated the current world supply of proved reserves of natural gas, i.e. traditionally supplied methane, at 187.3 Tcm, or 6614.1 Tcf,[27] at the end of 2012.[28] Another estimate for global conventional natural gas supplies places their volumes at 150 Tcm.[29] Englezos and Lee's research suggests a comparable number for traditional natural gas reservoirs at 370 Tcm.[30] At current levels of global production and consumption, this data would forecast a fifty-plus year supply of conventional natural gas, *ceteris paribus*.[31]

Current estimates suggest that offshore methane hydrate reserves dwarf conventional natural gas reserves. The U.S.'s Methane Hydrate Research and Development Act included an estimate of the world's methane hydrate reserves that would suggest that the world has over a hundred times more methane hydrates than currently booked natural gas reserves.[32] Walsh estimated the volume of global methane hydrates at between 100,000 Tcf and 100,000,000 Tcf, or 2,800 Tcm to 2,800,000 Tcm.[33] A consensus view reported by Englezos and Lee is that the global store of methane hydrates holds approximately 20,500 Tcm of methane.[34] They also state that any model that

Table 1: Comparative Estimates for Global Methane Hydrates

Scientist(s)	Tcm	Energy Source
BP Statistics	187	Natural Gas
Englezos and Lee	370	Natural Gas
Walsh–Low	2,800	Methane Hydrates
Chatti–Low	3,100	Methane Hydrates
Demirbas[38]	7,104	Methane Hydrates
Collett[39]	9,000	Methane Hydrates
Englezos and Lee–Low	10,000	Methane Hydrates
Englezos and Lee	20,500	Methane Hydrates
Kvenholden and MacDonald[40]	21,000	Methane Hydrates
U.S. Methane Hydrate R&D Act[41]	24,000	Methane Hydrates
Englezos and Lee–High	40,000	Methane Hydrates
Klauda Sandler[42]	120,000	Methane Hydrates
Walsh–High	2,800,000	Methane Hydrates
Chatti–High	7,600,000	Methane Hydrates

uses a range from 10,000 Tcm to 40,000 Tcm should be considered reasonable.[35]

This scale of resource could impact energy markets for the long term. Zhang *et al*. presented an assertion that there are probably enough producible methane hydrates to provide the whole world with sufficient energy supplies to last a millennium.[36] Similarly, Englezos and Lee suggested a calculation that if the annual global consumption of methane is 2.4 Tcm, then the global inventory of methane hydrates could yield a millennium of methane as contrasted against the century's worth of traditional natural gas.[37]

Location of methane hydrates

Methane hydrates are primarily an offshore energy strategy. While traditional oil and gas reservoirs have been found in fairly limited areas, methane hydrates have been found on almost every coastline and in most arctic regions.[43] As of 2009, methane hydrates had been drilled and recovered from upwards of two dozen countries in over 77 locations.[44]

Methane hydrates primarily occur in two geological formations, in permafrost and under subsea mud near coastlines.[45] When methane hydrates occur offshore, they often form within 200 km of the coast,[46] placing them generally outside of territorial waters (12 miles) [47] but well within general limits of exclusive economic zones. (200 miles).[48]

Without intending to overstate the point, substantial deposits are located within the following zones: the western shelf of Europe, including the EEZs of Spain, Ireland, and the U.K; the Mediterranean Ocean, except parts of the Adriatic, Tyrrhenian, and Aegean Seas; the whole west coast of the Americas, from Alaska to Chile; the eastern coast of North America. including the offshore areas of most Caribbean islands; the coasts of Argentina, Uruguay and southeastern Brazil; all of the coasts surrounding Africa, including the Red Sea and Madagascar; everywhere near the South Asian peninsula, including large zones of the Arabian Sea and the Sea of Bengal; areas offshore of South Korea, Japan, and the Russian islands north of Japan including offshore Kamchatka; almost all of the ASEAN waters, ocean, and seas; and the offshore of Australia and New Zealand.

When contrasted against the more limited locations of crude oil and traditional natural gas fields, the resource owners of methane hydrates form a much larger proportion of the global community, both developing and developed.

"While the technologies of green and renewable energies develop, the production of methane hydrates could provide an earlier window of opportunity to eliminate coal and crude oil as fuel sources."

Extracting Offshore Methane Hydrates

The technology to produce offshore methane hydrates is advancing rapidly. Japan drilled the first offshore well in 1999 and recently sustained the first successful continuous flow testing from an offshore well in 2013.[49] As of 2008, test wells had been drilled and produced from twenty-three locations, three in permafrost and twenty from offshore.[50] In the offshore wells, experience has been accumulated in all phases of a methane project's life cycle. Wells have been drilled, cemented and made viable, methane has been produced, processed and combusted, and wells have been plugged and abandoned.[51]

There are three main technologies to produce and extract methane hydrates: depressurization, thermal stimulation, and inhibitor injection.[52]

Depressurization extracts methane from a hydrate formation by reducing the pressure level until the phase boundary of the hydrate is breached, causing disassociation of the hydrate.[53] This method found practice at the Siberian hydrate field of Messoyhaka for several decades. Most current models prefer depressurization because it is the most energy efficient means of production, because it can be applied using current technologies, and because it can be effective in long-term operations.[54]

Thermal stimulation directly confronts the endothermic reaction of hydrate decomposition by heating the hydrates inside their reservoir.[55] Overall, the injection of hot water or steam into the reservoir is foreseen as causing methane hydrate formation near the well bore and frustrating extraction if there is not sufficient intragranular room for flow.[56] Thus thermal stimulation is advised primarily for secondary recovery.[57] A supplementary technology for thermal injection technologies is to use horizontal wells, wells that lay parallel to the mineral within its deposit.[58] Cranganu has suggested that certain combinations of horizontal wells plus injection of oxidized fuel gas into the hydrate layer might reduce overall inefficiencies.[59]

Inhibitor injection disassociates methane gas from the methane hydrate by injecting chemicals, *e.g*. methanol and glycol, which are known to prevent or inhibit the formation of the icy crystals around the methane.[60] As a primary extraction technology, however, large volumes of injectants would be required which would be both costly to supply and create environmental concerns of such injected volumes. As such, the inhibitor injection method is not expected for Class 1, 2, and 3 deposits.[61]

Safe offshore extraction of methane hydrates, even continuous and flowing extraction, has been achieved in practice; it is possible to extract safely. The risks can be managed, so long as reasonably stable methane hydrate beds are chosen at the beginning. The ability to categorize the risks of disassociation and their vectors of causation gives rise to hope, in that hydrate risks can be characterized and hydrate disturbances can be measured, thus the sources of the risks, hazards, and harms can be assayed and monitored for potential impact on the deposits of offshore methane hydrates.

Energy for Sustainability

Methane: More Green than Coal or Crude Oil

While the technologies of green and renewable energies develop, the production of methane hydrates could provide an earlier window of opportunity to eliminate coal and crude oil as fuel sources. Methane produces fewer carbon emissions than crude oil or coal.[62]

Table 2: Carbon Emissions from Energy Sources

Fuel Source	Carbon Emissions[63]
Coal	27 kg/GJ
Crude Oil	21 kg/GJ
Methane	15 kg/GJ

Methane hydrates provide a sweet, i.e. acid-free, natural gas with few impurities.[64] The overall environmental pollution from the combustion of methane is of a comparatively low degree when compared against the carbon dioxide and other harmful emissions from the combustion of coal, crude oil and less clean forms of natural gas.[65] The combustion of coal releases significant pollution beyond greenhouse gases that can cause substantial risk to human health. [66] Coal ash also contains surprisingly substantial quantities of radioactive materials, which are carcinogenic.[67]

Methane hydrates provide the potential to extract methane, combust that methane to electricity, and to re-sequester the produced carbon dioxide back into the hydrate formation.[68]

Carbon capture and sequestration ("CCS")

The production of methane hydrates enables the potential sequestration of other GHG in the methane-depleted hydrates.[69] All of the main methods of extraction can be combined with the sequestration of other gases into the hydrate lattice.[70] Research has focused on replacing methane with carbon dioxide to convert this fossil fuel extraction process into a carbon neutral or carbon negative activity.[71]

The production of methane hydrates could fit hand-in-glove with carbon capture systems/sequestration ("CCS") technologies.[72] For example, the German government's SUGAR-Projekt and its ECO2 project are designed with the goal of storing industrially produced carbon dioxide in methane hydrate deposits; the methane extraction is seen as a cost-recovery feature.[73] Additionally, it might be possible for the carbon dioxide by-products to be returned to the reservoir when producing hydrogen fuel by methane reformation.[74]

Japanese researchers have investigated the potential to combust the methane from the offshore methane hydrates onsite to generate electricity; again the by-product carbon dioxide could be sequestered and enable low-carbon electricity to arrive onshore by electrical cables.[75]

Production of hydrogen fuel

Hydrogen has been widely advocated as one of the cleanest fuel sources because its combustion with oxygen yields simply energy and water.[76] Should hydrogen transportation systems be sufficiently advanced, methane hydrates are likely one of the main feedstock for that future.[77]

Via methane reforming, methane hydrates are a major potential source of a global hydrogen fuel supply.[78] Methane reforming requires methane as a fuel and a feedstock along with steam.[79] Methane hydrates are unique in their coproduction of fresh water and methane enabling hydrogen to be produced at the point source.[80] The chemical reaction is endothermic, requiring an energy input such as heat from combusted methane.[81] The resultant carbon by-products are suitable for re-injection into the hydrate deposit.[82]

Co-production of fresh water

Methane hydrates are composed primarily of water and methane.[83] While the primary focus in methane production is the reduction of methane from the methane hydrates, there is a tremendous volume of water involved that can be captured as a by-product. The contrast between traditional gas wells, coal bed methane wells and methane hydrate production is essentially a sequence of vast differences.

Table 3: Comparison of Produced Water Volumes

Type of Well	Bbls per Million scf
Conventional gas well[84]	10
Coal Bed Methane[85]	100
Methane Hydrates[86]	1,000

Most models have associated the production of water as a disposal cost.[87] However, the water volumes could be marketed as fresh water volumes suitable for agricultural or consumer uses. Many of the coastal areas containing these offshore resources are arid onshore. The water volumes could also be engaged in carbon sequestration efforts as described above.

Replacement of LNG with GTS shipping

The technical understanding of methane hydrate formation and disassociation should enable a new and more energy efficient means of methane storage and transportation. This new form of methane transport has been called "Gas to Solids," or more simply GTS.[88] A cost estimate study found that the costs of shipping by LNG were ten-fold more expensive than the costs of shipping by GTS.[89] Based on this magnitude reduction in costs, it was noted that many smaller isolated natural gas fields that are not currently in development could be made commercially feasible with this mode of transport.[90]

Based on the emerging GTS technologies, methane hydrate transportation systems could be completely ship-based, requiring no local facilities other than methane feed-in pipes or offloading pipes.[91] The lower investment required for methane off-loading should enable a broader and more efficient market in methane; once extracted from the seabed, methane could be economically transported by hydrate shipping in lieu of subsea pipelines.[92] Mitsui Engineering & Shipbuilding Co., Ltd. built a pilot GTS plant to convert natural gas into hydrate pellets that can be stored at -15 C and loaded on-board a ship for transport. [93] In addition to the minimal investment in hydrate storage equipment, it is also safer and easier to ship GTS, versus LNG, because the hydrates can be kept stable for several weeks at only -10 to -20 C at atmospheric pressures. [94]

Environmental Challenges to Sustainability

For the development of offshore methane hydrates to become sustainable, it must overcome several substantial environmental concerns. The production of methane from methane hydrates will carry unique risks and hazards to the environment not present with the production of traditional natural gas. As seen in the Japanese environmental assessment,[95] the commercial development of methane hydrates contains a mixture of risks, those common to all offshore mining and those unique to methane hydrates.[96]

The greatest unique environmental problem is the uncontrolled release of methane hydrates. There are many activities that could lead to the onset of disassociation and that disassociation could occur in a variety of manners. Fast or slow, the uncontrolled release of methane is the primary risk to the environment from developing methane hydrates.[97]

Subsea Seepage of Methane

As part of the Japanese team operating offshore production tests from methane hydrate deposits, Yabe *et al.* provided a table of seventeen identified risk factors and likely impacts.[98] Yabe's chart provided sixteen basic events that could give rise to environmental hazards, but only six types of hazards.[99] The key hazards identified by the Japanese team are impacts to marine life, to fisheries, to aviary ecologies, to benthic ecologies, and the broader scale items of tsunamis and anthropogenic climate change. [100] A few of these items are unique to the production of methane from methane hydrates: seafloor subsidence, submarine landslides, and the combined risks from a cracked methane hydrate deposit bed.

Mechanism of Seabed Damages

Routine subsea mining risks are primarily related to the building and operating of seabed infrastructure. The Yabe *et al.* list of environmental impacts comes from a variety of exploration, development and early production activities.[101] These activities can impact the turbidity of the waters, cause re-suspension of sediments, and create a variety of seabed disturbances.[102] Depending on the depth of the seabed, a variety of eco-systems can be disrupted and damaged.[103]

Hazards of Dissolved Methane

Large amounts of methane could become dissolved into the benthic waters and substantially impact sea life.[104] While the resource assets at that depth are well studied, the ecologies of those depths are not.[105] Due to the location of methane hydrates, shallow within the seabed itself, it is expected that the development of methane hydrates would cause "significant impacts on the sediment dwelling fauna."[106] Additionally, the energy levels of the benthic oceans are generally much lower than upper levels of the ocean, preventing effective removal of polluting debris.[107]

When methane seeps are located at 300m below the water's surface, and unless high velocities and large volumes are involved, models suggest that ninety-eight percent of the seeped methane could be absorbed by bacteria prior to reaching the water's surface, metabolized into carbon dioxide.[108] Glasby provides a broad review of the recent literature and finds that both modellers and field researchers agree that when methane needs to transport through 300m or more of water then the probability of any methane reaching the ocean's surface is very minimal.[109]

When carbon dioxide increases its presence within the water column, several problems are found. First, the acidity of the water column is increased, causing stress to sea fauna.[110] Second, there is a risk of an affected area becoming a "mortality sink," wherein predators begin to prey off of the dead and dying fauna, further decreasing population sustainability within the zone.[111] Potential effects on the broader food chain are readily foreseeable.

Toxicity of Extraction Chemicals

A separate harm or damage can result from the extraction technologies. When chemicals are injected into the deposit to affect the dissolution of the hydrates, those chemicals are often toxic to those life-forms living near the hydrates.[112] Not only do micro-fauna such as zooplanktons and micronektons live near methane hydrates, but also macro-fauna such as tube-worms and mussels.[113]

Deepwater organisms already test positive for sea-borne chemical pollutants.[114] The types of chemicals used to aid in hydrate dissolution are generally solvents and not water-soluble. As such, they are the types of chemicals known to significantly affect the zooplanktons and micronektons at the bottom of the food chain. [115] Such chemicals often accumulate; they can become concentrated at magnitudes higher levels within the micro-fauna compared against the ambient water column within which they reside.[116] The problems of toxicity are not limited to the micro-fauna, the food-chain presents toxicity in birds and fish eaten by humans. [117] Those animals can carry toxicity levels higher than health limits for human consumption, making them effective poisonous to human diets. [118]

Venting of methane to the atmosphere

A key result from the Glasby meta-study was the potential for high-speed methane to reach the surface.[119] A second, but perhaps more rare exception, is when the widths of the seeps are greater than the depth of the waters; in that case the methane can reach the surface intact.[120] Once such damages occur and continuous methane venting was underway it might become very difficult to cease such conditions.[121]

Mechanism of Venting to Atmosphere

Generally, it is agreed that the amount of methane that would reach the atmosphere from seabed seepage is dependent upon three factors:[122] (i) the quantity and transfer rate of methane from the sediments to the water column, (ii) the volume of methane which dissolves in the water column, and (iii) the volume of methane which eventually escapes to the atmosphere.

The gas hydrate stability zones, wherein the deposits accumulate, are fragile on both pressure and temperature vectors, "[a]ny change in temperature and pressure will cause it to decompose ... ."[123] A rapid release of substantially large amounts of methane could result in near-term climate change. [124]

The resulting behavior of the venting methane is to create a chimney-like structure that connects the hydrate bed to the atmosphere above the ocean water, enabling a direct pipeline of methane ventilation.[125] Such accidental events have already been witnessed. An accidental chimney was formed on the Pechora shelf; a drilling attempt through a subsea permafrost encountered a hydrate layer.[126] The resulting surge of free methane created a gas-water fountain that rose over a 100m through the waters and shot into the air 10m above the drilling ship. [127]

> *"The extraction of methane from methane hydrates may always remain an extremely hazardous activity even if otherwise desirable."*

This perspective, when combined with an awareness that the expected extraction techniques will focus on warming the hydrates, on depressurizing the hydrates, and injecting chemicals which stimulate the disassociation of the hydrates, leads to the conclusion that the extraction technologies must effect a delicate balancing act to avoid triggering what could become a deposit wide disassociation event and a massive release of methane and freshwater from the hydrate deposits. The extraction of methane from methane hydrate deposits might always remain an extremely hazardous activity even if otherwise desirable.

Methane as Asphyxiant

Ambient methane is not toxic *per se*, but it is a simple asphyxiant.[128] Methane has no noticeable smell to humans; the smell associated with natural gas in home cooking fuel has a second class of chemicals added, mercaptans,[129] that provide that off-smelling stink to alert home owners to gas leaks. In an industrial accident of unmodified methane, the offshore workers would be challenged to evade an airborne poison that they cannot detect.

In the African nations of the Democratic Republic of Congo and Rwanda, there are lakes that emit noxious but odourless volumes of methane and carbon dioxide.[130] This type of emission is called *mazuku* in Kiswahili.[131] In Lake Kivu, *e.g.,* the hypo-limnion or upper-level of the lake waters contains fifty-four km3 of methane (CH4).[132] That is the equivalent of fifty-four billion cubic meters of methane or approximately two Tcf of methane. The dissolved gases can be triggered for emission by a variety of mechanisms such as seismic activity or down-swelling cold waters from rain run-offs.[133]

These *mazuku* emissions have been known to kill both livestock and humans.[134] Even marine life has been impacted; at the time of the emission from the lakes crawfish and crabs were observed struggling to exit the lake and many fish were found dead soon after.[135] The resultant ambient methane levels have been detected within the necessary concentrations to enable air-borne combustion.[136] There is essentially no escape for all respirant life forms close to the lakes.[137]

Surface-level Nuisances

Additionally, there are concerns that a field of leaking methane could cause buoyancy problems for waterborne craft.[138] Indeed, it has been modelled and discussed that certain conditions could lead to a field of methane hydrates disassociating in such a manner that a ship could lose its buoyancy and sink.[139] Non-buoyancy examples also exist. Offshore oilrigs and boats have been lost when methane suddenly erupted from below; the boats became upended by the displaced water pushed by the emerging methane.[140]

The resultant fizzy ocean waters, awash with gaseous methane, have been described in the literature as a 'fluidized bed' that does not support routine notions of naval buoyancy.[141]

Methane and Anthropogenic Climate Change

Any discussion on the risks of developing methane hydrates must include a discussion on the role of methane and climate change. Methane is a known greenhouse gas.[142] Methane has a global warming potential index ("GWP") 3.7 times stronger than carbon dioxide by mole number and twenty times stronger than carbon dioxide by mass weight.[143] Emissions of methane are generally seen as worse for accelerating anthropogenic climate change than emissions of carbon dioxide.

While the probabilities of sudden massive venting events from commercialized hydrate extraction events are difficult to gauge given a lack of historical data, the geological record strongly suggests that cataclysmic venting has occurred in prehistory and earlier periods: there are subsea craters that reflect massive sudden blow-outs of methane.[144] Up to one to five gigaton of carbon were released in those events, mostly in the form of methane.[145] Additionally, it is believed that massive venting of methane hydrate deposits were instrumental in causing the sudden global warming seen approximately 55.6 millions years ago at the Latest Paleocene Thermal Maximum.[146] During that event, the temperature of the northern hemisphere increased six to twelve C.[147]

The potential consequences of commercialized methane hydrate extraction on climate change are substantial. Such concerns should be firmly and squarely addressed prior to the onset of such developments.

Cataclysmic methane events

A cataclysmic event could see a large section of a hydrate field lose its internal structure and shear off, causing the overlying mud layers to fall deep into the ocean. Such an event might be correlated with earthquake-like impacts such as tsunamis. The physical energy of the shear-off would likely enable massive sudden venting of much of the reservoir's methane directly to the atmosphere. That methaneous eruption would also likely induce surface combustion to a broad area so long as the methane continued to vent from the shaken depths. The impacts to any local community of a tsunami that coincides with ambient combustion would be horrific.

Some geological locations are safer than others. The Beaufort Sea is seen as more likely to offer future landslide under commercial development, whereas the hydrates in the Gulf of Mexico may be more resilient to landslide events.[148] However, even the safest areas are seen as capable of landslides under sufficient conditions.[149]

Natural Cataclysmic Methane Events

There are numerous geological signs of earlier events that began as methane hydrate deposit destabilizations that led to landslides, tsunamis and earthquakes.

On the United States' Atlantic shelf, over 200 slump scars have been discovered; these are all believed to be methane hydrate events.[150] Additional slump scars have been identified off the west coasts of Africa, in the fjords of British Columbia, and in the Beaufort Sea offshore of Alaska's northern coastline.[151]

Mechanisms of Cataclysmic Events

Generally speaking, offshore methane hydrate deposits lay on inclined slopes, which are overlaid with mud.[152] If the hydrates start to disassociate and the methane is emitted, then there will also be a great release of the previously integrated waters.[153] As the hydrate disappears, its shear strength disappearing along with the hydrate, and the structural integrity of the overlaying mud will be lost.[154] The release of the water volumes will both physically lift and assist in the dissolution of the mud bed.[155] The result is that all of the mud and other overlaying materials will begin to fall downwards under the tug of gravity, causing a sub-sea landslide and surface level tsunami.[156]

There are two known natural triggers, lowering sea levels, which reduce pressure on the hydrates field-wide, and warmer oceans, which heat up the hydrates field-wide. Commercial hydrate development could also trigger events necessary for deposit-wide disassociation followed by a landslide.[157] The sub-sea disturbances categorized by Abe and the energies released to free the methane from the hydrates could all be instrumental in initiating a cataclysmic event.[158]

Social Challenges to Sustainability

The listing of countries and territories exposed to the risks of environmental harms posed by the commercial development of methane hydrates draws a line under the idea that addressing these environmental challenges is a common and global issue.[159] The variety of nations, economic development, legal institutions and institutional stability will all increase the regulatory challenges on balancing the interests of revenue seeking groups versus groups seeking sustainable environmental safety and comfort.

Differing Character of Legal Institutions

There are substantial differences in the stability and reliability of the legal institutions of the impacted areas.

First, the diversity of resource owners is stunning. Some of the resource owners have advanced legal systems and stable institutions whereas many other do not.[160] In an almost perfect inverse, the less legally developed locations are generally those with the lowest per capita incomes and thus those most likely to encourage the rapid deployment of methane hydrate production in order to obtain revenues therefrom. Thus, without broader regulatory efforts to divert initial investments into well-regulated zones, there might be an initial surge of investment into those areas least capable of regulating for environmental safety.

Second, the contrast of the small size of the methane hydrate technology owners versus the very large size of resource owners means that without regulation the technology owners have their pick of locations and resource owners. It would only be rational for those technology owners *cum Homines oeconomici* to seek out the lowest cost locations. Less stringent regulations would generally be expected to be lower cost, as costs of both precautionary measures and of accidents and harms could be externalized away from the technology owner.[161]

A singular solution might not be the answer; rather, a portfolio of solutions might be sought. Based upon the variety of legal systems and the quality of their institutions, different forms of optimal regulation may be needed in different locations; the optimal solutions may be dependent on local conditions. Such a portfolio of solutions has been proposed to address the environmental hazards of methane hydrates, one that would complementarily implement rules of strict liability and provide public and private regulations.[162] Existing laws and conventions have been found lacking when compared against these recommendations.[163] But even those recommendations would need to be tailored to fit the local institutions within the jurisdictions wherein the hydrates are located.

Transboundary Concerns

Many methane hydrate deposits stretch across multiple national borders and EEZ borders. This will cause several problems. Primarily, it raises the general concerns of waste and unitization to provide for multi-party balanced production and

Table 4: Countries with Immediate Exposure to Hazards and Harms from Offshore Methane Hydrate Installations[167]

Region	Nations with Risk Exposure
Africa	Algeria, Angola, Benin, Cameroon, Congo, Côte d'Ivoire, Democratic Republic of the Congo, Egypt, Equatorial Guinea, Eritrea, Gabon, the Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Liberia, Libya, Madagascar, Mauritania, Morocco (including Western Sahara), Mozambique, Namibia, Nigeria, Sierra Leone, Senegal, Somalia, South Africa, Tanzania, Togo, and Tunisia.
ASEAN	Brunei, Indonesia, Malaysia, the Philippines, and many of the smaller islands and nation states of Micronesia and Polynesia.
South Asia	Bangladesh, Burma, India, and Pakistan.
East Asia	China, Japan, North Korea, Russia,[168] South Korea, Taiwan, and Vietnam.
Europe	Albania, Denmark, Finland, France, Greece, Ireland, Italy, Montenegro, Norway, Portugal, Spain, Turkey, and the U.K.
Middle East	Cyprus, Israel, Iraq, Iran, Kuwait, Lebanon, Oman, Saudi Arabia, Syria, and Yemen.
North America	Canada, Caribbean islands,[169] Costa Rica, El Salvador, Guatemala, Mexico, Nicaragua, Panama, and the United States.
South America	Argentina,[170] Brazil, Chile, Columbia, Ecuador, French Guiana, Guyana, Peru, and Suriname.
ANZAC	Australia, including Tasmania, and New Zealand.

common regard for environmental safety within the unit of production. Transboundary solutions will need to be sought.

For example, North and South Korea's methane hydrates lay contiguous to each other in the East Sea.[164] Should North Korea decide to begin production of methane hydrates from near a bordering reservoir, then South Korea might fear accelerated depletion of its own adjacent resources and decide to try to match the extraction activity of the North Koreans.[165] While this type of problem exists in ordinary oil and gas production, in that case it merely leads to overproduction, pressure declines, and resource wastage. With methane hydrates, accelerated extraction and production could lead to structural failure of the methane deposit, resulting in cataclysmic methane venting and potential landslides.[166]

Environmental considerations to reduce and abate foreseeable hazards may require *ex ante* diplomatic efforts to result in coordinated extraction protocols. A coordinated extraction protocol might be created by regulating how closely methane hydrate wells might be located and how wells close to national territories accommodate revenue sharing or volume tracking and sharing. Perhaps a broader agreement could be reached amongst the technology owners to self-monitor their environmental safety standards even when local conditions and regulation do not otherwise require such measures.

Perhaps 'methane hydrate banking' could be an option. Owners of less safe deposit fields could receive revenue shares from other safer hydrate fields in exchange for deferring the exploitation of their own fields until they could be safely produced. When the deferred field eventually do go into production, they could return revenue shares to the owners of those 'safer' fields produced earlier. Such an arrangement would provide incentives to defer unsafe production and provide long run income for those that financially support such safety plans.

Uneven Economic and Industrial Capacities

There are differences in the economic and industrial capacities of the impacted areas. Many of the areas within East Asia, North America and Europe are technologically competent at advanced oil and gas extraction technologies and are well experienced with operational problems generally. These countries are likely to be able to manufacture their own methane hydrate infrastructure and maintain quality control processes in their implementation. Other areas will not be able to self-provide such manufacturing, servicing, and maintenance of methane hydrate facilities.

The potential impact is that one side of the list could self-cure its technology concerns whereas the other side would need to seek external assistance or accept lower quality from local sources. Essentially, one group can see the improvement costs as a "multiplier" type benefit of methane hydrate investment but the other group faces pure economic costs.

The existence of a strong technological asymmetry suggests an equally asymmetrical responsibility for the consequences of commercialization. One must ask a sequence of questions; does the small number of technology owners pose problems? Will the technology, especially as related to environmental safety, remain in the control of a few parties? Are there ways to share the intellectual property of environment safety technologies that enable broader safety levels? Will the small communities of researchers and scientists be culture-blinded to more various safety concerns of communities different from the researchers' and scientists' communities? And ultimately, could knowledge sharing be ensured so that safety and policy decisions are made with best available information?

As it is unlikely that most of the resource owners would become methane hydrate technology owners, and similarly that most of the impacted communities and their states would also likely not become methane hydrate technology owners, the ability to actually build, operate, and sustain commercial operations of methane hydrate fields will likely remain in the hands of a few nations and commercial operators without additional programs to ameliorate that asymmetry.

There might be several solutions to this problem. One might be to find a way to enable the resource owners to become joint owners of the technology so that their profit seeking aligns with the operators for sustained safety under agreed to governance mechanisms. Another is to jointly address safety and resource management policy concerns in conjunction with the technology owners, with the impacted communities, and with the resource owners as equals within a community of co-developers.

Haves and Have-Nots

The onset of commercialized methane hydrates would potentially provide many nations with new energy and water resources and provide for broad improvements to welfare. However, for those without the new hydrate reserves, the chasm between developed and undeveloped might widen without preventative policies to assist.

The commercial development of methane hydrates would enable many more countries in the world to become energy self-sufficient. As seen, *supra* "Location of Methane Hydrates," the industrialized nations of China, Japan, and South Korea could achieve energy sufficiency and be able to decrease expensive energy imports. Similarly, the EU would find itself surrounded by offshore methane hydrates and become able to reduce its reliance on natural gas imports from Russia. What energy supply problems those industrialized countries might have previously faced would be substantially altered by the commercialization of offshore hydrates. Indeed, an infusion of reliable and local energy supplies might provide for long-term economic growth in those regions.

This new energy resource might enable many areas to receive new streams of income, and thus affect global price levels on a wide front of commodities, but those countries sans hydrates would not be able to participate in the economy of methane hydrate development. Not only would those countries lack revenues from energy resources, but they would also lack the industrial capacities to benefit from industrial and service industry engagements with the emerging methane hydrate economies. They are likely to be wholly excluded from the new methane hydrate paradigm without exogenous intervention. Given the expected distribution of offshore methane hydrates, land-locked developing countries would be the hardest hit.

Another concern would be the impact on those areas reliant on crude oil and conventional gas revenues to sustain social stability, such as Saudi Arabia or Qatar. If a substantial portion of their current customers became energy producers and self-reliant, how might that affect stability in their regions?

Bifurcated Domestic Agendas on Development

While the communities most likely to be impacted by the harms of methane hydrate development lay within the self-same states in possession of the methane hydrate reserves, this is not to say that the beneficiaries of methane hydrate development are the same communities as those exposed to risks of harm within those states. In most cases they will be distinct and separate communities despite their common nationalities.

A unique problem could be presented by many of the developing countries that contain methane hydrates within their waters. It is foreseeable that certain countries and resource owners might find that their ambient level of risk and harms exceeds those posed by the development of methane hydrates. *E.g.*, Namibia has faced severe droughts and severe economic underdevelopment; methane hydrates could provide much needed revenues, energy supplies, and volumes of fresh water.[171] The needs of the nation at large might well outweigh the needs and concerns of the coastal communities at risk.

There could be reasonable judgements made that the risks of hydrates were lesser than the risks of not obtaining the revenues and resources obtainable therefrom. Ergo, rational actors might opt for greater risk in the future to better provide for those presently suffering; especially those political actors who might not remain in power if short-term problems are not resolved prior to near-term elections. In such cases, the traditional notions of liability and regulation might be insufficient to provide optimal development of methane hydrate resources; again methane hydrate banking might be a sustainable strategy.

The economic capacity of the actors who can afford to invest in methane hydrate commercialization projects must be seen in comparison against the economic capacity of the coastal communities likely to be invested in fishing and other forms of seaborn economies. A substantial inequality is present which could prevent serious or substantial efforts to respond to the concerns of the coastal communities. Additionally, if the nation becomes dependent on revenues from methane hydrate development, then those political processes that exist to address citizen concerns might be out-balanced by strategic and public policy arguments in otherwise democratic forums. The tension between governing elites and impacted communities would need to be addressed to enable sustainable development.

An important exception to the risk analysis of operators and sovereigns is when the two parties are in fact a singular body, when the operator benefits from sovereign immunity. The case can be extended to those cases where a sovereign resource owner might extend its immunity to private actors performing at its behest, or when that sovereign resource owner might offer indemnity or provide minimal safety regulations or liability rules to ensure faster development of its resources. Such actors may face perverse incentives to produce at risky levels as they may perceive all or some portion of the eventual costs of the hazards as externalities; they would be likely to choose activity levels higher than merited if those external costs were more correctly included in development decisions. In such cases, the bifurcation problem of impacted communities versus governing elites would only be worsened.

Conclusion

Planning for the onset of commercial development of offshore methane hydrate resources should be done prior to that development, not as a consequence of accidents following that development. Too often in the story of natural resource exploitation, the legal analysis lagged behind the story of development. Sustainable development is not likely to happen by accident, Epimetheus must be avoided.

Crude oil is no new industry, yet legal scholars found themselves addressing deep-sea oil catastrophes after the BP Macondo accident. Similarly, current legal debates on subsurface fracking technologies again lagged the onset of industrial development. Given the potential of offshore methane hydrates to engage in substantial and critical risks related to coastal communities, to the stability of the global climate, and to general public welfare, forethought and due consideration to these risks should occur now before such development begins.

The commercial development of offshore methane hydrates contains much promise. It could enable many energy resource-lacking countries to become energy producers. It could provide revenues, energy supplies, and fresh water resources to many developing countries. It potentially could enable several green energy alternatives. But such promises come with risks.

The risks attending the development of offshore methane hydrates include risks to oceanic biota and subsequent hazards to a greater food chain. They include the potential to unfurl large volumes of methane and cause substantial anthropological damage with regards to climate change. They include the potential for cataclysmic events such as offshore landslides, tsunamis, and coastal inundations.

But the risks are not only environmental or physical in character. There is also a wide range of social and political concerns that could be stimulated by the development of offshore methane hydrates. There are political questions on how to address the transboundary nature of methane hydrate deposits and to provide for regional safety. There are questions as to how to mitigate local incentives to exploit too early or to exploit resources that might not be safely producible. There are questions of how the new economics resulting from the massive shifts implied for the energy markets would raise certain economies and leave others behind.

To be sustainable, to ensure that sustainable development secures both physical and social solutions means that legal and policy analysis must proceed and accompany industrial action; Epimetheus must be avoided.

Endnotes: Avoiding Epimetheus: Planning Ahead for the Commercial Development of Offshore Methane Hydrates

1 The potential harms and injuries from escaping methane volumes are discussed, *infra* Environmental Challenges to Sustainability.

2 Y. F. Makogon et al., *Natural Gas-Hydrates—A Potential Energy Source for the 21st Century,* 56 J. Petroleum Sci. & Engineering 14, 16-18 (2007); J. Marcelle-De Silva & R. Dawe, *Towards Commercial Gas Production from Hydrate Deposits,* 4 Energies 215, 216 (2011).

3 Marcelle-De Silva & R. Dawe, *supra* note 2.

4 George J. Moridis et al., Toward Production from Gas Hydrates: Current Status, Assessment Of Resources, and Simulation-Based Evaluation of Technology and Potential 3 (2009), *available at* http://escholarship.org/uc/item/7hm710jd#page-1.

5 *See infra* Extracting Offshore Methane Hydrates.

6 A. Demirbas, *Methane Hydrates as Potential Energy Resource: Part 1–Importance, Resource and Recovery Facilities*, 51 Energy Conversion Mgmt. 1547, 1548 (2010); Makogon et al., *supra* note 2, at 16.

7 Matthew R. Walsh et al., *Preliminary Report on the Commercial Viability of Gas Production from Natural Gas Hydrates*, 31 Energy Econ. 815, 822 (2009).

8 A Class 1 field in Soviet-era Siberia called Messoyahka was the first known methane hydrate field to go into production. The produced gas was used for industrial purposes for many years. *See* Demirbas, *supra* note 6, at 1548. *See also* Makogon et al., *supra* note 2, at 16-18.

9 P. Englezos & J. D. Lee, *Gas Hydrates: A Cleaner Source of Energy and Opportunity for Innovative Technologies*, 22 Korean J. Chemical Engineering 671, 672 (2005).

10 Demirbas, *supra* note 6, at 1547.

11 Englezos & Lee, *supra* note 9, at 675, 677.

12 The time reference is stated as 3 decades at 675 and as 20-25 years at 677. *See id*.

13 Volker Krey et al., *Gas Hydrates: Entrance to a Methane Age or Climate Threat?,* 4 Envtl. Res. Letters 4 (2009), *available at* http://iopscience.iop.org/1748-9326/4/3/034007/fulltext/.

14 R. Boswell, *Resource Potential of Methane Hydrate Coming into Focus*, 56 J. Petroleum Sci. Engineering 9 (2007), *available at* http://www.sciencedirect.com/science/article/pii/S0920410506001847.

15 R. A. Dawe & S. Thomas, *A Large Potential Methane Source—Natural Gas Hydrates*, 29 Energy Sources 217, 218 (2007); Demirbas, *supra* note 6, at 1550; Z. G. Zhang, et al., *Marine gas hydrates: Future Energy or Environmental Killer?,* 16 Energy Procedia 933, 933 (2012), *available at* http://www.sciencedirect.com/science/article/pii/. Natural gas can sometimes include natural gas liquids, common understood to include ethane, propane, butane, pentane, and natural gasoline, so the term natural gas hydrates could suggest a variety of hydrates; for this study the term methane hydrate will be strictly used to indicate those hydrates rich in methane to the exclusion of other hydrocarbons.

16 Marcelle-De Silva & Dawe, *supra* note 2, at 217. *See* Englezos & Lee, *supra* note 9, at 673 (providing more general terms); Demirbas, *supra* note 6, at 1548.

17 Englezos & Lee, *supra* note 9, at 673. *See also* C. A. Koh, *Towards a Fundamental Understanding of Natural Gas Hydrates*, 31 Chemical Soc'y Rev. 157, 160 (2002) (providing a slightly different presentation of similar data by comparing ninety percent occupied methane hydrates as equivalent to 156 m3 of methane under standard conditions).

18 Sang-Yong Lee & Gerald D. Holder, *Methane Hydrates Potential as a Future Energy Source*, 71 Fuel Processing Tech. 181, 184 (2001), *available at* http://www.sciencedirect.com/science/article/pii/; Moridis et al., *supra* note 4, at 1. *But see* Demirbas, *supra* note 6, at 1548 (referencing it the other way around, that heat and depressurization leads to hydrate reversion to water and methane).

19 Dawe & Thomas, *supra* note 15, at 221. Makogon provides laboratory ranges of -200 C to 75 C, with the correspondingly required extreme pressure ranges of two GPa to twenty nPa. *See* Makogon et al., *supra* note 2, at 18.

20 Dawe & Thomas, *supra* note 15, at 223; Makogon et al., *supra* note 2, at 19.

21 *Id.*

22 Makogon et al., *supra* note 2, at 21; Marcelle-De Silva & Dawe, *supra* note 2, at 218.

23 *Id.*

24 Boswell, *supra* note 14, at 11; Makogon et al., *supra* note 2, at 19-21.

25 Dawe & Thomas, *supra* note 15, at 223.

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Endnotes: Mexican Energy Revolution: But is it a Solution?

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[1] Kent Paterson, *Does Mexican Energy Reform Invite Ecocide?*, Newspaper Tree (Dec. 14, 2013), http://newspapertree.com/articles/2013/12/14/does-mexican-energy-reform-invite-ecocide.

[2] Adam Williams, *Mexico Oil Opening May Release Gusher for Foreigners*, Bloomberg (May 13, 2014, 12:01AM), http://www.bloomberg.com/news/2014-05-13/mexico-oil-opening-may-release-gusher-for-foreigners.html.

[3] Will Grant, *Mexico Energy Reform Divides Opinion*, BBC News (Aug. 14, 2014, 6:27PM), http://www.bbc.com/news/business-28785506.

[4] Diana Villiers Negroponte, *Mexico's Energy Reforms Become Law*, Brookings (Aug. 14, 2014) http://www.brookings.edu/research/articles/2014/08/14-mexico-energy-law-negroponte.

[5] Everett Rosenfeld, *Mexico to Receive Major Economic Jolt, Experts Say,* CNBC (Aug. 26, 2014, 2:23 PM), http://www.cnbc.com/id/101948520.

[6] Juan Gavasa, *North America Should Look to Nafta on Oil Boom, Pemex CEO Says,* Panamericanworld (Feb. 17, 2014), http://www.panamericanworld.com/en/article/north-america-should-look-nafta-oil-boom-pemex-ceo-says.

[7] *See* Negroponte *supra* note 4

[8] *See* EIA, *Mexico*, U.S. Energy Information Administration (April 24, 2014), http://www.eia.gov/countries/analysisbriefs/Mexico/mexico.pdf (stating most of the remaining oil reserves in Mexico exist offshore and that a considerable amount of hydrocarbon resources are hypothesized to be in deepwater within the Gulf of Mexico and further emphasizing that the amount of recoverable shale gas is considerably less than the total resource base because it is located in regions with complex geology).

[9] AAN Editors, *Renew or Ruin? Mexico's Energy Reform*, The Global Call For Climate Action (Sept. 17, 2014) http://adoptanegotiator.org/renew-or-ruin-mexicos-energy-reform/.

[10] *See* Claire Ribando Seeke et al., *Mexico's Oil and Gas Sector: Background, Reform Efforts, and Implications for the United States*, CRS Report (Nov. 18, 2013) *available at* http://fpc.state.gov/documents/organization/218980.pdf (warning about the implication of hydraulic fracturing of Mexico's remaining hard to reach hydrocarbon resources). *See also* Madelon L. Finkel et al., *The Rush to Drill for Natural Gas: A Public Health Cautionary Tale*, American J. of Public Health (May 2011) *available at* http://www.fraw.org.uk/files/extreme/finkel_law_2011.pdf (noting that toxic mud, fluid byproducts, and oil spills resulting from fracking are not uncommon).

[11] Ley General de Cambio Climático [LGCC] [Climate Change Law], Diario Oficial de la Federación [DO], 06 de Junio de 2012 (Mex).

[12] SERN, *Mexico (2014): Energy Sources*, Reegle (last visited Nov. 11, 2014) http://www.reegle.info/policy-and-regulatory-overviews/MX.

[13] Editors of EL&P/ POWERGRID, *Mexico Energy Reforms Leave Solar Power Behind,* Elp.com, (Sept. 18, 2014), http://www.elp.com/articles/2014/09/mexico-energy-reforms-leave-solar-power-behind.html.

[14] *See id*.

[15] *See* Sergio Romero-Hernández et al., *Renewable Energy in Mexico: Policy and Technology for a Sustainable Future*, Wilson Center, 63 *available at* http://www.wilsoncenter.org/sites/default/files/Renewable_Energy_in_Mexico.pdf (stating that though taking action to implement green energy is costly, inaction will be even more costly).

[16] Id. at 64

Endnotes: Avoiding Epimetheus: Planning Ahead for the Commercial Development of Offshore Methane Hydrates

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[26] *See* J. F. Gabitto & C. Tsouris, *Physical Properties of Gas Hydrates: A Review*, 2010 J. Thermodynamics 1, 1 (2010); Moridis et al., *supra* note 4, at 2; Zhang et al., *supra* note 15, at 934.

[27] Much of the oil and gas industry utilizes Imperial Units instead of metric measures. One m3 of natural gas is generally deemed equivalent to thirty-five ft3 for commercial exchanges. *See* Dawe & Thomas, *supra* note 15, at 221. The BP Statistical Reviews lists the exchange ratio as 1 m3:35.3 ft3. *See BP Statistical Review of World Energy*, bp 44 (June 2013), http://www.bp.com/content/dam/bp/pdf/statistical-review/statistical_review_of_world_energy_2013.pdf [hereinafter *BP Statistical Review*].

[28] *BP Statistical Review*, *supra* note 27, at 20.

[29] Moridis et al., *supra* note 4, at 3.

[30] Englezos & Lee, *supra* note 9, at 674.

[31] *BP Statistical Review*, *supra* note 27, at 20-22. Also, these numbers can be contrasted against the annual energy demand budget for the U.S.A., which is one Tcm annually. *See* Moridis et al., *supra* note 4, at 3.

[32] *See infra* Table 1 (Comparing the U.S. estimate for methane hydrates against the BP estimate for booked natural gas reserves).

[33] *See* Walsh, *supra* note 7, at 815.

[34] Englezos & Lee, *supra* note 9, at 673.

[35] *Id*.

[36] Zhang et al., *supra* note 15, at 934; Moridis et al., *supra* note 4, at 2.

[37] Englezos & Lee, *supra* note 9, at 674.

[38] Estimate was stated as 6.4 Trillion tons of methane. Demirbas, *supra* note 6, at 1551.

[39] Marcelle-De Silva & Dawe, *supra* note 2, at 221.

[40] Referred to as the standard estimate, partially due to their age. MacDonald's numbers date from 1990. *Id.* at 219.

[41] This number is actually a statutory statement regarding the U.S.'s internal estimate of its own domestic supplies, which it estimates at a quarter of the world's supplies of methane hydrates. It provides an estimate of the domestic volumes at 200,000 Tcf. 800,000 Tcf converts to 24,000 Tcm. *See* 30 U.S.C. § 2001(2)-(3) (2014).

[42] Referred to as the most up-to-date model and likely the most accurate. Marcelle-De Silva & Dawe, *supra* note 2, at 219.

[43] *See* Englezos & Lee , *supra* note 9, at 674.

[44] Gabitto & Tsouris, *supra* note 26, at 2.

[45] Dawe & Thomas, *supra* note 15, at 219.

[46] *Id.*

[47] The United Nation's Convention on the Law of the Sea, sec. 2, art. 3, September 5, 2013 *available at* http://www.un.org/Depts/los/convention_agreements/texts/unclos/part2.htm.

[48] *Id*. at part V, art. 57 *available at* http://www.un.org/Depts/los/convention_agreements/texts/unclos/part5.htm.

[49] Moridis et al., *supra* note 4, at 3.

[50] *Id.*, at 23. *See also* Koh, supra note 17.

[51] Moridis et al., *supra* note 4, at 3. *See also* discussion on Japanese efforts in development in both the discussion on hazards from methane projects, *infra* Subsea Seppage of Methane .

[52] Dawe & Thomas, *supra* note 15, at 223; Moridis et al., *supra* note 4, at 2, 12-17; Marcelle-De Silva & Dawe, *supra* note 2, at 227.

[53] Lee & Holder, *supra* note 18, at 185; Marcelle-De Silva & Dawe, *supra* note 2, at 227. This method found practice at the Siberian field of Messoyhaka for several decades.

[54] Walsh et al., *supra* note 7; Moridis et al., *supra* note 4, at 2, 12-17; Marcelle-De Silva & Dawe, *supra* note 2, at 227.

[55] Dawe & Thomas, *supra* note 15, at 223; Koh, *supra* note 17, at 165-166; Walsh et al., *supra* note 7; M. J. Castaldi et al., *Down-Hole Combustion Method for Gas Production from Methane Hydrates*, 56 J. Petroleum Sci. & Engineering 175, 177 (2007); Englezos & Lee, *supra* note 9. Endothermic reactions require energy to be added for the reaction to occur. Exothermic reactions release energy as they occur. Fifty kJ/mol of energy is required to separate methane from the hydrate formation. Larger molecules require more energy; e.g., propane requires 130 kJ/mol. Lee & Holder, *supra* note 18, at 185.

[56] M. Kurihara, et al., *Gas Production from Methane Hydrate Reservoirs*, *in*: Proceedings of the 7th International Conference on Gas Hydrates (2011); Marcelle-De Silva & Dawe, *supra* note 2, at 227.

[57] Kurihara et al., *supra* note 56; Marcelle-De Silva & Dawe, *supra* note 2, at 227.
[58] G. J. Moridis, et al., *Gas Production from a Cold, Stratigraphically-Bounded Gas Hydrate Deposit at the Mount Elbert Gas Hydrate Stratigraphic Test Well, Alaska North Slope: Implications of Uncertainties*, 28 Marine & Petroleum Geology 517, 518-20 (2011).
[59] C. Cranganu, *In-situ Thermal Stimulation of Gas Hydrates*, 65 J. Petroleum Sci. & Engineering 76, 79 (2009).
[60] Castaldi et al., *supra* note 55; Englezos & Lee, *supra* note 9; Walsh et al., *supra* note 7; Kurihara et al., *supra* note 56; Dawe & Thomas, *supra* note 15, at 219-220.
[61] Marcelle-De Silva & Dawe, *supra* note 2, at 227.
[62] Englezos & Lee, *supra* note 9, at 671; Lee & Holder, *supra* note 18, at 183.
[63] *Id.*
[64] Zhang et al., *supra* note 15, at 934; Dawe & Thomas, *supra* note 15, at 217. *See also* discussion on methane hydrate chemistry, *supra* Basic Science of Offshore Methane Hydrates.
[65] Zhang et al., *supra* note 15, at 934. The combustion of coal and crude oil, especially as diesel fuel, is known to cause a variety of health and medical injuries to frequently exposed communities. The combustion of coal and crude oil provide the worst sources of fuel-based anthropogenic climate change. In Asia in particular, the health risks can be extreme. The delivery of a geographically diverse abundant supply of methane, or of hydrogen, is an opportunity to save lives and to save the climate.
[66] A typical 600 MW coal plant might release 14,100 tons of sulfur dioxide (SO2), 10,300 tons of nitrous oxides (NOx), 500 tons of small airborne particles, 170 pounds of mercury, and 114 pounds of lead annually. *See Coal Power: Air Pollution,* Union of Concerned Scientists, http://www.ucsusa.org/clean_energy/coalvswind/c02c.html (last visited Dec. 29, 2014).
[67] In a report from the Oak Ridge National Laboratory, UT Battelle for the U.S. Department of Energy, it was estimated that American coal combustion emitted more uranium as ash than America used as nuclear fuel. "According to 1982 figures, 111 American nuclear plants consumed about 540 tons of nuclear fuel, generating almost 1.1 x 1012 kWh of electricity. During the same year, about 801 tons of uranium alone was released from American coal-fired plants. Add 1971 tons of thorium, and the release of nuclear components from coal combustion far exceeds the entire U.S. consumption of nuclear fuels." Alex Gabbard, *Coal Combustion: Nuclear Resource or Danger*, web.ornl.gov (Feb. 5, 2008), http://web.ornl.gov/info/ornlreview/rev26-34/test/colmain.html.
[68] Krey et al., *supra* note 13, at 4.
[69] R. Kikuchi, *Analysis of Availability and Accessibility of Hydrogen Production: An Approach to a Sustainable Energy System Using Methane Hydrate Resources*, 6 Env't Dev. and Sustainability 453, 467-468 (2005).
[70] *See supra* Extracting Offshore Methane Hydrates.
[71] Englezos & Lee, *supra* note 9.
[72] Castaldi et al., *supra* note 55.
[73] See *SUGAR Projekt*, Geomar, http://www.geomar.de/en/research/fb2/fb2-mg/projects (last visited Dec. 2, 2014).
[74] Kikuchi, *supra* note 69, at 467-68.
[75] S. Maruyama et al., *Proposal for a Low CO2 Emission Power Generation System Utilizing Oceanic Methane Hydrate*, 47 Energy 340, 342 (2012).
[76] Kikuchi, *supra* note 69, at 454.
[77] *Id.* at 465.
[78] *Id.*
[79] The reaction equation is CH4 + H2O -> CO + 3H2; methane and water can produce carbon monoxide and hydrogen. *Id.* at 456.
[80] *Id.* at 467.
[81] The reaction equation for combusted methane is generally given as CH4 + 2 O2 -> CO2 + 2 H2O; combusting methane with oxygen yields carbon dioxide and water. *See id.* at 456.
[82] The reaction equation is CO + H2O -> CO2 + 3H2O; carbon monoxide and water can be combined to yield carbon dioxide and water. Kikuchi, *supra* note 69, at 456. *See also* Krey, *supra* note 13, at 4.
[83] *E.g.*, type sI methane hydrates are composed of forty-eight water molecules to eight gas molecules.
[84] Walsh, *supra* note 7.
[85] William M. Alley, *Desalination of Ground Water: Earth Science Perspectives,* USGS (Oct. 2003), http://pubs.usgs.gov/fs/fs075-03/.
[86] Walsh, supra note 7.
[87] *Id.*
[88] Englezos & Lee, *supra* note 9, at 676.
[89] J. Javanmardi et al., *Economic Evaluation of Natural Gas Hydrate as an Alternative for Natural Gas Transportation*, 25 Applied Thermal Engineering 1708, 1720 (2005).
[90] *Id.* at 1721. S*ee also* Kikuchi, *supra* note 69, at 468-469.
[91] Englezos & Lee, *supra* note 9.
[92] N. J. Kim et al., *Formation Enhancement of Methane Hydrate for Natural Gas Transport and Storage*, 35 Energy 2717, 2718 (2010); Englezos & Lee, *supra* note 9, at 676. GTS technology has been reported to be economic in the short and medium distances (less than 5,000 km) and low to medium volumes (less than billion cubic meters) that are not feasible for LNG investments.
[93] *Id.*
[94] *Id.*
[95] *See infra* Subsea Seepage of Methane.
[96] *See id.*
[97] This would be in contrast to traditional oil spill events, wherein the main hazard source is the spilt crude oil and its associated tars.
[98] Itsuka Yabe et al., Environmental Risk Analysis of Methane Hydrate Development, *in*: 7th International Conference on Gas Hydrates 4 (2011).
[99] The present hazards are somewhat vague and high-level, so it may not be sufficient for more careful enumerations of potential harms.
[100] The chart provided by also listed the impact upon telecommunication cables and production pipelines at the bottom of the sea bed. In short, subsidence could be the beginning of a very bad sequence of events. They also explain that the landslide case is a more severe case of subsidence. Subsidence might damage sea bed gathering systems, but the landslide would obliterate them. *See* Yabe et al., *supra* note 98.
[101] *Id.* at 4. Surface ships will have a variety of emissions and discharges. Mooring lines will need to be installed. The seabeds are disrupting with submersible drilling equipment. Noise and vibration will be frequent and pervasive. Drilling mud and cementing may reach the environment. Gathering lines and their connecting manifolds need to laid and installed. Drilling operations will require flaring as a safety system, but that implies potentially large flares and venting will be needed on occasion.
[102] *Yabe, supra note 98.*
[103] *Id.*
[104] G. P. Glasby, *Potential Impact on Climate of the Exploitation Of Methane Hydrate Deposits Offshore*, 20 Marine and Petroleum Geology 163, 170 (2003).
[105] Adrian G. Glover & Craig R. Smith, *The Deep-Sea Floor Ecosystem: Current Status and Prospects of Anthropogenic Change by the Year 2025*, 30 Envtl. Conservation 219, 220 (2003).
[106] *Id.* at 232.
[107] *Id.* at 220.
[108] Glasby, *supra* note 104; Keith A. Kvenvolden, *Potential Effects of Gas Hydrate on Human Welfare*, 96 Proc. of the Nat'l Acad. of Sciences of the United States of America 3420, 3420-3426 (1999) *available at* http://www.ncbi.nlm.nih.gov/pmc/articles/PMC34283/ (last visited Dec. 2, 2014).
[109] Glasby, *supra* note 104, at 170.
[110] Glover & Smith, *supra* note 105, at 225.
[111] *Id.*
[112] C.R. Smith et al., *The Near Future of Deep Seafloor Ecosystems, in* Aquatic Ecosystems: Trends and global prospects 334, 344-345 (2008).
[113] E. Allison & R. Boswell, Dept. Energy, Methane Hydrate, Future Energy Within Our Grasp, an Overview 9 (2007); *See also id.* at 22.
[114] *Id.*
[115] *Id.*
[116] *Id.*
[117] *Id.* at 23.
[118] *Id.*
[119] Glasby, *supra* note 104, at 170.
[120] There is an example given of a Gulf of Mexico seep. The seep was over 600m wide and the methane had been seen at the surface 540m above. *See id.*
[121] If repairs were to be made to the field at large, it would likely consist of some sort of entrapment and layering in mud, restoring the pressures necessary for stability.
[122] Marcelle-De Silva & Dawe, *supra* note 2, at 230. *See also* N. L. Bangs et al., *Massive Methane Release Triggered by Seafloor Erosion Offshore Southwestern Japan*, 38 Geology 1019, 1019 (2010).
[123] Zhang et al., *supra* note 15, at 935.
[124] *Id.*

[125] *See supra* Methane: More Green than Coal or Crude Oil. *See also* I. S. Leifer et al., *Engineered and Natural Marine Seep, Bubble-Driven Buoyancy Flows*, 39 J. Physical Oceanography 3071 (2009).
[126] N. Shakhova & I. Semiletov, *Methane Release and Coastal Environment in the East Siberian Arctic Shelf*, 66 J. Marine Systems 227, 240 (2007).
[127] *Id.*
[128] *See generally* methane, Wisconsin Department of Health Services, http://www.dhs.wisconsin.gov/eh/chemfs/fs/Methane.htm (last visited Dec. 29, 2014).
[129] *See* Center for Disease Control *Methal Mercaptan,* Agency for Toxic Substances and Disease Registry, *available at* http://www.atsdr.cdc.gov/mhmi/mmg139.pdf (providing additional information regarding exposure to methal mercaptan).
[130] D. Tedesco et al., *January 2002 Volcano-Tectonic Eruption of Nyiragongo Volcano, Democratic Republic of Congo*, 112 J. Geophysical Research, 1, 5 (2007). *See also* B. Smets et al., *Dry Gas Vents Mazuku in Goma Region (North-Kivu, Democratic Republic of Congo): Formation and Risk Assessment*, 58 J. African Earth Sci. 787, 788 (2010).
[131] Smets et al., *supra* note 130, at 788. Etymologically *mazuku* means "evil winds that travel and kill in the night" in Kiswahili.
[132] D. M. Wafula et al., *Natural Disasters and Hazards in the Lake Kivu Basin, Western Rift Valley of Africa*, *in* Report on the International Workshop on Natural and Human Induced Hazards and Disasters in Africa (2007) *available at* http://iugg-georisk.org/presentations/pdf/Lake-Kivu-hazards.pdf.
[133] Tedesco et al., *supra* note 130. *See also* Wafula et al., *supra* at note 132.
[134] Smets et al., *supra* note 130, at 787.
[135] Tedesco et al., *supra* note 130, at 6.
[136] *Id.* at 5.
[137] Smets et al., *supra* note 130, at 794.
[138] Leifer et al., *supra* note 125. *See also* E. A. Keller et al., *Tectonic Geomorphology and Hydrocarbon Induced Topography of the Mid-Channel Anticline, Santa Barbara Basin, California*, 89 Geomorphology 274 (2007)
[139] D. Adam, *Methane Hydrates: Fire From Ice*, 418 Nature 913, 914 (2002).
[140] *Id.*
[141] Dawe & Thomas, *supra* note 15, at 223.
[142] Zhang et al*., supra* note 15, at 935.
[143] *Id.*
[144] Krey et al., *supra* note 13, at 4.
[145] *Id.*
[146] Zhang et al., *supra* note 15, at 935.
[147] *Id.* at 935-36.
[148] M. F. Nixon & J. L. H. Grozic, *Submarine Slope Failure Due to Gas Hydrate Dissociation: A Preliminary Quantification*, 44 Can. Geotechnical J. 314, 321-322 (2007).
[149] *Id.* at 323-24.
[150] Marcelle-De Silva & Dawe, *supra* note 2, at 231.
[151] Nixon & Grozic, *supra* at note 148, at 315.
[152] Zhang et al*., supra* note 15, at 936.
[153] Nixon & Grozic, *supra* note 148, at 315.
[154] Marcelle-De Silva & Dawe, *supra* note 2, at 231. Zhang has shown that gas hydrates, *in situ*, can display ten times greater shear strength than water ice. *See id.*
[155] Zhang et al*., supra* note 15, at 936.
[156] *Id. See also* Glasby, *supra* note 1049, at 163-75.
[157] When oil is raised from the reservoir to the production platform, it is often quite a bit warmer than the adjacent seabed. There are known instances wherein oil platforms ran their production lines through hydrate deposits, which then destabilized as the production line warmed the seabed. Nixon & Grozic, *supra* note 148, at 315.
[158] *See* Yabe, *supra* note 98.
[159] *See* Table 4, *infra* Uneven Economic and Industrial Capacities.
[160] For a more complete discussion on these concerns, *see* M. G. Faure, M. Goodwin & F. Weber, *Bucking the Kuznets Curve: Designing Effective Environmental Regulation in Developing Countries*, 51 Va. J. Int'l L. 95 (2010).
[161] Such a non-stringent regulation need not be per se predatory on the part of the technology owner. A nation state might offer nationwide indemnification for all methane hydrate liabilities to the technology owners, with counterbalancing promises to provide due process handling of victim claims and rights. The technology owner might then engage in a multi-decade investment only to later discover that the bulk of the promised due process measures never manifested.
[162] For a discussion on the models and arguments supporting the application of a rule of strict liability to the risks and hazards of offshore methane hydrates, *see* R. A. Partain, *The Application of Civil Liability for the Risks of Offshore Methane Hydrates,* 26 Fordham Envtl. L.R. (forthcoming Jan. 2015).) For a discussion on the models and arguments supporting the application of public and private regulations to the risks and hazards of offshore methane hydrates, *see* R. A. Partain, *Governing the Risks of Offshore Methane Hydrates: Part II – Public and Private Regulations,* (On file with Rotterdam Institute of Law & Economics), *available at* SSRN http://papers.ssrn.com/sol3/papers.cfm?abstract_id=2466079.
[163] For a discussion on the existing laws and conventions that might apply to commercial development of offshore methane hydrates, *see* R. A. Partain, *A Comparative Legal Approach for the Risks of Offshore Methane Hydrates: Existing Laws and Conventions,* 32 Pace Envtl. L. Rev. (forthcoming Jan. 2015).
[164] What the Koreas refer to as the East Sea, Japan refers to as the Sea of Japan. It is a matter of substantial diplomatic debate, but herein both names are used interchangeably.
[165] Similar problems of split jurisdictions over continuous and singular deposits can be found in many places, because the legal jurisdictions do not well correlate with the natural incidence of hydrate formation. Thus, the U.S. and Mexico might have such concerns, as might South Korea and Japan in the East Sea/Sea of Japan or Angola and Namibia in the South Atlantic Ocean.
[166] Yabe, *supra* note 98.
[167] J. B. Klauda & S. I. Sandler, *Global Distribution of Methane Hydrate in Ocean Sediment*, 19 Energy & Fuels 459, 469 (2005), *available at* http://pubs.acs.org/doi/abs/10.1021/ef049798o.
[168] The eastern Pacific territories of Russia also have substantial methane hydrate reserves offshore including Sakhalin and Kamchatka around the Sea of Okhotsk.
[169] Assuming the Caribbean fits more into this area than other areas, practically every island is assumed to have methane hydrates offshore.
[170] The U.K.'s Falklands offshore of Argentina are forecasted to possess methane hydrates.
[171] *See* Susan Beukes, *Namibian Villagers Grapple with the Worst Drought in Three Decades*, UNICEF, August 7, 2013 http://www.unicef.org/infobycountry/namibia_70107.html.