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Maximizing Gas Utilization Using Gas To Hydrates Technology

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ABSTRACT: *Energy is essential to achieving the economic, social, and environmental goals of sustainable human development. Natural Gas provides about 22% of the world's energy and will continue to increase by 1.9% annually till 2040. Gas flaring is one of the most challenging energy and environmental problems facing the world today whether regionally or globally because it is a multi-billion-dollar waste, a local environmental catastrophe and a global energy and environmental problem which has persisted for decades. The technologies available today have not been able to proffer a solution to gas flaring because most of them are not economically viable when they are used to process stranded and flared gas scattered in different locations.*

In this paper a system for extraction, transportation and production of flared gas using gas to hydrate technology was established, a software for calculating the required temperature and pressure for hydrate formation to occur inside the reactor was developed and the economics was analyzed. From the economic analysis, it was seen that implementing gas to hydrate technology in Niger delta will yield IRR of 20% and breakeven of about 4.8 years.

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I. INTRODUCTION

Isolated oil and gas wells are reserves of oil and gas located at a distance far from processing location. This distance makes the financial implication of transporting excess gas gotten from these locations high therefore rendering the use of this gas infeasible. In order to reduce the excess gas produced, some of the gas will be flared to the atmosphere and this causes environmental issues and challenges. It is estimated that as much as 3 – 5% of the world's Natural Gas reserves are always flared. This is more than the energy represented by the oil reserves of some countries and embodies billions of dollars of unutilized assets. Most available gas processing technologies are only applicable for large-scale applications. That is, applications that are much larger than the amount of gas being flared. Thus, in order to maximize on the Natural Gas produced from isolated wells, a novel approach to design and applicability is required.

Gas Hydrates

Gas hydrate or clathrate is gas molecules (mostly methane) contained in the molecular cavities of a solid ice-like form of water. It is usually stable at about 500 meters water depths and at the seafloor. A diagram is shown below.

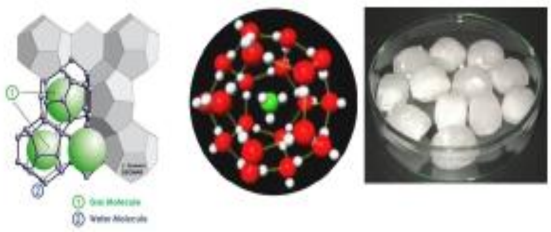

Figure 1: Structure of Gas Hydrate (Takaoki2006)

Over the years, industries have been looking for a more efficient means of solving flow assurance problems caused by hydrates in gas pipelines, storing natural gas for the purpose of transportation and search for an economical and efficient method of exploiting natural gas from the vast hydrate deposits on ocean floors. These researches led to the laboratory development of Natural gas hydrate technology in the area of hydrate formation, storage and transportation and re-gasification.

Chemistry of Gas to Hydrate Technology

The freezing point of water is zero degrees at atmospheric pressure but when there is substantial increase in pressure, water molecules begins to form complex solid structures at temperatures above the normal freezing point (2° – 10°). Unlike ice, these structures are unstable because they are made up of regular networks of large, open cavities. If cooling continues, a stable ice structure will ultimately form, unless some Guest (outside) molecules moves into the structure (Cox, 1983). This structure is called Hydrate. Methane is the most abundant guest molecule in nature and is commonly called methane hydrate. In Inorganic Chemistry the word 'hydrate' is used to define a fixed compound with water molecules as an essential part of the crystal. Natural gas hydrates are more appropriately grouped within a special class of non-stoichiometric compounds called clathrates because they do not have a definite stochiometric formula. For Methane hydrate, the best that can be written for it is $XCH_4{\bullet}46H_2O$, with X being between zero (0) to eight (8) molecules of methane and probably other guest gases

Gas Hydrate System

Different researches done in the past has provided information on the dynamics and uses of Gas Hydrates. Brinchi et al (2001) showed that methane hydrate could be formed by introducing water in a flowing gas at a pressure and temperature of about 120 bar and 3 - 4°C respectively. Also, Nazari et al (2011) after his experiments proved that hydrates can be stored at a pressure of 13 bars and -10°C for two to three weeks if a stabilizer was used when it was formed. Using a combination of these discoveries, a Gas Hydrate system was set up. Gas hydrate system is a system where by flared gases are captured using gas hydrate technology. This technology ensures that they are not flared to the atmosphere and enables them to be easily transported to locations where the gases can be recovered. The technology that is seen as one feasible solution to stalling gas flaring in the world if oil and gas production must continue is Natural gas hydrate. This is because the technology can convert natural gas to a solid of which the trapped gas can later be recovered. The technology involves Gas collection, Hydrate formation, Hydrate Storage, Hydrate Transportation, Regasification and Water recycling mechanism.

Gas Gathering

Gas gathering is a process whereby gases that are supposed to be sent to flare stacks are channelled to a place where they are compressed and stored. This is the first stage of converting gas to hydrates. It enables the operators to properly control factors such as flow rate, pressure, temperature, etc. when sending the gas to the hydrate reactor. Depending on the amount of gas, the gas gathering station can be used to collect gases from one or multiple sources of gas. A schematic of gas gathering is shown below.

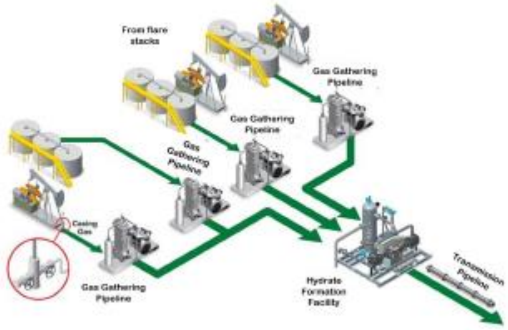

Figure 2: Gas gathering system (Takaoki 2006)

Hydrate Formation

After gathering the gas, it is sent to a reactor set at a pre-calculated pressure and temperature where the hydrates are formed. There are different reactors which can be used for hydrate formation. They are: Stirred Reactors, Bubble tower reactors and Spraying reactors. However, because the most common method used to improve mass transfer and heat transfer in methane hydration process is stirring, stirring reactors are the best options for converting gathered gas to hydrates.

Hydrate Storage and Transportation

After hydrate is formed, there is need to move the produced hydrates from the storage tank to the transport vessel. This can be done by conveying the hydrates through a pipe conveyor into an enclosed vessel operating under atmospheric pressure and a temperature of -20°C. A ship-loader installed on the jetty can be used to load the NGH pellet in the cargo hold of specialized NGH carrier (Figure 3). A silo type storage tank with a pellet catcher is used for storage in the ship. It collects the necessary amount of pellet which falls down to a passage at the centre of the tank for discharge from its lower part. Hydrate pellets dissociates slightly in the cargo hold of the vessel and it can be used for driving the generator engine of the carrier.

Figure 3: Three-dimensional illustration of Hydrates transportation (Raine et al, 2015 and Takaoki, 2006)

Figure 4 shows a detailed illustration of the proposed Gas to hydrate technology by Kanda (2006). The upper part of the diagram shows the 3d illustration and the lower part shows the chain in details.

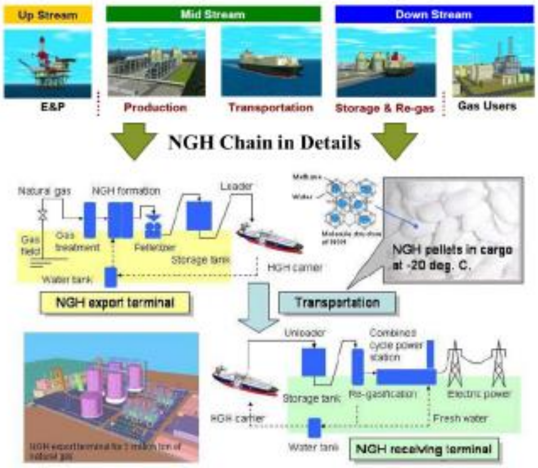

Figure 4: Overall Structure of Natural Gas Hydrate chain (Kanda, 2006)

Software Development

The knowledge of natural gas hydrate formation conditions such as temperature and pressure require a great number of petroleum engineering calculations. Ideally, the conditions for natural gas hydrate formation are determined experimentally in the laboratory. This is the best method for determining conditions of hydrate formation but because it is impossible to satisfy the infinite number of conditions for which measurements are needed, there is always a need to interpolate between measurements. Because of this, several accurate and simplified model for predicting natural gas hydrate formation have be proposed by various researchers:
Hammerschmidt (1934) proposed a correlation for gas hydrate formation shown below:

$$T(°F) = 8.9\, P_{(psi)}^{0.285} \quad \text{……………...…… (1)}$$

Where:
P = Pressure and
T = Temperature

The challenge with this equation is that it does not take into account the effect of gas specific gravity therefore in 1986, Berg proposed two T-explicit correlations for $0.55 \leq \gamma < 0.58$ and $0.58 \leq \gamma < 1$ with 11 and 10 adjustable parameters respectively (Carroll, 2009). Also, Kobayashi et al. (1987) recommended a complicated T-explicit correlation made of 15 adjustable parameters in order to provide more precise estimations of hydrate formation temperatures. In order to reduce the parameters that need to be adjusted Motiee (1991) suggested the equation below

$$\mathbf{T} = -283.24469 + 78.99667\log(P) - 5.352544\log(P)^2 + 349.473877\,\gamma - 150.854675\,\gamma^2 - 27.604065\log(P)\,\gamma \quad \ldots (2)$$

Because of the accuracy of this equation for natural gas mixtures, it is well known and widely used in the oil and gas industry.

Towler and Mokhatab (2005) recommended a relatively simple correlation for predicting hydrate formation temperature of natural gas mixtures. The modified form of their correlation is shown below

$$T = 13.47\ln(P) + 34.27\ln(\gamma) - 1.675\ln(P)\ln(\gamma) - 20.35 \ldots (3)$$

In most correlations, temperature is often calculated because it is a variable that should be estimated and pressure is usually specified by process and/or transfer requirements. However, some hydrate correlations for calculating pressure have also been proposed. Makogon (1997), presented a correlation that can be used to calculate pressure. This was later developed and modified by Elgibaly et al (1998) as shown below

$$\log P = \beta + 0.0497(t + kt^2) - 1 \quad .. (4)$$

Where:

$\beta = 2.681 - 3.811\gamma + 1.679\gamma^2$…..……..(5)

$k = -0.006 + 0.011\gamma + 0.011\gamma^2$ ……..…(6)

γ = gas specific gravity = $\frac{\text{MWGas}}{\text{MWAir}}$…….. (7)

Other correlations have been developed over the years but for the purpose of this study the correlations above were used to develop a software for determining the pressure and temperature of gas hydrate formation. The software named GTH_1.0 simply means Gas to hydrate version 1.0. It was developed using Virtual Basic 2010 and it is used to calculate the temperature and pressure of hydrate formation. The figures below shows the home window and calculation window respectively.

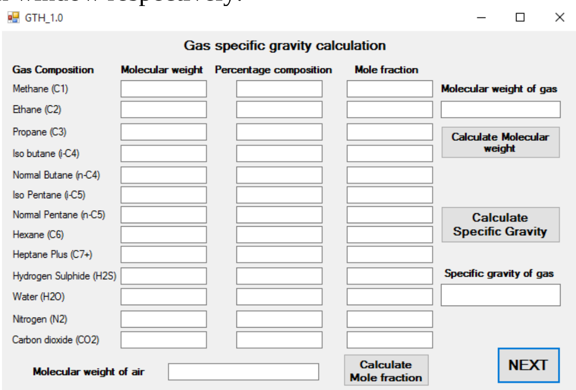

Figure 5: Home Window of GTH_1.0

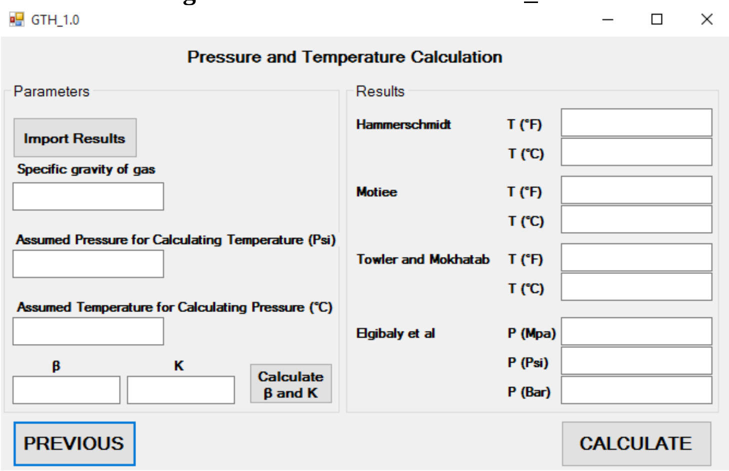

Figure 6: Calculation windows of GTH_1.0

The software was used to analyze different compositions of natural gas as shown in Table 1 below. The pressure and temperature used for analysis where required were 1160 Psi and 4°C respectively.

Table 1: Different Natural Gas samples (Uniongas, 2017)

Composition	A	B	C	D
C1	52.21	86.06	89.90	93.70
C2	18.94	6.40	5.05	3.28
C3	11.79	4.25	2.10	1.00
i-C4	1.01	1.18	0.56	0.30
n-C4	3.46	1.17	0.57	0.23
i-C5	0.63	0.31	0.19	0.10
n-C5	0.97	0.30	0.14	0.07
C6	0.42	0.13	0.15	0.05
C7+	0.16	0.08	0.16	0.10
H2O	-	-	-	-
N2	0.51	0.12	0.73	0.50
CO2	0.90	-	0.16	0.50
H2S	-	-	-	-
Total	**100.00**	**100.00**	**100.00**	**100.00**

Economic Feasibility Analysis of Gas to Hydrate Technology on two fields in Niger Delta, Nigeria

Two fields X and Y that produces gas and oil respectively were used to analyze the feasibility of Gas to hydrate technology. The details of the fields are shown below

Table 2: Profile of Field X and Y

	Field X	**Field Y**
Type of field	Gas field	Oil field
Production	320 MMScf/day	150 MMScf/day
Gas flared	3 MMScf/day	1.4 MMScf/day
Location	Niger Delta, Nigeria	

It was assumed that Hydrates will be transported across two distances – 1500 Nautical mile (NM) and 3500 Nautical Mile (NM) which is equivalent to 2778 and 6842 Kilometers (Km) respectively. For studying the economic feasibility of Gas to hydrate technology chain, investment cost and operation cost were calculated for the two fields in two cases. The cost of the project is tabulated below

Table 3: Cost details of Field X and Y for 1500 NM (2778 Km) Transportation distance

Cost (USD)	**Field X**	**Field Y**
Production and Storage	2,824,000	1,317,800
Transportation (Sea/Land)	1,694,400	790,680
Regasification/Storage	1,129,600	527,120
Total CAPEX	5,648,000	2,635,600
Fixed OPEX Annually	282,400	131,700
Gross Revenue Annually	3,175,000	1,481,900
Cost of Natural Gas	$2.90 per 1000 Scf	
Discount Factor	15%	
Inflation Factor	16%	
Income Tax Rate	35%	
State Tax Rate	20%	
Variable OPEX Rate	15%	

Table 4: Cost details of Field X and Y for 3500 NM (6842 Km) Transportation distance

Cost (USD)	**Field X**	**Field Y**
Production and Storage	4,100,000	1,913,250
Transportation (Sea/Land)	2,460,000	1,147,950
Regasification/Storage	1,640,000	765,300
Total CAPEX	8,200,000	3,826,500
Fixed OPEX Annually	400,000	200,000
Gross Revenue Annually	3,175,000	1,481,900
Cost of Natural Gas	$2.90 per 1000 Scf	
Discount Factor	15%	
Inflation Factor	16%	

Income Tax Rate	35%
State Tax Rate	20%
Variable OPEX Rate	15%

In this analysis, it was assumed that the Gas Hydrate pellet is produced at the site and such pellet is transported to a loading port by tankers where it is loaded to a ship and transported by sea to the unloading port. After unloading the ship, hydrates will be transported to regasification location.

The project is assumed to start in 2017 and the equipment's (Reactors, loading vessels, Regasification reactor, etc.) will be replaced after 20 years (2037). Variable operating cost is assumed to be 15% of the Capital cost (CAPEX) and Present Value Interest Factor (PVIF) was calculated using the formula

$$\text{PVIF} = \frac{1 + \text{Discount Factor}}{(1 + \text{Inflation Factor})^{\text{year}}} \text{……..} \quad (8)$$

Net present value (NPV) is calculated by

$$NPV = FutureValue\ (FV)\ xPresentValueInterestFactor\ (PVIF) \text{……..……………} \quad (9)$$

Straight Line Depreciation (SLD) is used to calculate the depreciation and the formula is written as

$$\text{SLD} = \frac{\text{Total CAPEX} - \text{Salvage Value}}{\text{Useful Life}} \text{……...…} (10)$$

Tax is calculated from taxable income which has the formula below

$$TaxableIncome = TotalRevenue - FixedOPEX - VariableOPEX - DepreciationCost - LossCarriedForward. \text{..……………..} \quad (11)$$

Transportation Cost Comparison with Liquefied Natural Gas (LNG)

Shin et al (2016) compared transportation costs of Liquefied Natural Gas and Gas hydrates for a shipping distance of 0 – 12000 km and concluded with the figure below.

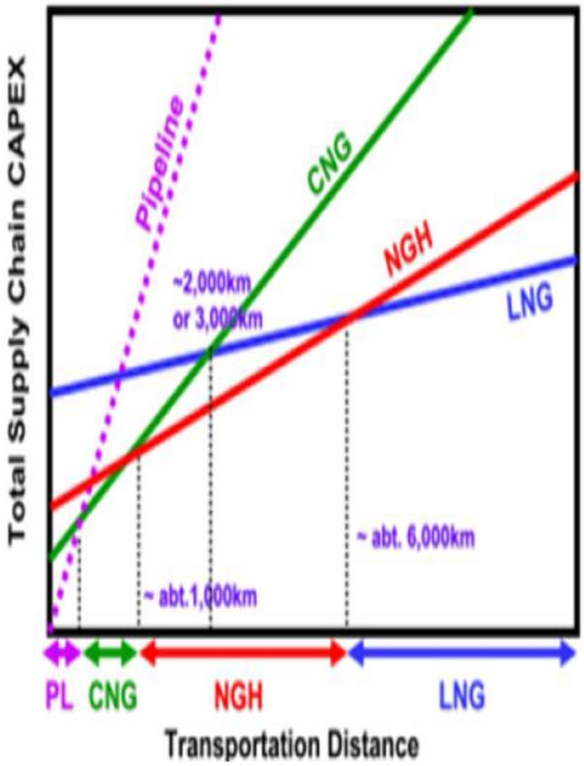

Figure 7: Cost comparison diagram of LNG and NGH transportation(Shin et al, 2016)

Results of Software Calculation

The hydrate formation temperature and pressures of different gas compositions are shown below. From the result below, we can see that the temperature for the given pressure matches the required temperature needed for hydrate formation.

Table 5: Hydrate formation temperature and pressures of Gas samples

Models	Gas	A	B	C	D
Hammerschmidt	T (°F)	41.55665195	41.55665195	41.55665195	41.55665195
	T (°C)	5.309293555	5.309293555	5.309293555	5.309293555
Motiee	T (°F)	43.45014703	39.87863476	37.97804391	36.39003957
	T (°C)	6.361243685	4.37705433	3.321162076	2.438930382
Towler and	T (°F)	44.09177385	41.22390794	40.25359033	39.51967632
Mokhatab	T (°C)	6.71770588	5.124434297	4.585364644	4.177631378
	P (MPa)	5.232491684	7.030676709	7.970537988	8.808467127
Elgibaly et al	P (Psi)	758.9085591	1019.713179	1156.028498	1277.559813
	P (bar)	52.32491684	70.30676709	79.70537988	88.08467127

Result of the Economic Feasibility Analysis

From the economic analysis, it was discovered that transportation of Natural gas using Gas to Hydrate Technology is a highly profitable technology. The Net Present Value (NPV), Internal Rate of Return (IRR) and Break Even are shown in the table below

Table 4.2: Result of Economic Analysis

	Field X	Field Y
	1500 NM (2778 Km) Transportation distance	
Net Present Value (NPV)	$14,144,710.13	$6,603,725.68
Internal Rate of Return (IRR)	20%	20%
Break Even	4.8 years	4.8 years
	3500 NM (6842 Km) Transportation distance	
Net Present Value (NPV)	$8,818,201.19	$4,005,736.87
Internal Rate of Return (IRR)	10%	10%
Break Even	8.1 years	8.2 years

Figure 8 is the plot of Net present value (NPV) vs. years for different Gas to Hydrate projects

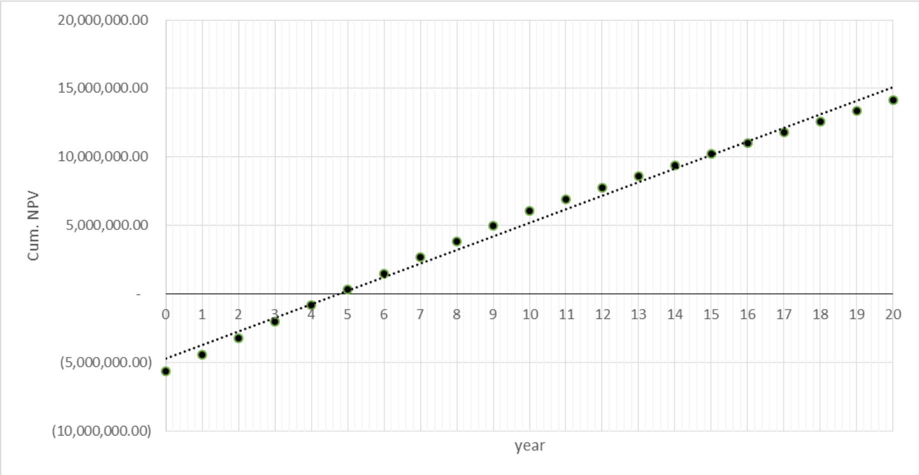

Figure 8: Plot of NPV vs. Year of 1500NM transportation distance for Field X

From figure 8, it can be deduced that if field X ventures into Gas to Hydrate technology and transports it through a distance of 1500NM it will breakeven in about 4.8 years

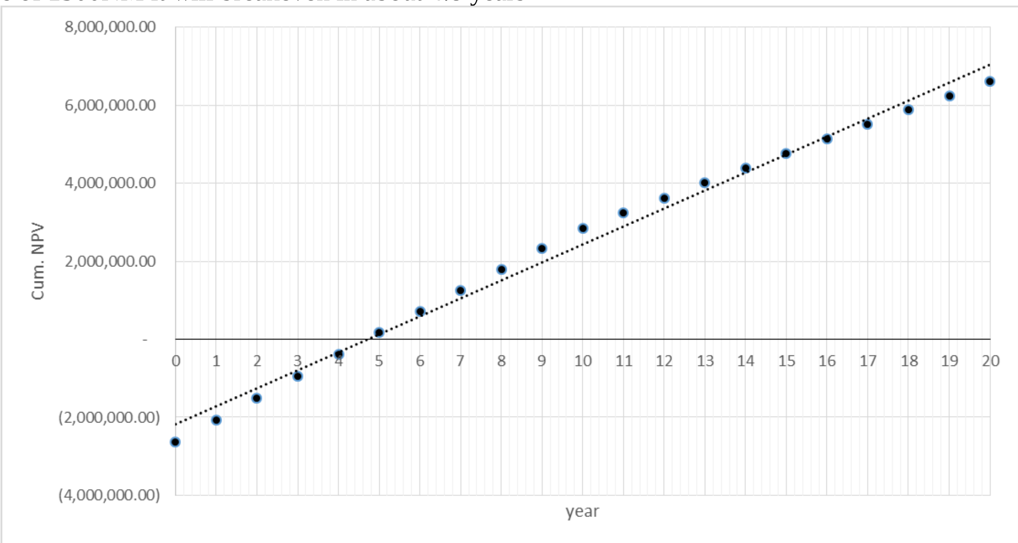

Figure 9: Plot of NPV vs. Year of 1500NM transportation distance for Field Y

From figure 9, it can be deduced that if field Y ventures into Gas to Hydrate technology and transports it through a distance of 1500NM it will breakeven in about 4.8 years

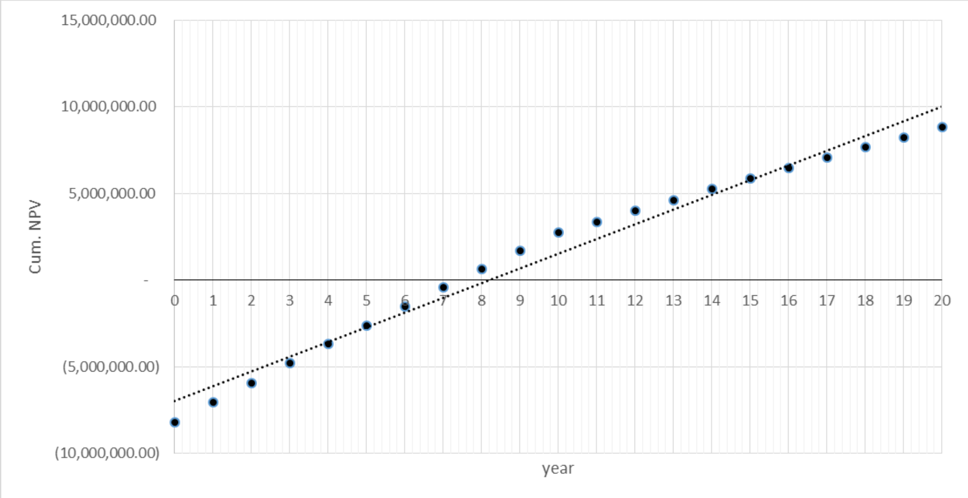

Figure 10: Plot of NPV vs. Year of 3500NM transportation distance for Field X

From figure 10, if field X ventures into Gas to Hydrate technology and transports it through a distance of 3500NM it will breakeven in about 8.1 years.

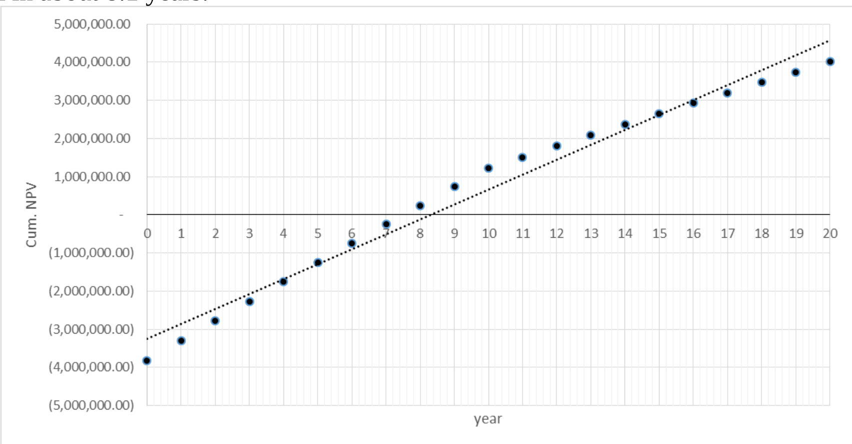

Figure 11: Plot of NPV vs. Year of 3500NM transportation distance for Field Y

From figure 110, if field Y ventures into Gas to Hydrate technology and transports it through a distance of 3500NM it will breakeven in about 8.2 years

From the economic analysis above, it can be seen that Gas Hydrate Technology is profitable not just in Niger Delta but can be used as a means of transporting Natural gas to continents that are within 3500NM range like South America, Europe etc. (Figure 12).

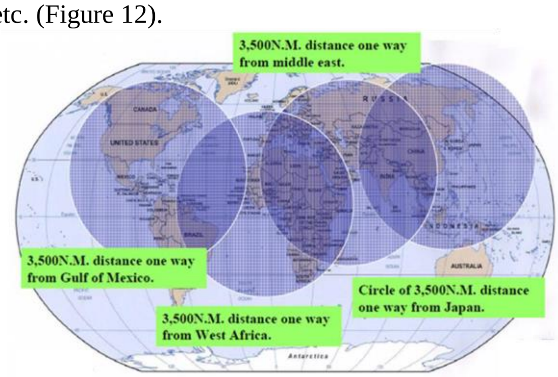

Figure 12: Market of Natural Gas Hydrate for a distance of 3500NM (Takaoki, 2006)

Gas to Hydrate Technology can help reduce gas flaring. Associated gas is usually flared due to the high cost of gas gathering facility. With Gas to hydrate Technology infrastructure on the field, gas flaring can be eliminated as associated gases can be converted to hydrates and easily transported to where they are needed.

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