

# **Natural Gas Flaring—Alternative Solutions**

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Abstract

Gas flaring is one of the major problems in the world. It consumes useful natural resources and produces harmful wastes, which have negative impacts on the society. It is one of the most tedious energy and environmental problems facing the world today. It is a multi-billion dollar waste, a local environmental catastrophe and environmental problem which has persisted for decades. From the year 1996-2010, in Nigeria, 12,602,480.25 million  $ft^3$  of natural gas was flared (NNPC). This is equivalent to losing about  $12,967.952 \times 10^{12}$  Btu of energy that would have been used to generate power or converted to other forms of energy. In 2015, the World Bank estimated that 140 billion cubic meters of natural gas produced with oil is flared annually, mostly in developing countries without gas processing infrastructures, or other means of utilizing the produced gas. It is widely known that flaring or even, venting of gas contributes significantly to greenhouse gas emissions, with negative impacts on the environment. Thus, alternative solutions to reduce or utilize the quantity of gas flared are crucial issues. Therefore, the need to study and provide detailed understanding of these alternative solutions to gas flaring is important. This paperoutlined the harmful effects of gas flaring and the different possible alternatives to gas flaring. The proposed alternative solutions are gas for secondary oil recovery, feedstock for petrochemical plants, domestic uses, LNG & CNG, as well as energy conservation by storing as gas hydrate for future use or other purposes. Gas hydrate is stable above the freezing point of water and sufficiently high pressure. It is relatively stable under its saturation temperature and pressure and also much denser than normal ice. This property of gas hydrate can be experimentally investigated and capitalized on, to effectively store natural gas as hydrate for energy conservation instead of flaring the gas wastefully. The alternative solutions will convincingly reduce and in the nearest future stop gas flaring globally.

# **Keywords**

Natural Gas, Gas Flaring, Harmful Effects, LNG, CNG, Gas Hydrate

## **1. Introduction**

Natural gas is a naturally occurring hydrocarbon gas mixture consisting primarily of methane, but also includes varying amounts of other higher alkanesethane, propane, butane, etc., and sometimes a small percentage of carbon dioxide, nitrogen, and/or hydrogen sulfide. It is formed when layers of decomposing plant and animal matter are exposed to intense heat and pressure over thousands of years. The energy that the plants originally obtained from the sun is stored in the form of chemical bonds in the gas. Natural gas is often informally referred to simply as "gas", especially when compared to other energy sources such as oil or coal [1].

It is a fossil fuel used as a source of energy for heating, cooking, and electricity generation. It is also used as fuel for vehicles and as a chemical feedstock in the manufacture of plastics and other commercially important organic chemicals. It is one of the cleanest, safest, and most useful forms of energy in our day-to-day lives [2].

Natural gas can be measured in a variety of ways, although the most common unit of measurement is the Gigajoule (GJ), which signifies one billion joules, the metric measure for heat or energy. A gigajoule (GJ) is the energy equivalent of about 30 liters of gasoline. (Alberta Energy Company). It can also be measured in Mcf (thousand cubic feet), Btu (British thermal unit) as well as Standard cubic metre (scm).

Natural gas can be "associated" (found in oil fields), or "non-associated" (isolated in natural gas fields), and is also found in coal beds (as coalbed methane). The natural gas industry is extracting an increasing quantity of gas from challenging resource types: sour gas, tight gas, shale gas, and coalbed methane. When the gas is produced with petroleum, it is often vented or flared.

In 2015, the World Bank estimated that 140 billion cubic meters of natural gas produced with oil is flared at thousands of oil fields worldwide, mostly in developing countries that do not have gas processing infrastructure. The result: emissions equivalent to that of 77 million automobiles, or translated into power generation, more electricity than the entire continent of Africa currently consumes.

#### Physical and Chemical Properties of Natural Gas

Natural gas is a naturally occurring gas mixture, consisting mainly of methane and other minor components. Table 1 outlines the typical components of natural gas on the Union Gas system and the typical ranges for these values (allowing for the different sources). Union Gas is an Energy company that gets most of their gas supply from western Canada; some gas is supplied from other sources, including the United States and Ontario producers.

Since the different gas supplies enter the Union Gas system at different locations, the exact value of each component at any site will vary among the different regions. The system average heating value will depend on the mix of gas supplies and therefore can vary from the values listed below.

Sulphur: In the Union Gas system, the typical sulphur content is 5.5 mg/m<sup>3</sup>.



S/N	Component	Typical analysis (mole %)	Range (mole %)
1	Methane	95.0	87.0 - 97.0
2	Ethane	3.2	1.5 - 7.0
3	Propane	0.2	0.1 - 1.5
4	Butanes (iso/normal)	0.03	0.01 - 0.3
5	Pentanes (iso/normal)	0.01	Trace - 0.04
6	Hexanes plus	0.01	Trace - 0.06
7	Nitrogen	1.0	0.2 - 5.5
8	Carbon Dioxide	0.5	0.1 - 1.0
9	Oxygen	0.02	0.01 - 0.1
10	Hydrogen	Trace	Trace - 0.02
11	Specific gravity	0.58	0.57 - 0.62
12	Gross heating value (MJ/m³), dry basis*	38.0	36.0 - 40.2

Table 1. Compositions of natural gas (union gas system).

\*The gross heating value is the total heat obtained by complete combustion at constant pressure of a unit volume of gas in air, including the heat released by condensing the water vapour in the combustion products (gas, air, and combustion products taken at standard conditions).

This includes the 4.9 mg/m<sup>3</sup> of sulphur in the odorant (mercaptan) added to gas for safety reasons.

*Water*. The water vapour content of natural gas in the Union Gas system is less than 80 mg/m<sup>3</sup>, and is typically 16 to  $32 \text{ mg/m}^3$ .

In its natural state, it is colorless, odorless and tasteless but in order to warn off its presence in case of leaks, an odorant (mercaptan) is added to it, giving it its characteristic smell of rotten eggs. Its relative density makes it lighter than air, so that leaks or emissions quickly dissipate into the upper layers of the atmosphere, making it less likely to form explosive mixtures in air. It is also non corrosive in nature [3]. Some of the physical and chemical properties of Methane (Major component of Natural gas) are shown in Table 2.

## 2. Natural Gas Flaring

Gas flaring is a process whereby natural gas associated with crude oil during production of crude oil is been burnt. Flaring is a major concern in petroleumproducing areas where there exists insufficient infrastructure to utilize the produced natural gas. It serves as a way of disposing the gas produced in those areas. This as simple as it may sound, creates series of negative impacts on the people in those arrears as well as the environment in general [4].

In the early days of petroleum exploration, natural gas was not considered a useful product because of the difficulties in transporting it to where it can be utilized or the problems associated with it storage. As a result, gas was simply burned off at the well or vented into the atmosphere, to create rooms for other operations and supposedly to save the whole system from being burnt down by gas explosion. **Table 3** shows the top ten gas flaring countries in the world as at

S/N	Property	Value
1	Molecular weight of mixture	18.2
2	Boiling point at 1 atmosphere	-160.0°C
3	Melting point	-180.0°C
4	Vapor density (air = 1) at 15.5	0.61
5	Liquid density (water = 1) at $0^{\circ}/4^{\circ}C$	0.554
6	Water solubility at 20°C	Slightly soluble (0.1% - 1.0%)

Table 2. Physical and chemical properties of natural gas.

Table 3. Top ten gas flaring countries in the world (world bank).

S/N	Country	Gas flared (10 <sup>6</sup> cm <sup>3</sup> )	Rank	
1	Russia	35,000	$1^{st}$	
2	Nigeria	17,000	$2^{nd}$	
3	Iran	10,000	$3^{rd}$	
4	Iraq	10,000	$4^{\mathrm{th}}$	
5	United States	5000	5 <sup>th</sup>	
6	Algeria	4800	6 <sup>th</sup>	
7	Kazakhstan	4700	$7^{\mathrm{th}}$	
8	Venezuela	4300	$8^{\mathrm{th}}$	
9	Saudi Arabia	4100	9 <sup>th</sup>	
10	Angola	4000	$10^{\text{th}}$	

#### 2012.

Even today, flaring and venting continue in locations where local markets and gas transportation infrastructures are not available, or where the gas itself is contaminated with other incombustible gases [5]. In 2015, the World Bank estimated that 140 billion cubic meters of natural gas produced with oil is flared at thousands of oil fields worldwide, mostly in developing countries that do not have gas processing infrastructure.

**Table 4** shows the total volumes of gas produced and flared in Nigeria-one of the major oil and gas producing countries in the world, from 1996-2010 [1]. Out of the total gas production of 846,655.4 million cubic metres, a total volume of 356,862.5 million cubic metres of gas was flared (approximately 42.15% of total gas production) during the 15 years period.

The Independent Statistic & Analysis Report from Energy Information Administration (EIA) in 2016 stipulated that the power (kWh) generated from a given fuel is a function of the heat rate of the power plant used and the heat content of the given fuel. Thus, to generate a kilowatt-hour (kWh) of electricity, the amount of fuel required can be calculated as;

$$A_{fuel}\left(\frac{physicalunit}{kWh}\right) = \frac{Heatrate(Btu/kWh)}{Fuelheatcontent(Btu/massorvolume))}$$
(1)

Table 5 shows the findings and reports during the analysis, (EIA, 2016), with



Year	Gas produced (10 <sup>6</sup> m <sup>3</sup> )	Gas flared (10 <sup>6</sup> m <sup>3</sup> )	% of gas flared
1996	35,450.00	26,590.00	75.01
1997	37,150.00	24,234.00	65.23
1998	37,039.00	23,632.00	63.80
1999	43,636.00	22,362.00	51.25
2000	42,732.00	24,255.00	56.76
2001	52,453.00	26,759.00	51.02
2002	48,192.45	24,835.58	51.53
2003	51,766.03	23,943.03	46.25
2004	58,963.61	25,090.91	42.55
2005	59,284.97	23,002.71	38.80
2006	82,036.86	28,584.39	34.84
2007	84,707.34	27,307.13	32.24
2008	80,603.61	21,811.00	27.06
2009	64,882.86	17,987.59	27.72
2010	67,757.65	16,468.18	24.30

Table 4. The statistic of gas flaring in Nigeria, 1996-2010.

#### Table 5. Fuel heat rates and heat contents of fossil fuels.

S	/N Fuel	Plant heat RATES (Btu/kWh	h) Fuel heat contents
	1 Coal	10,080	9710 (Btu/lbs)
	2 Petroleum	10,156	139,713 (Btu/US gal)
	3 Natural gas	10,408	1029 (Btu/ <i>ft</i> <sup>3</sup> )

Note: Heat contents of coal vary widely by types of coal.

three different types of fuels.

In **Table 5**, using a plant heat rate of 10,408 Btu/kWh, one  $ft^3$  of natural gas has a fuel heat content of about 1029 Btu. Therefore, from the year 1996-2010, in Nigeria, 12,602,480.25 million  $ft^3$  of natural gas was flared. This is equivalent to losing about 12,967.952 × 10<sup>12</sup> Btu of energy that would have been used for something profitable.

## 2.1. Flare Stack Configuration

A gas flare, which can also be referred to as a flare stack, is a gas combustion device used in industrial plants such as petroleum refineries, chemical plants, and natural gas processing plants as well as at oil or gas production sites having oil wells, gas wells, offshore oil and gas rigs and landfills.

In industrial plants, flare stacks are primarily used for burning off flammable gas released by pressure relief valves during unplanned over-pressuring of plant equipment. During plant or partial plant startups and shutdowns, flare stacks are also often used for the planned combustion of gases over relatively short periods. When industrial plant equipment items are over-pressured, the pressure relief valve is an essential safety device that automatically releases gases and sometimes liquids. Those pressure relief valves are required by industrial design codes and standards for safety purposes [6].

The released gases and liquids are routed through large piping systems called flare headers to a vertical elevated flare. The released gases are burned as they exit the flare stacks. The size and brightness of the resulting flame is a function of the flammable material's flow rate in joules per hour (or Btu/hour).

Steam is very often injected into the flame to reduce the formation of black smoke. When too much steam is added, a condition known as "over steaming" can occur resulting in reduced combustion efficiency and higher emissions. To keep the flare system functional, a small amount of gas is continuously burned, like a pilot light, so that the system is always ready for its primary purpose as an over-pressure safety system.

The flow diagram in Figure 1 depicts the typical components of an overall industrial flare stack system and the major components of a flare stack are:

- Knockout drums to remove any oil and/or water from the relieved gases.
- A water seal drum to prevent any flashback of the flame from the top of the flare stack.
- An alternative gas recovery system for use during partial plant startups and/ or shutdowns as well as other times when required. The recovered gas is routed into the fuel gas system of the overall industrial plant.
- A steam injection system to provide an external momentum force used for efficient mixing of air with the relieved gas, which promotes smokeless burning.
- A pilot flame (with its ignition system) that burns all the time so that it is available to ignite relieved gases when needed.
- The flare stack, including a flashback prevention section at the upper part of the stack.



Figure 1. Schematic flow diagrams of an overall vertical, elevated flare stack system.



There is also a safe method to divert the flare gas which is insertion of Liquid U seal with Liquid Hold up vessel. The Liquid U seal is designed to take pressure up to permitted back pressure of the system. This helps to divert the flare gas to recovery system. In case of plant upset, pressure rises and liquid in the U seal will move into Liquid Hold up vessel. On normalization, the Liquid U seal will start diverting the gas again.

## 2.2. Effects of Natural Gas Flaring

Gas flaring is one of the most challenging energy and environmental problems facing the world today. Environmental consequences associated with gas flaring have a considerable impact on local populations, often resulting in severe health issues. Generally, gas flaring is normally visible and emitted both noise and heat [7]. The effects of gas flaring are:

## 2.2.1. Climate Change

Gas flaring has serious implications on climate change. The burning of fossil fuel, mainly coal, oil and gas has led to warming up the earth and is projected to get worse according to the inter-governmental panel on climate change (IPCC). Climate change is particularly serious for developing countries, and Africa as a continent is regarded as highly vulnerable with limited ability to adapt. Gas flaring contributes to climate change by emission of carbon dioxide, the main greenhouse gas. Venting of the gas without burning, a practice for which flaring seems often to be treated as a synonymy, releases methane, the second main greenhouse gas.

#### 2.2.2. Acid Rain

The primary causes of acid rain are emissions of sulphur dioxide  $(SO_2)$  and nitrogen oxides (NO) which combine with atmospheric moisture to form sulfuric acid and nitric acid respectively. These acidify lakes and streams and damage vegetation. In addition, acid rain accelerates the decay of building materials and paints. Prior to falling to the earth,  $SO_2$  and  $NO_2$  gases and their particulate matter derivatives, sulfates and nitrates, contribute to visibility degradation and harm public health.

#### 2.2.3. Effects on Agriculture

The flares give rise to atmospheric contaminants. These include oxides of Nitrogen, Carbon and Sulphur,  $(NO_2, CO_2, CO, SO_2)$  particulate matter and hydrogen sulphide  $(H_2S)$ . These contaminants acidify the soil, hence depleting soil nutrient. In some cases, there is no vegetation in the areas surrounding the flare due to the tremendous heat that is produced and acid nature of soil pH. The effects of the changes in temperature on crops include stunted growth, scotched plants and such other effects as withered young crops.

#### 2.2.4. Pollution

Gas flaring leads to the emission of pollutants which are harmful to both humans and the society at large. Incomplete combustion of gas leads to the production of carbon monoxide which is one of the major pollutants with adverse effects on human health and the society at large. The economic and environmental ramifications of this high level of gas flaring are serious because this process is a significant waste of potential fuel which is simultaneously polluting water, air, and soil

## 2.2.5. Health Implications

The implication of gas flaring on human health are all related to the exposure of those hazardous air pollutants emitted during incomplete combustion of gas flare. These pollutants are associated with a variety of adverse health impacts, including cancer, neurological, reproductive and developmental effects. Deformities in children, lung damage and skin problems have also been reported. Hydrocarbon compounds are known to cause some adverse changes in hematological parameters. These changes affect blood and blood-forming cells negatively. Aside the health and environmental consequences of gas flaring, there are also loses of billions of dollars' worth of gas which is literally burnt off daily in the atmosphere. Much of this can be used for secondary oil recovery as well as to power he oil platforms through gas turbines and other means. Some can be converted for domestic use, LNG, CNG gas-to-liquid and for electricity generation [8].

# 3. Alternative Solutions to Gas Flaring

Flaring of natural gas doesn't solve any problem on the other hand, it creates more problems. It affects lives of people and pollutes the environment. There are so many alternative solutions to gas flaring. The different alternative solutions are as follows;

## 3.1. Reinjection for Secondary Oil Recovery

Natural gas produced in association with crude oil can be used for either gas injection or gas lift which is more profitable and economical compared to gas flaring. Gas injection is when gas is introduced into a depleted oil reservoir in order to increase the pressure within the reservoir and thereby increase the production of crude oil from the reservoir. This is not to be confused with gas lift, where gas is injected into the annulus of the well rather than the reservoir. After the crude has been pumped out, the natural gas is once again recovered. Since many of the wells found around the world contain heavy crude, natural gas can be used to increase the production of this heavy crude.

The process of injecting natural serves as a way of increasing the pressure in the oil well, thus causing more gas molecules to dissolve in the oil lowering its viscosity and thereby increasing the well's output. Air is not suitable for repressuring wells because it tends to cause deterioration of the oil, thus carbon dioxide or natural gas is used for this process.

## 3.2. Source of Energy and Feedstock for Petrochemical Plants

Natural gas is most times referred to as "clean burning" because it produces



fewer undesirable by-products per unit energy than coal or oil. Like other fossil fuels, its combustion emits carbon dioxide, but at about half the rate of coal per kilowatt hour of electricity generated. It is also more energy efficient [9].

Natural gas is a major source of electricity generation through the use of cogeneration, gas turbines and steam turbines. It is also well suited for a combined use in association with renewable energy sources such as wind or solar. Particularly high efficiencies can be achieved through combining gas turbines with a steam turbine in combined cycle mode. Natural gas burns more cleanly than other hydrocarbon fuels, such as oil and coal, and produces less carbon dioxide per unit of energy released. For an equivalent amount of heat, burning natural gas produces about 45 percent less carbon dioxide than burning coal for power. The US Energy Information Administration reports the following emissions in million metric tons of carbon dioxide in the world for 2012:

- 1) Natural gas: 6799.
- 2) Petroleum: 11,695.
- 3) Coal: 13,787.

Natural gas is also useful for domestic purposes. If dispensed in a residential setting, can generate temperatures in excess of 1100°C (2000°F) making it a powerful domestic cooking and heating fuel. In much of the developed world it is supplied through pipes to homes, where it is used for many purposes including ranges and ovens, gas-heated clothes dryers, heating/cooling, and central heating. Heaters in homes and other buildings may include boilers, furnaces, and water heaters.

Natural gas is a major feedstock for the petrochemical plants. It is used in the production of ammonia, via the Haber process, for making fertilizers. It is also used to produce hydrogen, with one common method being the hydrogen reformer. Hydrogen has many applications: it is a primary feedstock for the chemical industry, a hydrogenating agent, an important commodity for oil refineries, and the fuel source in hydrogen vehicles. Natural gas is also used in the manufacture of fabrics, glass, steel, plastics, paint, and other products.

#### 3.3. Liquefied Natural Gas (LNG)

Another alternative solution to gas flaring is to liquefy the gas and stored in vessels or bottles as liquid natural gas. This is relatively safer and more economical compared to flaring of gases. The natural gas produced from either a gas well or in association with crude oil production can be liquefied in series of processes. And in most cases, start with the removal of impurities like water, acid gases among others produced with the gas. Solid particles may also be present in the produced gas and must be removed before processing to maximize the mechanical efficiency the LNG equipment. The major composition of natural gas is methane and for liquefaction to occur *i.e.* to liquefy methane gas, the temperature of the system must be brought down to  $-160^{\circ}$ C. This of course is also a function of other factors such as the components part of the gas to be liquefied. The stored LNG can be used domestically and also for industrial purposes.

also create jobs and reduce the amount of pollutants released into the environment due to gas flaring. **Figure 2** shows the major breakdown/subsystems of the LNG system.

## 3.4. Compressed Natural Gas (CNG)

Compressed natural gas refers to methane stored at high pressure. It is made by compressing natural gas to less than 1% of the volume it occupies at standard atmospheric pressure. It is stored and distributed in hard containers at a pressure ranging from 20 - 25 MPa, usually in cylindrical or spherical shapes. In transportation, natural gas is used either as CNG or as liquefied natural gas (LNG) [10]. Because natural gas has a lower energy density than liquid petroleum fuels, it is either compressed or liquefied to store more energy. Therefore, to use natural gas, vehicles must have a CNG- or LNG-specific fuel storage and delivery system installed. The cost and placement of fuel storage tanks is the major barrier to wider/quicker adoption of CNG as a fuel.

CNG is also used in internal combustion engine automobiles that have been modified or in vehicles which were designed for CNG use, either alone or with a segregated gasoline system to extend range or in conjunction with another fuel such as diesel. Natural gas vehicles are increasingly used in different countries like Iran, Pakistan, and some parts in South America, Europe and North America because of rising gasoline prices and availability of natural gas. On CNG vehicles, natural gas must be compressed before being stored on the vehicle. This compression takes place at the fueling site, using specialized equipment.

In **Figure 3**, the costs of CNG are compared with those of Gasoline and Diesel fuels in United State, from 2006-2012. CNG vehicles can generally be operated longer between oil changes because natural gas produces less soot and combustion by-products. Gaseous fuels also do not "wash" the lubrication from the cylinder walls, so cylinder and ring wear are significantly reduced. This increases the engine overhaul interval-some CNG users have reported engine overhaul intervals two to three times greater than gasoline vehicles running similar duty cycles. The United States Environmental Protection Agency regulates emissions for all vehicles in the United States. In recent years, the emissions benefits of natural gas fueling have been reduced because all vehicles are held to higher standards [11]. Using CNG reduces some regulated emissions, including hydrocarbons, oxides of nitrogen, and carbon monoxide. These reductions differ based on the type of vehicle and its duty cycle.

#### 3.5. Natural Gas in Transportation

Natural gas can serve as an oil replacement in transportation markets in three









Figure 3. Costs of CNG compared to gasoline and diesel fuels in united state.

ways. Firstly, natural gas can be converted to methanol—an alcohol with similar properties to ethanol—that can be burned in internal combustion engines with slight vehicle modifications.

Secondly, light- and medium-duty vehicles using existing engine technologies can also burn compressed natural gas (CNG). Here the natural gas is stored at pressure, typically around 3000 psi. Because of the pressure, the CNG storage tanks are larger than existing gasoline storage tanks, so vehicles often have less trunk space and can cover less distance than conventional gasoline cars without refueling [12]. The Honda Civic GX, currently sold in the United States, for example, has a CNG capacity equivalent to eight gallons of gasoline. A number of CNG vehicles sold in Europe are bi-fuel vehicles capable of burning both CNG and gasoline in their engines, When the CNG tank empties, and the engine shift to the gasoline tank for fuel. Bi-fuel vehicles will frequently use gasoline first because the cold-start properties of gasoline are better than CNG.

Thirdly, medium- and heavy-duty vehicles can run off of either CNG or liquefied natural gas (LNG), which is stored at very low temperatures ( $-160^{\circ}$ C). The advantage of LNG over CNG is that it requires 30 percent less space allowing for longer driving distances. One disadvantage of LNG is that storing it for long periods is expensive, therefore LNG is often considered as a replacement fuel for vehicles that are in continuous use (e.g., heavy duty). Most industry followers envision LNG technologies as the likely replacement for diesel in the largest classes of heavy-duty vehicles [13].

#### 3.6. Gas Hydrate

Methane hydrate, commonly known as Gas hydrate is an ice-like crystalline compound formed when natural gas and water molecule exist together at relatively low temperature and high pressure. It is an assemblage of methane molecule ( $CH_4$ ) that is bounded within the cage-like structure (crystal lattice) formed

by water molecule (H<sub>2</sub>O). Gas hydrate is relatively stable above the freezing point of water and sufficiently high pressure. It is relatively stable under its saturation temperature and pressure and also much denser than normal ice.

In the sea bed, once the methane is saturated in ocean with the appropriate temperature and pressure, ice crystal will start to grow into a gas-like lattice that traps the dissolved methane. There is actually no major chemical bond between the water molecule and methane other than Van der Waals forces. But the major influence is the presence of a guest molecule inside the ice crystals that increases the melting point of ice to several degrees above 0°C and makes the structure more stable. This property of gas hydrate can be experimentally investigated and capitalized on, to effectively store natural gas as hydrate for energy conservation instead of flaring the gas wastefully. Figure 4 shows the crystalline cage-like structure formed when water molecules formed crystal lattice around methane gas.

The research work conducted by Belosludov et al., showed that the thermal expansion of methane hydrate is considerably larger than that of ice of relatively same quantity. For practical application, clathrate hydrates can be used as storage materials but it is vital to know the different temperatures and pressure where the compound is stable [14]. It was discovered that methane hydrate is thermodynamically stable under overheating. This was due to the fact that the thermal expansion of the hydrate is much larger than that of ice. The thermal expansion of methane hydrate increases with that of ice because it can stay in a region of stability on methane hydrate phase diagram.

Gas hydrate has been one of the major problems of multiphase flow in regions where low temperature exists and different approaches are been conducted to prevent it formation. But in recent years, it was discovered that gas hydrate deposits hold enormous amount of energy which when trapped can solve the problem of energy generation in the world. This has led to the exploration of gas hydrate deposits. A sample of crystalline methane hydrate is shown in **Figure 5**.



Figure 4. Gas hydrate cage-like structure (green: methane, red: water).





Figure 5. Sample of methane gas hydrate crystals.

The experimental work conducted by Ruffine *et al.* showed that when the pressure and temperature in the gas hydrate system are increase, and if the ice structure surrounding the hydrate is stable to some extent, the methane hydrate will have larger pressure than the ice phase [15]. Their experiment depicted the function of the hydrate skin, somewhat, as a barrier, and the effect of breaking that barrier on the kinetics of the hydrate-ice structure in a closed system. This property needs to be taken into consideration when developing any kind of hydrate-based technology for natural gas transportation and storage. This also occurs during hydrate formation within sediments and is one of the reasons free gas exists within the gas hydrate stability zone.

In **Figure 6**, the stability of methane hydrate at different temperature and pressure is depicted. The gas hydrate is stable at relatively low temperature and high pressure but when the temperature increases and the pressure reduces, the hydrate dissociate into gas and water.

# 4. Conclusions

Gas flaring has more negative impacts than the positive impacts. It pollutes the environment and also affects the health of people in the areas in which gas flaring is practiced. It can be convincingly said that gas flaring is an intentional wasting of abundant resources which can meet the different challenges facing the society at large, in terms of power generation, energy conservation, global warming of the earth among others. From the year 1996-2010, in Nigeria, 12,602,480.25 million  $ft^3$  of natural gas was flared (NNPC). This is equivalent to losing about 12,967.952 × 10<sup>12</sup> Btu of energy that would have been used for something profitable.

There are different ways the produced gas can be used instead of discarding it by flaring. Utilizing the gas in a safer way can solve the problems of energy generation, greenhouse effects and also create a safer environment. The produced gas can serve different purposes instead of being flared. It can be as simple as



Figure 6. Gas hydrate phase diagram showing its stable conditions.

using the gas to increase oil production, channeling the produced gas to power the oil and gas platform, and manufacturing of petrochemical products, as well as electricity generation and also fueling of automobiles.

The proposed alternative solutions are gas for secondary oil recovery, feedstock for petrochemical plants, domestic uses, LNG & CNG, as well as energy conservation by storing as gas hydrate for future use or other purposes. Gas hydrate is relatively stable under its saturation temperature and pressure and also much denser than normal ice. This property of gas hydrate can be used to effectively store the produced gas as hydrate for energy conservation instead of flaring. The alternative solutions will convincingly reduce gas flaring and create rooms for innovation and development that will ultimately stop gas flaring.

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