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Real- Time Monetization of the Flared Associated Stranded Natural Gas in Nigeria: Quantitative Analysis and Qualitative Values

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Abstract:
Repeatedly, through various medium, a lot of people have stated the daily, monthly and yearly quantities of the Nigerian Associated Natural Gas being flared, as well as the financial losses associated with the continued flaring, the possible alternative power and industrial values of the flared natural gas, the environmental and health impacts associated with flaring. This research paper is the first of more then, six papers in series, designed to evaluate the exact real-time quantitative analysis and establish the exact real-time qualitative values of the associated stranded natural gas flared by any particular flare line, hence, inform the development of the possible micro skid mounted/modular processing unit for that particular flare line. Each flare line could be proposed to mainly yield a specified end-product such as; Liquefied Natural Gas (LNG), Liquefied Petroleum Gas (LPG), conversion to synthetic liquids (GTL-gasoline, diesel etc), generation of electricity (power), raw materials (chemical feedstocks) for the chemical industry (i.e. for the manufacture of chemicals especially synthetic organic chemicals), thus making impact on secondary heavy industries that rely mainly on chemical industry for their raw materials, such as those manufacturing textiles, especially the artificial fibres, plastics of all description, rubber, nitrogen fertilizers, dyestuffs, detergents and pharmaceuticals. This opening paper gives an overview of the associated stranded natural gas that is currently flared or vented as well as the various Acts, Decrees, Agreements, Budget Pronouncement and penalties issued by the Nigerian Government starting from Decree 99 referred to as "associated gas re-injection Act of 1979" to the 1999 monetization policy that made the biggest impact. This paper also, contains the overview of the varying composition of natural gas depending on the source, the statistically computed typical composition (mole %) of the flared associated stranded natural gas in Nigeria and the computed possible sweetened quantitative real-time daily, monthly and yearly quantities of the various components of the flared associated stranded natural gas, expected to yield the various useful qualitative end products for monetization. Generally, this is expected to achieve zero point to point associated stranded natural gas flaring.

Keywords: Achieve zero point to point associated gas flaring, Monetization, qualitative values, quantitative analysis, statistically computed typical composition, Stranded Natural Gas.

1. Introduction

In the early days of the petroleum industry gas and crude oil were described as separate and distinct substances (katz et al., 1959), because, the shallow wells then in production either delivered natural gas or produced crude oil. With increased depth at which oil and gas were found, it was noticed that natural gas usually accompanied crude oil while hydrocarbon liquids on the other hand, usually condenses from natural gas. The term "petroleum" because the generic name covering the naturally occurring hydrocarbons (crude oil or natural gas)

Petroleum exist in all the three physical states of nature, i.e. as gas, liquid, semisolid or solid (Amyx et al., 1960; Gatlin, 1960; Levorsen, 1967). The number of carbon atoms present, determines the state, thus, gaseous state petroleum (C_1- C_4): natural gas, distillate or condensate gas or condensable vapour; liquid state petroleum ($C_5 – C_{17}$): crude oil, and waxy solid –semisolid/solid state petroleum (above C_{18}): bitumen, asphalt, coal tar, shale oil et cetera.

Conventionally, all petroleum reservoirs occurring in any of the physical states with few exceptions contain some natural gas, which is commonly measured in cubic feet, and the gas volume written in multiples of 1,000 abbreviated as M (Ikoku, 1980). The natural gas content of a petroleum reservoir may range from minute quantity dissolved in the petroleum i.e. a few cubic feet of gas in solution, to thousands of cubic feet per barrel and up to 100 % of the petroleum content. Previously, the oil and gas industry, distinguish between low pressure gas wells (10psi to 100psi); intermediate pressure gas wells (100psi to 500psi) and high-pressure gas/condensate wells (500psi to 1500psi). Nowadays as a result of the increased offshore and deeper drilling operations, higher temperatures and pressures are encountered at increasing depths. Particularly, reservoirs with pressures in excess of 10,000psi and temperatures more than 330 F or 166 C have been exploited in search of gas. Under reservoir conditions of high pressure (greater than 5000 to 6000 psi), and high

temperature, i.e. greater than 300 F or 150 C (petroWiki, 2015), natural gas and crude oil become physically indistinguishable. Ultra-high pressure, high temperature (UHPHT) reservoirs exist at pressures greater than 12,500psi and temperatures greater than 330 F or 166 C (Institution of Environmental Sciences, 2014).

In most cases, where the amount of natural gas solution is small, it is permitted to pass off into the air as the petroleum is produced, but where it is somewhat larger, the custom is to separate the crude oil and the natural gas and either burn the natural gas in flares (Levorsen, 1967), so as to prevent its accumulating in dangerous quantities in low places at the surface of the ground or it is saved and sold, used as a source of power on the property, or re- injected into the petroleum reservoir (for pressure maintenance or repressuring).

Stranded natural gas refers to natural gas that is wasted or unused (Lake and Warner Jr.,2007) i.e., that has been discovered but is not, or will not be developed due to their location or the economy of getting the natural gas delivered to the market place. Thus, we distinguish between the associated stranded (flared or vented) natural gas and the stranded natural gas reserve. Approximately 40 per cent of the world's available natural gas reserves 6846 trillion cubic feet (TCF) are classified as stranded natural gas, and statistically, the United States Department of Energy estimates show global stranded reserve totals of over 3,000 TCF, which, if captured and converted, the gas would make (after conversion losses) 300 billion barrels synthetics, from clean-burning diesel to jet fuel, almost equivalent to the Saudi Arabia's crude oil potential.

Associated stranded natural gas flaring has been a major problem in the petroleum world. It dates back to the very first production well and it is still a common and continuous exercise despite the huge amount of revenue lost as a result of this practice.

In Nigeria, associated stranded natural gas flaring commenced in 1956 with the first successful well drilled at Oloibiri by Shell D' Acry, (Ekejiuba,1990) present day Shell Petroleum Development Company (SPDC). Until 1984, the country flared (ignited) or vented (un-ignited) virtually all the produced associated stranded natural gas despite the fact, that in 1979 the Nigerian Government issued Decree 99 referred to as "associated gas-injection Act of 1979" (NNPC monthly petroleum information,1989; Aniefiok and Ibok,2013). The Act required the petroleum producing companies to either re-inject the gas or utilize it for industrial purpose and the penalty for non-compliance after 1st January, 1985 was forfeiture of license to operate. But early in December, 1984, the then minister of petroleum and Energy rationalized the decree, leading to the regulations, known as either the "associated gas re-injection (continued flaring of gas) regulation 1984" or "associated gas re-injection (amendment) decree, 1985", which spelt out the conditions for issuance of certificates by the minister to permit the continued flaring of gas in particular field or some fields by companies engaged in the production of petroleum. The regulations came into force on 1st January, 1985(Nigerian Petroleum News, 1989).

Under this arrangement, operators should pay a penalty of two kobo (Ekejiuba, 1990;Onyekonwu, 2008) for every thousand cubic feet (2k /M scf equivalent of U.S 4 sents/ M scf) of gas flared, and about 86 of the existing 120 producing fields then, would be exempted because it was observed that the issue of gas re-injection entailed certain problems which include the fact that not every reservoir is suitable for gas storage, in which case, re-injection may even adversely affect the production of petroleum. The penalty was increased to 50 kobo/ M scf in 1992, and subsequently to N10/M scf in 1998 and in 1999, to N20 /M scf.

That, not withstanding, until 1999, the country still flared well over 70 per cent of the associated stranded natural gas.

Notably, as a result of the decree in 1985, Nigerian Agip Oil Company (NAOC) in the same year 1985, built the first natural gas recycling plant at Akri- Oguta (in joint venture with Shell). Also in 1985 NAOC constructed the Obiafu-Obikom Gas plant, with initial capacity of 270 MM scf per day, which was later upgraded to 400 MM scf per day. This was followed by the Kwale – Okpai Gas plant in 1987, with capacity for 75 MM scf per day, and later upgraded to 150 MM scf per day. No other petroleum producing company in Nigeria made any positive move to conserve the flared gas, up to the late 1990's (Ekejiuba,1990), when on the other hand, government realized that the continued high gas flare was essentially because the economy lacks the consumptive capacity to utilize this magnitude of gas (i.e. low level of industrialization), as well as the fact that the economic development of gas project depends on long term gas sales contracts fixed for at least 20 years at stable prices with specialized processing installations and vessels required for development and transportation of gas to the markets.

Based on the foregoing, government saw the need to proved incentives through series of Acts, Agreements and Budget pronouncement, all aimed at, attracting investors in the development and utilization of gas in the country. Such gas incentives (NAPIMS,2016; Investment Incentives) are summed up in the following:

    (a) Nigerian liquefied Natural Gas (NLNG) Act 1990.
    (b) Associated Gas Framework Agreement (AGFA) 1991/1992
    (c) Financial (Miscellaneous Taxation Provision) Act 1998
    (d) Financial (Miscellaneous Taxation Provision) Act 1999
    (e) 1999 FGN Budget etc.

Some of the incentives are: Tax free (holiday) period of 3-5 years; import duty exemption on plant/machinery/ equipment; investment Tax credit; zero % Royalty; Capital Allowance; Tax deductible interest on loan for Gas project investment; Tax Rate etc. (Ososami,2008; Nigerian Investment Promotion Commission,).

It is this monetization policy that made the biggest impact, because it resulted in an influx of investors into the Nigerian gas industry, which reduced associated stranded natural gas flaring drastically from 70 % in 1999 to between 43-52 per cent in 2004, about where, it still remains up-to-date, while the penalty for gas flaring increased to $3/M scf in 2010 and currently it officially stands at $ 3.50/M scf., since 15 August 2011 (Ofoegbu, 2015).

According to Shell Petroleum Development Company (SPDC), on the average, about 1,000 scf of gas is produced in Nigeria with every barrel of oil.

With the continuous flaring of about 50 % of associated stranded natural gas, especially in Nigeria (Images), where the light crude contains substantial amount of the associated stranded natural gas, the importance of an alternative to flaring the associated stranded natural gas can hardly be over-emphasized.

At different times, various estimates have stated the daily, monthly and yearly quantities (Ejoh, 2016) of the associated natural gas being flared, as well as the financial losses (Eboh,2015; Okere,2015; Obasi,2017; Today,2017; Sweetcrude reports,2017) associated with the continued flaring, the alternative power (Ofoegbu,2015; Vangard,2016) and industrial values of the flared natural gas, the environmental and health impacts (Agbo,2008; Ite and Udo,2013; Mba,2015) associated with flaring.

On monetizing low volume associated gas (Rao, 2016) stated that, there is a truism in chemical processing: size matters. Bigger is better for economies of scale. Consequently, conventional processes fail to address the unique needs of low volume natural gas to be converted to something movable and saleable. His investigation revealed that the majority of, flared natural gas is from pads, producing as little as less than 50 MCF/D (50,000 cubic feet per day) to 200 MCF/D (200,000 cubic feet per day). Further, (Layfield, 2016) stated that existing solutions are mature for large-scale applications, but fewer technologies have been used commercially at a small scale.

The purpose of this research work is to initiate a new method of conserving the currently flared associated stranded natural gas by statistical determination of the exact real-time composition and other parameters of the continuously flared associated stranded natural gas in Nigeria. This is expected to reveal/highlight the actual quantities of the various components in the flare line flow stream, available for conversion or use to produce any of the numerous end-products of natural gas via small-scale chemical processing applications.

Subsequent research works would be aimed at developing customized scaled down processing units (plants) for each particular flare line stream (location), mainly for the production of one specific end product, such as power electricity generation, production of synthetic nitrogen fertilizer, conversion to synthetic liquid fuels (GTL- diesel ,gasoline, etc.),production of liquefied petroleum gas (LPG) ,production of liquefied natural gas (LNG),conversion of condensed natural gas liquids (NGLs) to petrochemical and chemical raw material/feedstock, integrated power/nitrogen fertilizer/GTL, against the usual conventional approach of central processing plant with bulk stream collections from various flare lines.

2. Background

Virtually hundreds of different compounds may be present in natural gas in varying amounts, such that, even two wells producing from the same reservoir may produce gases of different, composition as the reservoir is depleted, and also each gas stream produced from a well can change composition as the natural gas reservoir is depleted. Thus, there is no one composition or mixture that can be referred to as the natural gas since each stream produced has its own composition (Ikoku, 1980).

The major components in most natural gases are paraffin hydrocarbons with smaller amounts- usually only trace, of Olefin hydrocarbons, naphthenic hydrocarbons, mercaptans, and non- hydrocarbon compounds. Primarily natural gas is made up of methane (CH_4) with minor amounts of ethane (C_2H_6), propane (C_3H_8), butanes, pentanes, hexane, heptane, octane and heavier hydrocarbons. While the non-hydrocarbons components are: Nitrogen (N_2), carbon dioxide (CO_2), Hydrogen sulfide (H_2S), Helium (He), water vapour (H_2O), carbonyl sulfide (COS), carbon disulfide (CS_2), sulfur (S), mercaptans (RSH) e.g. methyl mercaptan and ethyl mercaptan.

Compositional analysis of natural gases is readily obtained by low-temperature distillation (fractionation), gas chromatography, analytical mass spectrometry and infrared absorption spectrometer (Katz et al., 1959) while the volume or mole percentages of the individual components present are ordinarily reported through heptanes plus. The heptanes-plus fraction includes heptanes and all heavier hydrocarbons, since usually, most of the trace components are insignificant. However, the presence of traces can be of extreme significance in process design.

Table 1 (Ikoku, 1980) shows some typical natural gas streams. Well stream 1 is typical of an associated gas, i.e., gas produced with crude oil. Well streams 2 and 3 are typical non- associated low-pressure and high-pressure gases respectively.

Component	Well No 1 Mol. %	Well No 2 Mol. %	Well No 3 Mol. %
Methane	27.52	71.01	91.25
Ethane	16.34	13.09	3.61
Propane	29.18	7.91	1.37
i-butane	5.37	1.68	0.31
n-butane	17.18	2.09	0.44
i – Pentane	2.18	1.17	0.16
n – Pentane	1.72	1.22	0.17
Hexane	0.47	1.02	0.27
Heptanes and heavier	0.04	0.81	2.42
Carbon Oxide	0.00	0.00	0.00
Hydrogen Sulfide	0.00	0.00	0.00
Nitrogen	0.00	0.00	0.00
Total	100.00	100.00	100.00

Table 1: Typical Natural Gas Analyses

NB: Production from many wells will contain small quantities of carbon dioxide, hydrogen sulfide, and nitrogen.

Source: Adapted from Ikoku, 1980.

3. Material

Chemical analysis using gas chromatography of the Nigerian flared Associated stranded natural gas composition (mole %) for 150 samples obtained from the various operating petroleum companies in Nigeria shows that methane values ranges from (61.18 to 92.21 %), ethane (2.07 to, 15.32 %), propane (0.29 to 12.44 %), iso- butane (0.22 to 5.12 %), normal- butane (0.15 to 5.04 per cent), iso-pentane (0.06 to 2.10 per cent), normal pentane (0.04 to 1.47 %), heptane –plus (0.02 to 3.29 %), carbon dioxide (0.35 to 9.97 per cent), nitrogen (0.00 to 1.10 %), gas gravity (0.607 to 0.996) and flow rate 5 to 63 MM scfd (0.1415 to 1.7829MM m^3/d).

Table 2 shows the data record for 36 of the samples used for the statistical computation of the individual components average percentage (tables 4 to 14). This results to the typical representative flare stream composition table 15 and conditions table 16, for average process plant design purposes. While table 3 shows 10 of the samples with flow rate indicated.

Practically, there are currently about 257 flow stations (with flare lines) in Niger Delta excluding flares at refining points, terminal operations, and over 100 offshore platforms etc. Therefore, in all, we expect to have between 350-500 associated stranded natural gas flare lines in Nigeria, with each burning between 5MM scf to 63MM scf of associated natural gas daily.

Sample No	C_1	C_2	C_3	iC_4	nC_4	iC_5	nC_5	C_{6+}	Co_2	N_2	Gravity (Air+1)
1	76.04	10.27	5.27	1.09	1.39	0.43	0.30	3.29	1.89	0.03	0.831
2	68.01	7.27	10.99	2.75	4.83	1.48	1.16	1.56	1.68	0.04	0.916
3	66.11	7.58	8.47	3.01	4.18	1.84	1.47	6	1.26	0.08	1.032
4	83.82	7.01	3.83	0.85	1.21	0.43	0.34	0.95	1.56	0.00	0.712
5	68.53	15.32	9.51	2.02	2.31	0.73	0.47	0.69	0.36	0.02	0.628
6	75.08	10.09	6.11	1.39	2.21	0.79	0.68	2.09	1.52	0.04	0.817
7	78.87	6.12	5.37	2.34	2.53	1.22	0.83	1.74	0.93	0.05	0.803
8	71.41	12.69	9.04	1.85	2.66	0.75	0.51	0.71	0.35	0.03	0.816
9	63.62	11.06	11.84	2.71	4.99	1.55	1.36	2.08	0.70	0.09	0.955
10	75.04	9.07	7.42	2.06	2.34	1.67	0.53	1.19	0.52	0.02	0.815
11	71.18	9.63	8.86	2.11	3.35	1.12	0.96	1.41	1.14	0.06	0.856
12	61.18	10.59	12.44	3.54	5.04	1.83	1.07	0.88	1.67	0.34	0.981
13	92.45	4.79	0.74	0.22	0.22	0.08	0.06	0.45	1.02	0.33	0.607
14	61.80	6.82	14.15	5.12	6.04	2.10	1.19	1.28	.00	0.50	0.996
15	70.72	12.75	8.16	1.99	2.50	0.88	0.61	1.21	.00	0.18	0.832
16	88.68	4.60	0.55	0.33	0.22	0.14	0.11	0.14	5.13	0.10	0.647
17	88.75	4.55	0.45	0.34	0.22	0.14	0.12	0.16	5.10	0.08	0.648
18	90.37	4.83	0.73	0.23	0.16	0.06	0.04	0.03	3.52	0.03	0.626
19	65.35	9.56	11.08	2.21	3.90	1.04	0.93	1.62	3.86	0.45	0.918
20	70.98	9.46	9.42	2.59	2.52	0.45	0.35	0.16	4.61	0.45	0.840
21	81.26	4.84	2.43	0.31	0.60	0.18	0.15	0.19	9.97	0.07	0.792
22	80.67	7.72	6.62	1.12	1.56	0.35	0.26	0.50	0.90	0.30	0.737
23	87.66	6.18	3.27	0.53	0.75	0.17	0.14	0.38	0.63	0.29	0.662
24	80.88	6.92	5.68	1.52	1.73	0.55	0.42	0.63	1.32	0.36	0.748
25	66.09	12.75	11.00	2.46	3.23	0.89	0.61	0.71	2.21	0.05	0.874
26	79.59	8.76	5.63	1.16	1.30	0.34	0.23	0.27	1.65	1.07	0.725
27	75.47	8.54	8.59	1.64	2.51	0.68	0.51	0.72	1.34	0.00	0.793
28	85.53	7.04	2.93	0.49	0.61	0.26	0.17	0.66	2.31	0.00	0681
29	75.04	8.73	8.85	1.69	2.61	0.66	0.50	0.34	1.53	0.04	0.790
30	90.34	5.17	2.39	0.38	0.67	0.17	0.14	0.02	0.68	0.04	0.630
31	82.95	8.26	4.37	0.86	1.25	0.40	0.29	0.21	1.33	0.08	0.698
32	82.02	6.93	5.65	1.07	1.90	0.52	0.42	0.63	0.71	0.34	0.721
33	81.54	7.62	4.83	1.46	1.50	0.67	0.35	1.15	0.78	1.10	0739
34	83.22	8.84	3.22	0.77	0.85	0.31	0.20	0.49	2.04	0.06	0.693
35	92.21	3.69	1.28	0.36	0.45	0.16	0.12	0.25	1.37	0.11	0.621
36	92.06	2.07	0.29	0.60	0.15	0.21	0.08	0.27	3.95	0.32	0.630

Table 2: Flare Stream Compositions (mole percent)

	1	2	3	4	5	6	7	8	9	10
C_1	61.18	63.62	68.53	71.18	75.08	79.59	83.02	88.68	90.37	92.21
C_2	10.59	11.06	15.32	9.63	10.09	8.76	8.84	4.60	4.83	3.69
C_3	12.44	11.84	9.51	8.86	6.11	5.63	3.22	0.55	0.73	1.28
iC_4	3.54	2.71	2.02	2.11	1.39	1.16	0.77	0.33	0.23	0.36
nC_4	5.04	4.99	2.31	3.35	2.21	1.30	0.85	0.22	0.16	0.45
iC_5	1.83	1.55	0.73	1.12	0.79	0.34	0.31	0.14	0.06	0.16
nC_5	1.07	1.36	0.47	0.96	0.68	0.23	0.20	0.11	0.04	0.12
C_6^+	0.88	2.08	0.69	1.41	2.09	0.27	0.49	0.14	0.03	0.25
C_{02}	1.67	0.70	0.36	1.14	1.52	1.65	5.04	5.13	3.52	1.37
N_2	0.37	0.09	0.02	0.06	0.04	1.07	0.06	0.10	0.03	0.11
Gravity	0.981	0.955	0.628	0.856	0.856	0.725	0.643	0.647	0.626	0.621
Rate	30	27	63	55	50	48	29	44	38	25

Table 3: Flare stream compositions (mol. Percent) and flowrate (MMscfd)

C_1	No of Samples	C_1 Mid Value	f_i Frequency	$C_1 f_i$
60-65	3	62.5	0.083	5.1875
65-70	5	67.5	0.139	9.3825
70-75	4	72.5	0.111	8.0475
75-80	7	77.5	0.194	15.035
80-85	8	82.5	0.222	18.315
85-90	4	87.5	0.111	9.7125
90-95	5	92.5	0.139	12.8575
	36		0.999	78.5375

Table 4: Statistical Computation of Average for Methane

C_2	No of Samples	C_2 Mid Value	f_i Frequency	$C_2 f_i$
Less than 3	1	1.5	0.028	0.042
3-5	6	4	0.167	0.668
5-7	6	6	0.167	1.002
7-9	11	8	0.305	2.44
9-11	7	10	0.194	1.94
11-13	4	12	0.111	1.332
13+	1	13	0.028	0.364
	36		1.000	7.788

Table 5: Statistical Computation of Average for Ethane

C_3	No of Samples	C_3 Mid Value	f_i Frequency	$C_3 f_i$
Less than 1	5	0.5	0.139	0.0695
1-3	4	2	0.111	0.222
3-5	5	4	0.139	0.556
5-7	7	6	0.194	1.164
7-9	6	8	0.164	1.312
9-11	4	10	0.111	1.11
11+	5	11	0.139	1.529
	36		0.997	5.9625

Table 6: Statistical Computation of Average for Propane

iC$_4$	No of Samples	iC$_4$ Mid Value	f$_i$ Frequency	iC$_4$f$_i$
Less than 0.5	8	0.25	0.222	0.0555
0.5-1.0	5	0.75	0.139	0.10425
1.0-1.5	4	0.25	0.111	0.13875
1.5-2.0	7	1.75	0.194	0.3395
2.0-2.5	6	2.25	0.167	0.369
2.5.-3.0	3	2.75	0.083	0.22825
3.5 +	3	3.0	0.083	0.249
	36		**0.999**	**1.48425**

Table 7: Statistical Computation of Average for Iso-Butane

nC$_4$	No of Samples	nC$_4$ Mid Value	f$_i$ Frequency x	nC$_4$f$_i$
Less than 0.5	6	0.25	0.167	0.04175
0.5-1.0	5	0.75	0.139	0.10425
1.0-1.5	4	0.25	0.111	0.13875
1.5-2.0	4	1.75	0.111	0.19425
2.0-2.5	3	2.25	0.183	0.18675
2.5.-3.0	6	2.75	0.167	0.45925
3.0-3.5	2	3.25	0.055	0.17875
3.5 +	6	3.5	0.167	0.5845
	36		**1.000**	**1.88825**

Table 8: Statistical Computation of Average for Normal-Butane

iC$_5$	No of Samples	iC$_5$ Mid Value	f$_i$ Frequency	iC$_5$f$_i$
Less than 0.25	9	0.125	0.25	9.93125
0.25-0.5	8	0.373	0.222	0.08325
0.5-0.75	6	0.625	0.167	0.104375
0.75-1.0	4	0.875	0.111	0.097125
1.0-1.25	3	1.125	0.083	0.093375
1.25-1.5	1	1.375	0.028	0.0385
1.5-1.75	2	1.625	0.055	0.089375
1.75-2.0	2	1.875	0.055	0.103125
2.0+	1	2.0	0.028	0.056
	36		0.999	
				0.696375

Table 9: Statistical Computation of Average for Iso-Pentane

nC$_5$	No of Samples	nC$_5$ Mid Value	f$_i$ Frequency	nC$_5$f$_i$
Less than 0.25	12	0.125	0.333	0.041625
0.25-0.5	9	0.373	0.15	0.09375
0.5-0.75	7	0.625	0.194	0.12125
0.75-1.0	3	0.875	0.083	0.072625
1.0-1.25	3	1.125	0.083	0.093375
1.25-1.5	2	1.375	0.055	0.075625
	36		**0.998**	**0.49825**

Table 10: Statistical Computation of Average for Normal-Pentane

C_6+	No of Samples	C_6+ Mid Value	f_i Frequency	$f_i C_6+$
Less than 0.25	7	0.125	0.194	0.02425
0.25-0.5	8	0.373	0.222	0.08325
0.5-0.75	7	0.625	0.194	0.12125
0.75-1.0	2	0.875	0.555	0.048125
1.0-1.25	3	1.125	0.083	0.093375
1.25-1.5	2	1.375	0.055	0.075625
1.5-1.75	3	1.625	0.083	0.134875
1.75+	4	1.75	0.111	0.19425
	36		**0.997**	**0.775**

Table 11: Statistical Computation of Average for Hexane Plus

N_2	No of Samples	N_2 Mid Value	f_i Frequency	$N_2 f_i$
Less than 0.10	18	0.05	0.545	0.02725
0.10-0.20	3	0.15	0.091	0.01365
0.20-0.30	1	0.25	0.030	0.0075
0.30-0.40	6	0.35	0.182	0.0637
	33		1.000	0.1729

Table 12: Statistical Computation of Average for Nitrogen

G(Air=1)	No of Samples	G_i Mid Value	f_i Frequency	$G_i f_i$
0.600-0.650	8	0.625	0.235	0.146875
0.650-0.700	4	0.675	0.118	0.07965
0.700-0.750	6	0.725	0.176	0.1276
0.750-0.800	2	0.775	0.059	0.045725
0.800-0.850	6	0.825	0.176	0.1452
0.850-0.900	2	0.875	0.059	0.051625
0.900+	6	0.900	0.176	0.1584
	34		**0.999**	**0.755075**

Table 13: Statistical Computation of Average for Gravity

CO_2	No of Samples	CO_2 Mid Value	f_i Frequency	$CO_2 f_i$
Less than 0.5	2	0.25	0.055	0.01375
0.5 - 1.0	8	0.75	0.222	0.1665
1.0 - 1.5	9	1.25	0.250	0.3125
1.5 - 2.0	7	1.75	0.194	0.3395
2.0 - 2.5	3	2.25	0.083	0.18675
3.5 - 4.0	3	3.75	0.083	0.31125
4.5 - 5.0	1	4.75	0.027	0.12825
5.0 -5.5	2	5.25	0.055	0.28875
9.5 -10.0	1	9.75	0.027	0.6325
	36		**0.996**	**2.0105**

Table 14: Statistical Computation of Average for Carbon dioxide

Component	Mole%
Methane	78.5375
Ethane	7.7880
Propane	5.9625
Butane	1.4842
n-Butane	1.8882
i-Pentane	0.6964
n-Pentane	0.4982
Hexane Plus	0.7550
Nitrogen	0.1729
Carbon dioxide	2.0105
Other Undesirables	0.2066
Total	**100.0000**

Table 15: Typical Representative Composition of Nigerian Flare Gas Steam

Other Parameters	Range	Value for the Study
Gas Gravity (Air = 1)	0.607 to 0.996	0.755
Flowrate MMscfd	5 to 63	20
Pressure Psig	7 to 75	10
Pressure Psia	21.7 to 89.7	25
Temperature $^\mathrm{O}$F	60 to 115	80
Base Temperature During		$60\,^{0}$F
Analysis		
Base Pressure During Analysis		14.7 psia

Figure 16: Typical Representative Conditions of Nigerian Flare Gas Steam

4. Theoretical Model

The qualitative conversion of the flared associated stranded natural gas to various useful end products, is a function of the unique chemical changes (reactions), associated with the organic chemistry of natural gas-alkanes or paraffins hydrocarbons homologous series.

We distinguish between the following principal types of chemical changes: combustion, combination, decomposition, replacement and double displacement or double replacement (Darrel, et al., 1995; Hess, 1980; Myer et al., 2007; Timberlake, 2006). Usually, all chemical changes involve one or a combination of these basic varieties and chemical changes results in such a thorough change in a substance that an entirely new substance is formed in the process. The new substance created has its own set of properties, thus physical changes accompanies chemical changes. Natural Gas (alkanes) undergoes all the chemical changes effectively:

- Combustion (oxidation) Reactions: It is a reaction of a substance with either pure oxygen or oxygen in the air with the rapid release of heat and the appearance of a flare.

$$CH_4(g) + 2O_2(g) \longrightarrow CO_2(g) + 2H_2O(g) + \text{Heat (energy)}$$

Combination (isomerization) Reactions –thermal or catalytic reforming, a process by which lighter hydrocarbon molecules are linked together to form larger hydrocarbon molecules.

- Decomposition Reactions – thermal (pyrolysis) or catalytic cracking, a process by which heavier hydrocarbon is split into two or more, lighter hydrocarbon molecules.

  Cracking is a breaking down process, while reforming is an isomerization process i.e. changing of compound into its isomers.

- Replacement (substitution) Reactions- which involves the substitution of one element for another in a compound and

- Double Displacement (replacement) Reactions- in which two compounds react to form two new compounds by exchanging parts.

Usually at temperatures of over 800OC alkanes cracks to alkenes, for instance ethane cracks to ethene (ethylene) and hydrogen: CH_3 $CH_3 \longrightarrow CH_2 = CH_2 + H_2$

While in another development referred to as "catalytic hydrogenation", hydrogen molecules split apart and add across the double bond of alkenes, converting it to alkanes:

$$CH_3\,CH \;=\; CH_2 + H_2 + H_2 \text{ Ni catalyst } CH_3\,CH_2\,CH_3 \longrightarrow$$
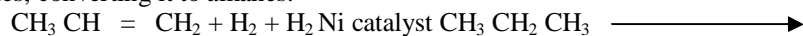
There are three different familiar phases (states) that we can identify by sight i.e., solid, liquid and gas or vapor (Sherman and Sherman, 1999; Myer, et al., 2007; Atkins, 1978)

Fundamentally, all the science, technology, engineering and otherwise that enables natural gas to be useful in different forms are based on the interchangeable states of matter in line with the law of conservation of matter, which states that matter is neither created nor destroyed during chemical change (Hess, 1980), rather it involves redistribution of electrons, either by transfer or by sharing, but no new electrons are formed, nor any destroyed.
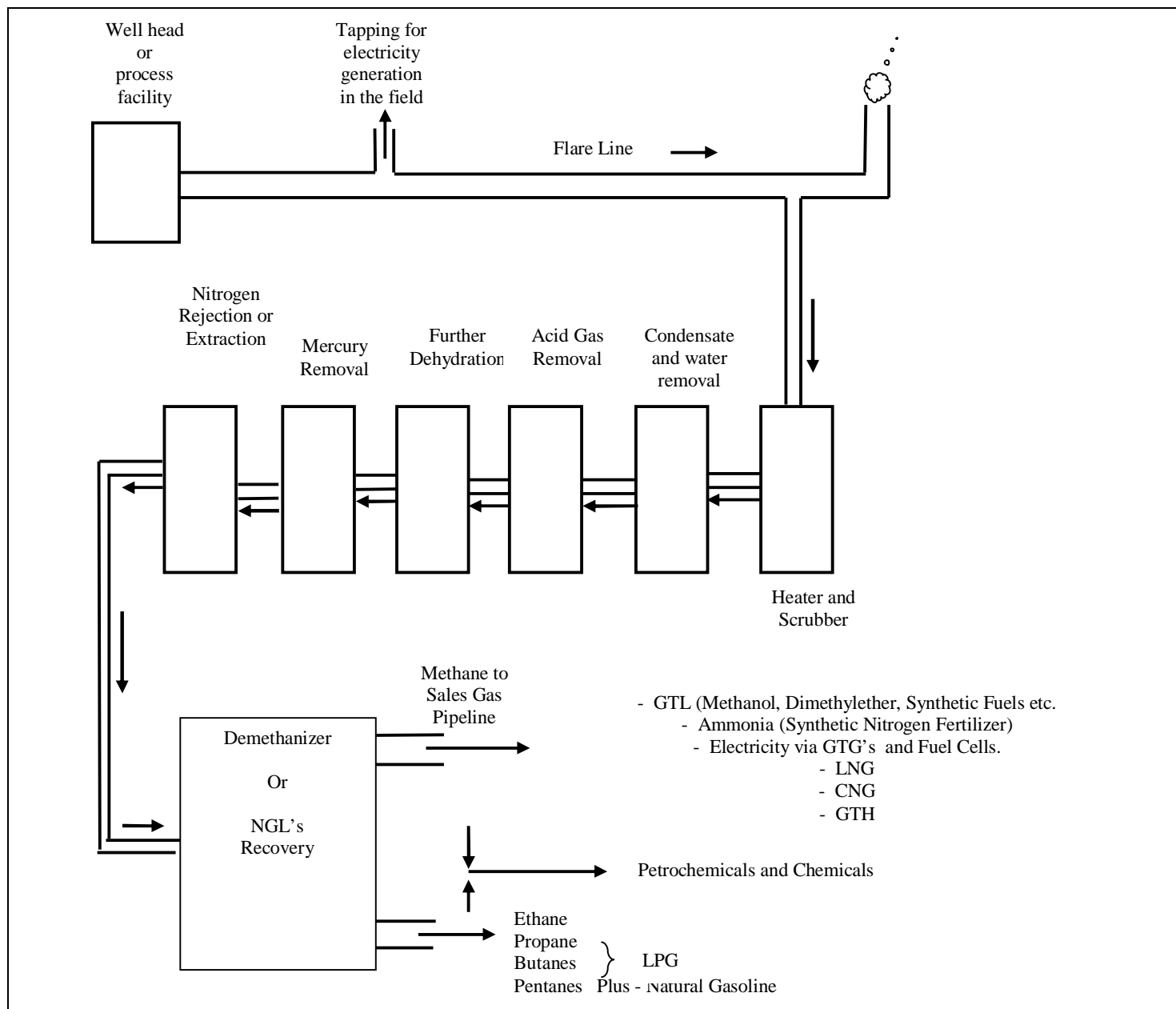
5. Model Application

Figure 1: Process Layout for the Overall Real-Time Monetization of Flare Stream

Conventionally, processing the flared associated stranded natural gas to remove undesirable components such as, carbon dioxide, hydrogen sulfide and other sulfur components, and nitrogen is termed sweetening (Campbell, 1976).

In the case of the typical representative flare stream composition for Nigeria as contained in table 15, the undesirable components, constitutes 2.39% of the flare gas stream, that is, the sum, for carbon dioxide and nitrogen, plus the other undesirable components in the stream.

For the purpose of this research, the assumption is that each molecular component released exactly, equal amount (moles) of the undesirable in sweetening the stream, that is $(2.39/97.61= 0.0244)$ per mole.

Therefore, the compositional (mole %) of methane for the sweetened typical representative flare stream becomes $78.5375 + (78.5375 \times 0.0244) = 80.4538$.

This is applied on all the components to yield the overall quantitative compositional (mole percent) of the sweetened flared associated stranded gas steam Table 17.

Components	Mole Percent
Methane	80.4538
Ethane	7.9780
Propane	6.1079
i-butane	1.5204
n-butane	1.9343
i- pentane	0.7134
n-pentane	0.5104
hexane plus	0.7734
permissible undesirable	0.0084
	100.0000

Table 17: Sweetened Composition of the typical flare Stream

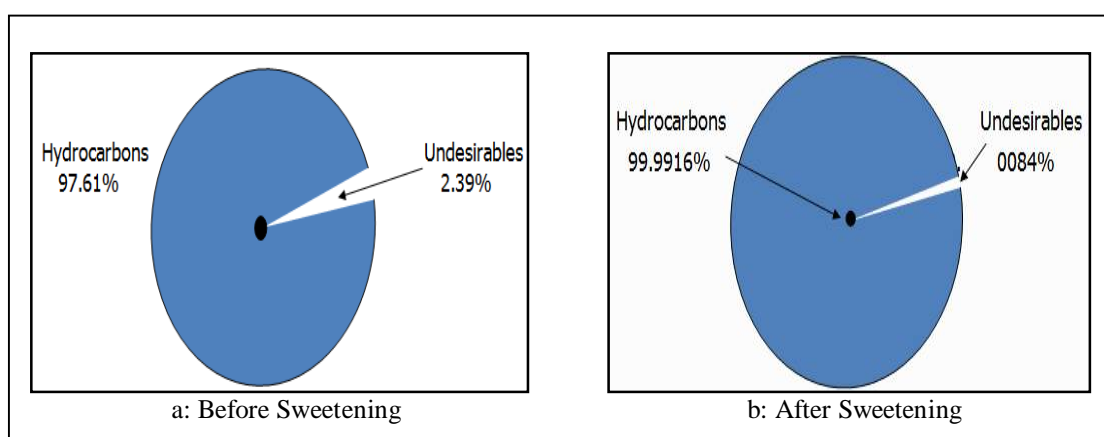This implies that, after sweetening, the feed stream yield is virtually hydrocarbons components with negligible and permissible percentage of   the undesirables, as depicted on figure 2

Figure 2: Feed Stream Composition

Next, introducing the flare stream flowing rate factor yields the real-time daily, monthly and yearly quantities being flared on component by component basis. For instance, with a flow rate of 20MMscfd, we obtain the values as shown in Table 18.

Component	Fractional Composition 1	Daily MM scfd	Monthly, (30days), MM scf	Yearly, (365 days), MM scf
Methane	0.8045	16.090	482.70	5,872.85
Ethane	0.0798	1.596	47.88	582.54
Propane	0.0611	1.222	36.66	446.03
i-butane	0.0150	0.300	9.00	109.50
n-butane	0.0193	0.386	11.58	140.89
i-pentane	0.0071	0.142	4.26	51.83
n-pentane	0.0051	0.102	3.06	37.23
hexane plus	0.0077	0.154	4.62	56.21

Table 18: Real-Time (Daily, Monthly and Yearly) Flare Stream Component by Component Quantities

6. Flared Associated Stranded Natural Gas Monetization Options

The overall qualitative conversion of the flared associated stranded natural gas to useful end products from the component by component quantitative daily, monthly and yearly yields from individual flare streams are, in any of the three forms (figure 3).
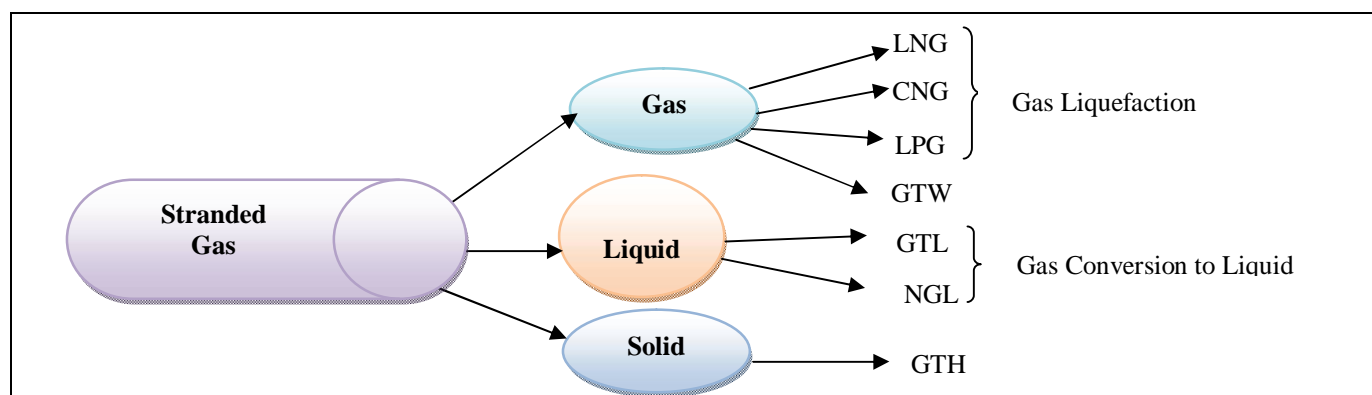
Figure 3: Forms of Qualitative conversion of natural gas.

Thus, the possible investment opportunities for monetizing the flared associates stranded natural gas using Field Development Planning methods such as (a) Front End Engineering design (FEED) and (b) Detailed Engineering Studies (DES) are:

1. Conversion to liquefied natural gas (LNG)
2. Conversion to Compressed natural gas (CNG)
3. Conversion to Natural gas hydrates (NGH)
4. Conversion to Electricity; Gas to wire (GTW) or Independent power plants (IPP) projects.
5. Conversion to hydrogen refineries fuel cell.
6. Conversion to miscible injectant(MI) for enhanced oil recovery (EOR)
7. Chemical conversion to transportation liquid fuel: Gas to liquid (GTL)
8. Chemical conversion to Methanol for vehicle fuel and feedstock to industry.
9. Chemical conversion to Ammonia and Urea (nitrogen fertilizer)
10. Chemical conversion to olefins: Gas to Olefins (GTO) or further to polymers (GTP).
11. Direct production of Di-methyl ether (DME) via syngas etc.
12. Extraction of natural gas liquids (NGLs).
13. Conversion to liquefied petroleum gas (LPG)
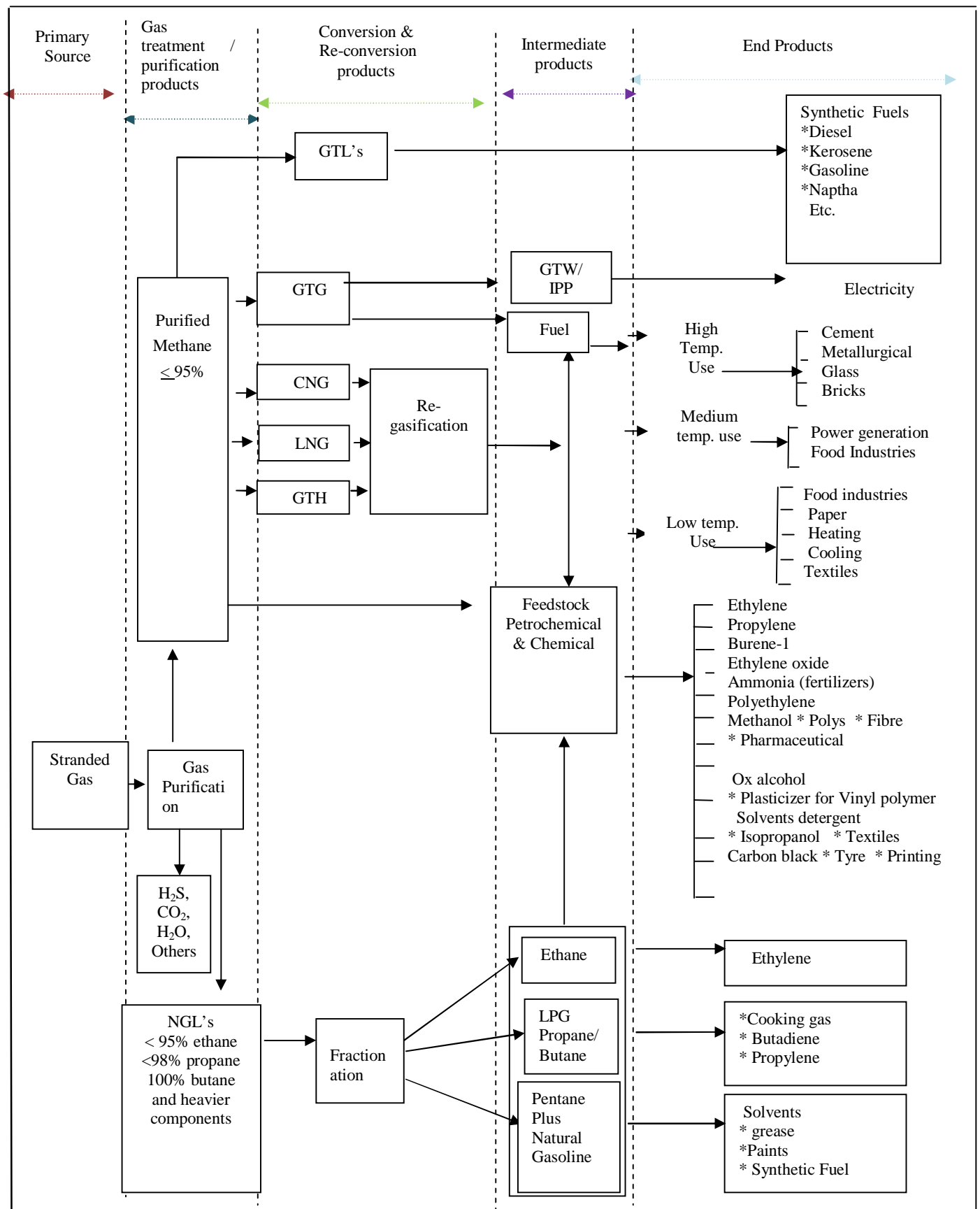14. Conversion to feedstock for petrochemical/chemical industries.

Figure 4: Various gas Monetization Options

7. Final End Products from the Associated Stranded Natural Gas

Natural gas conditioning treatment (processing) usually termed dehydration and sweetening involves:

(i) Dehydration i.e. conditioning the natural gas stream to remove condensable water vapor, free water and solids impurities which under certain conditions might cause hydrate formation.

(ii) Sweetening i.e. processing the natural gas stream to remove undesirable compounds (acid gases), such as hydrogen sulfide, carbon dioxide and nitrogen, which in presence of water, might form acids or acidic solution that are toxic, poisonous and corrosive.

(iii) Natural gas liquids (NGLs) recovery i.e. processing the natural gas stream to remove condensable hydrocarbons i.e. saleable liquid hydrocarbons.

The above treatments yield two main products.

(a) The methane rich stream i.e. very high purity methane (95 to 98%) polluted with minor ethane and propane.

(b) The natural gas liquids stream i.e. saleable liquid hydrocarbons, mostly ethane plus components.

A. The dry treated natural gas i.e. conditioned methane rich stream could be used for any of the following:

i. Directly as fuel: residential, industrial and power generation (electricity).

→ As a residential fuel, it is burned in furnaces, water heaters, cooking stoves; clothes dryers, refrigeration or space cooling and air conditioning.

→ As an industrial fuel, it is burned in kilns (special furnaces) used to bake bricks, and ceramic tiles and to produce cement.

→ Injected into transmission lines for supply to independent power plants (IPP) for electrical power generation; Gas-to-wire (GTW), as source of electrical and heat energy for iron smelting in iron and steel industry, Aluminum industry, glass and food processing industry.

ii. Directly as raw material for creating petrochemicals (i.e. as a precursor of a wide variety of compounds via synthesis gas) such as methanol, formaldehyde, ammonia and urea fertilizers, oxoalcohols, chloromethanes, detergents, pharmaceuticals, plastics etc.

iii. Liquefaction to obtain liquefied natural gas (LNGs) for export or later regasified for use as either fuel or raw material for creating petrochemicals.

iv. Directly compressed to yield Compressed Natural Gas (CNG) for vehicles etc.

v. As a liquid fuel energy source, i.e. conversion to liquid using Gas to liquid (GTL) plants, to yield fuel oil, diesel, gasoline, liquefied petroleum gas (LPG) etc.

vi. Conversion to hydrates using Gas-to- hydrate (GTH) technology.

B. The extracted natural gas liquids (NGLs), containing ethane, propane, butane and natural gasoline (C5+ hydrocarbons), can be used.

a. Directly as ethane, commercial propane, commercial butane, propane- butane mixture (LPG), and natural gasoline or

b. As a feedstock for petrochemical/ chemical end products, via conversion of alkanes to alkenes reactions, such as the conversion of ethane to ethene (ethylene):

$$CH_3CH_3 \longrightarrow CH_2 = CH_2 + H_2$$

C. All petrochemicals are derived from three sources:

(1) Reforming natural gas (methane) to synthesis gas (syngas): carbon monoxide /Hydrogen (CO/ H_2).

(2) Olefins from pyrolysis of ethane, propane –butane (LPG) or distillates.

(3) Aromatics from catalytic reforming.

The three main source of petrochemical lead to products which are marketable items in their own right, as well as raw materials for a great many other petrochemicals used both as intermediates and as finished products.

A petrochemical is any chemical compound obtained or derived from petroleum or natural gas hydrocarbons and utilized in chemical market (it includes a whole range of aliphatic, aromatic and naphthenic organic chemicals and inorganic materials such as sulfur and ammonia.

The basic petrochemical products are ethylene, propylene, Butene-1, ethylene oxide, polypropylene, polyethylene, ethylene glycol, terephtalic acid, isopropanol, ethanol amines (Mono, Di, Tri), carbon black etc. which are in turn used in different commercial chemical industries to produce hundreds of finished specific chemicals for the medical, pharmaceutical, agricultural, textiles, printing etc such as plastics of all descriptions, soaps and detergents, solvents, drugs, fertilizer (ammonia), pesticides, explosives, paints, synthetic (artificial) fibres and rubbers, epoxy resins, flooring and insulating materials, and products as diverse as aspirin, luggage, boats, automobiles, aircraft, polyester clothes, recording discs and tapes etc.

Currently, there are well over 2000 product made to individual formula by natural gas and allied petrochemical/chemical plants. The limit in number and diversity of product and the extension of their application has by no means been reached. Through advanced technology and practical research, new products (constantly growing number of commercially manufactured products from natural gas/petrochemical/chemical plants) will continue to be added to the long list of those recovered or made from natural gas, with a continually widening range of consumer applications.

Despite the fact that these petrochemical products have already penetrated virtually all the material markets such as the agricultural, pharmaceutical, plastics and resins, building, automotive, electrical, synthetic fibres, synthetic rubber, cleaning agents etc.; an incipient attack on the most important of all 'the food markets' is indicated by the construction of plants in which protein will be made from hydrocarbons.

 The different process designs to maximize the production of any particular desired end use (petrochemicals, chemicals, feedstock, energy source, etc) from individual flare stream will be the focus of the subsequent research topics in the series.

8. Conclusion

In Nigeria, flaring of associated stranded natural gas commenced in 1956 with the first successful well drilled at Oloibiri by Shell D'Arcy, present day Shell Petroleum Development Company (SPDC). Until 1984, the Country flared (ignited) or vented (unignited) virtually all the produced associated stranded natural gas, while between 1984 to 1999, the flaring reduced to 70%. The introduction of monetization policy in 1999 further reduced, flaring from 70 per cent to between 43-52 % in 2004, about where it still remains up-to-date.

With the continuous flaring of about 50 % of associated stranded natural gas in Nigeria, where the light crude contains substantial amount of the associated stranded natural gas, the importance of an alternative to flaring can hardly be over-emphasized.

Statistical computation using 36 samples of the Nigerian flared associated stranded natural gas composition from various operating fields, resulted to the typical representative Nigerian flare stream composition (table 15) for Average process plant design purposes.

Subsequently, the typical sweetened representative Nigerian associated stranded natural gas flare stream was computed (table 17), which is virtually hydrocarbons components with negligible and permissible percentage of the undesirables. And, introducing the flare stream flow rate factor (20MMscfd) yielded the real-time sweetened, daily, monthly and yearly quantities being flared on component by component basis (table 18).

It is these real-time sweetened quantities that are available for monetization through any of the three qualitative conversion processes:

  Gas via LNG, CNG, LPG and GTW.
  Liquid via GTL and NGL.
  Solid via GTH.

To the various petrochemicals, chemicals, and many other useful end-products
 (Fig. 4).

Practically, the main factor that enables natural gas to be converted to high quality useful end-products is the susceptibility of natural gas to various chemical changes (reactions) such as, combustion, combination, decomposition and replacement.

The other series of the research will investigate the monetization of the sweetened flared associated stranded natural gas using field development planning methods such as Front-End Engineering Design (FEED) and Detailed Engineering Studies (DES) for the production of each of the various useful end- products.

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