OPTIMIZING OPERATIONS OF AN OIL & GAS PROCESSING FACILITY USING THE ENERGY-WATER NEXUS APPROACH

A Thesis

by

BABAFUNTO OLUDAMILOLA FADAIRO

Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Chair of Committee,	Mahmoud El-Halwagi
Committee Members,	Stratos Pistikopoulos
	Joseph Kwon
Head of Department,	Stratos Pistikopoulos

August 2019

Major Subject: Energy

ABSTRACT

Natural gas is an extremely important fossil fuel. It is widely used for provision of electric power, residential and commercial heating, and several other industrial uses. It can be produced via both conventional and unconventional means. This project aims to optimize the overall operational efficiency of an oil and gas production facility using the Water-Energy Nexus approach.

The Water-Energy Nexus approach presents systematic and state-of-the-art techniques for the design of energy and water systems associated with industrial processes. Particularly the optimization, management, and integration of water and energy systems and the connections that link them using a variety of visualization, algebraic, and mathematical optimization approaches. This project's case study is an actual oil and gas production facility located in Nigeria.

For this project, two scenarios are considered- The "Grass-roots" case and the "Retrofit" case. For both scenarios, power and heat generation are integrated into the facility's operations using "stranded" gas which is currently being flared. Cost Benefit Analysis and Carbon Footprint Assessment are performed. The "Retrofit" case is the more optimal scenario as it can be implemented at minimal overall cost (including the economic value of emissions) and the facility becomes "self-sufficient".

In addition, flaring of natural gas is minimized (thereby-reducing greenhouse gas emissions) and making the oil and gas production process safer and more environmentally sustainable.

ACKNOWLEDGEMENTS

I give all the glory to God Almighty, for life, good health and ability. I would also like to thank my committee chair Professor Mahmoud El-Halwagi for his guidance, inspiration, constant cheery disposition and availability throughout the course of this research. I also want to extend my gratitude to my committee members Professor Stratos Pistikopoulos and Dr. Joseph Kwon for their support.

I would like to thank Oando Plc. for the release of case-study data used for this thesis work. I would like to specially recognize my husband, Adewale Adeyemi, for being the wind beneath my wings and the driving force for me embarking on this journey! I want to thank my mum, Mrs. Ayowole Fadairo, for her constant sacrifice and being the greatest support system ever and to my son Emimoreoluwa Adeyemi for undertaking this adventure with me. Mummy did it!!!

Finally, a thank you to my colleagues (worthy of mention is Oreoluwa Adetimirin, my optimization tutorial and study buddy) at the Texas A&M Energy Institute, who have now become life-long friends, for making this year a truly memorable experience.

CONTRIBUTORS AND FUNDING SOURCES

Contributors

This work was supervised by a thesis committee consisting of Professor Mahmoud El-Halwagi [advisor] and Professor Stratos Pistikopoulos of the Texas A&M Energy Institute and Dr Joseph Kwon of the Department of Chemical Engineering. All data analysis and other work conducted for the thesis was completed by the student independently.

Funding Sources

No external sources provided funding for this work.

NOMENCLATURE

IOC	International Oil Company
MMboe	Million barrels of oil equivalent
API	American Petroleum Institute
BS&W	Basic Sediments & Water
Bopd	Barrels of oil produced
LPG	Liquefied Petroleum Gas
MMscfd	Million Standard Cubic Feet per day
Tcf	Trillion Standard Cubic Feet
Bcf	Billion Standard Cubic Feet
MMBtu	Million British Thermal Unit
Bcm	Billion standard cubic meter
kWh	Kilowatt-hour
DPR	Department of Petroleum Resources
GGFR	Global Gas Flaring Reduction Partnership
CHP	Combined Heat and Power
CCGT	Combined Cycle Gas Turbine
HRSG	Heat Recovery Steam Generator
D-ICE	Derated Internal Combustion Engine
ECU	Electronic Control Unit
RDG	Retrofitted Diesel Generator

TABLE OF CONTENTS

Page

LIST OF FIGURES

Page

LIST OF TABLES

Page

CHAPTER I

INTRODUCTION

Flaring

Gas flaring is defined by the Canadian Association of Petroleum Producers as the controlled burning of natural gas that cannot be used or processed for sale because of technical or economic constraints[1]. Flaring can be classified into three major groups: Emergency Flaring, Production Testing Flaring and Process (Routine) Flaring [2].

Emergency Flaring occurs primarily for safety purposes; to relieve trapped pressure in the case of a break-down, process upset, equipment malfunction or during some start-up operations. During emergency flaring, a large volume of gas with high velocity is burned for a short time. Production testing flaring usually occurs during the evaluation of a potential oil/gas reservoir (at well-construction stage) to determine the capacity of the well for production. Testing is important in order to determine the pressure, flow and composition of the oil/gas from the well. Flaring in this case lasts for several days or weeks until the flow of liquids and gas from the well and pressures are stabilized. Process flaring occurs as "waste" gases are continually removed from the production stream. It occurs at a lower rate but is sustained over-time. Usually, process (routine) flaring occurs from stranded reserves.

A basic flare system consists of a flare stack and pipes that feed gas to the stack. The flare stack may be vertical, or it may occur at ground-level in a burn pit. Flare size and brightness are related to the type and amount of gas or liquids in the flare stack. Gas flaring has several environmental and economic implications. Flaring results in waste of finite material and energy Gas flaring is defined by the Canadian Association of Petroleum Producers as the controlled burning of natural gas that cannot be used or processed for sale because of technical or economic constraints[1]. Flaring can be classified into three major groups: Emergency Flaring, Production Testing Flaring and Process (Routine) Flaring [2].

Emergency Flaring occurs primarily for safety purposes; to relieve trapped pressure in the case of a break-down, process upset, equipment malfunction or during some start-up operations. During emergency flaring, a large volume of gas with high velocity is burned for a short time. Production testing flaring usually occurs during the evaluation of a potential oil/gas reservoir (at well-construction stage) to determine the capacity of the well for production. Testing is important in order to determine the pressure, flow and composition of the oil/gas from the well. Flaring in this case lasts for several days or weeks until the flow of liquids and gas from the well and pressures are stabilized. Process flaring occurs as “waste” gases are continually removed from the production stream. It occurs at a lower rate but is sustained over-time. Usually, process (routine) flaring occurs from stranded reserves.

A basic flare system consists of a flare stack and pipes that feed gas to the stack. The flare stack may be vertical, or it may occur at ground-level in a burn pit. Flare size and brightness are related to the type and amount of gas or liquids in the flare stack. Gas flaring has several environmental and economic implications. Flaring results in waste of finite material and energy resources which could be used to support economic growth and progress. Flaring also affects the health and quality of life of the local population close to the flaring site.

Gas flaring has significant environmental impacts; In addition to the high noise levels and heat emitted by the flares due to the volume and velocity of gas going through the flare stack, the combustion of flare gases results in the emission of hazardous chemicals including several gases such as Carbon-dioxide (CO_2), Water-vapor (H_2O, Nitrous oxides(NO_x) and Sulphur oxides

(SO_x) , several identified toxins including carcinogens such as benzopyrene, benzene and toluene, metals such as mercury, arsenic and chromium and Volatile Organic Compounds (VOC) which pose a significant health risk. The flare gas is substantially dominated by methane and carbon dioxide. These gases are generally referred to as "Greenhouse gases".

A Greenhouse gas is any gas in the atmosphere which absorbs and re-emits heat, and thereby keeps the planet's atmosphere warmer than it otherwise would be[3]. Greenhouse gases occur naturally in the atmosphere however anthropogenic activities are increasing the levels in the atmosphere. (About 75% of the anthropogenic emissions of carbon dioxide come from the combustion of fossil fuels[4]. These high gas levels trap more heat in the atmosphere by absorbing long-wave radiation while letting the sun's energy pass through (Greenhouse effect)

The quantity of generated emissions from flaring is dependent on the combustion efficiency of the flare [5]. The combustion efficiency is essentially the amount of hydrocarbon converted to carbon dioxide. Several factors affect the efficiency of the combustion process in the flares such as the heating value of the gas, entry velocity of gases to the flare, meteorological conditions and its effects on the flare size [6]. Many studies conclude that flares have high variable efficiencies ranging from 62-99%[7].

For flares which burn at lower efficiencies, the release of methane is a very important concern as methane has about 25times greater global warming potential than CO2 on a mass basis. [8]

The increasing levels of greenhouse gases in the atmosphere contribute to the following:

- Warming of water bodies
- Warming of land masses, putting human crops at risk
- Mass extinction of species (The UN estimates that the world is losing some 200 species a day primarily due to global warming causing loss of habitat, droughts, and other problems from invasive species now able to survive on a warmer planet [9]).

In addition, CO2 contamination results in the occurrence of white or red brown spots on the surface of plant leaves, consequently the production of agricultural produce is decreased in the long run. In summary, the unnecessary combustion of fossil fuels violates the principles of sustainable development.

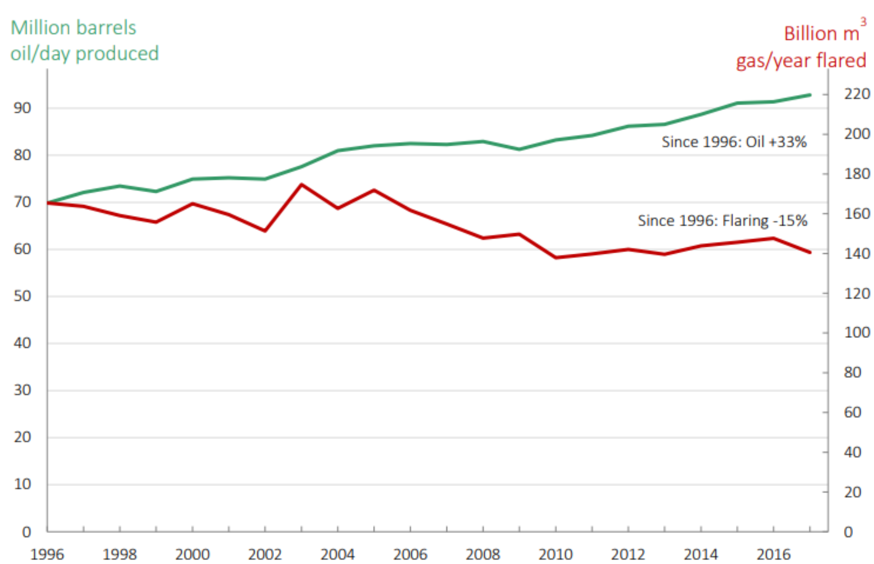

Figure 1 Global Gas Flaring and Oil Production 1996-2017 (Reprinted from GGFR, based on NOAA/GGFR/BP/EIA data)[11]

Over the years, due to increasing attention from researchers, environmentalists and decision makers, there has been a reduction in the overall gas flaring volumes (as seen in Figure 1) due to numerous protocol , legislative acts and international agreements such as the Kyoto Protocol, United Nations Environment Programme (UNEP) and the World Bank Global Gas Flaring Reduction Partnership (GGFR). The Kyoto Protocol is an international treaty for controlling the release of GHGs from human activities and the GHGs controlled under the treaty are shown in Table 1 below[10].

Table 1 Kyoto Gases IPCC Fourth Assessment Report[4]

Greenhouse Gas	**Global Warming Potential (GWP)***
Carbon dioxide $(\boldsymbol{CO_2})$	1
Methane $(\boldsymbol{CH_{42}})$	25
Nitrous Oxide $(\boldsymbol{N_2O})$	298
Hydrofluorocarbons $(\boldsymbol{HFCs})$	124-14800
Perfluorocarbons $(\boldsymbol{PFCs})$	7390-12200
Sulfur hexafluoride $(\boldsymbol{SF_6})$	22800
Nitrogen trifluoride $(\boldsymbol{NF_3})$[3]	17200

**The global warming potential (GWP) of a GHG is an index which indicates the amount of warming a gas causes over a given period of time (normally 100 years)*

However, current global gas flaring data indicates that 141 billion cubic meters (bcm) of natural gas was flared in 2017 [11]. This number is equivalent to 5% of global gas production and about 300 million tons of CO2 emissions [12]. The impact is staggering when considering that 147bcm of gas if used for power generation could provide about 750 billion kWh of electricity, or more than the African continent's current annual electricity consumption. Also 400 million tons of CO2 emission per year equals the annual emission rate of 77 million cars[13]. In terms of economics, the loss is about $10-$15billion based on gas prices of $2-$3 per MMBTU. [13]

Stranded Reserves

A stranded reserve is one which is unusable due to economic reasons. Natural gas reserves are plentiful around the world, but many are too small or too remote from sizable population centers to be developed economically. These "stranded" gas reserves are usually flared, vented or injected back into the ground. Estimates of stranded gas reserves range from 40 to 60% of the world's proven gas reserves[14,15]. These global reserves are largely untapped and conventional means of development face logistical and economic barriers. A volume of gas can be economically "stranded" because the resource is located in a remote area without a market or direct access to distribution systems or the resource is located in a region where the demand for gas is saturated and the cost of exporting gas beyond this region is excessive. Most stranded gas reserves are in gas fields that are totally undeveloped. It is claimed that there are approximately 1,200 stranded fields, of different sizes, worldwide[16]. There are more than 100 marginal fields in Africa with reserves greater than 0.25Tcf. Marginal fields account for approximately 15% of the world's proven reserves and approximately 20% of this can be considered stranded[17]

Table 2 Global Stranded Gas Potential (Reprinted from Society of Petroleum Engineers: Monetizing Stranded Gas)[17]

Source	**Tcf**
Associated gas	423
Deep Offshore	282
Marginal Fields	141
Remote Gas Fields	847 to 1412
Total	1693 to 2258

Stranded gas is a problem for both small and large oil producers. Turning stranded gas into distributed generation is a viable solution to this problem, by utilizing stranded gas to generate useful electricity in the field at a reasonable cost, there is direct economic and environmental benefits as waste gas will be consumed rather than vented, flared or incinerated, decreasing potential impacts to the environment. Producers will experience a decrease in operational expenses and an increase in production.

The focus of this thesis is the reduction/elimination of process (routine) flaring of stranded gas via flare gas utilization in a cogeneration system. The case study is an oil and gas processing facility located in a stranded field in the South Western part of Nigeria.

CHAPTER II

CASE STUDY

The E-field is a “marginal” field located in the Southern part of Nigeria. A “marginal” field is an oil field which has been discovered by a major International Oil Company (IOC) in the course of exploring larger acreages but has left undeveloped for more than 10 years[18]. The Government of Nigeria, by the provisions of the Petroleum (Amendment) Act of 1996 is empowered to legally recover the “marginal” fields from their owners and allocate them to other medium-sized firms who are willing and able to promptly exploit and develop them. The Government has taken this step “to respond positively to the increasing global demand for crude oil and thus enhance supply security and market stability[19].

The E-field is located onshore and covers an area of approximately 65 square kilometers. The field has 2P reserves of 57 MMboe (barrels of oil equivalent) [20]. Crude obtained from the field is generally light (typically 45-48deg API) and sweet with large volumes of associated gas. The concentration of Basic Sediments and Water (BS&W) in the crude is low [21].

The field currently has 9 producing wells with a combined production capacity of about 7,000bopd. Crude from the field is processed at the E processing facility which has a processing capacity of 10,000 bopd. Surrounding the facility is a strong network of oil pipelines, however there is limited to no gas distribution infrastructure.

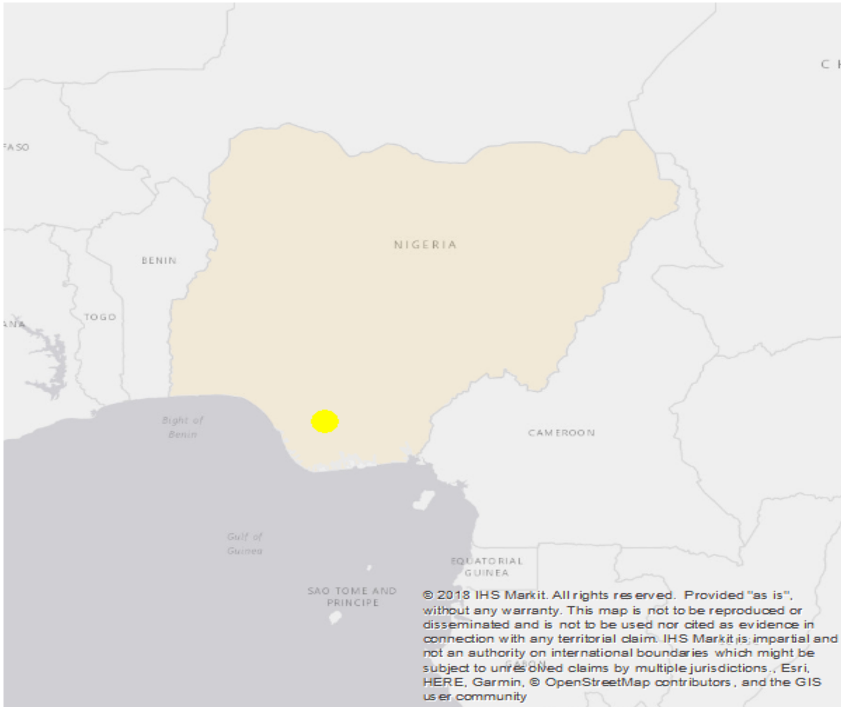

Figure 2 Map of Nigeria showing the location of the E-field (Reprinted from IHS Markit 2018)[21]

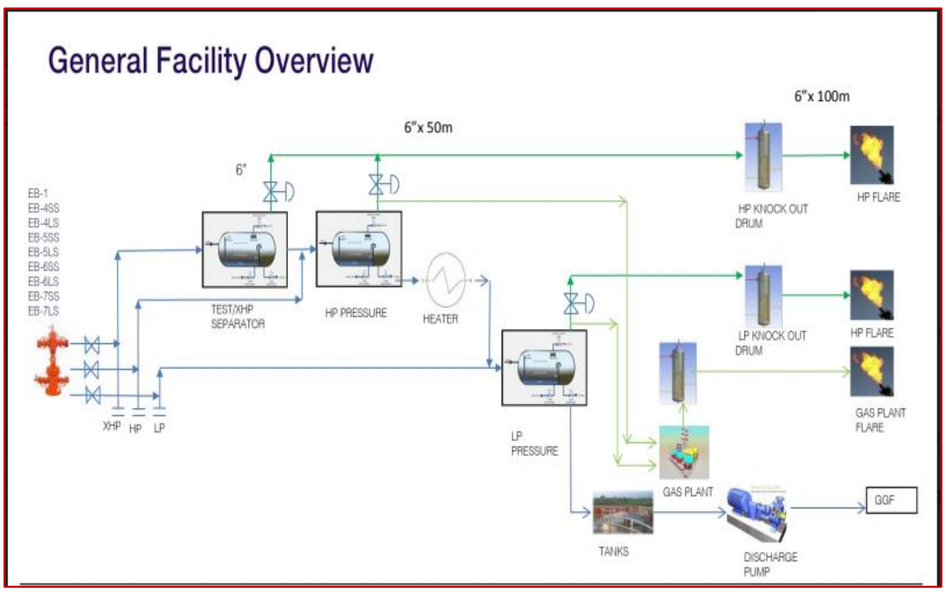

Figure 3 The E-production facility overview (Reprinted from Oando Energy Resources 2012)[20]

The primary focus of the E-processing facility is oil production. The crude is processed via a two-stage separation process (High Pressure & Low Pressure), the oil is stored in tanks prior to evacuation via oil pipelines to terminal for sale.

{See table below for typical composition of the associated gas}

Table 3 Characteristics of associated gas from E-field (Reprinted from Oando Energy Resources 2012)[23]

Characteristics	
S.G (relative to air)	0.64
Heat of combustion (Btu/scf)	1070
Methane (mole %)	85.9
Ethane (mole %)	7.1
Propane (mole %)	4.1
C4 and paraffins (mole %)	2.4
Others	0.5

The wet gas is sent to a mini Liquefied Petroleum Gas (LPG) facility (co-located at the production facility). The wet gas enters a scrubber, where condensate is stripped from the stream. The outlet stream is purified, propane, butane and iso-butane fractions are further stripped from the gas stream and refrigerated into Liquefied Petroleum Gas (LPG) [22]. The LPG is bottled and sold at the local market, while the left-over methane is sent to the flare. Historically, approximately 70% of the field's produced gas is flared [23]

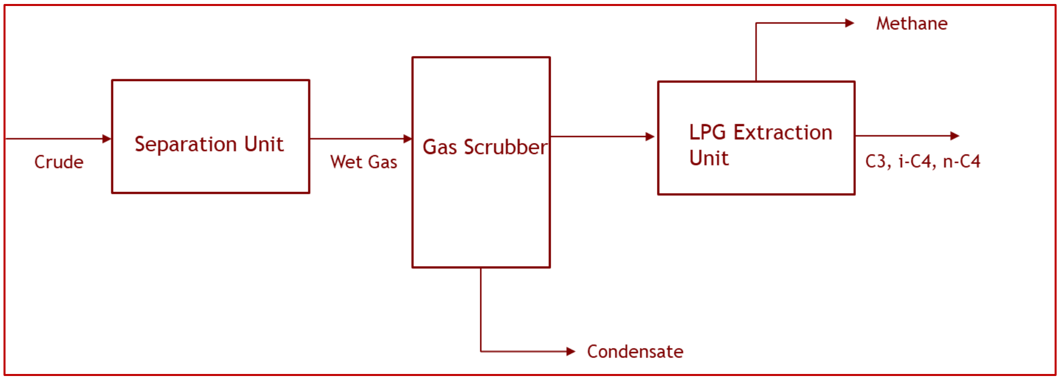

Figure 4 Block Flow Diagram of the LPG Production Process (Reprinted from Norwegian University of Science and Technology LPG Process Design 2010)[22]

According to the Department of Petroleum Resources (DPR), the regulator of the Nigerian Petroleum Industry, Nigeria's current proven natural gas reserves are estimated at 192 trillion scf of gas[24]. Nigeria has the largest natural gas reserves in Africa (its natural gas reserves are estimated to be twice its crude oil reserves) and has 9th largest proved reserves in the world, with a combined total of proved, probable and possible reserves estimated at 300 trillion scf. It is estimated that about 1000scf of gas is produced with every barrel of oil[25].

Absence of large-scale mid-stream gas infrastructure to aggregate gas from proximate producing fields for processing and distribution has prevented the harnessing of this tremendous potential[26]. Due to these factors, routine gas flaring is an extremely common phenomena, as in most cases, it is relatively cheaper for producers to flare the associated gas than bear the heavy cost of constructing stand-alone gas processing infrastructure for domestic and other uses.

The Nigerian Government, recognizing the losses resulting from flaring of associated gas (financial and energy value) and the resultant environment damage as a result of the adverse effects of pollutant emissions proposed a zero-flare target in 2008 and in recent years, has invested in several efforts to reduce gas flaring, including construction of a liquefied natural gas facility, pipeline to transport gas to neighboring countries as well as stricter measures to ensure enforcement of policies to better utilize the produced gas.

According to the World Bank's Global Gas Flaring Reduction Partnership (GGFR), there has been an 18% reduction in gas flare volumes in Nigeria from 2013 to 2017 [27], however there is still a lot of work to be done as Nigeria is the 6th largest gas flaring county globally (Figure 5). In 2017, about 7% of total gas produced in Nigeria, was flared [28]. This translates to about 277 billion scf of flared gas.

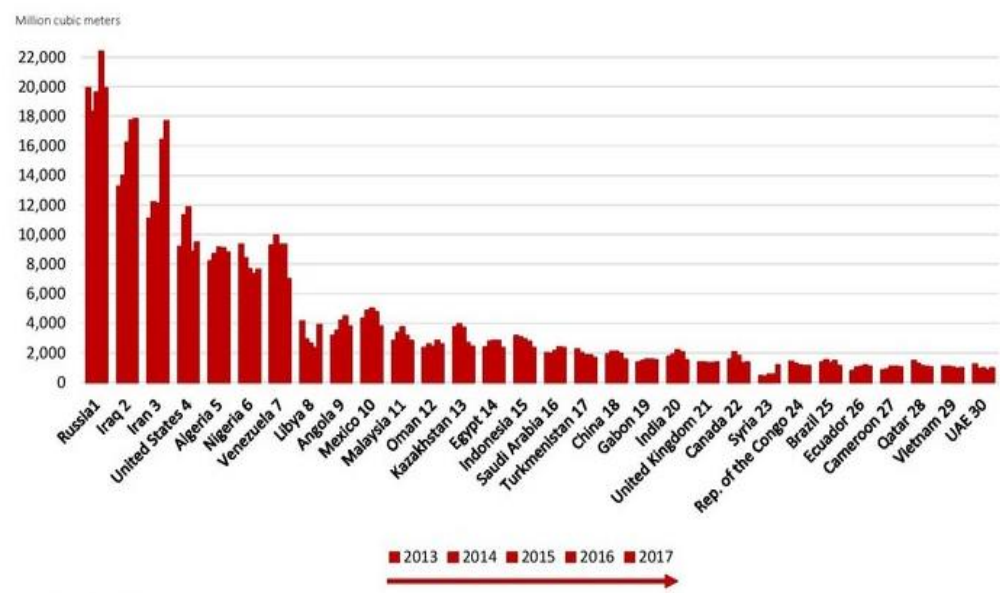

Figure 5 Top 30 flaring countries (2013-2017) (Reprinted from NOAA/GGFR)[27]

In 2017, it is estimated that 15.1 million tons of carbon dioxide [29] was emitted from gas flaring activities in Nigeria. This is equivalent to four times UK's annual emissions from gas use[30]

It is proposed that the facility (case study) be optimized as below:

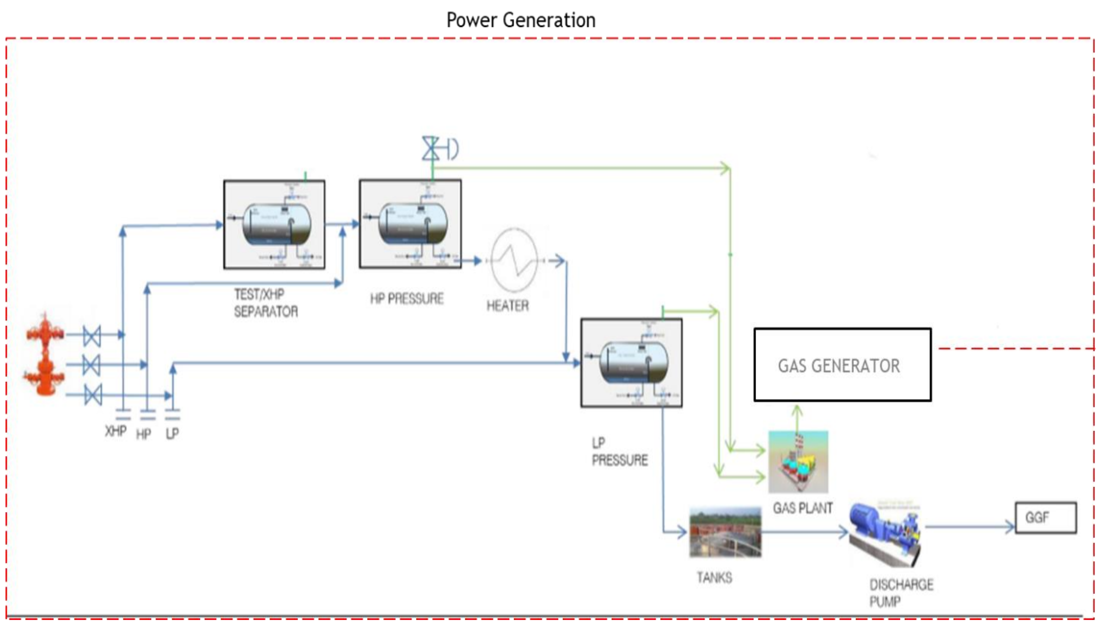

Figure 6 "Optimized" E-production facility overview with co-generation

The volumes of natural gas sent to the flare daily (The average gas daily production of the E-field in 2017 was 21mmscfd [31]), can be used instead to power the facility and its environs via an installed co-generation system. The facility is currently being powered by diesel generators.

CHAPTER III

PROBLEM STATEMENT

Given a stranded gas field with a known historical record of flaring which includes the quantity and composition of the flared gas as well as the frequency and duration of flaring.

It is desired to develop a process to install a cogeneration system which will use the flared gas to produce electricity for powering the facility as well as a heating utility (for future water treatment purposes). (The power demand of the facility is known)

Thesis Objective

The overall objective is to establish the most cost-effective process which will provide economic benefits from the effective utilization of the flared gases as well as a reduction in overall GHG emissions from the facility.

To achieve our objective of minimizing operational cost and emissions, two scenarios are considered

- Scenario 1: Purchase a gas-fired turbine to utilize the flared gases and replace the facility’s existing power generators which run on diesel fuel
- Scenario 2: Retrofit the existing power generators to allow for the utilization of flared gases

CHAPTER IV

LITERATURE REVIEW

There are several methods used for flare gas recovery and utilization. Some include:

1. Compression and Re-injection
2. Gas to Liquid Technology (GTL)
3. Power generation / Co-generation systems

The focus of this thesis is co-generation and this concept is thus explained further below

Cogeneration/Combined Heat and Power Systems

An important option for managing flaring is the use of process cogeneration systems. Co-generation also known as combined heat and power (CHP) is the concurrent production of electricity or mechanical power and useful thermal energy (heating/cooling) from a single source of energy. CHP plants capture and utilize heat that is generated as a byproduct of electricity generation and is normally wasted in conventional power plants [32] .The combined efficiency of traditional methods of generating power and heat separately can be substantially enhanced using cogeneration systems. Furthermore cogeneration increases the cost effectiveness of the energy systems and reduces the CO2 emissions [33]

Several methods have been used to assess the cogeneration opportunities of a process[34], El-Halwagi [35] proposed a method for identifying the cogeneration target for a process. Considering a process with a number of combustible wastes and by-products, specific heating and cooling demands as well as non-heating steam demands. It is desired to identify a target for power cogeneration that makes effective use of the combustible wastes while fulfilling all process demands for heating and non-heating steam.

Firstly,consider that the combustible wastes that can be burned in existing boilers and industrial furnaces provide heat typically in the form of steam. Depending on the specific boiler or industrial furnace, the steam is generated at a specific pressure and is fed to the appropriate steam header. The steam demands can be determined through heat and mass integration. Heat integration (e.g., grand composite analysis) can be used to determine the heating steam requirements and their levels. Mass integration can be used to determine the nonheating steam demands. The result of the mass integration analysis is the identification of the process supply of steam (from the combustible wastes) and the process demand of steam (for nonheating purposes). The supplies and demands are determined in terms of quantities and levels of the steam headers. Those supplies and demands are now known both in terms of quantities and pressures (or header level). A typical industrial process has several pressure levels in its steam system. Consider a process with the following headers: very high pressure (VHP), high pressure (HP), medium pressure (MP), and low pressure (LP). Depending on the supply and demand to each header, the net balance of steam for each header will be positive (surplus) or negative (deficit).

When the objective is to target cogeneration potential for a process, it is advantageous to determine this target without detailed calculations. Conventional turbine models require individual-turbine calculations to evaluate the outlet enthalpy at constant entropy and the flowrate of steam passing through the turbine. As such, it is useful to develop expressions for estimating turbine power using easily determined terms. Turbines are placed between steam headers with known temperature and pressures. Consequently, the specific enthalpies of these steam headers are also known. An approximation of the turbine power based on the header enthalpies exists. The term extractable energy, is based on the header levels that the turbine actually operates between, rather than the isentropic conditions at the outlet pressure.

$$e_{Header} = \eta_{Header} * H_{Header} \tag{1}$$

Where e_{Header} is the extractable energy for a given header, η_{Header} is an efficiency term and H_{Header} is the specific enthalpy at a given set of conditions for the header. The extractable power, E_{Header} of a header is defined as

$$E_{Header} = m\eta_{Header} * H_{Header} = me_{Header} \tag{2}$$

The advantage of this definition is that it does not involve detailed turbine calculations such as isentropic outlet enthalpy. Then, the power generation expression can be rewritten as the difference between the inlet and outlet extractable power:

$$W = E^{in} - E^{out} \tag{3}$$

Where E^{in} is the extractable power at the header conditions feeding the inlet steam to the turbine and E^{out} is the extractable power at the header conditions receiving the outlet steam from the turbine. The representation of this form of power evaluation on a Mollier diagram.

Based on the concept of extractable energy, a graphical targeting procedure was developed that identifies cogeneration targets and can serve as the basis for developing feasible turbine network designs that meet the predicted target. According to this method, the extractable power expressed is plotted for each header versus the net flowrate of the header. First, the extractable power is plotted versus the steam flowrate for each surplus header in ascending order of pressure levels. The result of this superposition is the development of a surplus composite line. Similarly, the extractable power for the deficit headers is plotted in ascending order leading to the deficit composite line. Hence, the cogeneration potential of the system can be evaluated by shifting the deficit composite line to the right and up until it is directly below the terminal point of the surplus line. The vertical distance (of the "jaw") between the two terminal points of the surplus and the deficit composite lines is the target for cogeneration potential. This diagram is referred to as the extractable power cogeneration targeting pinch diagram.

In order to guarantee that the cogeneration target is feasible, higher pressure surplus headers must be directly above lower-pressure deficit headers. By letting down steam from the higher-pressure headers to the lower pressure headers the deficit is removed while power can be generated by virtue of the difference between the extractable powers. Therefore, both steam demands (heating and non-heating) are satisfied while power is cogenerated. The steam flowrate of the portion of the surplus composite line that does not overlap with the deficit composite line represents excess steam. Since there is no header demand for this excess, it can be used for power generation (not cogeneration) by letting it down through a condensing turbine, used for other process purposes, or simply vented.

Dhole and Linnhoff [36]proposed to use exergy analysis as part of total site source-sink profile to allocate utilities and provide cogeneration. Exergy is a measure of the useful work available in a heat source. Raissi[37] developed the TH-shaft work targeting model. This model is based on an observation first made by Salisbury [38], that the specific enthalpy at the turbine outlet minus the specific enthalpy of saturated water is relatively constant regardless of the outlet conditions. The TH-shaft work target combines this observation with the observation that specific power can be approximated by a linear function of the outlet saturation temperature. The TH shaft work target is based on the following expression:

$$W = \frac{\varepsilon}{q}\,(T_{in}^{sat} - T_{out}^{sat}) * Q \qquad (4)$$

Where W is the overall power output, Ɛ is the power coefficient, q is the constant observed by Salisbury, T_{in}^{sat} and T_{out}^{sat} are the saturation temperatures at the inlet and outlet conditions of the turbine and Q is the heat load to be supplied by the turbine.

Mathematical programming techniques have also been made in the area of modeling and optimization of turbine network systems. The turbine hardware model[39] is based on the Willans line (commonly used in turbine modeling to represent steam consumption versus rated power of the turbine) and utilizes typical maximum efficiency plots and rules of thumb to target cogeneration potential. The turbine hardware model also incorporates complex turbines by modeling them as sets of simpler turbines.

Gas turbines are used extensively for CHP applications, particularly at industrial and large institutional sites. Simple cycle gas turbines are also called micro-turbines. A micro turbine is a high speed gas turbine which has the advantage of flexibility in connection methods (they can be stacked in parallel to serve larger loads {Multipac systems}), reduced number of moving parts, ability to provide stable and reliable power and low emissions compared to other technologies. Gas turbines are constant pressure open cycle heat engines. The power generation process is best illustrated by the Brayton Thermodynamic Cycle[40] in Figure 7 below

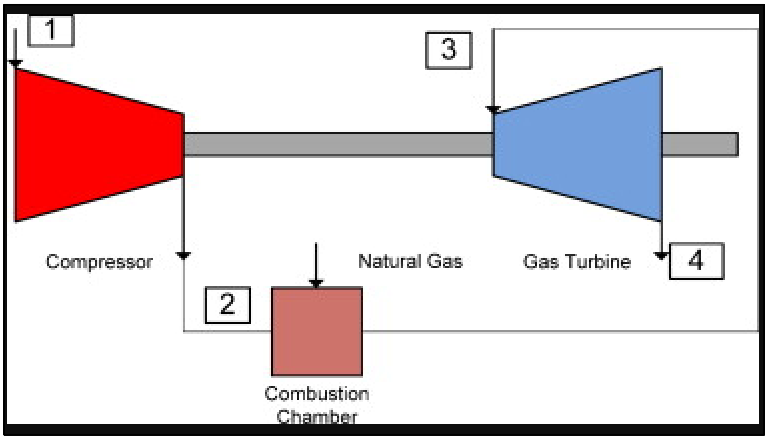

Figure 7 The Brayton Cycle (Reprinted from Gas Turbine Theory)[40]

At point 1, atmospheric air enters a compressor and the pressure is increased from atmospheric to high pressure. At point 2, the compressed air passes to a combustion chamber and is blended with natural gas where combustion takes place. At point 3, the hot air and combustion gas mixture drive an expansion turbine where they expand to atmospheric pressure, producing enough energy to provide shaft power to the generator. This shaft power converts into electricity in a generator. At point 4, the exhausted gases come out from the gas turbine. The heat from this exhaust gases can be further utilized to supply other required thermal energy needs.

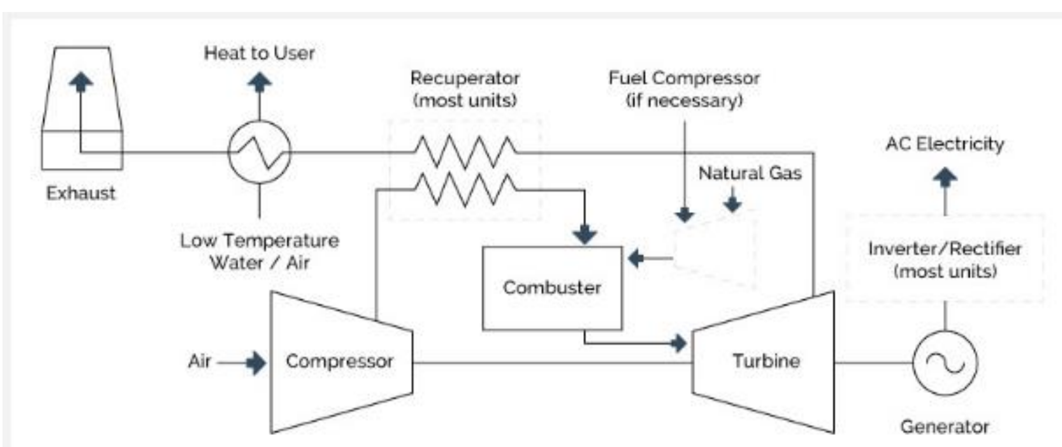

Figure 8 Components in a micro turbine (Reprinted from Energy Solutions Center)[41]

The power produced by an expansion turbine and consumed by a compressor is proportional to the absolute temperature of the gas passing through those devices. It is advantageous to operate the expansion turbine at the highest practical temperature consistent with economic materials and to operate the compressor with inlet airflow at as low a temperature as possible. As technology advances permit higher turbine inlet temperature, the optimum pressure ratio also increases. Higher temperature and pressure ratios result in higher efficiency and specific power. Thus, the general trend in gas turbine advancement has been towards a combination of higher temperatures and pressures. However, micro turbine inlet temperatures are generally limited to 1,800ºF or below to enable the use of relatively inexpensive materials for the turbine wheel, and to maintain pressure ratios at a comparatively low 3.5 to 4.0[41]

The basic components of a micro turbine are the compressor, turbine generator, and recuperator. The heart of the micro turbine is the compressor-turbine package, which is commonly mounted on a single shaft along with the electric generator. Two bearings support the single shaft. The single moving part of the one-shaft design has the potential for reducing maintenance needs and enhancing overall reliability. There are also two-shaft versions, in which the turbine on the first shaft directly drives the compressor while a power turbine on the second shaft drives a gearbox and conventional electrical generator producing 60 Hz power. The two-shaft design features more moving parts but does not require complicated power electronics to convert high frequency AC power output to 60 Hz. Recuperators are heat exchangers that use the hot turbine exhaust gas (typically around 1,200ºF) to preheat the compressed air (typically around 300ºF) going into the combustor, thereby reducing the fuel needed to heat the compressed air to turbine inlet temperature.

Depending on the presence of the recuperator, micro turbines are generally classified as recuperated or un-recuperated[42]. In an unrecuperated (single-cycle) gas turbine, combustion gases power the turbine directly without requiring heat transfer to a water/steam cycle. Compressed air is mixed with fuel and ignited under constant pressure. These micro turbines have lower efficiencies (15 percent) but have a higher reliability, while Recuperated gas turbines recover heat from their exhaust to increase the temperature of combustion and enhance efficiency. The fuel-to-electrical conversion is approximately 20 to 30 percent. Additionally, recuperated units can produce up to 50-percent fuel savings from preheating. Turbine Electrical efficiency is a function of the temperature drop across the turbine expansion stage while micro turbine CHP total system efficiency is a function of exhaust temperature. Unrecuperated micro turbines are better for CHP applications as Recuperators lower the temperature of the micro turbine exhaust, reducing the micro turbine's effectiveness in CHP applications.

In Combined Cycle Gas Turbines the heat in the exhaust system is used to raise steam, which powers a steam turbine producing additional power. The steam is raised via a heat recovery steam generator (HRSG) which is situated in the exhaust stream of the primary turbine and is connected to it by ducting that also serves to expand the flow in order to obtain appropriate velocities for optimum heat transfer. The exhaust gas temperatures usually range from 300C-600C[43]. To compensate for these temperatures, many industrial scale CCGT utilize a supplementary duct burner, situated in the gas turbine exhaust. This utilizes the residual oxygen in the gas turbine exhaust to raise extra process steam. A fan may be used to supply additional air, which may also enable the burner to be used in auxiliary mode, whereby it can operate independently to provide heat when the gas turbine is not operating.

Gas turbines account for about 53GW of installed CHP capacity in the United States representing 72% of the total installed CHP capacity. [44] More than 80% of this gas turbine CHP capacity is in large combined cycle plants that export power to the electric grid. The remaining gas turbine CHP capacity is made up of simple cycle gas turbine CHP systems, typically less than 40MW.

The power generation process from gas turbines has significant advantages

1. This process produces stable and reliable (up to 99% uptime) power outputs at high efficiencies and low emissions (low NO_x, SO_x, and CO_2 emissions)
2. Natural gas which is the turbine's feedstock is readily available,
3. Gas turbines have limited moving parts and are thus easier and cheaper to maintain.
4. Longer intervals are required between required gas turbine services when compared to conventional engines.
5. Gas turbines have good operating flexibility and short installation time
6. Gas turbines are modular and can be scalable depending on the end-use demand
7. Gas turbines have lower lifecycle costs
8. Gas turbines are suitable for use in cogeneration with fuel energy utilization up to 90% and electric power generation efficiency of more than 55%.

Technical Feasibility of flare gas to power solutions

Research and applicability of dual-fuel technology isn't new. [55] The technology was first demonstrated as early as the 1960s. Recently, there has been an increased demand for this technology, as a result of low natural gas prices. This has led engine makers to fine-tune the technology to meet emissions requirements and displace as much diesel as possible while still maintaining performance.

Several companies such as GE, Westport and Caterpillar have been in the forefront of flex-fuel technology. Diesel engines can be made to run on natural gas with relatively small modifications. Diesel engines work on the principle of compression ignition. Diesel fuel is injected into the cylinder at high pressure, near the point of maximum compression. The combination of diesel fuel and heated compressed air within the cylinder, results in ignition. The fuel and air combination burns rapidly, increasing pressure and temperature, driving the piston back down the cylinder with great force. The sudden release of energy generates the power of the engine[56]. Compression ignition, doesn't work well with natural gas alone, as it is too difficult to control exactly when combustion occurs, and the natural gas can detonate, damaging the engine. In a dual-fuel engine, the problem is solved by injecting a small amount of diesel into the engine to trigger combustion.

In a dual fuel engine, there is no change to the basic architecture of the diesel engine or to the diesel combustion principle. The main addition needed to convert a diesel engine to a dual-fuel one is a system to inject the natural gas and an externally fitted Electronic-Control Unit (ECU). Beyond that, it's mostly a matter of altering the combustion timing and air-to-fuel ratio via simple adjustments. GE researchers have also designed a control system that takes into account the load being put on the engine and ambient temperatures, and adjusts the ratio of natural gas to diesel accordingly. Tests have shown that retrofitting an existing diesel engine by the addition of dual-fuel components do not affect the base engine's robustness or durability. Also a quick and economic return to pure diesel at the end of the ownership, ensures that residual values are not compromised. Dual-fuel technology does have its shortcomings. Most dual-fuel engines available on the market today can burn no more than 65 to 80 percent natural gas. However, there are some new engines which can run on up to 95 percent natural gas. Diesel is still required to trigger combustion but the engines are optimized to run on natural gas.

Flex-micro turbine technology is currently being developed as part of the Department of Energy's OFFGASES project. This technology is suitable for extreme oil field conditions and capable of converting a wide range of gases of different pressures and quality (high BTU, low and ultra-low BTU) into electricity generation. The flex-micro turbine technology also eliminates the need to install compressors because it accepts fuel gas at atmospheric pressure. This technology produces substantially lower NOx, CO2 and VOC emissions than its traditional counterparts.

Dual fuel technology applicability has been demonstrated extensively in vehicle and locomotive engines. There is limited information currently available on its applicability for power generators

Wobbe Index

The Wobbe index is an important metric used to assess the interchangeability of different natural gas supplies for end-use applications. It is calculated from the higher heating value (HHV) and the specific gravity of the fuel stream. The Wobbe index is a unit less number given by

$$Wobbe\ Index = \frac{higher\ heating\ value}{\sqrt{specific}gravity}$$

The Wobbe index was created as a measure of the rate of thermal input through a fixed orifice or nozzle to a stationary burner. Methane has a unique property; the number of moles required for complete combustion of one mole is proportional to the HHV of methane. Also the Wobbe index of methane is also linearly related to the amount of oxygen required for complete stoichiometric combustion. For gas-powered engines the Wobbe index can be similarly related to engine power and the optimum fuel to air ratio[57] as illustrated below. For fuels which have higher Wobbe Index, the amount of oxygen required to combust a given volume of fuel increases[58].

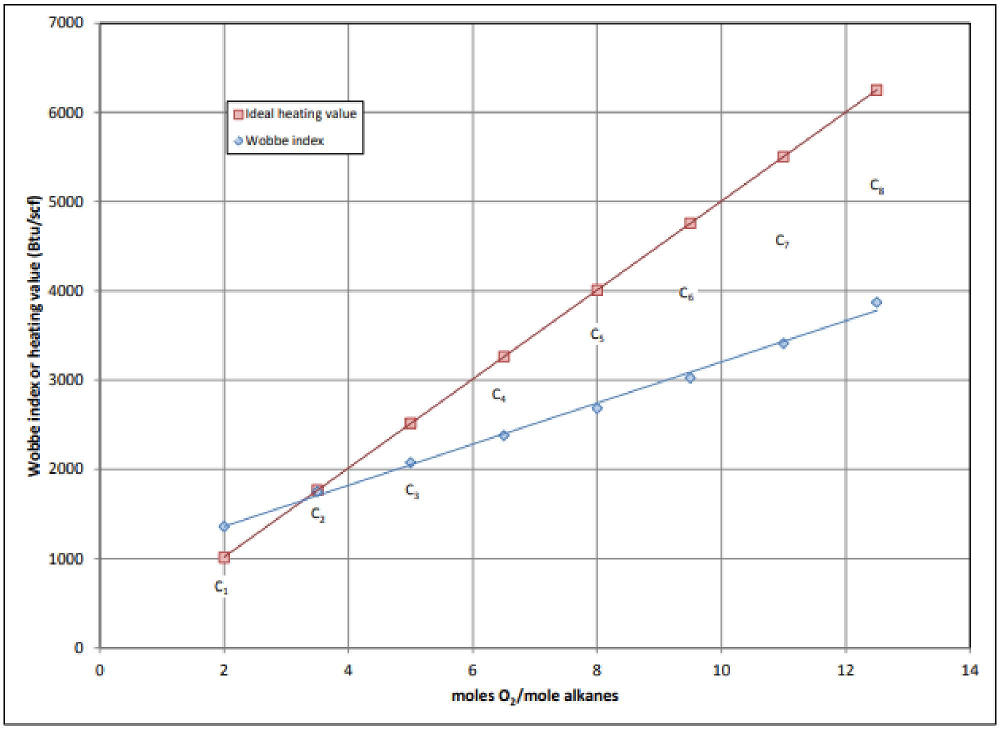

Figure 9 Trends in Heating Value and Wobbe Index for Alkane Hydrocarbons (Reprinted from DieselNet Technology Guide)[58]

Safety Considerations

There are several safety considerations when using natural gas for electricity generation.

- A key issue for the safe operation of Combined Cycle Gas Turbine is the potential for a flame out to occur in the Gas Turbine power unit, leading to the flooding of the system downstream of the fuel injection point with a flammable gas which could then be ignited. The risks associated with such an occurrence are not insignificant because of the high fuel flow rates required to power mega-watt output systems[59].
- The output voltage and residual capacitor voltage from the gas turbine can injure or kill.
- Micro turbine fuel is flammable and explosive. Natural gas in the compressors can leak, cause explosions and subsequent fires. Natural gas is dangerous in quantity of over 5%. When natural gas reaches 5-15%, it can explode when temperatures reach 1,165 degrees. Natural gas also has the added danger of being colorless and odorless... Another issue is natural gas' tendency to reignite once extinguished
- There is possibility of failure of relief valves for hot water and steam. High internal temperatures can reach well over 800F.

- Hazardous sound-pressure levels may exist when a unit is operating.

The best protection for gas turbine operation is gas detection and fire sprinklers. Gas detection can alert plant personnel of a gas leak before it grows out of control. An automatic fire sprinkler system will keep the fire under control before it can spread and possibly extinguish it.

CHAPTER V

METHODOLOGY

The proposed methodology is shown in Figure10 below:

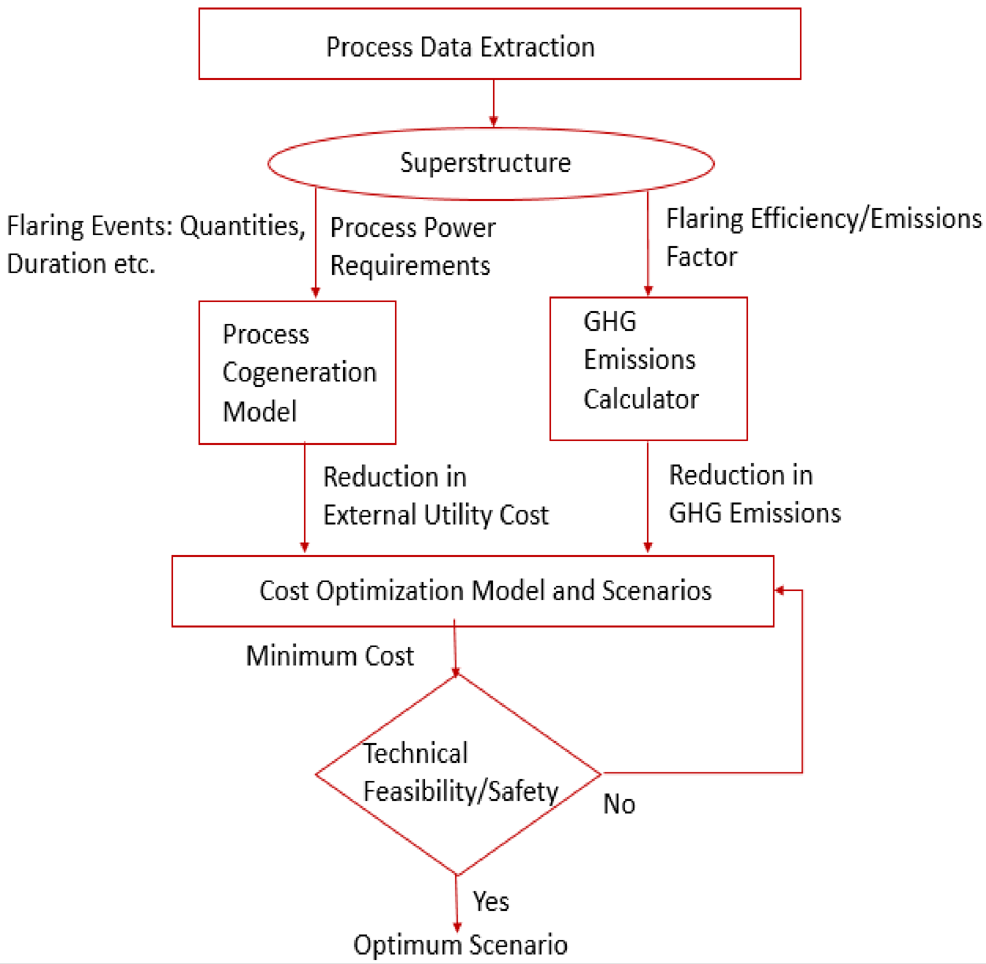

Figure 10 Process Approach to manage flares through co-generation

Field data was reviewed, and estimates obtained for daily gas production at the facility, annualized cumulative gas produced, annualized cumulative gas flared, annualized average daily oil production, annual operations cost and daily power requirement at the facility.

A super structure of the problem was developed and utilizing an effective optimization approach, the problem was modelled as a Mixed Integer Linear Optimization Problem (MIP) with the primary objective being the minimum cost scenario with ROI of at least 10% including constraints for demand, performance and solved with the General Algebraic Modeling System (GAMS) (2014) CPlex solver. Technical feasibility and safety was also considered in determining the optimal solution. Sensitivity analysis was carried out with different values of the flare penalty to determine the economic impact of emissions on the model result. A Carbon Footprint Assessment considering the two scenarios was also performed to determine the qualitative impact on the environment.

Model Superstructure

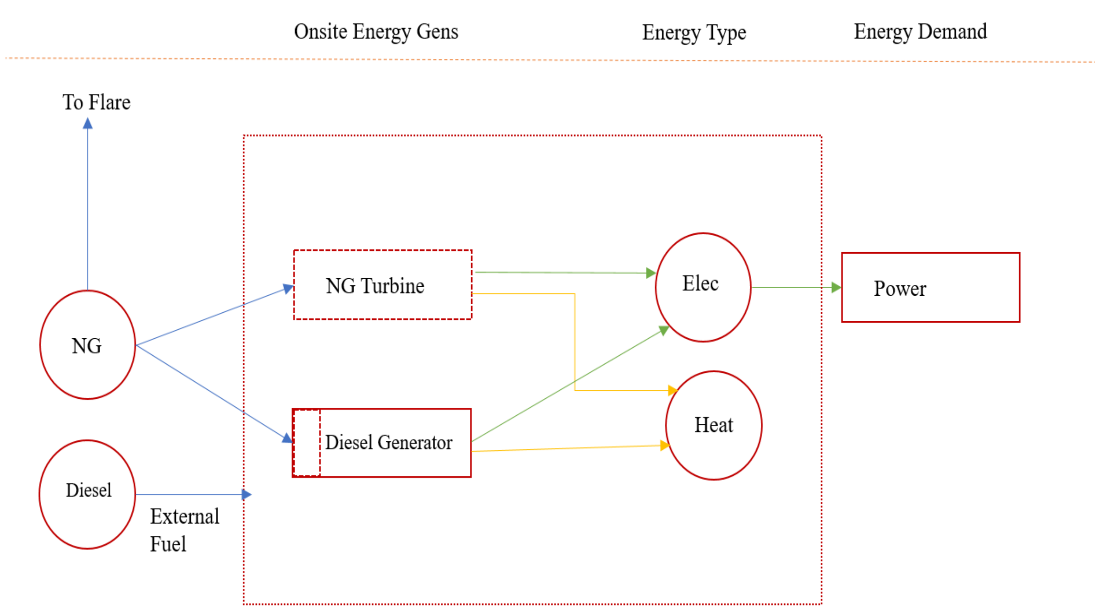

Figure 11 Model Superstructure

Mathematical Representation of the Optimization Model

To properly represent the system a mixed-integer mathematical model must be formulated.

In this case, a Mixed Integer Linear Program (MIP) is formulated.

Decision Variables

The model seeks to minimize cost by selecting which fuel/generation technology combination is the best cost option and delivers a minimum ROI of 10%. The variables include the input into the energy generation technology which is a function of the primary fuel input, the output from the energy generation technology which is a product of the input energy and the energy conversion efficiency of the technology. The energy delivered by the generation technology which must be within the capacity constraints of the technology itself. The cost variables include the total capital investment cost, operations and maintenance cost of the technology and the primary fuel cost. Annualized income is defined as the product of the energy delivered by the generation technology less the power demand of the facility itself and the electricity price. Depreciation is considered straight-line over the operating horizon of the facility.

Objective Function

The objective function is to minimize cost

$$z = c\_total + c\_emissions \tag{5}$$

<u>Fuel consumption equations</u>

And $$Input_{egt} = \sum_{fuelEGT} Con_{FuelEGT} \tag{6}$$

Describes the quantity of fuel consumed each generation technology

$$Con_{Fuel1} = Fuel_{Fuel1EGT1} + Fuel_{Fuel1EGT2} \tag{7}$$

This represents the consumption of fuel 1

$$Con_{Fuel2} = Fuel_{Fuel2EGT1} + Fuel_{Fuel2EGT2} \tag{8}$$

This represents the consumption of fuel2

<u>Energy Generation equations</u>

$$Output_{egt} = Input_{egt} * \eta_{egt} \tag{9}$$

$\eta_{fuelegt}$ Is the energy conversion efficiency of the generation technology with the given fuel

$$Output_{EGT1} = Fuel_{Fuel1EGT1} * \eta_{Fuel1EGT1} + Fuel_{Fuel2EGT1} * \eta_{Fuel2EGT1} \tag{10}$$

This represents output from Energy Generation Technology 1

$$Output_{EGT2} = Fuel_{Fuel1EGT2} * \eta_{Fuel1EGT2} + Fuel_{Fuel2EGT2} * \eta_{Fuel2EGT2} \tag{11}$$

This represents output from Energy Generation Technology 2

<u>Cost equations</u>

Total cost is a function of capital investment cost, operating and maintenance cost and fuel costs

$$C_{total} = C_{investment} + C_{opmain} + C_{fuel} \tag{12}$$

$$C_{emissions} = Emissions_{total} * FlP \tag{13}$$

Cost of emissions is the economic implication of flaring should a flare penalty be introduced

But,

Emissions is a product of primary fuel consumed and the CO_2 emissions factor for the fuel use

$$Emissions_{total} = \sum_{fuel} Con_{fuel} * EF_{fuel} \quad (14)$$

EF_{fuel} is the CO_2 emissions factor of each fuel type

But $$Cap_{egt} \geq Output_{egt} \quad (15)$$

Also $$(CapL_{egt} \leq Cap_{egt} \leq CapU_{egt}) * j_{egt} \quad (16)$$

Where $CapL_{egt}$ is the lower capacity of the energy generation technology

and $CapU_{egt}$ is the upper capacity of the energy generation technology

and j_{egt} is a binary variable that describe which energy generation technology should be selected

Constraints

This modelling formulation includes several operating constraints based on typical conditions. For example the power demand has to be less than or equal to the power generated by the technology

$$Demand \leq \sum_{egt} Output_{egt} \text{ (Demand constraint)} \quad (17)$$

$$ROI = (Income - C_{opmain} - Deprec)/(C_{investment}) \text{ (Profitability constraint)} \quad (18)$$

where

$$Income = (\sum_{egt} Output_{egt} - Demand) * Elect \text{ (Annual Income)} \quad (19)$$

Elect is electricity price

$$C_{opmain} = \sum_{egt} Cap_{egt} * OM_{egt} \text{ (Annual Operations \& Maintenance Cost)} \quad (20)$$

OM_{egt} is the annual Operations & Maintenance Cost for each technology

$C_{investment} = (\sum_{egt} Cap_{egt} * INV_{egt})/Y$ (Investment Cost) (21)

INV_{egt} is the annual Investment Cost for each technology

$Deprec = (C_{investment} - SV)$ (Straight Line Depreciation) (22)

SV is the salvage value

And Y is the operating horizon of the energy generation technology

Model Input Parameters

The following are the key input parameters used in the model

Table 4 Model Input Parameters

Parameter(units)	Value
End-use demand (kW)	750
Salvage Value ($)	0
NG Unit Fuel Price ($/GJ)	0
Diesel Unit Fuel Price ($/GJ)	20.5
CO2 emissions factor NG (kg/GJ)	50.3
CO2 emissions factor Diesel (kg/GJ)	69.3
Flare Penalty ($/tonCO2)	36.7
Lower Capacity Gasgen (kW)	500
Lower Capacity Dieselgen(kW)	500
Upper Capacity Gasgen (kW)	1000

Table 4 continued

Parameter(units)	Value
Upper Capacity Dieselgen (kW)	1000
Annual Utilization (hrs)	8760
Unit Investment Cost Gasgen ($/kW)	2500
Unit Investment Cost Dieselgen ($/kW)	42
Unit Operations/Maintenance Cost Gas gen ($/kW/yr)	115
Unit Operations/Maintenance Cost Dieselgen ($/kW/yr)	15
Operation Horizon (yr)	10
Electricity Price ($/kW/year)	1292
ROI	0.10
Energy conversion efficiency Gasgen using Natural gas	0.65
Energy conversion efficiency Gasgen using Natural gas	0.00
Energy conversion efficiency Dieselgen using Natural gas	0.40
Energy conversion efficiency Dieselgen using Diesel	0.40

CHAPTER VI

RESULTS & DISCUSSION

Optimization Results & Analysis

To achieve the overall objective which is to minimize overall cost (Sum of Investment, Operations and Maintenance cost and fuel cost as well as the economic cost of emissions), the optimal route to satisfy current power demand at the facility would be to combust Natural gas in retrofitted diesel generators. For this case study, 1875 KW of natural gas equivalent to 0.2 mmscfd of natural gas will be sufficient to meet 750 KW of current power demand at the facility.

To determine which parameters has the greatest effect on the result, sensitivity analysis was carried out as below

Sensitivity analysis was carried out with different values of gas prices and at a diesel price of $20.5/GJ, only with a natural gas price of $30/GJ will the optimizer pick diesel fuel to satisfy power demand

Table 5 Sensitivity Analysis with different values of Natural Gas Prices

Gas Price ($/GJ) *Flare penalty ($36.7/tonneCO2)	Selection (Fuel, Generation Technology)
0	NG, RDG
10	NG, GT
20	NG,GT
30	Diesel,RDG

*RDG Retrofit Diesel Generator; GT Gas Turbine

Sensitivity analysis was carried out with different values of flare penalty as can be seen below and at a natural gas price of $0/GJ and a diesel price of $20.5/GJ

Table 6 Sensitivity Analysis with different values of Flare Penalty

Flare Penalty ($/ton CO2) *Gas price $0/GJ, Diesel price $20.5/GJ	Selection (Fuel, Generation Technology)
0	NG,RDG
20	NG,RDG
40	NG,RDG
60	NG,RDG

A change (increase or decrease) in the value of flare penalty has no result on the optimal outcome, the optimal path is still the combustion of natural gas in the retrofitted diesel generator

The investment cost is another important metric which has a direct result on the outcome, as keeping other parameters constant, the optimizer selects the route with a lower investment cost. For this case study, should the price of retrofitting the diesel generators exceed $2500/KW, the optimizer selects the natural gas turbines as the optimal power generation route.

Clearly, the parameters which most directly influence the decision outcome are the primary fuel price and the investment cost for the energy generation technology.

Carbon Footprint Analysis

Carbon Footprint Analysis, also referred as Greenhouse Gas Emissions Assessment, analyzes the greenhouse gas emissions by the production of a product or any given activity that contributes to global warming[60].

First of all, the emissions resulting from the use of diesel as primary fuel was assessed. Based on the demand at the facility, the volume of fuel required to meet this demand is calculated and the output is converted into carbon dioxide equivalents (CO2e). The results indicate that choosing the route of natural gas in retrofitted diesel generators to power the facility saves annual emissions of 4758 tons Co2 emissions.

In addition, the combustion of the fuel by an energy generation technology also leads to a 3% reduction in methane emissions as a result of the increased combustion efficiency of the energy generation technology compared to the flare stack. Converting the resultant savings into carbon dioxide equivalents (CO2e) results in an estimated savings of 1016.88 tons CO2e emissions.

CHAPTER VII

CONCLUSIONS

This work through a multi-objective optimization framework has shown that the operational efficiency of an oil and gas facility can be improved by utilizing “flare gases” for cogeneration.

The multi-objective optimization model is generic and can be applied to a wide range of industrial processes or systems, and the user has the flexibility to include a range of process, environmental and economic constraints.

Natural gas is an extremely useful resource, although it is usually passed over in favor for the seemingly more “valuable” oil. The long-term effect of sustained green-house gas emissions have far-reaching consequences on the environment.

For this project’s case study (an oil & gas processing facility in Nigeria), utilizing the currently flared natural gas in a retrofitted diesel generator for combined heat and power generation is a perfectly viable option. The current volumes of natural gas generated are sufficient to supply both the facility’s current power demand as well as to power the surrounding communities. In addition, there are sufficient gas volumes for a future possibility of supplying power to the national grid. The flexible fueling option also provides an added advantage should there be unforeseen shortages in gas supply as a result of force majeure conditions.

This approach will optimize operational efficiency, increase profitability and reduce green-house gas emissions. It is a win-win for both the facility, government and environment.

REFERENCES

[1] Canadian Association of Petroleum Producers, Flaring & venting, Retrieved Oct. 10, 2012, http://www.capp.ca/environmentCommunity/airClimateChange/Pages/FlaringVenting.aspx

[2] SENES Consultants Limited. Retrieved Oct. 13, 2012, 25 from The Science and Community Environmental Knowledge (SCEK), (May 2007). Available at: http://scek.ca/documents/scek/Final_Reports/RA%202006-08%20Sour%20Gas%20Final%20Report-May%2017_%202007.pdf

[3] Matthew Brander: Greenhouse Gases, CO2, CO2e and Carbon: What do all these terms mean? https://ecometrica.com/assets/GHGs-CO2-CO2e-and-Carbon-What-Do-These-Mean-v2.1.pdf

[4] IPCC Climate Change Report 2001 https://www.ipcc.ch/reports/

[5] Gzar, H.A.; Kseer, K.M.: Journal of Al-Nahrain University, 2009

[6] McMahon, M.: Estimating the atmospheric emission from elevated flares. BP Amoco Suhubury Report, 1994.

[7] Leahey, D.M.; Preston, K.; Strosher, M.: J. Air Waste Manag. Assoc., 2001, 51, 1610-1616.

[8] Johnson, M.R.; Coderre, A.R.: Canada, International Journal of Greenhouse Gas Control. 2012, 8, 121–131

[9] UN Statistics Division, Environment Statistics, Conference on Climate Change and Official Statistics, 2008

[10] Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report: Climate Change 2007

[11] World Bank Global Gas Flaring Reduction Partnership http://www.worldbank.org/en/programs/gasflaringreduction

[12] BMonsure-Khoda Kazi, Fadwa Eljack, Nesreen A Elsayed and Mahmoud M El-Halwagi Integration of Energy and Wastewater Treatment Alternatives with Process Facilities to manage Industrial Flares during Normal and Abnormal Operations: Multi-objective Extendible Optimization Framework

[13] Farina M, 2010. GE Energt, Flare Gas Reduct

[14] Stranded Gas Utilization-Methane Refineries of the Future. 2002. Report prospectus, ChemSystems, San Francisco

[15] Chabrelie M.F and Rojey A 2000 Prospects for Exploiting Stranded Gas Reserves. Presented at Gastech 2000, Houston

[16]Thackeray F and Leckie G. 2002 Stranded Gas: A Vital Resource Petroleum Economist

[17] Society of Petroleum Engineers: Monetizing Stranded Gas https://petrowiki.org/PEH:Monetizing_Stranded_Gas

[18] What are marginal fields? https://www.yourbudgit.com/oil/report/WhatareMarginalfields

[19] Statement by Chief Dan Etete, Nigerian Minister of Petroleum Resources

[20] Oando Energy Resources, 2013. Oando Energy Resources Prospectus

[21] E- Field Summary Report, 2018

https://edin.ihsenergy.com

[22] Norwegian University of Science and Technology, Department of Chemical Engineering, LPG Recovery Technology Report, 2010

[23] Oando Energy Resources; E-Field Production Records 2009-2017

[24] Department of Petroleum Resources Oil & Gas Annual Report, 2015 https://dpr.gov.ng/wp-content/uploads/2015/01/2015-Oil-Gas-Industry-Annual-Report.pdf

[25] Nigeria Oil and Gas Monthly Journal, September 1998; Why we must turn to gas

[26] Energy Mix Report; Emerging Rules for Gas Flaring in Nigeria http://energymixreport.com/emerging-rules-for-gas-flaring-in-nigeria/

[27] The World Bank Global Gas Flaring Reduction Partnership Report, 2013-2017 https://www.worldbank.org/en/news/press-release/2018/07/17/new-satellite-data-reveals-progress-global-gas-flaring-declined-in-2017

[28] Nigerian National Petroleum Corporation; NNPC Monthly Finance & Operations Report. 2017. http://nnpcgroup.com/NNPCBusiness/BusinessInformation/PerformanceData/MonthlyPerformanceData/tabid/617/FolderID/211/Default.aspx

[29] US Energy Information Administration; Carbon Dioxide Emission Coefficients https://www.eia.gov/environment/emissions/co2_vol_mass.php

[30] The Guardian UK; Nigeria's penalty for gas flaring will not curb emissions, 2012 https://www.theguardian.com/environment/2012/may/31/nigeria-penalty-gas-flaring

[31] Oando Energy Resources; E-Field Production Records 2017

[32] What is Combined Heat and Power? Texas Combined Heat & Power Initiative. Gulf Coast Clean Energy Portal

[33]Deneux O, Hafni BE, Pechine B,Di Penta E, Antonucci G, Nuccio P (2013) Establishment of a model for a combined heat and power plant with ThermosysPro library, Procedia Comput Sci 19:746-753

[34] Mahmoud El-Halwagi, Dustin Harell, H.Dennis Spriggs (2009) Targeting cogeneration and waste utilization through process integration

[35] Mahmoud M El-Halwagi: Sustainable design through process integration: Fundamentals and Applications to Industrial Pollution Prevention, Resource Conservation and Profitability Enhancement

[36] Dhole VR, Linnhoff B (1992) Total site targets for fuel cogeneration, emission and cooling

[37] Raissi K. Total site integration; PhD Thesis; (1994) University of Manchester Institute of Science and Technology, Manchester UK

[38] Salisbury JK.ASME Trans 1942; 64:231-45

[39] Mavromatis SP Conceptual design and operation of industrial steam turbine networks Ph.D. Thesis, University of Manchester Institute of Science and Technology, Manchester UK, 1996

[40] T. Giampaolo Gas Turbine Handbook: Principles and Practices (3rd ed.), the Fairmont Press (2006)

[41] Understanding CHP: Technology Description Energy Solutions Center https://understandingchp.com/chp-applications-guide/4-2-microturbines/

[42] Microturbines and the Fire Service; Fire Engineering

https://www.fireengineering.com/articles/print/volume-167/issue-5/features/microturbines-and-the-fire-service.html

[43] SJ Hawksworth et al Safe Operation of Combined Cycle Gas Turbines and Gas Engine Systems using Hydrogen Rich Fuels

[44] US DOE Combined Heat and Power Installation Database, data compiled through December 31, 2015

[45] Kamrava Serveh, Kerron J. Gabriel, Mahmoud M El-Halwagi, Fadwa T Eljack: Managing abnormal operation through process integration and cogeneration systems

[46] BMonsure-Khoda Kazi, Fadwa Eljack, Nesreen A Elsayed and Mahmoud M El-Halwagi Integration of Energy and Wastewater Treatment Alternatives with Process Facilities to manage Industrial Flares during Normal and Abnormal Operations: Multi-objective Extendible Optimization Framework

[47] Javier Tovar Facio, Fadwa Eljack, Jose M Ponce-Ortega and Mahmoud M El-Halwagi: Optimal design of Multi-plant Cogeneration Systems with Uncertain Flaring and Venting

[48] Iora P, Bombarda P, Gomez Alaez S.L, Invernizzi C, et al Flare gas reduction through electricity production

[49] Jacob G, Victor H, Rui W On-site Flare Gas Utilization: Generating Electricity and Flue Gas for EOR

[50] Rahimpour Mohammad, Seyyed Mohammad Feasibility of flare gas reformation to practical energy in Farashband gas refinery: No gas flaring Journal of Hazardous Materials

[51] Birnur Buzcu-Guven Gas Flaring and Venting: Extent, Impacts and Remedies

[52] The Interstate Oil and Gas Compact Commission 2008 Oil field flare gas electricity systems (OFFGASES) project: Final technical progress report to the US Department of Energy, National Energy Technology Laboratory

[53] World Bank Global Gas Flaring Reduction Public-Private Partnership 2004 Report 3: Regulation of Associated Gas Flaring and Venting: A Global Overview and Lessons Learnt from International Experience

[54] New flare gas project launched by SaskPower: Weyburn Review October 2017 https://www.weyburnreview.com/news/new-flare-gas-project-launched-by-saskpower-1.23062767

[55] MIT Technology Review: Cleaner Long-Haul Engines Guzzle Diesel or Natural Gas

[56] Clean Air Power: How Dual-Fuel Works http://www.cleanairpower.com/howitworks.html

[57] Darin L. George et al Compressed Natural Gas Vehicle Fuel Survey: Final Report

[58] Hannu Jaaskelainen Natural Gas Quality DieselNet Technology Guide Revision 2019.04

[59] Curtis S Massey; The Dangers of Redundant Power Supplies https://www.disasterplanning.com/media/articles/dangers-redundant-power-supplies-part-3-microturbines-and-fuel-cells?page=3

[60]Similarities and Differences between Carbon footprint and Life Cycle Analysis https://www.thebalancesmb.com/carbon-footprint-vs-life-cycle-2878059

APPENDIX A

GAMS CODE

```
Sets

pri  primary energy    /NG,Diesel/
egt  energy generation technology  /Gasgen,DieselGen/

Scalar

Demand  end use demand (KW)/
750 /
*enduse demand at facility is known
EV salvage value ($)/
0/

Parameters

FP(pri)  unit fuel price ($ per GJ) /
        NG      0.0
        Diesel  20.5/
*based on diesel fuel prices in Nigeria
EF(pri) emission factor (kg per GJ) /
```

NG 50.3

Diesel 69.3/

*From EIA Emisison factor for Greenhouse Gas Inventories

CAPL_egt(egt) (kW) /

Gasgen 500

DieselGen 500/

CAPU_egt(egt) (kW) /

Gasgen 1000

DieselGen 1000/

UH(egt) annual utilization hour hr /

Gasgen 8760

Dieselgen 8760/

*Energy generation technology to function 24hrs/day

INV_egt(egt) unit investment cost ($ per kW) /

Gasgen 2500

Dieselgen 42/

*Gasgen costs inclusive of engine costs, fuel gas compressor, heat recovery hardware, installation/construction costs

*Diesel gen costs inclusive of conversion kit, fuel gas compressor, installation/construction costs

OM_egt(egt) unit OM cost ($ per kW per year) /

Gasgen 115

```
        Dieselgen       15/
Y        operation horizon (year)      /10/


FlP   Flare penalty ($ per tonne CO2) /36.7/
*based on current Nigerian Flare penalty of $2/1000scf
Elect Electricity price ($ per KW per year) /1292/
*based on standard grid electricity in Nigeria
ROI Return on Investment /0.10/;


Table


EFF_egt(egt,pri) electricity generation efficiency of generation technology
                 NG       Diesel
Gasgen          0.65     0.00
Dieselgen       0.40     0.40          ;


Positive variables
fuel_con(pri)
em(pri)
em_pri_egt(pri,egt)
fuel_pri_egt(pri,egt)
ei_egt(egt)
eo_egt(egt)
```

cap_egt(egt)

c_inv

c_inv_egt

c_inv_total

c_om

c_om_egt

c_fuel

Income

Deprec

emissions

cemissions

IncomeT

Variable

c_total

*ROI

objective

emissions

Binary variables

j(egt)

Equations

EQfuel_con

EQfuel_con2

EQeo_egt

EQeo_egt1

EQCAP1(egt)

EQCAP3(egt)

EQCAP4(egt)

EQDemand

EQIncome

EQIncomeT

EQDeprec

EQc_inv

EQc_inv_egt

EQc_inv_total

EQc_om

EQc_om_egt

EQc_fuel

EQc_total

*EQROI

*EQROIL1

*EQROIL2

EQobj

EQcemissions

```
EQemissions

;


****************************Fuel consumption and Energy
generation********************

*------------------------------??????,??kW---------------------------


EQfuel_con.. fuel_con('NG')=e=fuel_pri_egt('NG','Gasgen')+
fuel_pri_egt('NG','DieselGen')  ;

EQfuel_con2..fuel_con('Diesel')=e=fuel_pri_egt('Diesel','Dieselgen')  ;

EQeo_egt..eo_egt('Dieselgen')=e=
fuel_pri_egt('NG','DieselGen')*EFF_egt('Dieselgen','NG')+
fuel_pri_egt('Diesel','DieselGen')*EFF_egt('Dieselgen','Diesel')  ;

EQeo_egt1..eo_egt('Gasgen')=e= fuel_pri_egt('NG','Gasgen')*EFF_egt('Gasgen','NG');

****************************Capacity
Limit************************************

EQCAP1(egt)..          cap_egt(egt)=g=eo_egt(egt)                   ;

EQCAP3(egt)..          cap_egt(egt)=g=CAPL_egt(egt)*j(egt)          ;

EQCAP4(egt)..          cap_egt(egt)=l=CAPU_egt(egt)*j(egt)          ;

EQDemand..             Demand=l=sum(egt,eo_egt(egt))                ;

**************************Emissions**********************************
********
```

EQemissions..   emissions=e= sum(pri,fuel_con(pri)*EF(pri))*8760*3600*10**(-
9);

*emissions is defined in tonnes of CO2 output

EQcemissions..   cemissions=e=emissions*FlP;

*cost of emissions in $

**************************Income&Depreciation*************************
****

EQIncome..   Income =e= (sum(egt,eo_egt(egt))-Demand) * Elect ;

*annual income

EQIncomeT..   IncomeT =e= Income*Y;

*total income

EQDeprec..   Deprec =e=(c_inv_egt-EV);

*linear depreciation

*************************Cost**
***

EQc_inv..   c_inv=e=c_inv_egt   ;

EQc_inv_egt..   c_inv_egt=e=sum(egt,cap_egt(egt)*INV_egt(egt))/Y;

*annual investment cost

EQc_inv_total..   c_inv_total=e=c_inv_egt*Y;

*total capital investment

EQc_om..   c_om=e=c_om_egt   ;

EQc_om_egt..   c_om_egt=e=(sum(egt,cap_egt(egt)*OM_egt(egt)))   ;

*annual OM cost

```
EQc_fuel..          c_fuel=e=sum(pri,fuel_con(pri)*FP(pri)*8760*3600*10**(-6));
*fuel price is defined in $/KW of fuel input
EQc_total..         c_total=e=c_inv+c_om+c_fuel             ;

*************************ROI*****************************************
******
*EQROI..             ROI*(c_inv_total)=e=(Income-c_om-Deprec);
*EQROIL1..             ROI=g=0.1;
*EQROIL2..             ROI=l=0.2;

*******************************************************************
******
EQobj..             objective =e= c_total + cemissions;

Model Problem /All/;
Option optca=0.000001;
Solve Problem using mip minimizing objective ;

Display
c_total.l,cap_egt.l,c_inv.l,c_om.l,c_fuel.l,fuel_con.l,Income.l,IncomeT.l,Deprec.l,ROI,emissions.
l,cemissions.l,objective.l;
```