Project Title:

# Life Cycle Analysis (LCA) of Liquefying Natural Gas Process (LNG)

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## Abstract

Natural gas is considered as eco-friendly fuel because it is less polluting compared to other fossil fuels. The use of natural gas as fuel is examined for its green house gas emissions and for its harmful effects to the environment. Natural gas is used commercially as fuel in the areas of power generation and transportation, fertilizer production and aviation. These usage are looked into for its harmful emission potential during combustion. Emissions are possible in different stages of natural gas and explained for the main stages namely extraction, processing and liquefaction. The methods of life cycle analysis are used in understanding the environmental impact when natural gas is processed and used as fuel. The report also provides a comparative analysis of natural gas as fuel along with fossil fuels such as coal and diesel. An understanding on important theories such as LCA, LCT, processes of LNG, inventory and impact assessments are provided for the process of cradle-to-gate. Discussions related to human health (pollutants, toxicity, etc) and ecological effects when natural gas is used as fuel in power plants is provided as an example. Discussions on greenhouse gas emissions to the environment are compared for natural gas with coal and diesel.

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# CHAPTER ONE

## Introduction

Development activities involve impacting the environment or the depletion of natural resources significantly. Such impacts are assessed and measured using methods of LCA. In this project the methods of LCA are applied to understand the environmental hazards in the liquefaction of liquefied natural gas (LNG). LNG refers to liquefied natural gas, a fossil fuel that has immense benefits and can be used in a variety of applications. The processes of LNG include extraction of material, purification, processing, manufacturing, transporting, and recycling or disposal. In each stage in the handling of LNG, harmful emissions such as carbon dioxide, hydrocarbons, and many more hazardous compounds are released to the atmosphere.

The extraction of LNG is a challenging process, the extracted LNG needs to be stored and/or transported in controlled environments because it is lighter than air and can escape easily. The LNG when released adds to Greenhouse Gases (GHG) which in turn leads to global warming. In this project, the LCA methods are applied to study the effects of GHG emissions in the processes of liquefied natural gas. Natural gas is seen as an alternative energy resource for petroleum because of its low carbon dioxide discharge. The project aims to understand the environmental impact in LNG and the effects it can cause to humans. The environmental impact is studied in liquefaction of LNG using the life cycle assessment framework (ISO 14040 and ISO 14044), applied at the liquefaction stages of LNG (Rebitzer et al 2003).

## Life Cycle Assessment (LCA)

As industries seek to reduce the environment impact, tools and methods are required by understanding the environmental impact which is a result of their actions. One such tool is called the "Life cycle analysis (LCA)" which helps corporations or industries to understand the environmental impact associated with their process and/or in the product development activity (Rebitzer et al 2003). LCA is a methodology followed globally by companies or organizations involved in oil and natural gas production and natural resources or in energy management. The objective of LCA is not to provide an answer to reduce environmental impact in the natural resource management processes, rather it provides important and useful inputs by which engineers and scientists can develop their plans strategically to reduce the environmental impact (Foss, 2007). LCA is found to be useful when companies are planning for new imperatives such as designing environmentally sound processes and products.

LCA is a framework which can methodologically estimate and evaluate the environmental impacts by attributing an impact to the life cycle of the products/processes. The environmental impacts assessed by LCA include climate change, global warming, stratospheric ozone depletion, troposphere ozone (smog) creation, acidification, toxicological stress on human health and ecosystems, global warming, and so on. The LCA framework also includes depletion of water, soil and land use, creation of high noise levels, carbon dioxide emissions and many others (Rebitzer et al 2003). Hence, LCA provides the methods and techniques to tabulate emissions due to the consumption of resources and the interaction with other environmental exchanges which are relevant in every stage of product development. This life cycle will include raw material extractions, energy acquisition, materials production, transportation, manufacturing, distribution, use, re-use, recycling and finally disposal. The generic life cycle processes are shown in figure 1:

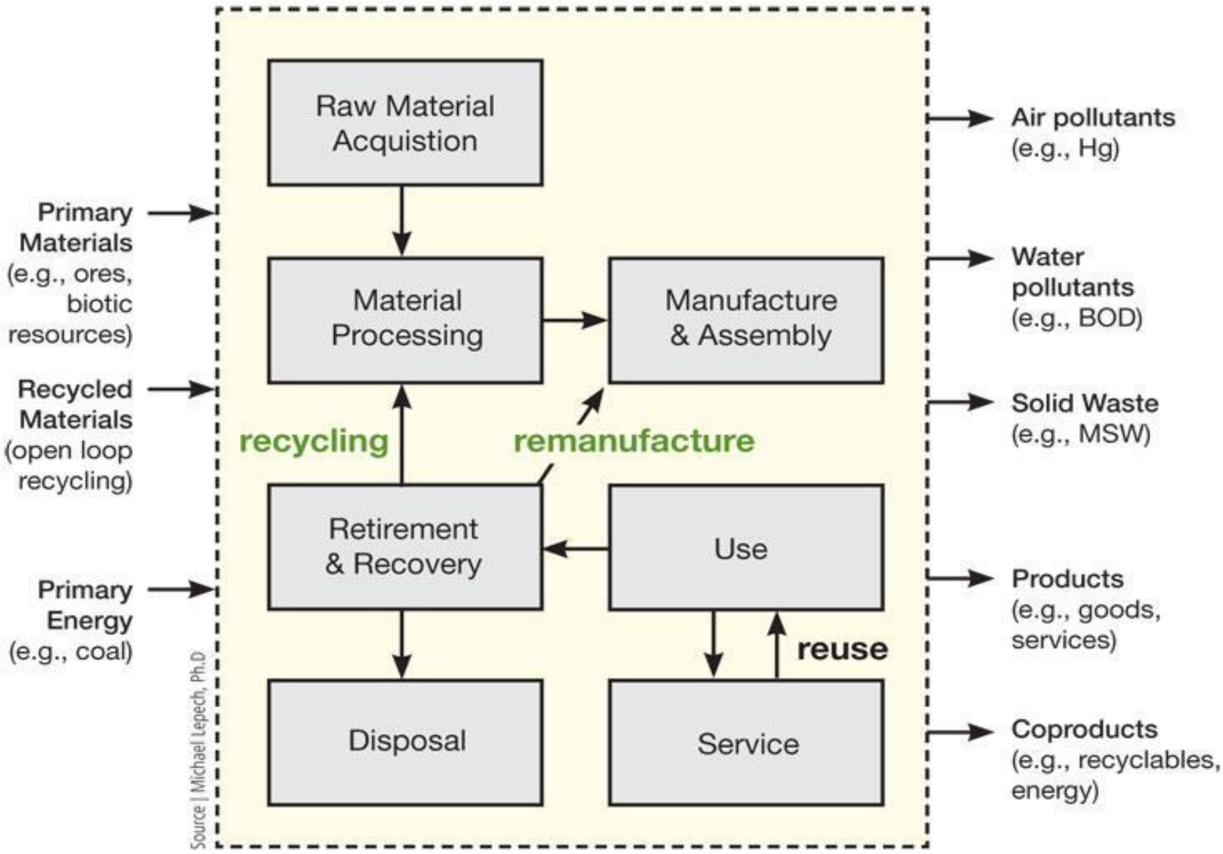


Figure 1 Generic life cycle processes in product development (Fawer, 2001).

## A brief history about Life Cycle Assessment (LCA)

The LCA framework took shape in 1960s when there was a need for more energy globally and scientists became concerned about the rapid depletion of fossil fuels. Fossil fuels are fuels obtained from nature. These fuels are coal, petroleum, natural gas, wood, etc. Studies related to global modeling predicted the increase in human population across continents is driving the need or more energy and demands are growing for finite raw materials. The studies also revealed that depletion of fossil fuels is resulting in drastic climate changes in many countries and this created interest in assessing environmental impact due to industrial processes. Global atmospheric changes such as these brought the academic and research community together to develop a comprehensive framework for assessing detailed energy calculations on industrial processes.

## Life Cycle Assessment (LCA) stages

In simple terms, the LCA framework is developed to reduce the pollution size by conserving non-renewable resources. The main objective of LCA is to develop and utilize clean technologies which will conserve ecological systems by applying the appropriate mitigation techniques (ISO 14041, 2006).

LCA tools and standards evaluate the environmental consequences of a particular product or process. LCA systematically assesses each stage of the process for its impact by including the components namely; Scope and Goal definition, Inventory, Impact and Interpretation. These components can be evauated by using ISO 14040 and ISO 14044 standards which is shown in figure 2.

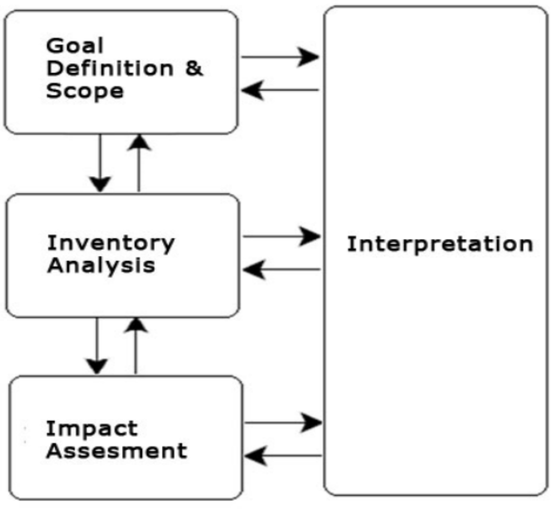


Figure 2 Life cycle assessment steps by ISO (ISO 14044, 2006).

### Scope and Goal definition:

In LCA, defining the scope and goal is crucial because it determines the essential aspects which are aims of the insight interest. The scope concerns the selection of parameters that corresponds to impact assessment and the interpretations that are possible within the LCA framework. Goal is defined the concrete area that is fixed in defining the objective for LCA. The goal also mentions the role of LCA that plays in decision making process in relation to economics, technology, social factors and so on.  Further when the results are communicated it is important to make it clear for which questions the LCA is suitable, leaving out the questions that are not suitable (ISO 14040 and ISO 14044, 2006).

### Inventory:

Inventory provides the objective for data-based process of quantifying energy and raw materials which are the inputs. Inventory also provides information on air emission, solid waste, waterborne effluents and other environmental releases incurred in the lifecycle of process, product or activity which forms output (ISO 14040 and ISO 14044, 2006).

### Impact:

Impact assessment evaluates the effects of the environmental assessment results identified in the inventory component.  The impact assessment must address the health impact for humans and ecological effects as well as social, cultural and economic impacts (ISO 14040 and ISO 14044, 2006).

### Interpretation:

This phase of the LCA includes the findings from analysis of inventory or impact assessment or both.  Interpretations have to be consistent with the scope and goal definitions and must provide conclusions and recommendations (ISO 14040 and ISO 14044, 2006).

LCA focuses on the inventory component because the elements can be measured more objectively and the inventory component is considered the main area for LCA development (Svoboda 1995).  In this project the life cycle assessment of liquefied natural gas (LNG) is performed for is environmental impact.

Based on the standard guidelines suggested by ISO 14040 and ISO 14044, there are various types of life cycle assessment in which it can be categorized. The assessment types as shown in figure 3 are:

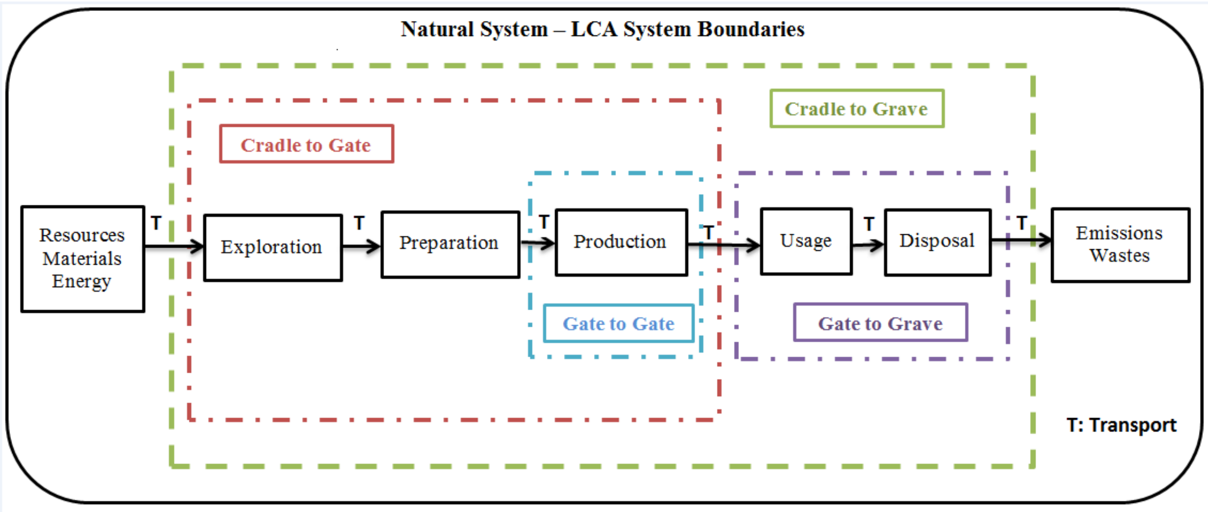


Figure 3 System boundaries of Life cycle assessment (ISO 14044, 2006).

1. The first type of assessment includes the first few stages; raw material extraction to the end of production. This is called 'cradle to gate'.
2. The second type in assessment includes all the stages; raw material extraction till disposal. This is called 'cradle to grave'.
3. The third assessment includes recycling and reuse mechanism to dispose the waste. This is called closed loop production or 'cradle to cradle'.
4. In the last type assessment takes one stage at a time; beginning of one stage to the beginning of the next stage. This is called 'gate to gate'.

In this project, the first kind of LCA is used on the liquefaction process of liquefied natural gas (LNG) which is cradle to gate.

## Natural Gas

Natural gas consists of various hydrocarbons and non-hydrocarbons as byproducts. The prime constituent of natural gas is methane ($CH_4$), whereas, ethane ($C_2H_6$), propane ($C_3H_8$), and butane ($C_4H_{10}$) are considered as heavy hydrocarbons. In addition, it contains some non-hydrocarbons like carbon-dioxide, nitrogen, sulphur, oxygen and water. In addition, there are various additional stages for processes like re-gasification, transport, shipping, etc. The entire process of production, processing, transmission, storage, distribution, liquefaction, tanker transport or shipping, and re-gasification is called liquefaction natural gas process (Howarth, et. al, 2011).

## Natural Gas Processing

In the process of liquefaction, a series of processes are used to convert a raw gas to a LNG. The process involves the following steps, which is shown in figure 4.

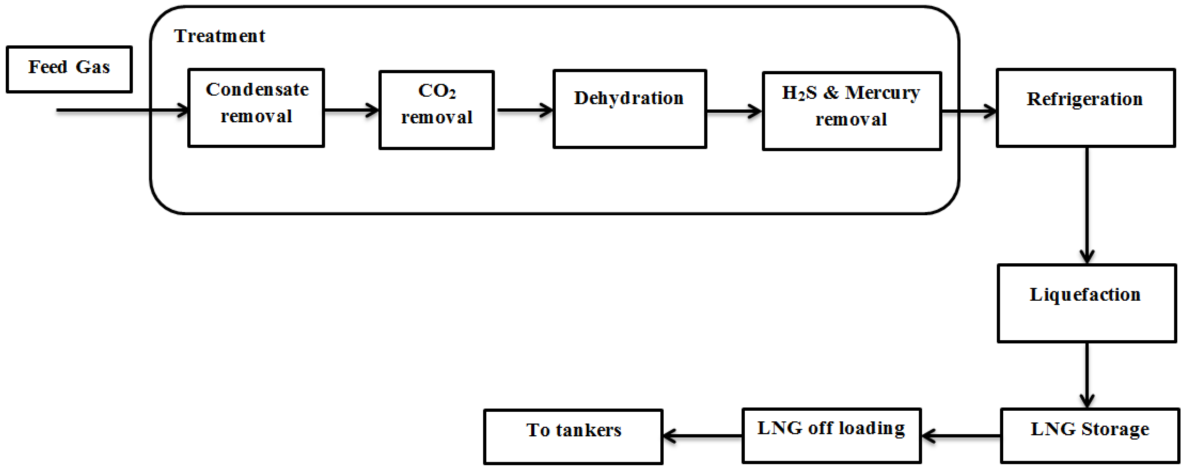


Figure 4 Liquefaction process steps (Foss, 2007).

1. Initially, the feed gas is sent to the liquefaction plant through a pipeline after extracting it from a well such as gas well or oil and gas well.
2. Several processes like compression, condensation, and expansion, are involved to remove gases such as carbon dioxide ($CO_2$), nitrogen dioxide ($NO_2$), hydrogen sulphide ($H_2S$), water and mercury.
3. Gases like methane, when discharged to the atmosphere effects the environment and human health by emitting hazardous gases.

In each of the above steps a number of physiochemical processes are involved at each stage in natural gas so it can be used as fuel in place of other fossil fuels. When LNG is used as a fuel to generate power, such as in like in power plants and refrigerators various toxic gases including the Carbon dioxide equivalent ($CO_2$-e) are emitted to the atmosphere. The fuel that is consumed to generate power depends upon the quality of the liquefaction process. A better liquefaction process in reducing the percentage of toxic substance contained in it (Foss, 2007).

### Natural Gas Usage

Natural gas is used as fuel in domestic and in transport. It is also a major source of electricity generation and seen as an ideal fuel alternative to coal. Natural gas is used in power generation through the use of gas turbines and also in steam turbines. Further, Hydrogen is produced by using natural gas. Hydrogen has a variety of beneficial usages in different applications. Natural gas in its compressed form is used as transport fuel. However to transport natural gas, it must be liquefied first. Natural gas in its purest form contains less than 1 ppm (parts per molecule) of $CO_2$. Natural gas needs processed to remove impurities before it can be used for commercial purposes. Natural gas as fuel is used in the following applications such as:

- Power generation
- Transportation
- Mid-stream natural gas
- Fertilizer production
- Aviation

## Liquefied Natural Gas (LNG)

Liquefied natural gas (LNG) is fuel made from natural gas which has found its use in many applications such as power generation, heating for homes and industries and used in chemical plants. The benefits of LNG are many; they include the use in the manufacture of a wide variety of products from fibres to clothing, to plastics, to healthcare, computing, etc. LNG is meant for transportation purposes and offers more flexibility than pipeline gas. LNG is considered as a clean alternative for use in public transportation as fuel. LNG is already used by the transportation industry for maintenance and emergencies. This is more economical to transport and LNG is a cryogenic liquid because it liquefies below -73$^{o}$C (-100$^{o}$F). Other common cryogenic liquids include nitrogen, oxygen, helium, hydrogen and also LNG.

This gas is cooled and condensed to liquid form at atmospheric pressure. At this state, the temperature of LNG is around (-162 $^{o}C$). The key component of LNG is Methane ($CH_4$) which makes up around 85% - 95%. The chemical properties of LNG are, it is colorless, odorless, non-corrosive and non-toxic. When LNG is exposed in atmosphere it can cause suffocation for humans because it displaces oxygen in the atmosphere (Pettersen 2012).

Natural gas comes from beneath the earth's surface. Sometimes the process occurs naturally. It is produced by itself, also known as non-associated gas. LNG sometimes comes to the surface with crude oil, known as associated gas. Natural gas is a fossil fuel and constitutes of hydrocarbons, the main component in LNG is methane. During the production of natural gas from the earth, many other molecules such as ethane, propane and butane are also included with it. The molecules of ethane ($C_2H_6$), propane ($C_3H_8$), and butane ($C_4H_{10}$) are used in manufacturing, as backyard grills and as lighters respectively. Since LNG is liquefied at high sub-zero temperatures liquefaction is very important process in handling LNG (Howarth, et, al, 2011).

The idea of natural gas liquefaction began during 19$^{th}$ century when noted British chemist Michael Faraday conducted experiments with liquefying different gases along with natural gas (Foss, 2007). The chronology of events in the making of LNG is provided below:

In 1873 a German engineer named Karl Von Linde built the first practical compressor refrigeration machine in Munich (Howarth, et, al, 2011). In the year 1917 the first LNG plant came into operation in West Virginia (Foss, 2007). The year 1941 saw the first commercial liquefaction plant for LNG, built in Cleveland, Ohio, USA (Elcock, 2007).

Liquefaction provides the benefit of transporting LNG to other destinations that are far away. In 1959 the world's first LNG tanker was built. LNG is stored in steel tanks made of specialized insulation (Pettersen 2012). The world's major supplier of LNG is Algeria; in 1964 UK became the world's largest LNG importer from Algeria (Elcock, 2007). In 1970s more liquefaction plants were built in Atlantic and Pacific regions. From 1970 onwards more and more countries across the world became consumers of LNG and the industry is growing constantly (Howarth, et. al, 2011).

## Liquefied Natural Gas processing (LNG)

Natural gas extracted in this liquefied form can be used as a fuel in many applications. The applications include generating electricity in power plants. In addition, LNG is used in vehicles and in domestic consumption like cooking, cooling, heating, etc. The transformed liquefied form of natural gas can be used as a raw material in other manufacturing products. There are various products or the material produced even at the advanced level of production can be used as a raw material for various other activities. The process involved in obtaining LNG consists of a sequence of stages. The value chain of LNG includes exploration and production, liquefaction, shipping, re-gasification and storage (Pettersen 2012). The general block diagram is shown in figure 4.

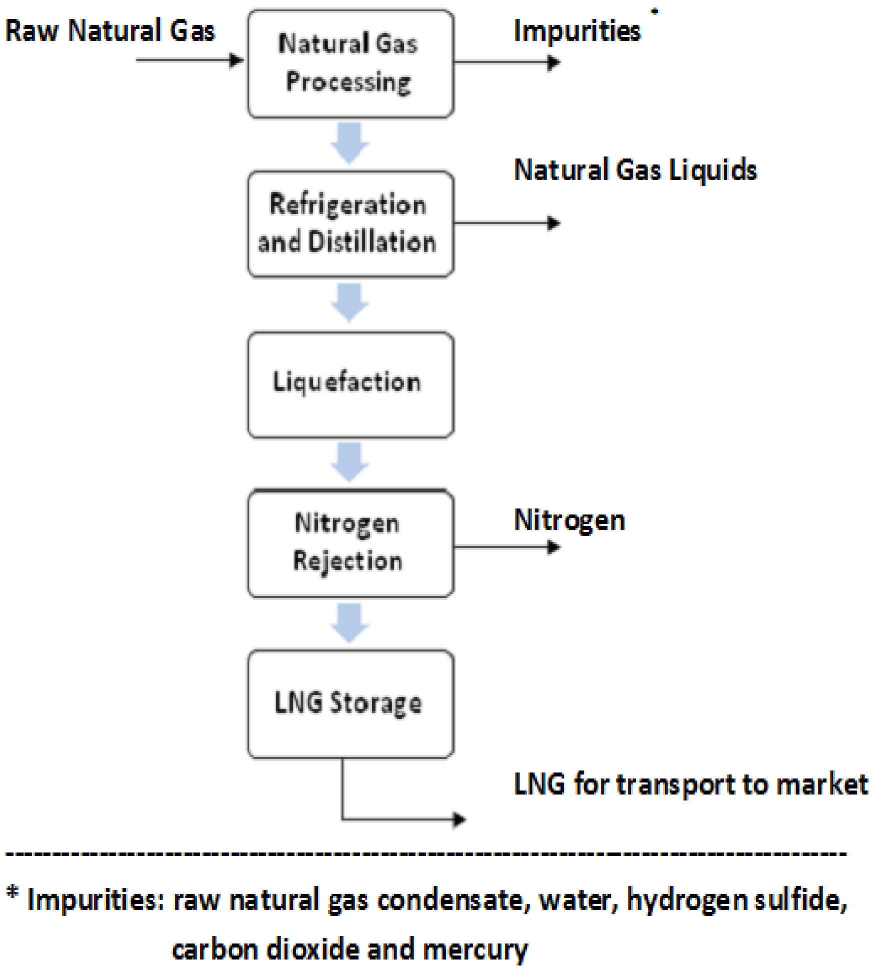


Figure 5 Diagram showing the processing stages of LNG (Howarth, et. al, 2011).

# CHAPTER TWO

## Literature Review

The chapter on literature review provides theoretical foundations on life cycle assessments in the liquefaction of liquefied natural gas. LNG is a fossil fuel and less toxic in comparison to petrol or coal, however vents out significant greenhouse gas emissions during its processing stages. The environmental impact of liquefying LNG is critical to understand and achieve necessary trade-offs in terms of reducing $CO_2$ and other emissions that contribute to increased global warming. In order to understand the LCA of LNG, the LCA methods applied to natural gas is also examined. The use of the LCA framework provides the necessary parameters for assessment to measure environmental impact in liquefying LNG. The technological aspects in liquefying LNG are also explored to examine the processes better. In order to understand the application of LCA in LNG, existing literature found in books, academic journals, research publications, industry white papers and articles are reviewed and presented under various sections below.

### Life Cycle Assessment in Natural Gas

Natural gas is considered a major alternative source of energy which accounts of 21% of world's energy supply till 2010. Natural gas is obtained from underground reservoirs and extracted along with other fossil fuel. Natural gas is made up of odorless, color less gases and large quantities of methane along with other hydrocarbons such as ethane, propane, iso-butane and normal butane, etc. Natural gas is a fossil fuel and when burnt as fuel vents out less amounts of GHGs almost 25% less compared to coal. Natural gas is made up of hydrocarbons along with traces of $CO_2$, Oxygen, Nitrogen, $H_2S$, and also rare gases (helium, neon, etc) (Webster 2013).

The Canadian Natural Gas Initiative (CNGI) (2012) report explains further on benefits of using natural gas in many applications such as electricity generation. During the recent years natural gas is gaining attention because of its low emission in GHGs. This gas has the lowest carbon content in comparison to other fossil fuels, lower sulfur than coal or grades of petroleum to result in lower sulfur dioxide (SO2) and particulate emissions (PM). The combustion of natural gas can be controlled effectively which allows the minimal emission of nitrogen oxides (NOx) and PM in comparison to other fuels.

The LCA analysis of the different processes involved in the production and life phases of natural gas are investigated by many research studies. The studies involved several aspects such as energy-use, material flow, air pollution, GHG emissions, etc. Fischedick et al (2004) highlighted the importance of unavoidable or indirect emissions of GHGs in the processing of natural gas. When natural gas is released into the atmosphere as uncombusted methane, it is very harmful and a potent GHG. However, the risk to humans is less because natural gas is lighter than air and hence this gas will not settle on the floor. CNGI (2012) report explains on Global Warming Potential (GWP) which is a method followed to determine the warming effect of GHGs. GWP is determined by the ratio of GHG warming effect relative to $CO_2$. For instance methane has a GWP of 25i. This implies the warming effect of one tone of methane is equivalent to the warming effects of 25 tones of $CO_2$. The LCA of natural gas must include emission levels in its production chain because methane is vented out in its stages which leads to GHG effects resulting in high GWP.

## Life Cycle Assessment in Liquefying Natural Gas

ISO 14040 (2006) states that by using LCA's potential, environmental impacts of a product or a system can be analyzed throughout its life cycle. Here the product studied is liquefaction of LNG which forms the product system. A product system basically has well defined functions which are separate processes that are connected by energy or material flows. Since the LCA basically consists of data inventory steps for analysis, impact analysis and interpretations, the data obtained from each processes involves energy consumption which are translated into emissions to finally result in impact which is quantitative. Sevenster and Croenzen (2006) illustrated the application of LCA is studied for its impact assessment and green house gas (GHG) emissions in LNG processes. Figure 14 illustrates steps involved in LNG unit process.

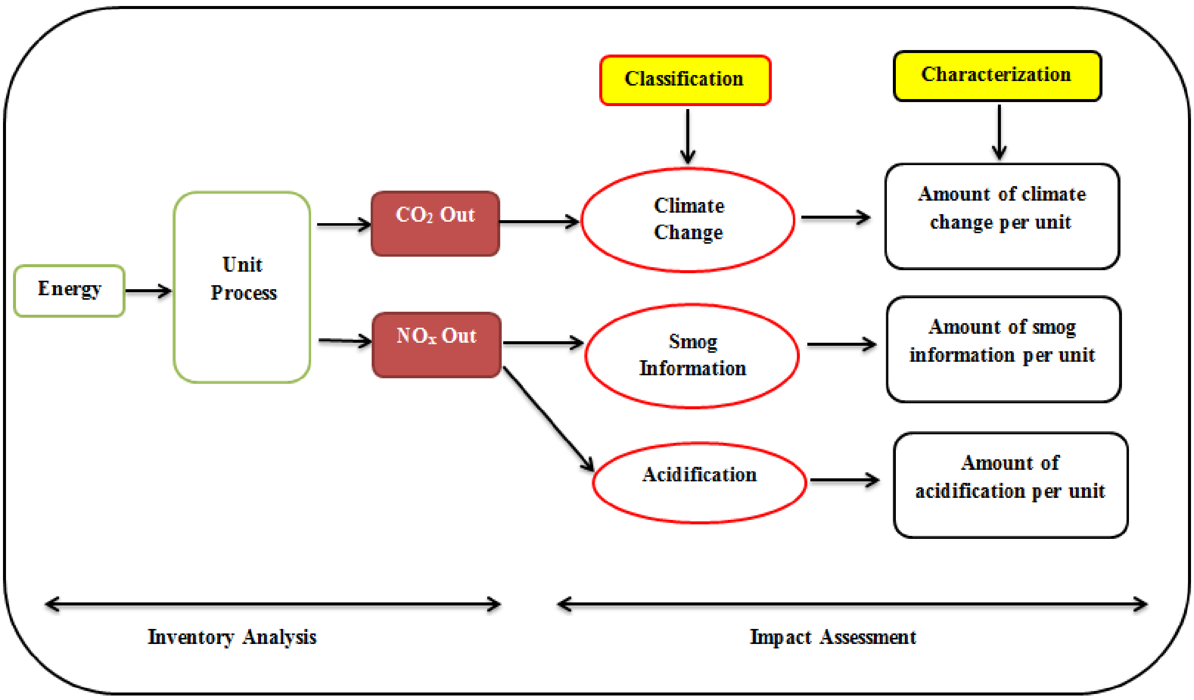


Figure 6 The steps involved in LCA as applied to a unit process (Sevenster and Croenzen, 2006).

United Nations Environment Programme (USDOE) (2005) report explains that LNG is cleaner than coal and oil in terms of GHG emissions and has gained more recognition compared to coal or petroleum. There are major components to LNG in the providing of natural gas to end user. They are: Extraction, Liquefaction, and Storage. These components also are involved in the value chain in the global LNG business.

The emissions of LNG during extraction, liquefaction and storage are an interesting area for LCA application to study on emissions. All emissions have an impact on the environment ecosystem. Around the world, fossil fuels are still dominant and all energy for the world is derived from ecologically un-expectable energy sources (Our-Energy 2007). Coal is the base fuel and normal combustion of coal produces $CO_2$. GHGs include $CO_2$, carbon monoxide, $H_2S$ and many more. All these GHGs displace oxygen and increase global warming. Apart from $CO_2$ and CO released from combustion of coal, particle emissions such as nitrogen and sulphur oxides ($NO_x$ and $SO_x$) are released by burning of oil.

The combustion of LNG reduces particle emissions by almost 99%, sulfur oxide (SOx) emissions are almost reduced to 100%, nitrogen oxide (NOx) to 80% and GHG emissions are few (Tamura et al 2001). Zhang and Noam (2006) emphasizes on the issue of reducing emissions in the liquefaction process of LNG which is a big challenge. Further, when LNG is burnt for power generation, sulfur and carbon dioxide emissions are significantly reduced. Due to this reason LNG is used as clean fuel and can significantly reduce green house gas in the atmosphere. Clean fossil fuel with complete carbon capture is highly essential to make low-carbon and is investigated in future energy generation portfolios (IEA 2011). The Environmental Protection Agency (IEA) (2006) study also emphasizes on benefits in using LNG as a fuel and as alternative source of energy in the future.

During the liquefaction of LNG, $CO_2$ emissions are discharged, particularly when LNG is used as fuel in gas turbines. Tamura et al (2001) explains that the productive capacity and efficiency of the liquefaction plant determines fuel consumption. Arteconi et al (2010) provided three types of GHGs in the liquefaction of LNG, these emissions include;

- Emissions from fuel consumed by the equipment such as in driving turbines and motors in the plant
- Emissions vented out in the combustion process. A lot of waste gases and flares are finally released into the atmosphere.
- Loss of gas due to pre-treatments, maintenance and loss from pipelines, etc.

Hondo (2005) illustrated the application of LCA through a study on GHG emission from power plants for producing 1 kWh electricity in a Japanese power plant. The emission factor is determined to evaluate the emission characteristics in power generation technologies from the perspective of global warming. GHG emission for 1 kWh electricity is given by:

$$LCE = \frac{\sum_i GWP_i * (Ef_i + Ec_i + Eo_i + Ed_i)}{Q} \quad (1)$$

Here LCE = Life cycle emission

$E_f$ = direct emission due to combustion of fossil fuel

$E_c$ = emission associated with construction

$E_o$ = emissions in operations and maintenance

$E_d$ = emission during decommissioning of the plant

GWP stands for the global warming potential factor and subscript *i* indicates the type of GHG namely $CO_2$ or $CH_4$.

In liquefaction process of LNG, amines are used as a solvent to remove $CO_2$ from LNG. Tamura et al (2010) explained that small quantities of $CO_2$ and $CH_4$ are dissolved in the regeneration process where $CH_4$ is extracted and used as fuel for turbines. In each stage of liquefying process purifying LNG inflows is important. Emissions due to re-gasification are also an issue. In this process emissions are $CO_2$ which are a result of electrical energy consumption by pumps that transfer LNG from ships to storage facilities. Re-gasification is normally done in close proximity to the ship's receiving terminal. GHG emissions have other environmental effects such as acidification and eutrophication in addition to global warming.
The balance equation for calculating proportional division of grams of carbon per mega Joule of heating energy (g – C/MJ) is shown in table 1.

Table 1 Formula to calculate proportional division of CO2 emissions (Tamura et al, 2010).

| Name | Process | **Proportional Division Formula (g-C/MJ)** |
|---|---|---|
| Liquefaction | Fuel consumption | $\frac{CO_2\ from\ fuel\ consumption}{(Condensate + LPG + LNG)}$ |
| | Flare Combustion | $\frac{CO_2\ from\ flare\ consumption}{(Condensate + LPG + LNG)}$ |
| | CH4 from venting | $\frac{CH_4\ from\ venting}{(Condensate + LPG + LNG)}$ |
| $CO_2$ in input gas | | $\frac{CO_2\ in\ raw\ gas}{(Condensate + LPG + LNG)}$ |
| Emissions | | $CO_2 + CH_4$ |
| Product | | Condensates + LPG+ LNG |

Okamura et al (2007) provided results for the life cycle $CO_2$ emission analysis ($LCCO_2$). $LCCO_2$ includes emissions of both $CO_2$ and $CH_4$ in the production to liquefaction stages for LNG. The average values are provided in table represent values for data obtained in 2003 below:

Table 2 Results of LCA obtained from liquefaction of LNG from plants in Qatar and Abu Dhabi in 2003.

| **Liquefaction Stage** | **Average (g–$CO_2$/MJ)** |
|---|---|
| $CO_2$ emission from fuel consumption | 5.60 |
| $CO_2$ emission from flare combustion | 0.42 |
| Emission of $CH_4$ | 0.47 |
| $CO_2$ found in raw gas | 1.87 |

Primarily, life cycle approaches are used for product development and also in strategy development up to a certain extent.  According to UNEP and SETAC, LCA is a practical and integrated framework to minimize environmental hazards. However there are many other factors that play a major role in LNG life cycle namely life cycle thinking approach when combined with LCA methods makes it more effective in minimizing environmental hazards.

## Common Environmental Impacts

The life cycle methodology emphasizes on economic, social and environmental aspects. There are many impacts due to venting of methane which is detrimental to the eco system (flora and fauna) including humans (ICCA 2013). The type of effects are given below;

**Global warming**: This includes clime changes, extinction or migration of eco-systems (flora and fauna), damage or loss of coral reefs, increased hurricanes and many others(ICCA 2013).

**Acidification**: This category is the effect due to emission of acidic gases such as sulfur oxides, nitrogen oxides, ammonia, etc. Air acidification causes respiratory and cardiovascular problems in humans. Acidification also contributes to acid rain which causes death of animals, plants and results in huge damage. Plants do not grow because the soil becomes infertile (ICCA 2013).

**Eutrophication of water**: This effect results in overgrowing of algae in water bodies which prevents nutrients in water bodies. Eutrophication results in extinction of aquatic life, deterioration of water quality, increased turbidity in water, increases in sedimentation thus reducing the life span of water bodies (ICCA 2013).

**Ozone Depletion**: The depletion of stratospheric ozone in the atmosphere due to GHG emissions is another major issue. Depletion of ozone results in temperature increase in the earth, exposure to ultraviolet light which leads to cancer in humans, life cycle of food chain is altered and affects microorganisms (ICCA 2013).

## Case Study

In this section the work done in research titled "A Life Cycle Comparison of Coal and Natural Gas for Electricity Generation and the Production of Transportation Fuels" done by Pauline Jaramillo is examined. This study was conducted in 2007 at Carnegie Mellon University, Pittsburg, Pennsylvania (Jaramillo 2007). In this research, the author explores answers for identifying which fuel is better for electricity generation, whether is it coal or natural gas. The study explores demand for natural gas, its usage in different application areas and future trends. The focus is to understand the benefits of LNG versus coal as fuel in electric power and for production of transportation fuels and how LNG can reduce GHGs emissions. The main motivation of this study is that electricity generation and transportation fuel accounts for maximum amount of GHG emissions in the atmosphere. Increased consumption of coal or petroleum fuels will have long term implications for GHG emissions. The study also attempts to determine which fuel is better in terms of cost, energy resources, and minimize effects to the environment. For example, in the case of USA, petroleum and coal accounts for 40% and 23% is the consumption for transportation and for electricity respectively. Out of the total energy fuel needs, natural gas accounts for 24% out of which 70% is used by chemical industries and the remaining for commercial and residential consumers. 18% of electricity generated in USA uses natural gas as fuel.

For example, the emission of sulfur and nitrogen oxides when fossil fuels used in power generation in US is shown in table 3.

Table 3 The emissions of SOx and NOx compared with fossil fuels (Jaramillo, 2007).

| Fuel | | $SO_x$ (lbs/MWh) | | $NO_x$ (lbs/MWh) | |
|---|---|---|---|---|---|
| | | Min | Max | Min | Max |
| **Current Electricity Mix** | | 6.04 | | 2.96 | |
| **Coal** | Combustion | 1.54 | 25.5 | 2.56 | 9.08 |
| | Life cycle | 1.60 | 25.8 | 2.83 | 9.69 |
| **Natural Gas** | Combustion | 0.00 | 1.13 | 0.12 | 5.20 |
| | Life cycle | 0.04 | 1.49 | 0.17 | 9.40 |
| **LNG** | Life cycle | 0.094 | 2.93 | 0.25 | 15.4 |
| **SNG** | Life cycle | 0.30 | 3.88 | 0.65 | 8.08 |

The objective of using natural gas as fuel in electricity generation is due to the lower combustion emissions of LNG than coal. In this research the cradle to grave cycle of product is analyzed. The LCA comparison of emissions associated liquefaction of LNG is provided by Tamura et al (2011) is shown in table 4:

Table 4 Liquefaction emission factors (Tamura et al, 2011).

| **Liquefaction** | **Emission Factors (lb $CO_2$/MMBTU)** | | |
|---|---|---|---|
| | Min | Average | Max |
| **$CO_2$ from Fuel combustion** | 11 | 12 | 13 |
| **$CO_2$ from flare combustion** | 0.00 | 0.77 | 1.5 |
| **$CH_4$ from vent** | 0.09 | 1.3 | 9.8 |
| **$CO_2$ in raw gas** | 0.09 | 4.0 | 6.6 |

Pauline Jaramillo's report emphasizes on the importance of life cycle assessment to verify emissions when using fossil fuels such as LNG for electricity generation. The study concludes by comparing natural gas with other fuels in power plants and highlights that natural gas is a better fuel due to its low emission of GHGs. Further suggestions are made to reiterates that LNG can be a better alternative to coal and other fossil fuels. This is quite apparent as the demand for natural gas is increasing globally. Based on studies such as these, the benefits of LCA and LCT, the research in this project is explained in the further sections.

The sections on literature review highlighted the methods of LCA, the importance and usefulness of LCT for its role in LCA. The section also provides brief details on case studies found from few industry resources.

# CHAPTER THREE

## Methodology

In the earlier sections, the importance of natural gas and the processes of LCA are highlighted. Natural gas is gaining considerable attention as clean fuel and as an alternative to conventional fuels such as petroleum or coal. Natural gas provides the major advantage of releasing less carbon per unit of energy during combustion compared to other fossil fuels (Kavita 2010). In spite of its advantages as fuel, uncertainty about net environmental effects on using LNG as fuel remains up to a considerable extent. The main issue of GHG emissions that impact LNG is the energy needed for the processes in extracting, liquefying and storage of natural gas. There is also possibility of leakage of natural gas during these processes as the gas is lighter than air this contributes to the overall GHG emission. Cradle to gate refers to energy resource starting from extraction till it leaves the factory gate for consumption. The major processes involved in cradle to gate are extraction, liquefaction and storage. The main reason behind applying LCA for cradle to gate processes in natural gas is to understand the production of LNG to offset potential climate benefit in spite of the big challenges.

## Process Steps in Natural Gas

Natural gas is obtained from underground reservoirs. Natural gas contains other gases in addition to methane. A considerable amount of non-hydrocarbons such as nitrogen, $H_2S$ and $CO_2$ are also present. Traces of helium, carbonyl sulphide and other compounds that are saturated with water are also present (EPA, 2011). The composition of natural gas in its pure form is shown in table 5.

Table 5 Composition of natural gas (Kavita 2010).

| Typical composition of Natural Gas | | |
|---|---|---|
| Methane | $CH_4$ | 70-90 % |
| Ethane | $C_2H_6$ | 0-20 % |
| Propane | $C_3H_8$ | |
| Butane | $C_4H_{10}$ | |
| Pentane | $C_5H_{12}$ | 0-2 % |
| Hexane+ | $C_6H_{14}$ and Higher | |
| Carbon Dioxide | $CO_2$ | 0-8 % |
| Oxygen | $O_2$ | 0-0.2 % |
| Nitrogen | $N_2$ | 0-5 % |
| Hydrogen Sulphide/ Organo Sulphur compounds | $H_2S$ | 0-5 % |
| Helium | He | 0-5 % |
| Other Rare Gases | A, Ne, Xe | Trace (<0.01%) |

Natural gas is processed in order to make it usable for commercial purposes. Natural gas in its pure form cannot be used as fuel, extensive processing is required to remove by-products and to make it methane rich (Pereira. et, al, 2014). Processing also involves the removal of acid compounds such as $H_2S$ and $CO_2$ and this is important for environmental reasons. For example $H_2S$ must be converted to sulphur. Free liquids such as hydrocarbons and water must also be removed from natural gas. Natural gas in its refined form is delivered through pipelines to its point of use. The gas free of contaminants makes it compatible with requirements of pipeline transportation and conforms to end user specifications (Foss, and Michelle Michot, 2007). The processing of natural gas is done through physiochemical processes shown in figure 15.

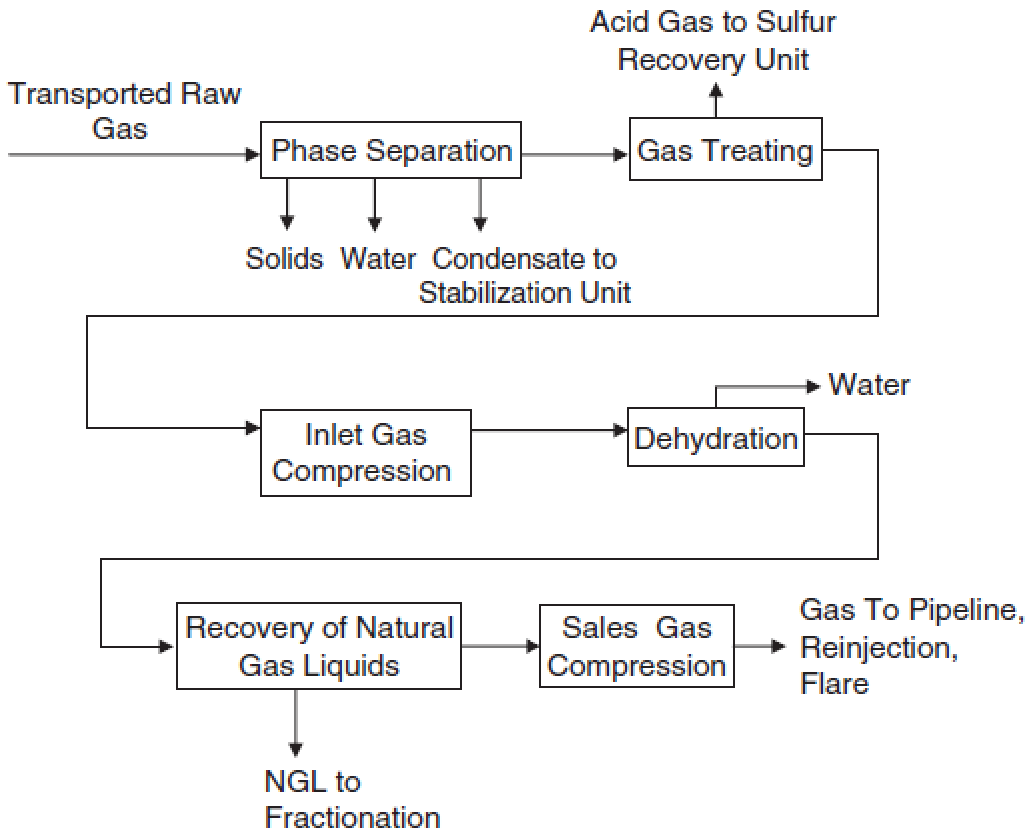


Figure 7 Typical process operation in natural gas processing (Mokhatab et al 2006).

Each of the modules shown in the figure 15, is a single of a group of equipment to perform a specific function. All the modules may not be found in all natural gas processing facilities. It is important to note that the main objective of gas processing plant is to remove impurities, excess hydrocarbons, water, etc., to make it void of hydrocarbons and to control the delivery pressure (Frankl and Rubik, 2000).

The process modules are explained briefly. The first unit module named phase separation physically separates gas, liquid hydrocarbons, liquid water and/or solids. This separation is performed in an inlet separator. The input gas is bit complicated because the transmission lines providing inlet gas operate in more than one phase to result in liquid slugging. Liquid slugging is formed due to elevation changes in inlet supply pipes, changes in pressure and temperature, and gas supply flow rates due to transmission (Arteconi,2010). If inlet flow is not uniform, slugging may occur in pipelines. Slugging must be avoided because it can result in processing equipment impact such as mechanical problems (high velocity, momentum) and process problems (surges and trips, liquid levels). The flow lines are designed to minimize or avoid slugging however in practice this can be difficult. There are methods such as slug catchers used in pipelines to avoid slugging and minimize turbulence, the function of slug catcher is to separate gas, hydrocarbon condensate and inlet water. The gas stream is passed o the inlet separators (Mokhatab et al 2006).

The inlet separators use rotating vane elements to form a group of liquids. Inlet separators may also include filters for the removal of particulate matter and may contain suction scrubbers if compressors are required to increase the pressure gas from low pressure to high pressure for further processing. The separator has three phases to separate hydrocarbon condensate, water/methanol and water/glycol as outputs. Overhead gas obtained from three phase separator is recompressed as required for use as fuel (Frankl and Rubik, 2000).

The hydrocarbon condensate recovered from natural gas must be stabilized before it can be safely transported. This is because un-stabilized condensates can easily vaporize in storage tanks because they contain large percentages of methane and ethane which can easily vaporize in storage tanks. The light fractions from the condensate must be fully removed to make it stabilized. Stabilized liquid has definite pressure limitations, such as the reid vapour pressure 1of < 10 psi. This product after stabilization is injected into pipeline or transport pressure vessel (Mokhatab et al 2006).

Acid gas treating is the next step in natural gas processing. In addition to hydrocarbons and water, natural gas contains many contaminants that have to be removed. Some compounds like $CO_2$, $H_2S$ and other sulphur containing compounds have to be removed completely. These gases are known as acid gases, natural gas with $H_2S$ and other sulphur compounds is called ‘sour gas’ and natural gas with $CO_2$ is called as ‘sweet gas’. These compounds are not required and must be removed fully because the lead to corrosion and pose a major safety risk (Arteconi, et, al, 2010).

The processing of natural gas also involves the removal of sulphur and $CO_2$. The natural gas wells contain these two compounds in high quantities. This is also called sour gas and it is highly important to remove sulphur because it is dangerous if inhaled by humans (Frankl and Rubik, 2000). Further sulphur also damages the pipelines used in distribution, hence this is important to be removed. Sulphur is also removed using the process of condensation and cryogenic expansion. In natural gas processing valve fugitive emissions and other point source emissions also occur. These emissions are a result of valves opening and closing resulting in leaks. Similarly leaks are possible also from control equipment. In the natural gas processing plant it is not feasible to install vapour recovery equipment at all valves and control devices. Other point source emissions in gas processing equipment include leaks from processing equipment. Similarly fugitive emissions are also not possible to capture or control during processing. In natural gas processing venting and flaring processes are similar to extraction and processing (EPA, 2010).

The next stage in processing is inlet compression, which is typically compressing the gas to 300-400 psi or also known as dew point control and natural gas liquid recovery. The main challenge is to avoid gas hydrate formation because this can cause choking or plugging of pipelines and leads to other problems. Water dew formation must meet certain specifications and controls the hydrate formation. Methods to prevent hydrate formation in plant equipment include reducing hydrate formation temperature, using chemical inhibition or dehydration technique to remove water (Frankl and Rubik, 2000).

Cooling the gas and condensing liquids is the recovery process in hydrocarbons. Dew Point control in hydrocarbons is either done through dehydration followed by cooling and condensation. When substantial liquid recovery is required the temperature of the gas is reduced to meet commercial gas specification. Dehydration process is used to remove water from natural gas. Dehydration makes natural gas suitable for pipeline transport and also to increases its value in heating. This process involves an absorber vessel with glycol based solution coming into contact with natural as stream. There is a stripping column on which the rich glycol is heated to remove water and the glycol solution is regenerated, this regenerated glycol solution is again circulated to the absorber vessel (Arteconi,2010).

In the dehydration process methane emissions occur as a result of combustion and venting. This data is used in the analysis to estimate fuel requirements and venting losses of dehydration to determine total methane emissions. Here the amount of emissions depends on concentrations of gas and water that enter and leave the dehydration process. Water content found in untreated natural gas is 49 lbs per MMcf (million cubic feet) of natural gas and for natural gas to achieve pipeline transport requirement, this must be reduced to 4 lbs/MMcf (EPA, 2006).

Gas is transported in high pressure in pipelines (>1000 psi) to keep it dense thus preventing condensation and overcome other challenges mentioned. When gas is separated and has no available pipeline, this is flared which contribute to GHG emissions. The gas which is separated us conserved by compression into producing formations of further recovery and for commercial usage (Frankl and Rubik, 2000).

The main objectives of natural gas processing are:

- Produce gas steams with specifications to satisfy conditions in pipeline requirements and fulfill industrial and domestic use
- Removal of hydrocarbons, acid gas, and other impurities and improve the percentage of methane
- For commercial purposes

To highlight the uses of natural gas, for many years this gas has found its use in many applications. Some of the major areas where natural gas is used as fuel are listed below:

1. **Power Generation:** Electric power industry is the largest consumer of natural gas in many countries across the world. In the US, around 34% of electric generation is made by using natural gas as fuel. Natural gas is used in power sector because of less emission of $CO_2$ when compared to other fossil fuels such as coal or oil. Natural gas when burning emits 30% less $CO_2$ and also emits lower levels of $NO_x$, $H_2S$, particulates when compared to coal and oil (Agrawal, et al, 2014).

2. **Industrial use:** A variety of manufacturing processes use natural gas. Natural gas as fuel is used as a source for heating, and used as raw material for making plastics and other materials. NG is also used in antifreeze industries, pharmaceuticals and fabrics. A range of chemicals such as ammonia, methanol, ethane, acetic acid and propane are manufactured using natural gas. Other industrial application areas include glass, ceramics, bricks and many other commodities and also for incineration purposes in industrial facilities (Arteconi, et, al, 2010).

3. **Transportation:** Natural gas is used as fuel to drive motors, as an alternative to petrol and diesel. Compressed natural gas (CNG) costs less than petrol which has octane number 76 which is equivalent of petrol. This extends engine life and emissions comply with Euro-4 environmental standards. Conventional vehicles such as road and railway transport use natural gas as fuel. Similarly natural gas is used to power ships and other equipment such as generators and in agriculture machinery. The number of natural gas driven vehicles is increasing constantly and is seen as an alternative to gasoline. Natural gas powered vehicles emit around 60-90% less smog producing pollutants and emit 30-40% less GHGs (Arteconi,2010).

4. **Aviation:** Natural gas in liquefied form along with hydrogen is used in flying aircraft. Some experiments in Russia showed results while operating one ton roughly resulted in 60% significant reductions in CO, hydrocarbons and nitrogen dioxide emissions. In order to minimize emissions alternatives to current fuel such as natural gas is researched (Pereira. et, al, 2014).

In spite of the many benefits GHG emissions are analyzed using Life Cycle Assessment (LCA) methods to understand environmental impact while using natural gas.

## Liquefaction of Natural Gas Processing

LNG is used as fuel in power generation plants. The emissions are calculated especially in power generation plants and compared with similar fossil fuel such as coal or oil. The Natural Gas Combined Cycle (NGCC) of thermal power plant is assessed using LCA methods explained earlier. Liquefaction begins when feed gas from upstream well head entering liquefaction plant under pressure. In the processing state hydrocarbons, water and other particulate matter are removed from the feed gas which is further treated in the acid gas recovery unit to remove $CO_2$, $H_2S$, water and mercury (Danesh 1998).

The inflow gas concentration of impurities and gas quality determines the intensity of feed gas treating process. In this process $CO_2$ is vented, and in industrial processing this vented carbon dioxide is collected for geo-sequestration or used in other processing. When methane gas will become liquid carbon dioxide needs to be removed to below 0.5 mol % to prevent plugging during liquefaction.  This process is done to prevent blockages caused by frozen $CO_2$ causing the plant to shut down and cleaning which is time consuming and expensive. Along with $CO_2$, sulphur dioxide must also be removed before liquefaction in order to prevent acid corrosion of the pipe networks. Feed gas when has higher concentration of carbon dioxide will increase GHGs significantly unless it is effectively captured and securely stored via geo-sequestration. Low concentrations of feed gas will incur lower processing cost and lower emissions (Danesh 1998). Figure 16 illustrates the process of LNG.

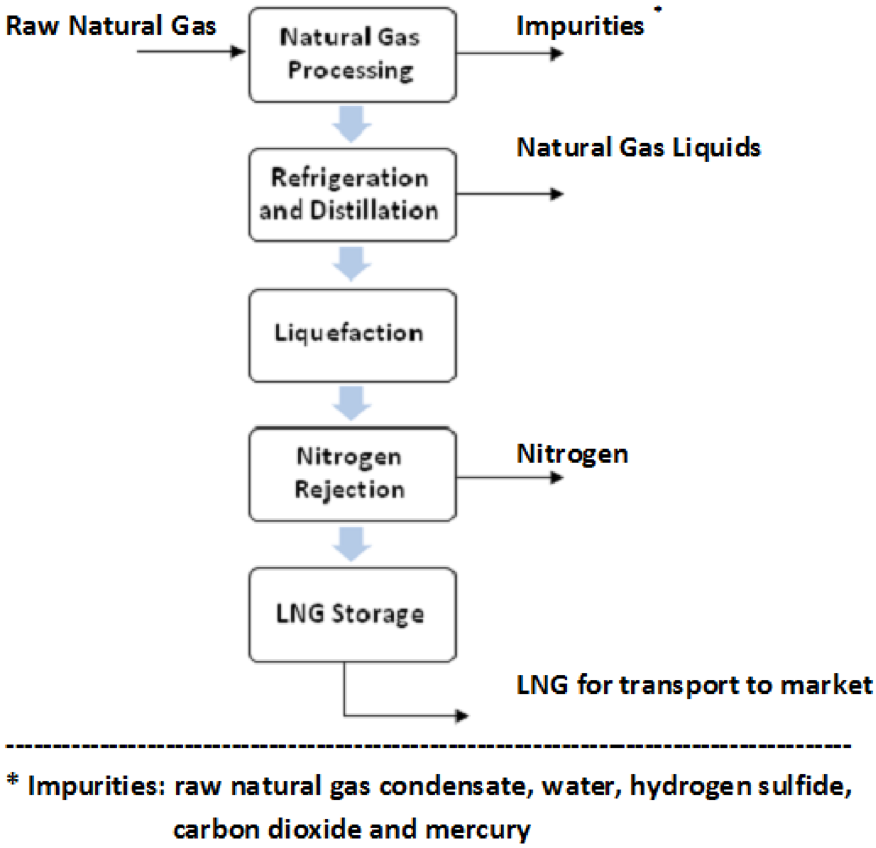


Figure 8 Liquefaction Natural Gas processing (Kikkiwa and Liu 2001).

The process of removal of hydrocarbons is called natural gas liquids (NGL) which is another process done by absorption or cryogenic expander process. Though this is similar to water absorption method, absorbing oil is used here instead of glycol. The temperature of the gas is reduced to result in condensation of hydrocarbons in order to separate them from natural gas. Absorption method is used in the removal of heavy hydrocarbons and the lighter hydrocarbons can be removed by cryogenic expansion process (Kikkiwa and Liu 2001).

The overall thermal efficiency of LNG is improved and the concept of zero $CO_2$ is being initiated by the LNG industry (Kikkiwa and Liu 2001). In order to achieve zero emission, the concept of carbon capture and storage (CCS) systems must be integrated in the plant design. “The process of CCS removes or significantly reduces $CO_2$ content of streams which is normally released to the atmosphere. The captured $CO_2$ is transported to the location for storage, this $CO_2$ is captured from wide range of single point sources such as process streams, heater and boiler exhausts and vents in the plant such as refining, chemical, steel and natural gas treating. The captured $CO_2$ is compressed, dried and shipped to a suitable storage location such as depleted gas reservoirs and oil wells" (Danesh 1998).

## Life Cycle Assessment (LCA) in Liquefying Natural Gas (LNG)

The founding principles of LCA are to objectively analyse processes in LNG to evaluate the environmental impact. This analysis is done by identifying and quantifying energy and usage of material released in the environment. The next stage is to assess the impact of these effects to evaluate and implement opportunities to improve the processes. LCA of cradle to gate analysis is studied in this section follow the procedures of ISO 14040 an ISO 14044 standards (EPA 2010). The life cycle stages of cradle to gate is illustrated in this figure 17.

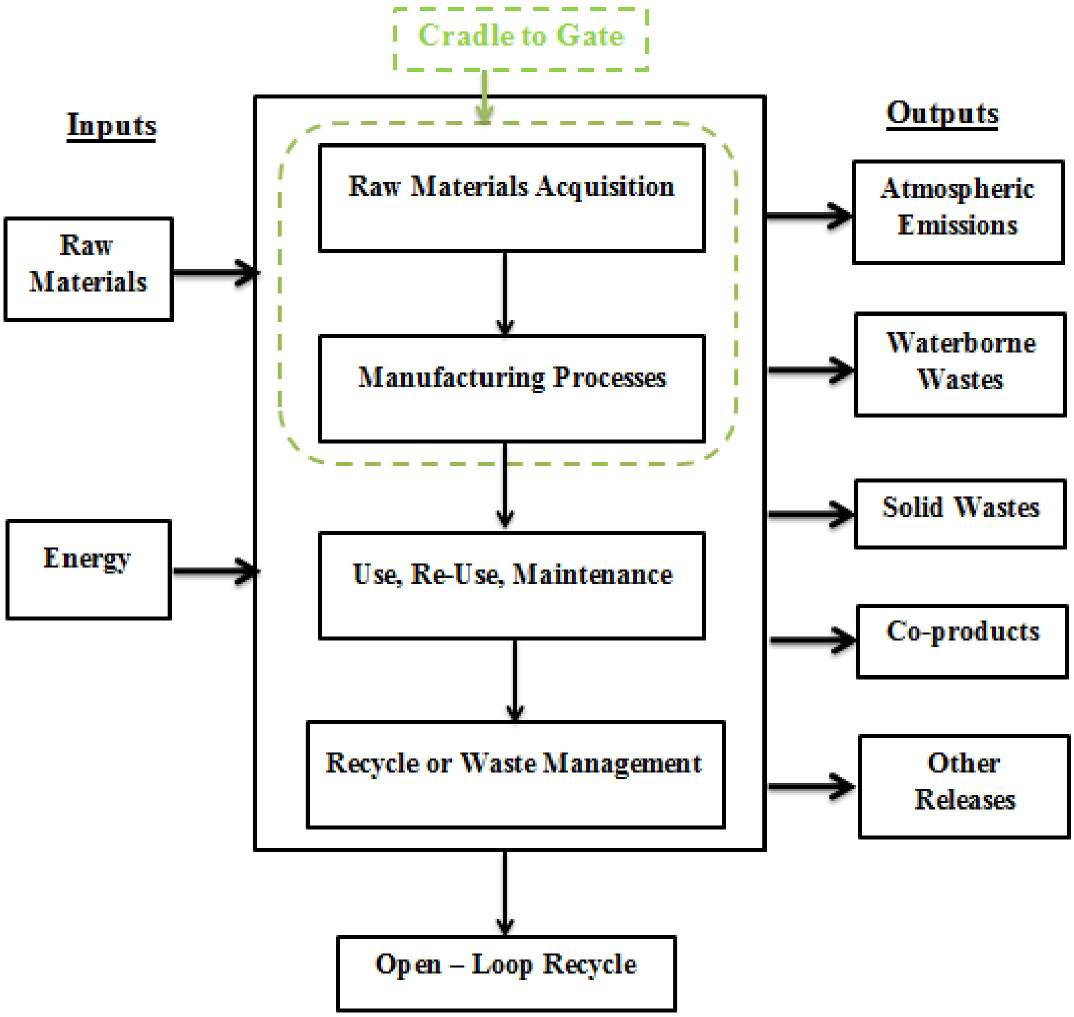


Figure 9 Life cycle stages of LNG related to Cradle to Gate processes (EPA 2010).

## LCA for assessing LNG processes

The focus of this work is to assess emissions that lead to GHGs and environmental impact in the stages of extraction, liquefaction and storage. The LCA approach identifies emissions in the form of $CO_2$-e during the phase of cradle to gate. The LCA can be quantified for GHGs such as $CO_2$, $CH_4$, and $N_2O$. Normally as LNGs are being used more in electric power generation and in transportation or in other usages. GHGs are a result of natural gas combustion which is vented in the atmosphere. LCA processes are normally based on delivering a function or equivalent service such as the delivery of 1 KWh electricity to consumers. Such a life cycle GHG inventory includes the upstream (extraction to storage) and this includes many different processes. While handling natural gas, there are issues such as venting, fugitive emissions and leaks in liquefaction process. Gases such as $SF_6$ (sulphur hexafluoride), hydro-fluorocarbons (HFC), per-fluorocarbons (PFCs) contribute to GHG emissions which adds to the overall effect in global warming. In the first step the boundary conditions are defined

### Boundaries

In the cradle to gate GreenHouse Gas (GHG) inventory the focus is on raw material extraction and transport for liquefaction and storage. This is also referred as upstream because this processed gas is further transported to power plant. The figure 19 shows the life cycle stages and the definition of boundaries.


Figure 10 Definition of boundary conditions in life cycle stages (ISO 14040, 2006).

In figure 19, the stage 1 will include the processes involved in extracting fuel from the well. The extracted fuel is prepared and made ready for transporting to plant for liquefaction. In such cradle to gate processes the analysis on emissions are done and are compared with other fossil fuel such as coal.

The functional unit in defining the scope and boundaries of natural gas establishes the basis of comparison. Within cradle to gate boundary of analysing natural gas, functional unit is 1 MMBtu of fuel delivered at the gate of energy conversion facility. When power production is included in the boundary the functional unit is 1 KWh of electricity delivered to consumer. In such contexts the time period considered is 30 years.

GHGs inventory is reported on $CO_2$-e which is the common mass basis using Global Warming Potential (GWP) mentioned in 2007 IPCC fourth assessment report (Forster et al 2007). In this assessment report the default GWP is shown for 100 year period and for some cases 20 year period is used. The IPCC global warming potential is shown in table 1.

Table 6 The rate of GWP for GHG inventory (Skone, 2011).

| GHG | 20-year | 100-year (Default) | 500-year |
|---|---|---|---|
| $CO_2$ | 1 | 1 | 1 |
| $CH_4$ | 72 | 25 | 7.6 |
| $N_2O$ | 289 | 298 | 153 |
| $SF_6$ | 16,300 | 22,800 | 32,600 |

This table shows the Global Warming Potential (GWP) for GreenHouse Gas (GHG) inventory used in the study by Skone (2011).

The boundary conditions are defined for the LNG, the following assumptions are made:

- Extraction and production of natural gas as fuel.
- LCA processes include extraction from wells, liquefaction and storage.
- LCA boundary includes processes in each stage and the emissions in these stages. The LCA does not include emissions in commissioning of infrastructure, decommissioning of plant, transportation in trains, ships, etc.
- LCA quantifies emissions that are directly attributable to fugitive leaks, venting and fuel usage and results are presented in terms of pounds of $CO_2$-e per mega watt hour power generation.

## Life Cycle Inventory of Natural Gas

The production stage of LNG includes extraction and field processing. For this data provided by Tamura et al (2001) is considered. In their survey gas fields in LNG exporting countries such as Indonesia, Malaysia, Brunei, Australia and Alaska are considered. In these areas the emissions include,

- $CO_2$ from combustion of natural gas. Combustion in gas turbines that drive compressors for extracting from wells.
- $CO_2$ results from burning of purge gas and this is discharged in flare slack.
- During dehydration process $CH_4$ is vented out.
- Fugitive emissions of $CH_4$ from compressors

Tamura’s study revealed the emission rate of 2.13 lbs of $CO_2$e/MMBtu. In order to determine fuel consumption this value may be used as a reference point.

The details of National Energy Technology Laboratory (NETL) report in 2011 are used to understand inventory results. The data for inventory is gathered from different sources to represent a temporal period, geographic location and the technology. These three categories are used in combination to assess the inventory results. The upstream inventory results of natural gas are represented in 2009 show good results. This is because they used EIA natural gas production data to analyse the domestic average data by using a mix of natural gas sources. However, with each year the values change and the results can be represented for the period 2004 to 2012.

The results were calculated by NETL’s LCA model for natural gas system by using a model structure. The model is a network of operation and construction blocks that are interconnected. The inputs of units include natural gas fuel and the output includes air emissions, water effluents, solid waste and products. The role of LCA model is to converge all values for intermediate flows within the interconnected network of unit processes. This convergence is done by scaling all unit processes to a functional unit.

The sources of natural gas used in NETL report is extracted from conventional offshore, coal bed methane, shale formations, tight sands and conventional onshore. The data collected for inventory analysis include high and low values along with nominal value. Since natural gas is found in many parts of the world, the mix of conventional and unconventional extraction data is used since 2009. Vertical drilling techniques are used for acquiring natural gas in conventional onshore method. Significant preparation or stimulation for recover of natural gas is not required when a conventional onshore well is discovered. Compressors are used to transport natural gas through all the process equipment and pressurized for transporting it in the pipeline. For example in the USA, 25% of natural gas production is from conventional onshore wells (EPA, 2011).

The composition of natural gas depends on its source and the amount of pure gas within that source. A simple composition of natural gas is prepared and modified for pipeline. The pipeline quality natural gas composition does not have CO2, H2S, water and other volatile compounds. Methane is present in higher content in pipeline natural gas. The table 2 shows the composition of natural gas in raw form and the pipeline quality.

Table 7 Natural gas composition in production and pipeline quality (EPA, 2011).

| Component | Production | Pipeline Quality |
|---|---|---|
| $CH_4$ (Methane) | 78.3% | 92.8% |
| NMVOC (Non-methane VOCs) | 17.8% | 5.54% |
| $N_2$ (Nitrogen) | 1.77% | 0.55% |
| $CO_2$ (Carbon dioxide) | 1.51% | 0.47% |
| $H_2S$ (Hydrogen Sulfide) | 0.50% | 0.01% |
| $H_2O$ (Water) | 0.12% | 0.01% |

The construction of natural gas well head plays a role in the analysis of emissions for extracting natural gas. Data related to well construction has aspects such as linear drill speed, diesel powered drilling rigs, depth and casing material used. Normally the construction and installation of one time activities are apportioned for each unit of natural gas extracted by dividing all emissions arising out of construction, installations in lifetime years and production in millions cubic feet of well. Well completion data describes emissions of natural gas during the development of well. EPA provides the methane emission factors in the completion of conventional and unconventional wells (EPA 2011).

## Inventory of Natural Gas Processing

The inventory of key gas processing operations is also used in LCA analysis. Gas processing includes acid gas removal, dehydration and sweetening. In this stage calculations are based on the application of extraction and production engineering methods to determine energy and material balances for natural gas equipment operations. Acid gas removal is the removal of hydrogen sulphide ($H_2S$) which is found in raw gas. This is a toxic gas and reduces the heat content of natural gas. Acid gas removal (AGR) processes use technologies that use amine based processes in removing $H_2S$. The amine solution absorbs $H_2S$ along with a portion of methane from natural gas. This methane is released into the atmosphere when the amine solvent is regenerated, and this is unavoidable. Gas research institute provides the emission factors for this process which is also called natural gas sweetening. Sweetening of natural gas releases 0.000971 lb of methane per 1 lb of natural gas sweetened (API, 2009).

In the inventory of natural gas processing, compression process is also involved. Compression is done to increase the pressure of gas and it becomes easier to transport gas in the pipeline. Three types of compressors are used in processing plants namely gas-powered reciprocating compressors, centrifugal compressors and electrically-powered centrifugal compressors. Venting emissions are unavoidable in these compressors (EPA, 2011).

## Liquefying Natural Gas Life Cycle Emissions

Emissions from natural gas start with extraction and end with combustion. Natural gas can be extracted from oil wells and from natural gas wells. The gas extracted from oil and gas wells are processed for commercial use, mainly for consumes. The natural gas used by consumers is rich in methane. The processing plants for natural gas are constructed in locations where gas is extracted. As mentioned earlier the gas is removed of impurities, natural gas liquids, hydrocarbons and water through different methods. Cryogenic expansion process is another method used in removal of hydrocarbons from extracted natural gas. In this process the temperature of hydrocarbons are dropped causing it to condense and they can be separated from natural gas. The last stages in natural gas processing are the removing of sulphur and carbon dioxide. Sulphur is toxic and can cause serious health problems when breathed by humans. In addition to its toxicity, sulphur also causes corrosion in distribution pipelines when gas is distributed in pipelines. Carbon dioxide is another green house gas which when emitted contributes to global warming. Hence it is important to remove these two gases (Jaramillo et al 2006).

The natural gas in its processed state is fed through the pipeline transmission system for consumer use. The pipeline transmission involves compressors, pumps, valves and other metering and monitoring equipment to manage and regulate gas flow. The figure 18 shows the processing of natural gas for its life cycle stages and also includes LNG (Jaramillo et al 2006).

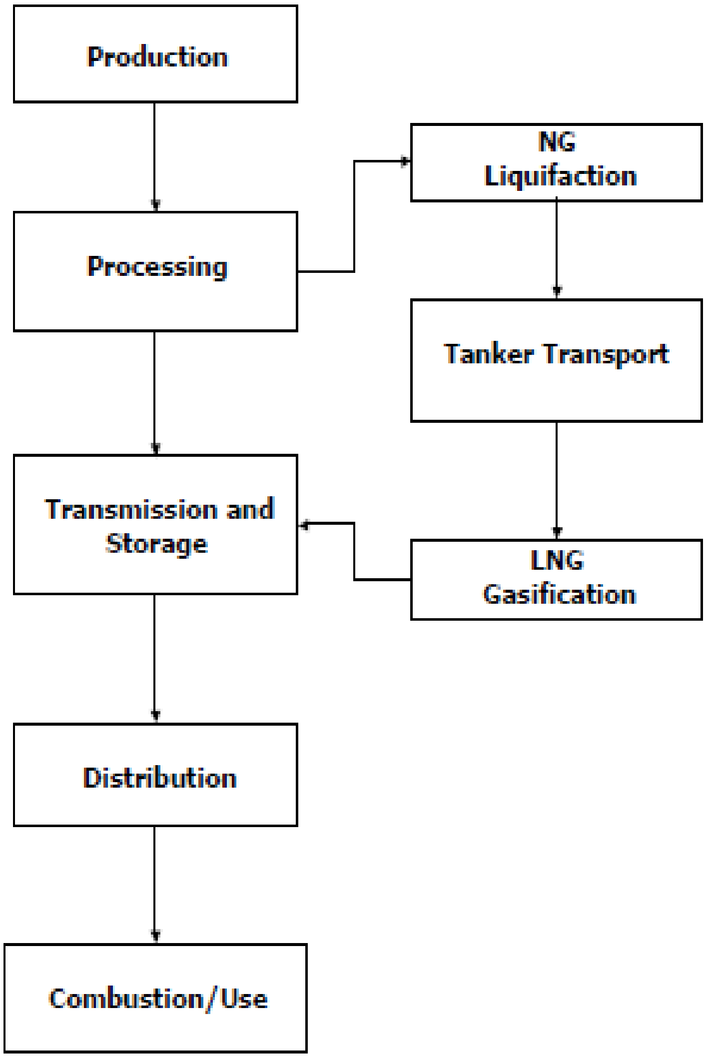


Figure 11 Natural Gas Processing stages in life cycle (Jaramillo et al 2006)

Liquefaction is required for natural gas in order to transport gas from one location to another. Transportation can be done in rail, ships, etc. Normally liquefaction plans are built in coastal areas, the liquefied gas must be re-gasified in order to make it usable for consumers. In all these processes emissions are inevitable.

## GHG Emissions from Liquefying Natural Gas Processing

GHG emissions from natural gas processing, liquefaction and re-gasification processes are analyzed by EPA and other international bodies. The studies involve comprehensive analysis of activities from all areas of natural gas industry. Emissions are calculated using data obtained from different usage and processing facilities and also from field measurements. The table 8 presents the percentage of produced natural gas emission to the atmosphere during lifecycle and the source of emissions are also given (EPA, 2011).

Table 8 Emissions as percentage of gas produced in each processing stage (EPA, 2011))

| Lifecycle Segment | Emission Sources | Emissions as a Percentage of Gas Produced |
|---|---|---|
| Production | Pneumatic Devices | 0.38% |
| | Fugitive Emissions | |
| | Underground Pipeline Leaks | |
| | Blow and Purge | |
| | Compressor | |
| | Glycol Dehydrator | |
| Processing | Fugitive Emissions | 0.16% |
| | Compressor | |
| | Blow and Purge | |
| Transmission and Storage | Fugitive Emissions | 0.53% |
| | Blow and Purge | |
| | Pneumatic Devices | |
| | Compressor | |
| Distribution | Underground Pipeline Leaks | 0.35% |
| | Meter and Pressure Stations | |
| | Costumer Meter | |

In addition to methane emissions, carbon dioxide emissions from combustion of natural gas are taken into consideration in lifecycle stages. The amount of natural gas used in production, processing, transmission, storage and distribution is taken into the life cycle emission analysis. The total emission factors are flare gas, pipeline and distribution use, lease and plant fuel are found assuming 100% of processed natural gas is methane. Using thermodynamic calculations, CO2 emissions are found. Similarly GHG emissions from liquefaction, tanker transport and re-gasification processes are also included in the life cycle analysis of natural gas when determining lifecycle stages (EPA, 2011).

## Life Cycle Environment Assessment of LNG

Natural gas is a good source of energy and viewed as an alternative to coal and other fossil fuels due to its less GHG emissions. Natural gas is clean fuel as shown in table 7 below, data comparisons compiled by Environmental Protection Agency (EPA) as of 2011.

Table 9 Fossil Fuel Emission Levels. Pounds per Billion Btu of Energy Input (Natural Gas, 2014)

| Pollutant | Natural Gas | Oil | Coal |
|---|---|---|---|
| Carbon Dioxide | 117,000 | 164,000 | 208,000 |
| Carbon Monoxide | 40 | 33 | 208 |
| Nitrogen Oxides | 92 | 448 | 457 |
| Sulfur Dioxide | 1 | 1,122 | 2,591 |
| Particulates | 7 | 84 | 2,744 |
| Mercury | 0.000 | 0.007 | 0.016 |

Methane is primarily found in NG, which emits less CO2 compared to oil and coal. More complex molecules make up coal and oil which higher levels of various harmful emissions as can be found in table. Some of the effects due to emissions include the following heading:

**Green House Gas Emissions:** GHGs include water vapour, methane, carbon dioxide, nitrogen oxides and other chemicals such as chloro-fluoro carbons (CFC). Most of these gases occur naturally in the atmosphere but distributed use of fossil fuels by humans increases the level of each gas in the atmosphere leading to green house effect and global warming. Global warming is a climate change issue where trapped GHGs capture heat and warms the earth leading to a sequence of disastrous environmental effects. Natural gas usage can reduce the level of GHG emissions when compared to other fossil fuels (EPA, 2011).

**Issues of Smog and Acid Rain:** Smog is an issue in urban areas. Smog is formed by the chemical reaction of CO, nitrogen oxides, volatile organic compounds and heat from sunlight. The gases such as CO, nitrogen oxides, etc. are emissions from vehicle exhaust, factories and other sources such as paints, solvents to result in poor air quality leading to respiratory problems in humans (EPA, 2011).

Acid rain is a result of the reaction between sulphur dioxide, nitrogen oxides and water vapour in the presence of sunlight to form acidic compounds in air. The main source of acid rain is rain causing pollutants, sulphur dioxide and nitrogen oxides from coal fired power plants. Acid rain damage water bodies such as lakes, rivers, etc and also soil that harm crops and other living organisms in the eco-system (EPA, 2011).

**Eutrophication:** Eutrophication is a phenomenon of over growth of algae due to excess nutrients (nitrides and phosphates) thus choking the life of aquatic organisms. This is mostly due to the result of human activity when fields or lawns use excess fertilizers. These fertilizers are washed away into lakes and rivers when it rains. Algae and plankton feed on these fertilizers and this leads to algal bloom which blocks sunlight entering the water bodies to finally affect aquatic life such as fish or crabs, etc (EPA, 2011).

**Ozone Layer Depletion:** In the earth's atmosphere ozone layer plays the role of a filter to prevent harmful ultraviolet (UV) rays from the sun to fall on the earth's surface. UV rays from sun are harmful for humans and also for crops. The ozone layer is affected due to use of CFCs and hydro-fluoro carbons and other ozone depletion substances used in industries, refrigerants, etc. It is important to note that naturally occurring emissions do not harm the ozone layer to break apart (EPA, 2011).

In spite of the major effects of emissions, there are many other effects due to GHGs. For example, the Green House Emissions of Gas in 2008 are shown in figure 21.

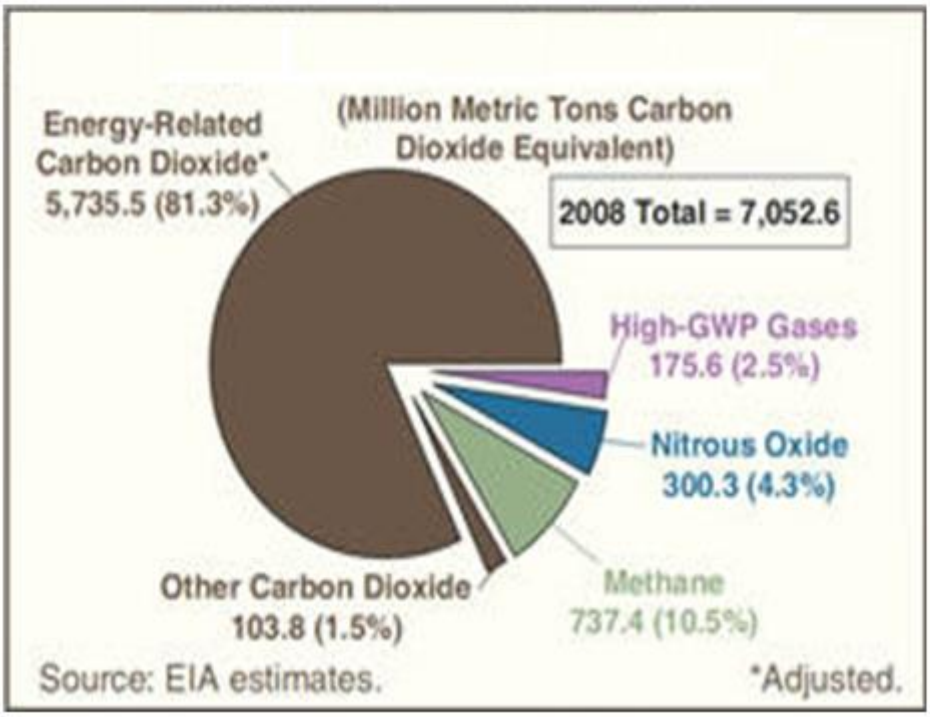


Figure 12 Emissions of GHGs in 2008 in USA (EIA, 2009)

## An Analysis of LCA in Power plant by using LNG

The full life cycle of natural gas can be understood in electricity production plants. The LCA analysis of GHG emissions from power generation plants is done from the perspective of global warming. In this work, the LNG fired power generation system is examined for life cycle green house gas emission per KW (Kilo-Watt) of electricity generated. Since natural gas is considered a clean fuel as compared to coal more and more countries are using natural gas combined cycle (NGCC) in power generation. Many studies are carried out across the world that focuses on GHG emissions and environmental impacts such as global warming, acidification, eutrophication and ozone depletion. In this study one natural gas powered power station is examined for its life cycle emission effects. The case investigated in this report is taken from Agrawal et al (2014).

The goal and scope is to examine the impacts from NGCC power generation plants. In such study the main pollutants generated have an impact on human health and alter the ecosystem in the long run. The primary data collected for life cycle analysis in power generation plants relates to air emissions, waste water, fuel used, and the technical details such as power plant capacity, efficiency and load factor. The resource consumption and air emissions stages to generate 1KWatt electricity illustrate in the following stages which are based on the life cycle assessment stages:

**Life Cycle Assessment:** Environmental impact assessment of Natural Gas combine cycle thermal power plant.

**Stage 1: Goal and Scope Definition**

The system boundary is Cradle to Gate and functional unit is 1 KWatt.

**Stage 2: Life Cycle Inventory (For 1KWatt Electricity Generation)**

Data Collection:

**Inputs:** Resources, Materials and Energy.

| Material and Resources | | Energy | |
|---|---|---|---|
| Natural Gas (Feed Gas) from Gas well | 0.249 $m^3$ | Natural Gas CV | 8200 kcal/SCM |
| Water | 0.75 litter | Electricity | 0.03 kw/h |
| Acid | 0.032 gram | Heat rate | 2025 kcal/kWh |
| Caustic | 0.025 gram | | |

**Outputs:** 1 KWatt Electricity and Emissions, with Wastes.

| Emissions (gram/KWh) | | | | | | | |
|---|---|---|---|---|---|---|---|
| CO | $CO_2$ | $CH_4$ | $NO_x$ | $SO_2$ | PM | HCHO | $NMVOC_s$ |
| 0.031 | 426.2 | 0.045 | 0.104 | 0.013 | 0.63 | 0.011 | 0.013 |

**Stage 3: Life Cycle Impact Assessment**

The methods used CML 2001 and Eco-Indcator 99 (H).

CML is based on problem oriented approach Midpoint and quantified impacts. However, Eco-Indicator 99 (H) is based on damage oriented approach Endpoint.

Hierarchist maintains balance between short and long term effects.

Carcinogenic substances
Respiratory effects (organic)
Respiratory effects (inorganic)
Climate change and Global warming
} Human Health Daily

Acidification
Eutrophication
Eco-toxicity (Marine and Aquatic)
} Eco-system Quality (PAF x $m^2$ x year)

**Stage 4: Life Cycle Impact Interpretation**

The results have been interpreted by using uncertain analysis.

In the above stages are explained the air emissions and power generation to generation (1kwatt) by using the natural gas based on the (Agarwal et al) reports in 2014.

The system boundary in such NGCC assessment of any technology process is based several factors such as time restriction, and the data available for carrying out the study. In lieu of these factors the cradle to gate process as the system boundary is considered. The schematic diagram of NGCC power plant is shown in figure 22.

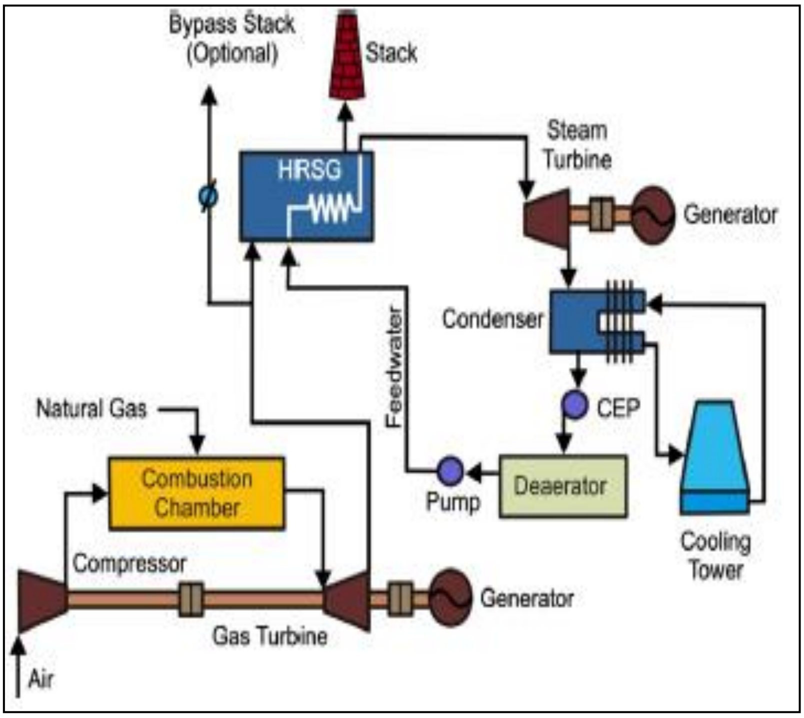


Figure 13 Schematic illustration of NGCC power generation plant (Agarwal et al, 2014)

Since natural gas is used in the fuel cycle for this plant the composition of natural gas is shown in table 10 for this example.

Table 10 Composition of natural as in NGCC power generation plant (Agarwal et al, 2014)

| Natural Gas Composition | Percentages |
|---|---|
| Methane | 98.43 |
| Ethane | 0.44 |
| Propane | 0.19 |
| i-Butane | 0.0275 |
| n-Butane | 0.0275 |
| i-Pentane | 0.0275 |
| n- Pentane | 0.0275 |
| Carbon dioxide | 0.415 |
| itrogen | 0.415 |
| Hydrogen | 0 |
| Lower heating value | 11,728 kcal/kg |

In the next figure the upstream processes and combustion is illustrated. This also shows the processes involved in the power plant boundary such as water usage, electricity, combustion of natural gas and waste water disposal. The air emissions are also sown within the boundary conditions.

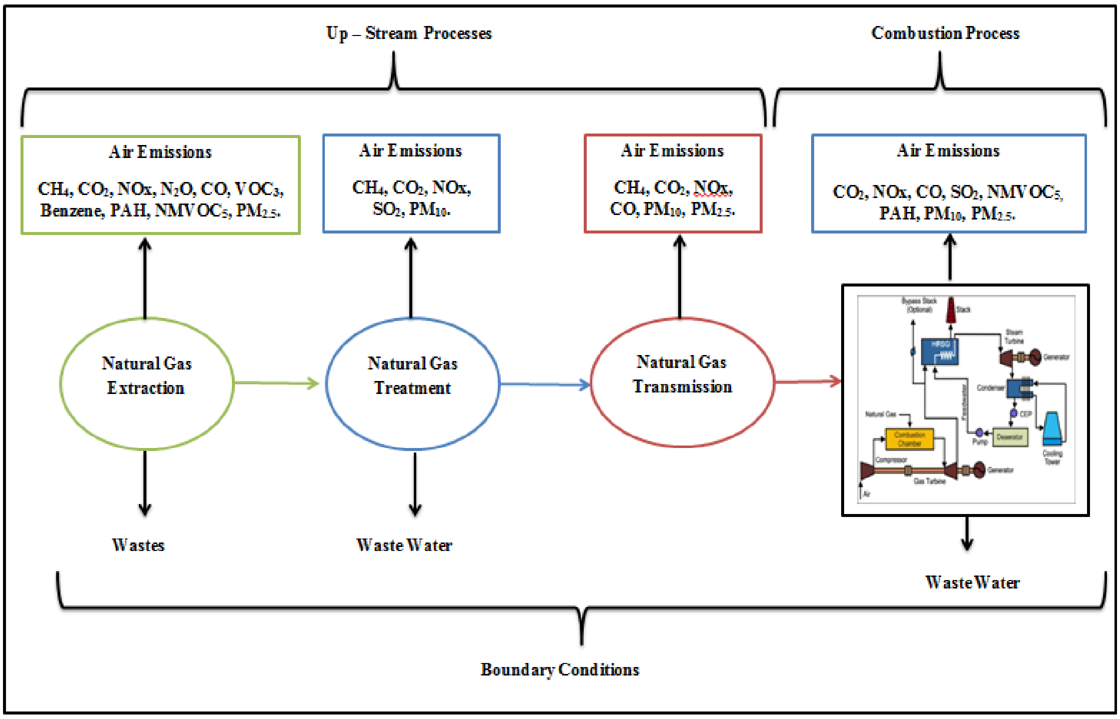


Figure 14 Illustration of boundary conditions in NGCC power generation plant (Hischier et al 2010)

In this chosen example the data for upstream processes is adopted from eco-invent database v2.2 (Hischier et al 2010). GHG emissions are calculated using secondary data (IPCC 2000).

The first stage of LCA which is goal and scope definition, the functional unit for this study is 1 KWh as net electricity generated from NGCC power plant and all the inputs are normalised to the functional unit.

The remaining stages that the impact assessment and interpretation is an important part in this LCA study. The LCA will include impact categories to assess the overall environmental impacts of the process. For calculating environmental impact CML 2001 method is based on problem oriented approach which quantifies impacts for acidification, eutrophication, global warming and human toxicity. Another method called the Eco-indicator 99 (H) is used to assess the damage and this method provides the result for impacts in terms of human health and also for plants and animals. This result is based on the concentration of toxic substances as the product of area and year for damage to ecosystem quality.

The method of normalization is followed in the chosen study to combine all impact categories and to find out the relative contribution of each impact category with the normalized results. The impact categories in CML 2001 use the world normalization factor in 1995 (Bosch et al, 2007). Thermal power plants burn natural gas and release toxic chemicals into the atmosphere to result in damage to human life.

The LCA results and discussions of NGCC study done by Agrawal et al are summarized below. The global warming potential (GWP) and climate change potential (CCP) is shown in the bar graph which is developed using CML 2001 an eco-indicator 99 (H) respectively.

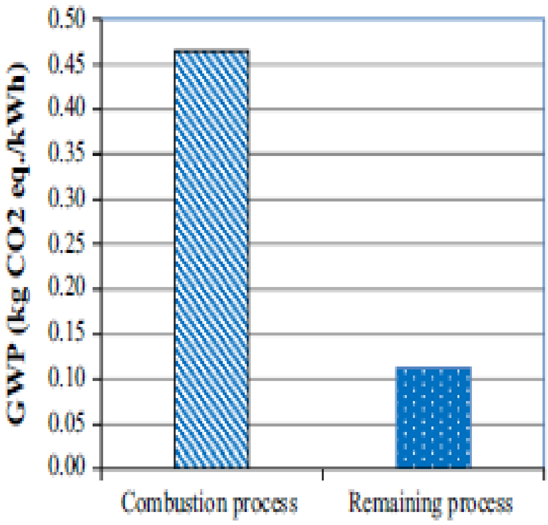


Figure 15 Results of GWP produced in NGCC thermal power plant

The GWP is measured in kg of $CO_2$-e per KWh of electrical power produced. This graph is generated using data from upstream processes (natural gas extraction, production and transmission) and combustion. The combustion contributes to almost 80.6% of GWP in this chosen study. It is also estimated that ~94% total GWP is because of $CO_2$ emissions. Approximately 5.5% emissions are due to $CH_4$ and the other emissions are in values less than ~0.05% from $N_2O$ and CO. In this study it is important to note that~94% of $CH_4$ emissions are due to storage of natural gas and transmission from production centre to the plant location. Hence this implies that ~99.9 of GWP is because of three major GHGs namely $CO_2$, $CH_4$ an $N_2O$. The next output shows the climate change potential in DALY for each KWh of electricity produced in NGCC plant.

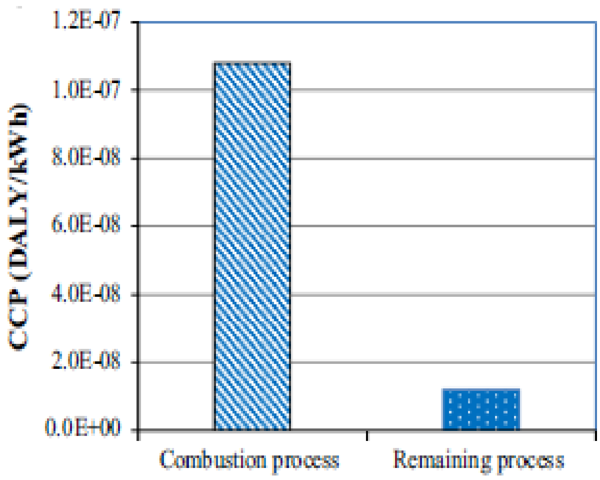


Figure 16 CCP of 1 KWh electricity in NGCC thermal power plant

More than 99% of GWP is mainly from $CO_2$ emissions and with very less emissions due to $CH_4$ and $N_2O$. The output for human health impact is found to be in the range of ~94% of $CO_2$, ~5.5% of $CH_4$, and 0.5% of other substances. While calculating GWP time frame of GWP is important because methane has far reaching long term consequences of GHG compared to $CO_2$, but is found to have a short lifespan in the atmosphere.

$CO_2$-e is calculated by a simple process but the steps involved in the calculation are time consuming and obtaining commercially sensitive data is difficult. During the reporting period, calculation steps involved collection and evaluation of all fuels used in producing electric power for the calculated period. The next table summarizes typical fuels consumed for emissions from energy source during liquefaction, shipping and re-gasification (Gas Strategies 2010). Applicable GWP and emissions factors are applied or calculating emissions depending upon the type and volume of fuel used. The emissions are provided in g $CO_2$-e/MJ of LNG delivered to consumer market. The table 12 shows the emission factors for diesel fuel as compared to natural gas.

Table 11 Emission of natural gas and fuel for 3 GHGs

| | CO2 | N2O | CH4 |
|---|---|---|---|
| **Natural Gas** | 49.68 (t/TJ) | 0.52 (kg/TJ) | 1.1 (kg/TJ) |
| **Diesel Oil** | 2830 (kg/m³) | 0.013 (kg/m³) | 0.006 (kg/m³) |

Natural gas is used in various applications in varying amounts. Due to its low emissions of GHG during combustion, it is the cleanest of fossil fuels available currently. Natural gas is seen as a viable alternative to coal and other fossil fuels and its adoption as clean fuel is gaining momentum already. Environmental groups, researchers and the natural gas industry are committed to producing natural gas to minimize environmental damage.

# CHAPTER FOUR

## Discussion

LNG consists of methane, but also has other gases such as ethane, propane and heavy hydrocarbons. LNG also contains small quantities of nitrogen, oxygen, carbon dioxide, sulphur compounds and water (Danesh 1998). In the processing of natural gas and in liquefaction stages these non-methane compounds is removed from natural gas to prevent the gas from impurities. Impurities are removed NG is liquefied at temperatures of (-170 oC). After all the impurities are removed, natural gas will consist of more than 95% methane. In applying the LCA method for LNG, it is important to understand the value chain of the gas. The value chain consists of four interdependent components namely exploration and production, liquefaction and storage in the final destination. The term value refers to the amount of work or processes or investments made transform natural gas from unusable stage to a stage of optimal use to finally achieve LNG as the critical energy fuel. The LCA method also analyses greenhouse gas emissions in its different stages of liquefaction.

In natural gas processing a number of physiochemical processes are involved. These processes are important because emissions are possible in the processing stages due to leaks. Similarly in LNG processing fugitive emissions are unavoidable. Fugitive emissions are emissions that cannot be practically recovered by the use of control technologies. Some examples of fugitive emissions are pneumatic or leaks in flanges or valves. In processing, release of methane during venting and flare converts CH4 into CO2. Finally GHG emissions are possible in natural gas usage. When gas is used as fuel, natural gas emits green house gases during combustion, however the level of emissions is less compared to other possible fuels. Some examples of application areas where natural gas is used as fuel are in transportation, power generation, industrial use, etc. (Skone 2014).

Emissions from natural gas are not defined consistently. According to EPA, inventory of GHG is defined as vented emissions. Vented emissions are emissions of gas that are deliberately made during a process. For example release of CH4 or CO2 due to process designed flow into the atmosphere, maintenance of equipment and venting due use of gas in power equipments. Fugitive emissions are those that occur because the gas cannot pass through vent, chimney or stack or other opening. Combustion emissions are the result of natural gas usage as fuel in equipments such s furnace, engines, etc in petroleum and gas plants (EP 2010).

The intergovernmental panel for climate change (IPCC) provides the definition for fugitive emissions from oil and natural gas systems. Fugitive refers to venting of natural gas and waste gas or vapour from gas facilities. Flaring of NG, waste gas or vapour streams. Leakage is also possible from equipment (loss due to storage, pipeline breaks, leakage from well, etc) that is not accounted in emissions such as venting or flaring. Hence fugitive leaks are unintended leaks during processing, transmission or transportation of NG. There is another type of emission due to leak called the extraction loss which occurs at the production site of NG (Picard 2006). Due to these emissions and losses of NG in its cradle to gate process a better understanding of CH4 and other emissions needs to be measured. Fugitive emissions are taken into account in LCA along with combustion because they have an impact on GHG. This is highly important to develop strategies for reducing GHG impact in LNG.

In the LC inventory of LNG, naturally occurring CO2 contributes to acidity of natural gas. Data provided by NETL indicates that 0.013 lb of CO2 is vented for each 1 lb of natural gas processed. This is shown as the mass balance of a unit of AGR balance the gas input with vented mass of gas and the natural gas product. The co-products of AGR are non-methane volatile organic compounds (NMVOC). NMVOC amounts to 84% of vented gas which are shown as mass balance in the processes of AGR (acid gas removal).

Natural gas due to its low emission characteristic is considered as green fuel and can help moderate the amount of emissions and pollutants in the atmosphere. Using natural gas in combustion in place of other fuels result in less emission of harmful gases as can be found from table 7. Due to these reasons there is an increased reliance on natural gas mainly for its property to reduce harmful pollutants in the environment.

The main green house gas in the atmosphere is carbon dioxide. However, it is interesting to note that carbon dioxide does not trap heat like other greenhouse gases, thus making it a less potent green house gas. However, the amount of CO2 found in the atmosphere is substantially high mainly because of burning of fossil fuels. From figure 21 it can be seen that 81% of all GHG emissions in USA is mainly due to energy generation, which is CO2.

Similarly the low levels of emission from vehicle exhaust do not contribute to smog formation when natural gas is used as fuel. Emissions of nitrogen oxides are very less from natural gas powered vehicles and particulate matter is virtually absent. Hence natural gas is used as an alternative to petrol and diesel in the area of transportation by many countries. This can significantly improve ground level air quality and help prevent smog in densely populated urban centres.

## Discussions related to GHG emissions

GHG such as nitrogen oxide is a result of fossil fuels used in areas of electric utilities, motor vehicles and industrial plants. The use of natural gas in industrial applications can prevent pollutants such as NOx in the atmosphere. Further, industrial areas in close vicinity to urban cities compounds the problem of smog, this can be avoided when natural gas is used as fuel.

From the studies discussed and methods reviewed from secondary sources explained in the Methodology chapter the following observations are derived.

From the results and discussions of NGCC study done by Agrawal et al (2014) it can be found the global warming potential (GWP) and climate change potential (CCP) are determined CML 2001 an eco-indicator 99 (H) respectively indicated. From figure 24, it can be seen the GWP is measured in kg of CO2-e per KWh of electrical power produced. The graph is obtained using data from upstream processes (natural gas extraction, production and transmission) and combustion. The value of GWP from combustion is 80.6%. The study shows that ~99.9% if GWP is due to major green house gases, where ~5.5% of emissions is due to methane and other emissions are less than ~0.05%. The graph is shown in figure 24. Similarly in figures 24 and 25, the graph sows the acidification and eutrophication effects of one KWh of electricity generation using natural gas combined cycle. It can be found that NGCC power plant ~67% of total eutrophication potential in the atmosphere. From the NGCC power plant study the overall environmental impact is only found in the upstream processes and the GWP is significant only during combustion of natural gas.

The data obtained from study done by Aube (2011), assessments are done by calculating GHG emissions associated with use of energy. In this study the focus is mostly on three green house gases namely, carbon dioxide, methane and nitrous oxide, the values are shown for its effects over 100 year period, table 11.

From table 12, Emission of natural gas and fuel for 3 GHGs , the emission factors for diesel fuel as compared to natural gas as fuel for one KWh of electricity generation. The values indicate that using natural gas as fuel the emissions of CO2, N2O and CH4 are substantially lower when compared to diesel oil as fuel, shown in table 12. The study done by Aube (2001), calculations of CO2-e in LNG is obtained by the sum total of emissions per ton of LNG processed in liquefaction plants. From table 13, it can be found the emissions of LNG is 2.4173 t CO2e/t LNG and for Diesel oil is 3.406 t CO2e/t diesel oil. In table 13, the values for tons of CO2e are obtained for each tone of LNG and diesel. The calculation process indicates

LNG produces less emissions compared to diesel. In liquid form, natural gas has a potential energy of 48.48 GJ/t compared to diesel at 46.49 GJ/t. LNG provides 20.06 GJ/t $CO_2$-e of GHG emissions, compared to diesel which provides 13.65 GJ/t $CO_2$-e. This implies LNG as fuel when compared to diesel as fuel provides almost 31.95% more energy for the same greenhouse gas emissions.

The emissions obtained from LNG liquefaction plants is 75% of total $CO_2$ emissions as explained by Rabeau et al (2007). The emissions of $CO_2$ in liquefaction plants are mainly due to fuel combustion in the plant. In any LNG liquefaction plant almost 90% of $CO_2$ is due to fuel combustion.

Natural gas is used in various applications in varying amounts. Due to its low emissions of GHG during combustion, it is the cleanest of fossil fuels available currently. Natural gas is seen as a viable alternative to coal and other fossil fuels and its adoption as clean fuel is gaining momentum already.

## Environmental Benefits of using NG as fuel

Natural gas when used in electric power generation offer a variety of environmental benefits including;

**Low Emissions:** Emissions such as NOx, CO2 are significantly low in the combustion of natural gas, especially in electricity generation. Particulate emissions are very low and virtually there is no SO2, mercury and other harmful emissions. Hence natural gas as a fuel is beneficial when compared to emissions from other fossil fuels (coke, coal, oil, etc).

**Minimum Sludge:** Sludge is formed in combustion of coal mainly in electric power plants and in industrial uses. Industrial boilers and power plants use scrubbers to minimize SO2 which generate thousands of tons of harmful sludge. The combustion of natural gas produces no sludge and hence eliminates the need for scrubbers in industrial processes.

Re-burning: In this process natural gas is injected into coal or oil fired boilers. The mix of natural gas with fuel results in almost 50-70% reductions of NOx and 20-25% reductions in SO2 emissions.

**Co-generation:** natural gas is a preferred fuel for co-generation applications. In this case the production of heat and electric energy systems uses less fuel with low pollutions.

Natural gas combined cycle (NGCC): NGCC units are used in electricity generation. This process captures wasted heat energy and is used to generate more electricity. This process is similar to co-generation applications but increases energy output with less combustion of fuel. NGCC electric generation units are energy efficient up to 60% in natural gas, compared to 30-35% efficiency in the case of coal.

**Benefits in Transportation:** Natural gas when used as fuel in buses, cars, trucks, ships and even as aviation fuel can drastically reduce pollution levels when compared to vehicles that run on petrol and diesel. According to EPA (2009), natural gas has low carbon monoxide emissions and reductions of about 25% in carbon dioxide. Nitrogen oxide emissions are reduced to almost 35-60% and other hydrocarbon emissions reduced to almost 50-75%. In addition to this the relatively low toxic and carcinogenic emissions from natural gas powered vehicles offer no particulate emissions, which further makes it a clean fuel and an alternative to petroleum.

The inflow gas concentration of impurities and gas quality determines the intensity of feed gas treating process. In this process CO2 is vented, and in industrial processing this vented carbon dioxide is collected for geo-sequestration or used in other processing. When methane gas will become liquid carbon dioxide needs to be removed to below 0.5 mol % to prevent plugging during liquefaction. This process is done to prevent blockages caused by frozen CO2 causing the plant to shut down and cleaning which is time consuming and expensive. Along with CO2, sulphur dioxide must also be removed before liquefaction in order to prevent acid corrosion of the pipe networks. Feed gas when has higher concentration of carbon dioxide will increase GHGs significantly unless it is effectively captured and securely stored via geo-sequestration. Low concentrations of feed gas will incur lower processing cost and lower emissions.

The process of removal of hydrocarbons is called natural gas liquids (NGL) which is another process done by absorption or cryogenic expander process. Though this is similar to water absorption method, absorbing oil is used here instead of glycol. The temperature of the gas is reduced to result in condensation of hydrocarbons in order to separate them from natural gas. Absorption method is used in the removal of heavy hydrocarbons and the lighter hydrocarbons can be removed by cryogenic expansion process.

The overall thermal efficiency of LNG is improved and the concept of zero CO2 is being initiated by the LNG industry (Kikkiwa and Liu 2001). The process of CCS removes or significantly reduces CO2 content of streams which is normally released to the atmosphere. The captured CO2 is transported to the location for storage, this CO2 is captured from wide range of single point sources such as process streams, heater and boiler exhausts and vents in the plant such as refining, chemical, steel and natural gas treating. The captured CO2 is compressed, dried and shipped to a suitable storage location such as depleted gas reservoirs and oil wells. In order to achieve zero emission, the concept of carbon capture and storage (CCS) systems must be integrated in the plant design.

To summarize, essentially industrial applications, transportation, electric power generation require energy. Energy is required for heating purposes and use fossil fuels in their combustion process. Natural gas because of its low emissions of harmful green house gases is an ideal choice instead to reduce the emissions of harmful pollutants.

## Reference


Agrawal, K. Kuldeep, Suresh Jain, Arvind K. Jain and Sunil Dahiya, (2014). *A life cyle environmental impact assessment of natural gas combined cycle thermal power plant in Andhra Pradesh.* India: Environmental Development.

Alvarez, A. Ramon, E, Arvind K. Jain and Polonara (2012). Greater focus needed on methane leakage from natural gas infrastructure. *Proceedings of the National Academy of Sciences.* 109 (17), 6435-6440.

American Petroleum Institute (API), (2009). *Compendium of Greenhouse Gas Emissions for the Oil and Natural Gas Industry.* USA: American Petroleum Institute.

Burnham, Andrew, et al, (2011). Life-cycle greenhouse gas emissions of shale gas, natural gas, coal and petroleum. *Environmental Science and Technology.* 46 (2), 619-627

CALCAS (2007). *Coordination Action for innovation in Life-Cycle Analysis for Sustainability*. [ONLINE] Available at: http://fr1.estis.net/sites/calcas/default.asp. [Last Accessed 02-Jul-2014].

Cathles, M. Lawrence, (2012). Assessing the green house impact of natural gas. *Geochemistry, Geophysics, Geosystems.* 13 (6), 120-128.

Chamberlain GA (2006). *Management of large LNG hazardous.* Amsterdam: World Gas Conference.

Council for Solid Waste Solutions, (1990). *Resource and Environmental profile analysis of Poly-ethylene and Unbleached Paper Grocery Sacks.* USA: *CSWS 800-243-5790.*

Curran, Mary Ann (1996). *Environmental Life Cycle Analysis*. CANADA: McGraw Hill Publishing.

Curran, Mary Ann (2000). Life Cycle Assessment: An International Experience. *Environmental Progress.* 19 (2), pp. 65-71

Danesh, Ali (1998). *PVT and Phase Behaviour of Petroleum Reservoir Fluids.* USA: Elsevier.

Dinca, C., P. Rousseaux and A. Badea (2007). A life cycle impact of natural gas used in the energy sector in Romania. *Journal of Cleaner Production.* 15, pp.1451-1462

Eco Smart Design Project Management, (2005). A business guide to Life Cycle Thinking and LCA. *Report by Craigavon Industrial Development Organisation and Product Ecology Pty Ltd.* (19), pp. 1805-1829.

Environmental Protection Agency (EPA), (2010). *Green House Gas Emissions Reporting from the Petroleum and Natural Gas Industry*. US: Environmental Protection Agency.

Environmental Protection Agency (EPA), (2011). *Greenhouse Gas Emissions Reporting from the Petroleum and Natural Gas Industry Background Technical Support Document. Climate Change division.* Washington DC, USA: Environmental Protection Agency.

European Commission (2008). *Welcome to the European Platform on Life Cycle Assessment*. [ONLINE] Available at: http://eplca.jrc.ec.europa.eu/. [Last Accessed 02-Jul-2014].

Frankl P. and Rubik, F (2000). *Life Cycle assessments in Industry and Business, Adoption Patterns, Applications and Implications*. Berlin, Heidelberg, New York: Springer.

Fawer, M, (2001). *Concepts of Life Cycle Assessments (LCA).* Seminar on environmental tools - a cometitive option, EMPA, St: Gallen, Unpublished.

Gas Strategies, (2010). LNG - *The commercial imperatives.* Training Manual 2010. Perth, Australia: Alphatania.

Grießhammer, R., Benoıˆt, C., Dreyer, L.C., Flysjo¨ , A., Manhart, A., Mazijn, B., Me´thot, A.-L., and Weidema, B.P., (2006). Feasibility Study: Integration of Social Aspects into LCA. *UNEP-SETAC Life Cycle Initiative,* Paris: Alphatania

Hondo, Hiroki, (2005). Life cycle GHG emission analysis of power generation systems: Japanese case. *Energy.* 30, pp.2042-2056

Howarth, R., R. Santoro, A. Ingraffea, (2011). *Methane and the Greenhouse-gas footprint of Natural gas from shale formations. Climate Change Letters.* USA: Kluwer Academic Publishers.

Howarth, Robert, et al, (2012). Methane emissions from natural gas systems. *Background papers prepared for National Climate Assessment, Reference 2011-0003.*

ISO 14040 (2006). *ISO 14040 International Standards in: Environmental Management - Life Cycle Assessment - Principles and Framework*. Geneva, Switzerland: International Organisation for Standardization.

ISO 14040 (2006). *ISO 14041 International Standards in: Environmental Management - Life Cycle Assessment - Principles and Framework*. Geneva, Switzerland: International Organisation for Standardization.

ISO 14042 (2006). *ISO 14042 International Standards in: Environmental Management - Life Cycle Assessment - Principles and Framework*. Geneva, Switzerland: International Organisation for Standardization.

ISO 14044 (2006). *ISO 14044 International Standards in: Environmental Management - Life Cycle Assessment - Requirements and Guidelines*. Geneva, Switzerland: International Organisation for Standardization.

Jaramillo, P., W.M. Griffin, H.S. Matthews, (2006). Comparative Life-cycle carbon emissions of LNG versus coal and gas for electricity generation. *Report.*

Jaramillo, Paulina, (2007). *A Life Cycle Comparison of Coal and Natural Gas for Electricity Generation and Production of Transportation Fuels.* Research submitted or the Degree of Doctor of Philosophy, Pittsburgh, Pennsylvania: Carnegie Mellon University.

Jensen, Allan Astrup, Leif Hoffman, Birgitte T. Moller and Anders Schmidt, (1997). *Life Cycle Assessment: A Guide to approaches, experiences and information sources*. Denmark: European Environment Agency.

Jiang, Mohan et al, (2011). Life cycle green house gas emissions of Marcellus shale gas. *Environmental Research Letters.* 6 (3), 148-182.

Jørgensen, A., A. Le Bocq, and M.Z. Hauschild, (2008). Methodologies for Social Life Cycle Assessment. *Review of International Journal of Life Cycle Assessment.*13.96-103.

Kikkiwa, Y. and Y. Liu, (2001). *Zero CO2 emission for LNG power chain*. Paris: LNG13 International Conference.

Life Cycle Initiative (2013). *What is Life Cycle Thinking?*. [ONLINE] Available at: http://www.lifecycleinitiative.org/starting-life-cycle-thinking/what-is-life-cycle-thinking/. [Last Accessed 02-Jul-2014].

Lindfors L.G., K. Chistiansen, L. Hoffmann, Y. Virtanen, V. juntilla, OJ Hanssen, A. Ronning, T. Ekvall and G. Finnvenden (1995). LCA Nordic. *Technical Report No.10 and Special Reports No.1-2, TeamNord.* 503.

Lowell, Dana, Halfeng Wang and Nlc Lutsey, (2013). *Assessment of the fuel cycle impact of liquefied natural gas as used in international shipping*. Denmark: White paper by International Council on Clean Transportation (ICCT).

Mayer, Brooke (Dr), (2013). *Sustainability Fundamentals: Introduction to Life Cycle Assessments. Life Cycle and Systems Innovation in Design (short course).* Denmark: White paper by International Council on Clean Transportation (ICCT).

Manfredi, Simone and Rana Pant, (2011). Supporting Environmentally Sound Decisions for C&D Waste Management - A practical guide to LCT and LCA. *Joint Research Center (JRC), Institute for Environment and Sustainability (IES), Sustainability Assessment Unit.*

Natural Gas Organization (2014). *Natural Gas Emission*. [ONLINE] Available at: http://naturalgas.org/environment/naturalgas/. [Last Accessed 02-Sep-2014].

Ness, B., E. Urbel-Piirsalu, S. Anderberg and L. Olosson (2007). Categorizing tools for Sustainability Assessment. *Ecological Economics.* 60 (2), 498-508

Nillsson, M and K. Eckerberg (2007). *Environmental Policy Integration in Practice*. Paris: Shaping Institutions for Learning, Earthscan.

Okamura, T., M. Furukawa and H. Ishitani, (2007). Future Forecast for Life-cycle greenhouse gas emissions of LNG and city gas 13A. *Applied Energy*. 84 (13),1136-1149.

Our-Energy (2007). *Energy and Ecology*. [ONLINE] Available at: http://www.our-energy.com/energy_and_ecology.html. [Last Accessed 03-July-2014].

Pettersen, Jostein, (2012). LNG Plant Overview. *Seminar with Supplier Association Murmanshelf, Murmansk, Statoil.*

Skone, J. Timothy, (2011). Life Cycle Greenhouse gas inventory of Natural Gas Extraction, Delivery and electricity production. *Final report: DOE/NETL-2011/1522, NETL.*

Skone, J. Timothy, (2014). Understanding the Life Cycle Environmental Footprint of the Natural Gas Value Chain. *NARUC, Gas Subcommittee Meeting, DOE, National Energy Technology Laboratory (NETL).*

Skone, T.J., (2012). Role of Alternative Energy sources: Natural gas technology assessment. *NETL Office of Strategic Energy Analysis and Planning, DOE/NETL-2012/1539.*

Stilwell, J., R. Canty, P. Kopf and A. Montrone, (1991). *Packaging for the Environment*. New York: American Management Association.

Sustainable Materials Management Coalition, (2014). Guidance on Life cycle thinking and its role in environmental decision making. *Report by Sustainable Materials Management Coalition.*

Svoboda, Susan, (1995). Note on Life Cycle Analysis. *Pollution Prevention in Corporate Strategy, National Pollution Prevention Center for Higher Education, University of Michigan Corporate Environmental Management Program (CEMP).*

Thesecrelifeofthings.com (2013). *Life Cycle Assessment, Getting your head around life cycle thinking*. [ONLINE] Available at: http://openraam.eu/system/files/Getting%20your%20head%20around%20life%20cycle%20thinking.pdf. [Last Accessed 9-Jul-2014].

Tamura, I., T. Tanka, T. Kagajo, S. Kuwabara, and T. Nagata, (2001). Life Cycle $CO_2$ analysis of LNG and city gas. *Applied Energy.* 68, pp. 301-319

Venkatesh, Aranya, Paulina Jaramillo, W. Michael Griffin and H. Scott Matthews, (2011). Uncertainty in Life Cycle Greenhouse Gas Emissions from United States Natural Gas End-Uses and its Effects on Policy. *Policy Analysis Report in Environmental Science & Technology.* 45, pp.8182-8189

Wenzel, H., M.Z. Hauschil and L. Alting, (1997). *Environmental Assessment of Products, Methodology, Tools, Techniques and Case Studies, Vol. 1*. UK: Chapman & Hall.

Zhang N and L. Noam, (2006). A Novel near zero CO2 emission thermal cycle with LNG cryogenic energy utilization. *Energy.* 31, pp. 1666-1679.