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TECHNICAL AND ECONOMIC ANALYSIS OF LARGE SCALE LIQUEFIED NATURAL GAS (LNG) LIQUEFACTION PLANT

Master's Thesis

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Author’s Declaration of Originality

I hereby certify that I am the sole author of this thesis. All the used materials, references to the literature and the work of others have been referred to. This thesis has not been presented for examination anywhere else.

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Abstract

The aim of this research is to investigate and analyze the technical and economics of a typical Large Scale Liquefied Natural Gas (LNG) Liquefaction Plant to assist in decision making on the viablity and profitability of the project or to consider if the project is not to be ventured into.It should be noted that LNG plant processes are now inproved to increase energy efficiency and with high cost of saving on liquefaction processes.

An economic analysis of a typical Nigeria Liquefied Natural Gas (NLNG) Liquefaction Plant with a capacity of 6.0 Million tonnes per annum (MTPA) was undertaken using the Monte Carlo simulation method in which a probabilistic approach of economic analysis was used to determine the influencial factors to the profitability of the LNG Liquefaction plant.

Chapter 1 gave the general introduction in which LNG production capacity is increased due to low carbon emission and LNG is the prefered method to put end to gas flaring.

The history of natural gas,sources of LNG,the graphs showing the main sources of LNG supply for a period of 20 years (2015−2035) and various forecasts of world energy demand were discussed in Chapter 2.

Similarly,the recent developments in LNG plants,benefts and demerits of LNG were enumerated.

Chapter 3 highlighted the technical analysis of LNG Liquefaction plant and gave comprehensive description on configuration of liquefaction processes such as POC, PRICO, C3MR,DMR,PMR,CII,APX and MFC.Criteria for LNG process selection,LNG transportation,receiving terminals,storage tanks,safety and hazards are also analyzed with the economic analysis of a typical Nigeria Liquefied Natural Gas (NLNG).

Chapter 4 reveals the methodology used in the research which is the Monte Carlo simulation method in which an economic analysis of 6.0 million tonnes per annum (MTPA) LNG Liquefaction plant with an initial investment of $3.0 billion was

undertaken. The Monte Carlo simulation method generated values of the key parameters such as Royalty, LNG Revenue, Total Operating Expenses, Feed cost, EBITDA, Total depreciation, Operating Earnings (FOP Margin), Income Tax and Cash flow from operations corresponding to the economic measures such as Net Present Value (NPV), Internal Rate of Return (IRR), Profitability Index (PI), Present Value Ratio (PVR), Pay Back Time (PBT), Profit to Investment (PIR) under 1,000 simulations.

Chapter 5 gave the executive summary reslting from the 6.0 MTPA plant Financial analysis,Sensitivity analysis of NPV,IRR,PBP,PVR and PIR and the The Monte Carlo simulation results of the LNG project.

Chapter 6 enumerated the analysis and discussion of the results which showed positive and encouraging outcomes about the profitability of the LNG project.It resulted in a positive and large NPV after tax of $6.072 billion at a discount rate of 10%.The decision rule is to accept all projects with positive NPV values. The discount factor is assumed to take care of inflation and some uncertainty in the time value of money.The undiscounted cumulative profit to investment ratio is 3.45.This implies that the profit is 3.45 times as huge as the initial investment and it is a good ratio for an investment without considering the time value of money.The Present Value Ratio (PVR) evaluates the effects of inflation rate and other uncertainty in the investment.It also helps to quantify the size of the investment.The decision rule is to accept investment with positive PVR.of 2.024 at a discount factor of 10%.

Similarly, an Internal Rate of Return of 32.90% was obtained which is quite impressive as it is above the standard hurdle rate for investors in Nigeria.

Keywords

Liquefied Natural Gas (LNG), Regasification, Liquefaction, NPV, IRR, PI, PBP, PVR, PIR, Probabilistic approach, Sensitivity analysis.

This thesis is written in English and is 79 pages long, including 7 chapters, 33 figures and 11 tables.

Annotatsioon

Suurmahulise veeldatud maagaasi terminali tehniline ja majanduslik analüüs

Otsingu eesmärk on uurida ja analüüsida tüüpilist tehnilist ja majanduslikku LNG-d. Aidata teha otsus projektis elujõuliseks ja kasumlikuks . Peaks olema märgitud, et LNG taime protsess on nüüd täiustatud, et tõsta energia efektiivsust ja säästa vedeldamise protsessi.

Tüüpiline NLNG taim koos mahuga on 6.0 miljonit tonni anuma kohta, kohustab kasutama Monte Carlo simuleerimismeetodit, mille tõenäosuslik majanduslik käsitlus kasutati, et märkida sõltumatuid faktoreid LNG kasumlikkuses.

Esimene peatükk andis üldise tutvustuse selle kohta, kuidas LNG tootmine on suurenenud tänu selle väikesele süsiniku eraldumisele. LNG on eelistatuim meetod gaasipõletamise lõpetamiseks.

Naturaalse gaasi ja LNG ajaloo graafik näitab peamiseid LNG resursse 20 aasta kohta (2015-2035). Mitmed ennustused maailma energianõudluse kohta on käsitletud teises peatükis.

Sarnaselt on välja toodud viimased arengud LNG jaamade kasulikkuse kohta.

Kolmandas peatükis on välja toodud LNG veeldamise jaamade tehniline analüüs. Seal on põhjalikud kirjeldused erinevate veeldamise protsesside kohta nagu POC, PRICO, C3MR, DMR, PMR, CII, AP-X ja MFC.

Nigeeria LNG (NLNG) majandusanalüüsiga paralleelselt analüüsitakse ka LNG protsessi valikukriteeriume, LNG transporti, vastuvõtuterminale, gaasihoidlaid, ohutusnõuded ja ohtusid.

Neljas peatükk vaatleb uurimustöös kasutatud metoodikat, milleks on Monte Carlo meetodil baseeruv simulatsioon, mille käigus analüüsiti 3 miljardi dollari suuruse

alginvesteeringuga ja 6 miljoni tonnise aastase võimsusega (MTPA) LNG veeldamisterminali. Monte Carlo simulatsiooni läbiviimisel 1000 simulatsiooni ulatuses saadi teiste hulgas väärtused parameetritele nagu honorar, LNG müügitulu, Ärikulud, sisendikulu, Ärikasum, amortisatsioon, brutokasumimäär, ettevõtte tulumaks ja äritegevuse rahavood, mis vastasid majanduslikele näitajatele nagu projekti nüüdispuhasväärtus (NPV), sisemine intressimäär (IRR), kasumiindeks (PI), tasuvusaeg (PBT), PVR and PIR.

Viies peatükk andis kokkuvõtte kuuendast MTPA finantsaruandest, tundlikkuse analüüs NPV, IRR, PBP,PVR ja PIR kohta ja Monte Carlo simulatsiooni tulemused LNG projektile.

Kuues peatükk näitas analüüsi ja arutelu positiivseid ja julgustavaid tulemusi LNG projekti äri kasumlikkuse kohta. See põhjustas positiivse ja suure NPV peale 6.072 miljardi dollari maksu allahindlusprotsendiga 10%. Otsus mis vastu võeti oli aktsepteerida kõik projektid positiivsete NPV väärtustega. Allahindlusprotsent peaks olema piisav, et tegeleda inflatsiooni ja ebakindlusega mõne aja jooksul. Kommutatiivne kasum investeerimise suhtes on 3.45. See ütleb seda, et kasum on 3.45 korda suurem kui alginvesteering ja, et see on tuleviku perspektiivis hea investeerimisvõimalus. PVR hindab inflatsiooni efekte ja igasugust ebakindlust investeeringutele. See aitab ka mõõta investeeringu suurust. Otsus mis vastu võeti oli aktsepteerida investeeringuid, millel on positiivne PVR määraga 2.024 allahindlusfaktoriga 10%.

Sarnaselt, IRR protsendiga 32.90 omistati, mis on imetlusväärne kuna see on üle standardse piiri investoritele Nigeerias.

Lõputöö on kirjutatud inglise keeles ning sisaldab teksti 79 leheküljel, 7 peatükki, 33 joonist, 11 tabelit.

List of Abbreviations and Terms

LNG	Liquefied Natural Gas
MTPA	Million Tonnes per annum
EPC	Engineering, Procurement and Construction
POC	Phillips' Optimized Cascade
TEALARC	Technip/Air Liquid
C3MR	APCI Propane Precooled Mixed Refrigerant
DMR	Dual Mixed Refrigerant
PMR	Parallel Mixed Refrigerant
CII	Integral Incorporated Cascade
PFHE	Plate fin Heat Exchanger
MFC	Mixed Fluid Cascade
BLEVE	Boiling Liquid Expanding Vapour Explosion
MCS	Monte Carlo simulation
NPV	Net Present Value
IRR	Internal Rate of Return
PBP	Pay-Back Period
PVR	Present Value Rate
PI	Profitability Index
PIR	Profit to Investment Ratio
NGL	Natural Gas Liquid
CAPEX	Capital Expenditure
LPG	Liquefied Petroleum Gas
TAM	Total Addressable Market
EBITDA	Earnings Before interest, Taxes, Depreciation and Amortization

Glossary

LNG: Natural gas that has been cooled to -259°F (-161°C) and condensed into a liquid which is colourless, odourless, non-corrosive and non-toxic. It is known as a cryogenic liquid.

Natural Gas: A hydrocarbon gas that is in association with petroleum and coal deposits and contains a high percentage of methane and inert gases.

BLEVE: Boiling Liquid Expanding Vapour Explosion is an explosion caused by the rupture of a vessel containing a pressurized liquid above its boiling point.

Monte Carlo simulations: are used to model the probability of different outcomes in a process that cannot easily be predicted due to the intervention of random variables.

Net Present Value (NPV): is the difference between the present value of cash inflows and the present value of cash outflows. NPV is used in capital budgetting to analyze the profitability of a projected investment or project.

$$NPV = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} - C_0$$

C_t = net cash inflow during the period t,

C_o = total initial investment costs,r =discount rate, and t = number of time periods

IRR: Internal rate of return is a discount rate that makes the Net Present Value (NPV) of all cash flows from a particular project equal to zero. IRR calculations rely on the same formula as NPV does.

Payback period: is the time required to recover the cost of an investment. The payback period of a given investment or project is an important determinant of whether to undertake the position or project, as longer payback periods are not desirable for investment positions.

Payback Period = Cost of Project / Annual Cash Inflows

Profitability index (PI), also known as profit investment ratio (PIR) and value investment ratio (VIR), is the ratio of payoff to investment of a proposed project. It is an index that attempts to identify the relationship between the costs and benefits of a proposed project through the use of a ratio calculated as: $= \frac{\text{PV of Future Cash Flows}}{\text{Initial Investment}}$

Capital expenditure: (CAPEX) is an expense where the benefit continues over a long period, rather than being exhausted in a short period and are funds used by a company to acquire or upgrade physical assets such as property, industrial buildings or equipment.

Liquefied Petroleum Gas: (LPG) gas consist mainly propane, propylene, butane, and butylene in various mixtures and stored as a liquid by increasing pressure.

Regasification – The process by which LNG is heated until it returns to its gaseous state.

Liquefaction: The process by which natural gas is converted into liquid natural gas through the application of refrigeration technology which makes it possible to cool the gas down to -162 °C (-256°F) when it becomes a liquid.

PVR: Present Value of a future cash flow represents the amount of money today which, if invested at a particular interest rate, will grow to the amount of the future cash flow at that time in the future.

PIR: Profit to Investment Ratio is the ratio of the Net Operating Income to the investment.

EBITDA - Earnings before interest, taxes, depreciation and amortization is an indicator of a company's financial performance calculated as EBITDA = Revenue - Expenses (excluding tax, interest, depreciation and amortization).It is essentially net income with interest, taxes, depreciation, and amortization added back to it, and can be used to analyse and compare profitability between companies and industries because it eliminates the effects of financing and accounting decisions.

Boil-off: The amount of LNG that evaporates from the tank during transportation or storage.

Regasification terminal:Marine or waterfront facilities in which LNG carriers deliver the LNG and then stored before undergoing regasification which converts the LNG back into its gaseous form.

Cryogenic: The science of producing very low temperatures such as those required for natural gas liquefaction.

Discount Rate: It is a rate at which present and future cash flows are traded off. It incorporates -(Higher inflation**,**Higher Discount Rate results in Higher Risk)

Total Addressable Market (TAM): is the total market demand for a product or service.

Total Addressable Market shows the potential scale of the market.

(https://www.thebusinessplanshop.com/blog/en/entry/tam_sam_som#sthash.sx2N7WJ7.dpuf)

(http://www.energy.ca.gov/lng/glossary.html)

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1 Introduction

As Gas flaring is condemned from political and environmental impact ground, LNG is the preferred transport method for economical, technical, safety and political reasons that will put an end to gas flaring.

Global energy consumption is projected to increase at an average rate of 0.9−1.6% per year. Fossil fuels are expected to remain the main energy sources into the future. Natural gas is the fastest growing major energy source in the world; its consumption is expected to increase at an average rate of 1.4−1.6% per year from 2008 to 2035,due to its lower environmental impact. The natural gas supply will need to increase by almost 50% before 2035 to meet the projected demand.

The global trade in natural gas is currently under rapid transition because several countries have been steadily increasing their LNG production capacity.Since 2007, there has been a 40% increase in the global LNG production capacity. The liquefaction capacity is projected to be more than double from 8 trillion cubic feet in 2008 to 19 trillion cubic feet in 2035.

A LNG project is considered one of the most expensive energy projects and comprises a set of unique values in the supply chain known as the LNG value chain.The cost of a liquefaction plant is the greatest in the value chain, accounting for more than 40% of the total cost. The costs of exploration and production vary greatly according to natural gas field. Efficient cost projection of a LNG project depends on factors such as site conditions, safety, and traded volumes. From an economic perspective, the liquefaction plant is the most important component in the LNG value chain.

1.1 Aim of the Thesis

The aim of this research is to investigate and analyze the technical and economics of a typical Large Scale Liquefied Natural Gas (LNG) Liquefaction Plant to assist in decision making on the viablity and profitability of the project.

1.2 Research Problem Statement

Low energy efficiency and high cost of liquefaction processes poses challenges in LNG plant and the study hope to ensure high energy efficiency at moderate cost.

1.3 Research Methodology

An economic analysis of a typical Nigeria Liquefied Natural Gas (NLNG) Liquefaction Plant with a capacity of 6.0 Million tonnes per annum (MTPA) was undertaken using the Monte Carlo simulation method in which a probabilistic approach of economic analysis was used to determine the influencial factors to the profitability of the LNG Liquefaction plant.

1.4 Topicality and Novelty

A typical Nigeria Liquefied Natural Gas (NLNG) Liquefaction Plant with a capacity of 6.0 Million tonnes per annum (MTPA)and capital cost of 3.0 billion dollars was analyzed.

2 Literature Review

2.1 History of Natural Gas

The first commercial LNG liquefaction plant was built in Cleveland, Ohio, in 1941 and the LNG was stored in tanks at atmospheric pressure, which raised the possibility that LNG could be transported in vessels.

In January 1959, the world's first LNG carrier containing five small, insulated aluminium tanks transported 5000 m^3 (about 2,250 metric tons) of LNG from the USA to Canvey Island in England's Thames river.

The world's first commercial liquefaction plant was built in 1964 in Algeria and was based on the cascade liquefaction process which was then applied in Alaska LNG plant in 1969. In 1970 in Algeria, the single mixed refrigerant (SMR) process was adopted to simplify the complex equipment configuration of the cascade liquefaction process using three pure refrigerant cycles. Due to the low thermodynamic efficiency of the SMR process, it was replaced with the propane precooled mixed refrigerant (C3MR) process comprising a propane precooling cycle and a mixed refrigerant cycle. The C3MR process designed by Air Products and Chemicals, Inc. (APCI) has remained the dominant liquefaction process in the LNG plant market; over 60% of currently installed base load LNG plants use this process.

2.2 What is LNG?

Liquefied Natural Gas (LNG) is natural gas chilled to -160°C or -260°F in order to convert into a liquid form.After it has been liquefied,natural gas is compressed so it reduces its volume by approximately 600 times less than natural gas.

Once compressed, LNG gas can be loaded on to specially equipped ships and transported overseas for sale into export markets. At its destination the LNG is returned back into a gaseous form for use.

Liquefied Natural Gas is colourless, odourless, non-corrosive and non-toxic and less dense than water. If a spill occur,the natural gas would warm and evaporate, leaving no substances behind.

Table 1

Thermo–physical properties of LNG

Parameter	Value
Boiling point	-160 °C to -162 °C
Molecular weight	16−19 g/mol
Density	425−485 kg/m3
Specific heat capacity	2.2−3.7 KJ/kg/°C
Viscosity	0.11−0.18 mPa.s
Higher heat value	38−44 MJ/m3

(Dobrota, Đ., Lalić, B., & Komar, I. (2013).91-100)

Table 2

Classification of LNG by Density

Composition (%)	LNG (low)	LNG (medium)	LNG (high)
Methane	98.00	92.00	87.00
Propane	1.40	6.00	9.50
Buthane	0.10	0.00	0.50
Nitrogen	0.10	1.00	0.50
Density(kg/m3)	427.74	445.69	464.83

(Dobrota, Đ., Lalić, B., & Komar, I. (2013). 91-100)

2.3 Sources of LNG

A majority of the world's LNG supply comes from Qatar,Indonesia,Australia, Algeria, Malaysia and Nigeria. There are 19 countries that export LNG and it is imported in large quantity by Japan,South Korea,Europe and China and India and there are 91 LNG receiving terminals located worldwide and the Industry has experienced growth of some 7.5% per year for the past 20 years and expected to increase as emission restrictions favor gas over coal for power generation.

Table 3

LNG Importing countries in 2012

Importer	**MMT Imported**	**Total Tons (%)**
Japan	88.08	37.3
South Korea	36.77	15.6
China	14.65	6.2
Spain	14.46	6.1
India	13.27	5.6
Taiwan	12.67	5.4
UK	10.38	4.4
France	7.17	3.0
Turkey	5.63	2.4
Italy	5.16	2.2
Mexico	3.52	1.5
Argentina	3.36	1.4
USA	3.09	1.3
Chile	2.77	1.2
Brazil	2.70	1.1
Kuwait	1.99	0.8
Belgium	1.82	0.8
Portugal	1.52	0.6
Canada	1.30	0.6
Dubai	1.05	0.4
Thailand	1.02	0.4
Puerto Rico	0.97	0.4
Dominican Republic	0.92	0.4
Greece	0.76	0.3
Indonesia	0.72	0.3
Netherlands	0.56	0.2
Total Imports	**236.31**	**100**

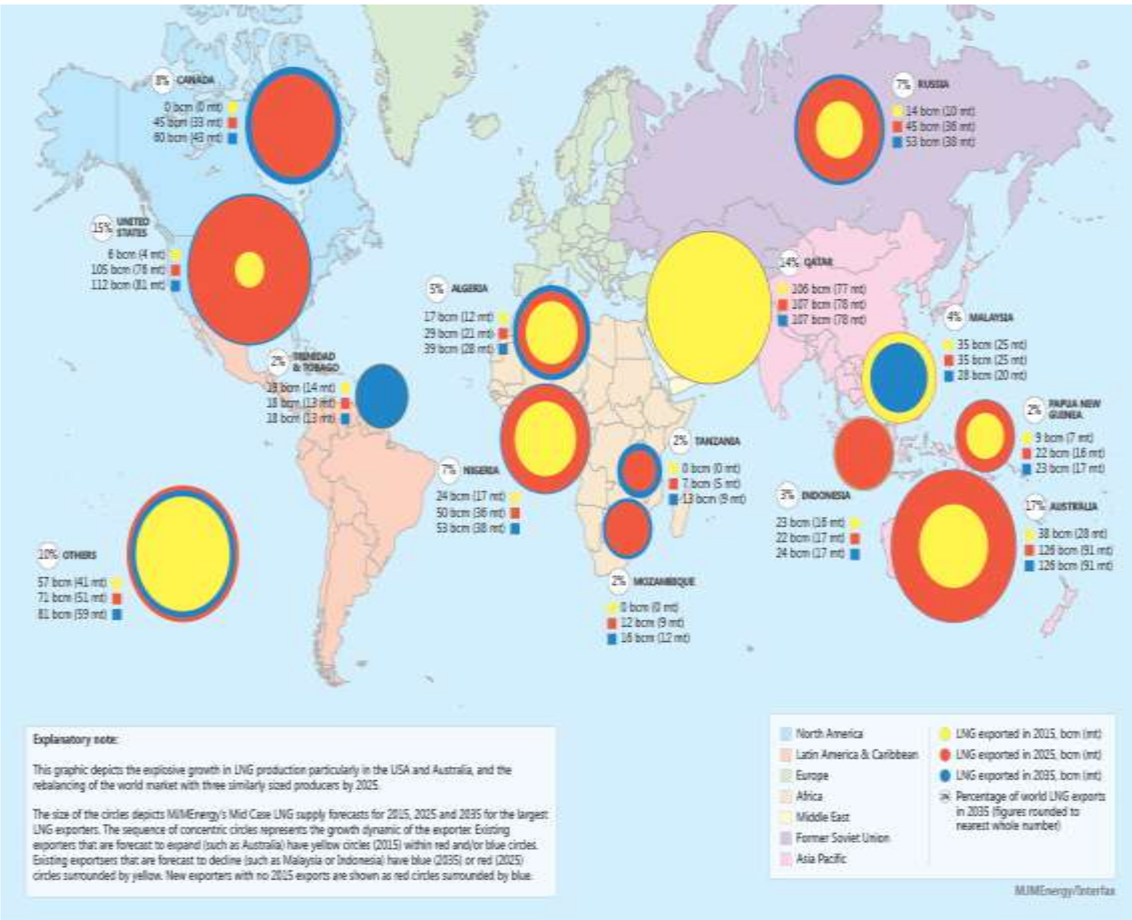
www.giignl.org

Table 4

LNG Exporting countries in 2012

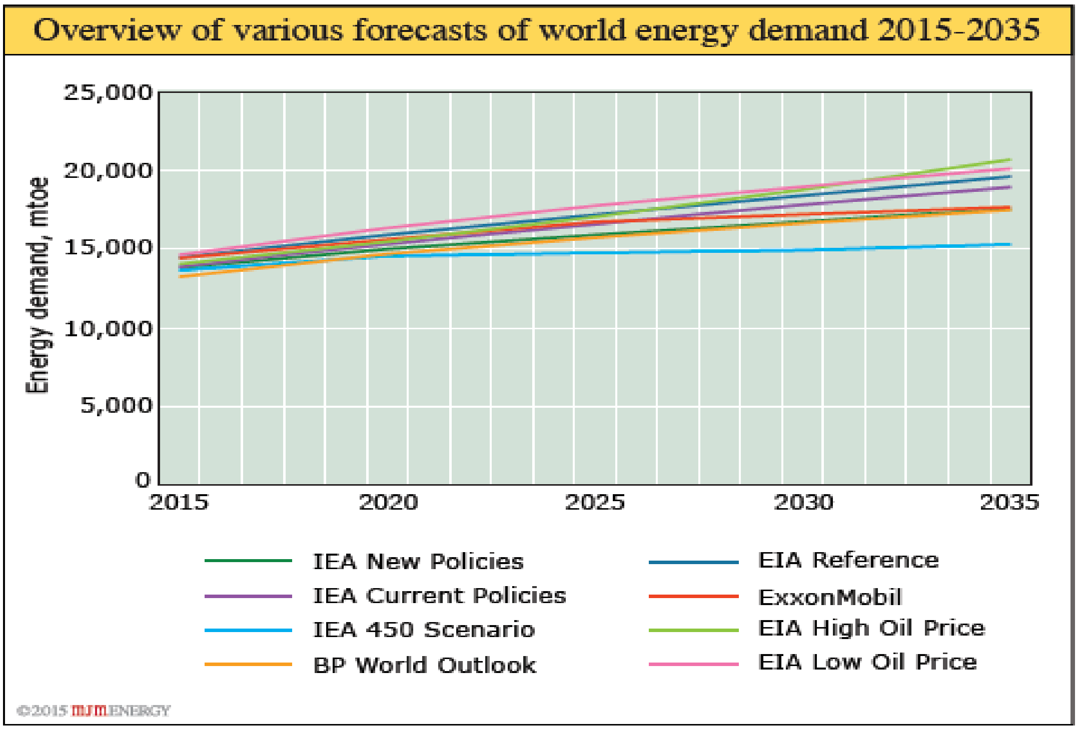
Exported	**MMT Exported**	**Total Tons (%)**
Qatar	76.39	32.3
Malaysia	23.72	10.0
Australia	20.88	8.8
Nigeria	19.58	8.3
Indonesia	18.97	8.0
Trinidad and Tobago	13.48	5.7
Algeria	11.21	4.7
Russia	10.86	4.6
Oman	8.15	3.4
Brunei	6.82	2.9
Abu Dhabi	5.66	2.4
Yemen	4.89	2.1
Egypt	4.74	2.0
Peru	3.86	1.6
Equatorial Guinea	3.62	1.5
Norway	3.31	1.4
USA	0.17	0.1
Total Exports	**236.31**	**100.0**

www.giignl.org



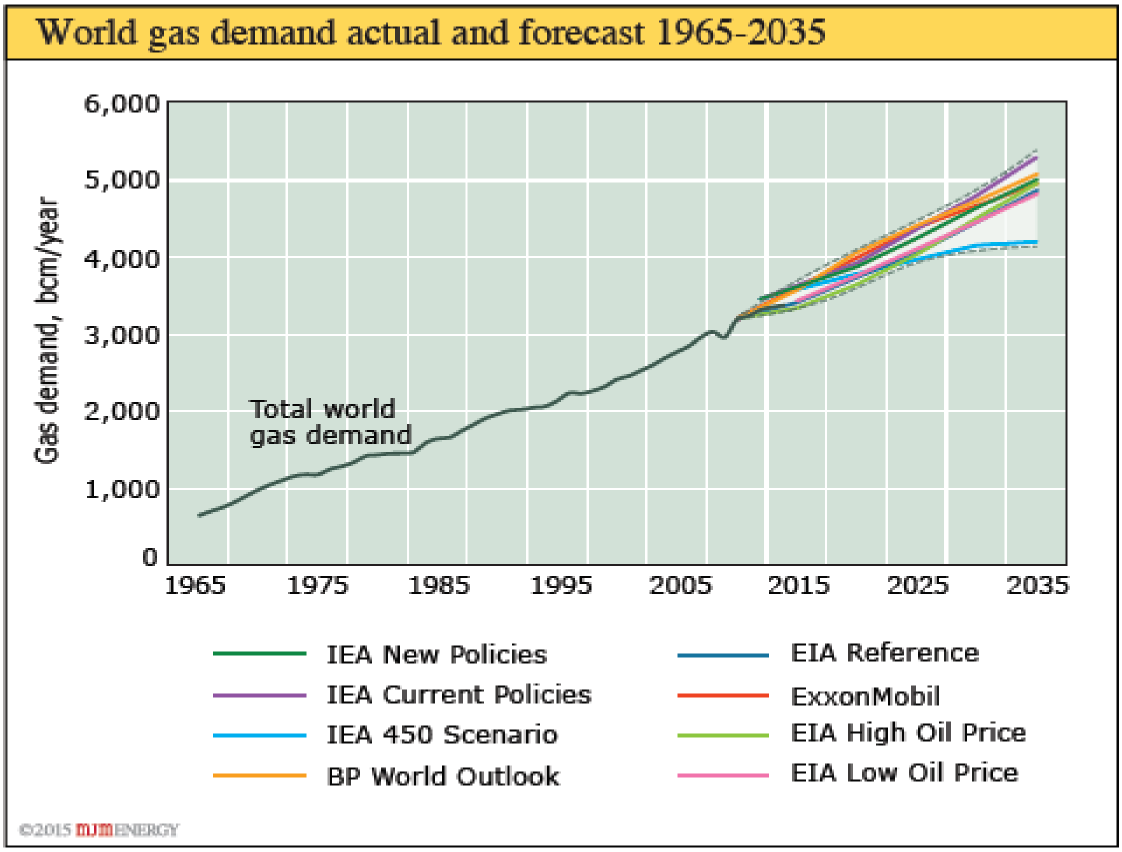
(Catriona, 2015)

Figure 1. **Breakdown of the main sources of LNG supply in 2015, 2025 and 2035**



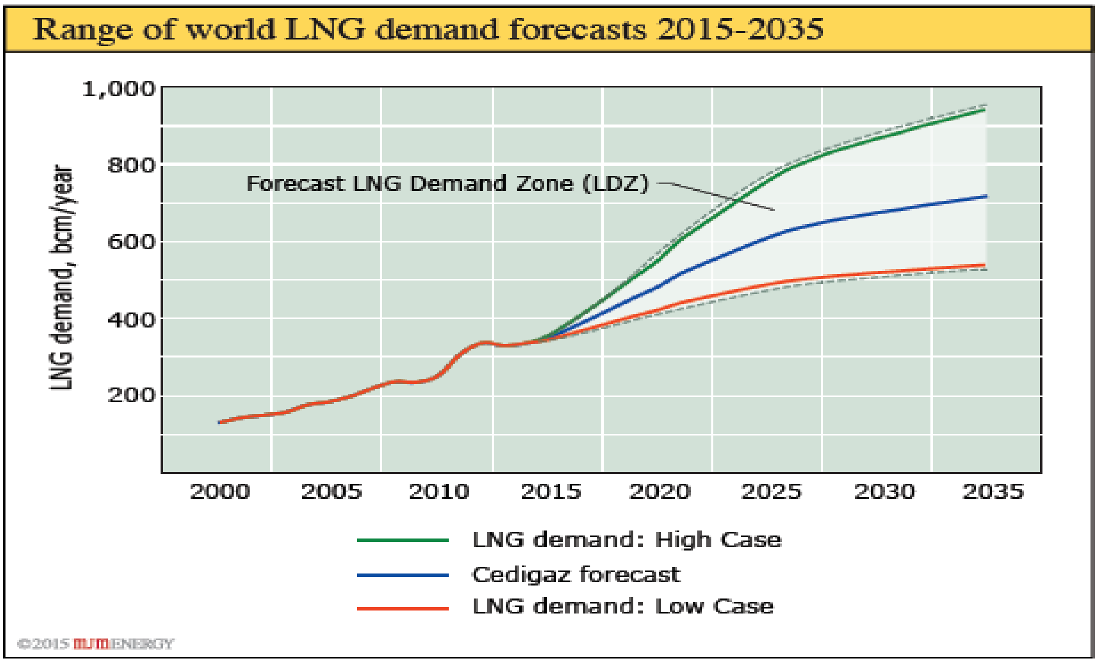
(Catriona, 2015)

Figure 2. **Breakdown of the main sources of LNG supply in 2015, 2025 and 2035**



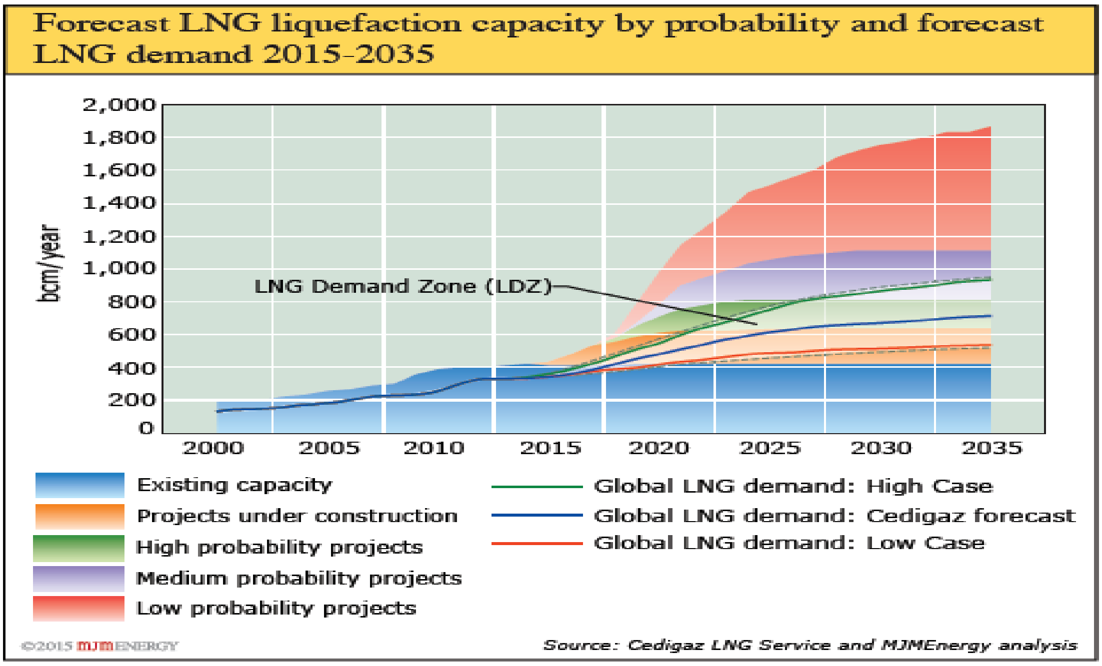
(The MJM Energy LNG Supply Handbook 2015−2035)

Figure 3. **World gas demand actual and forecast 1965-2035**



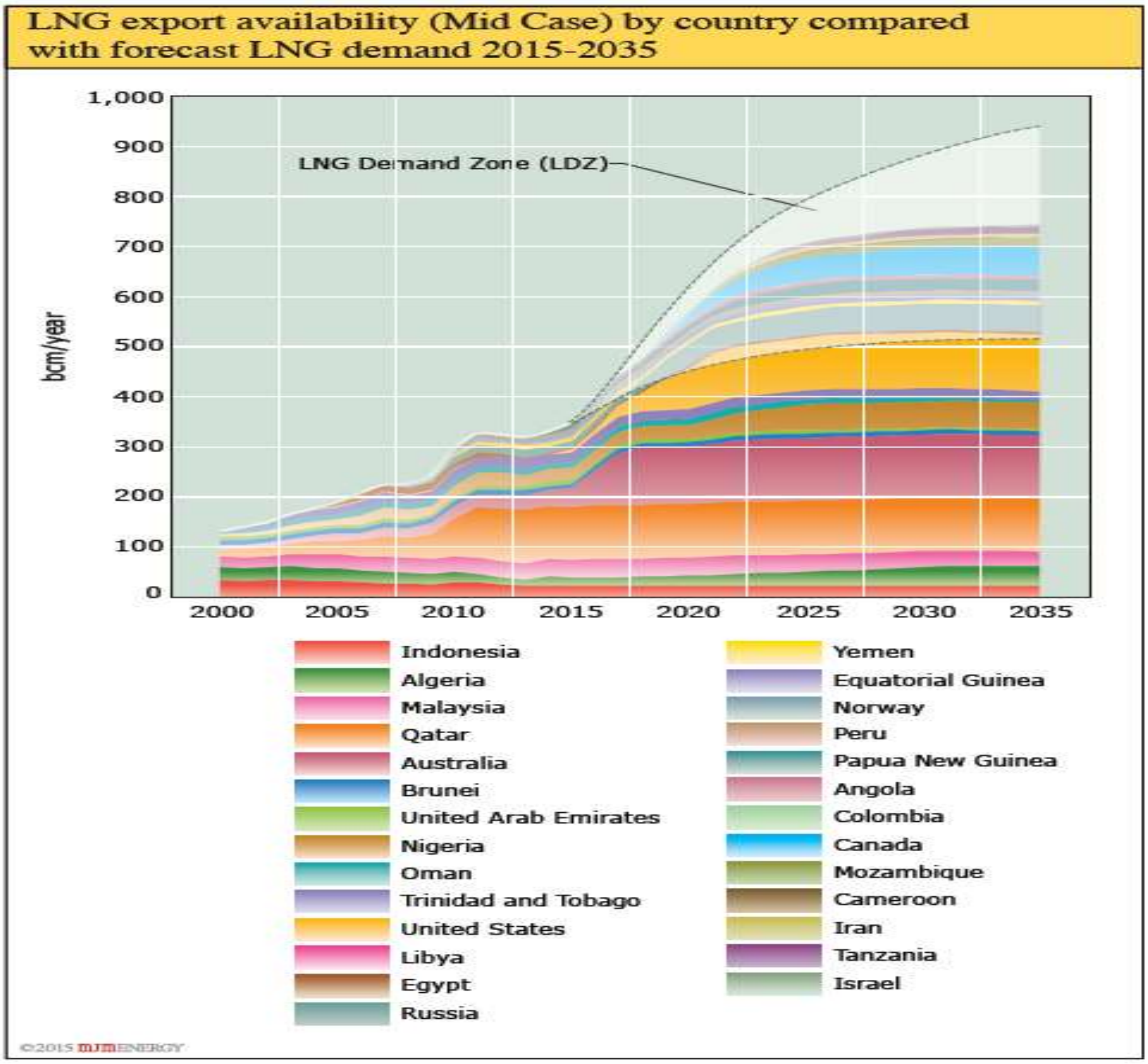
(The MJM Energy LNG Supply Handbook 2015−2035)

Figure 4. **World LNG demand forecast 2015-2035**



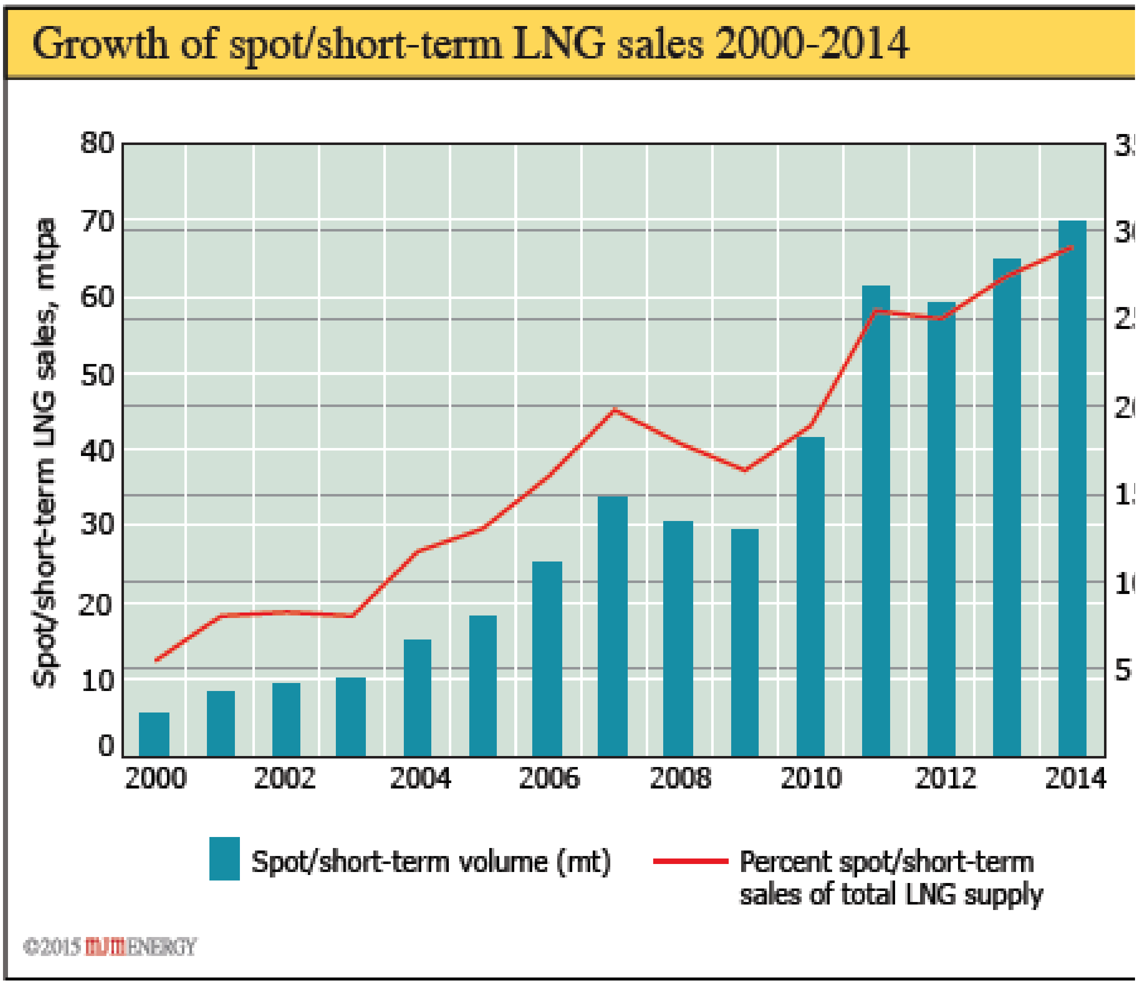
(The MJM Energy LNG Supply Handbook 2015−2035)

Figure 5. **Forecast LNG Liquefaction capacity 2015-2035**



(The MJM Energy LNG Supply Handbook 2015−2035)

Figure 6. **LNG export avaialability by country 2015-2035**



(The MJM Energy LNG Supply Handbook 2015−2035)

Figure 7. **Growth of spot LNG sales 2000-2014**

2.4 Recent Developments in LNG Plants

LNG has been steadily increasing its market share in the global gas trade and now accounts for about 9% of demand for natural gas or 299 billion m3. Steady progress has been made in liquefaction technology with improvements in thermodynamic efficiency, a reduction in capital cost, and an expanded capacity per train.

The main purpose of the majority of early LNG projects was capacity expansion with the addition of production facilities to existing operating gas fields. However, to meet the rapid growth in demand for LNG, a number of new gas fields for use as LNG plant construction sites have been explored, and vendors are competing to develop new high-performance, low-cost technologies and processes.

Due to innovations in liquefaction technology and related equipment such as heat exchangers, gas turbines, compressors, and other utilities, LNG production costs per tonne have decreased excessively. Infact,liquefaction costs were around \$560/tonne in 1995, but decreased to \$222/tonne in 2004. Similarly, recent liquefaction costs have increased to some extent due to an increase in engineering, procurement, and construction (EPC) costs. The liquefaction costs commissioned in 2005−2008 were around \$430/tonne. The construction costs in 2009−2013 are expected to reach \$830/tonne.

The size of a single liquefaction train has been increasing to strengthen price competitiveness, with the goal of using fewer trains to achieve the same capacity. Furthermore, the profitability of stranded gas fields has increased greatly. Development of liquefaction process efficiency has focused on the replacement of expansion valves with liquid expanders or two-phase expanders,power reduction in the liquefaction process, or an increase in LNG production throughput at the same power. In the early days of the industry, the capacity of the majority of trains was approximately 1−2 million tonnes per annum (MTPA). But now, the largest train has a capacity of 7.8 MTPA. (Walter Chukwunonso Ikealumba and Hongwei Wu (2014), 28 (6), 3556−3586)

2.5 Benefits of Liquefied Natural Gas

- Modest capital costs, high fuel efficiency, operating flexibility, rapid deployment, and low greenhouse gas and pollutant emissions.
- New natural gas power plants are growing at an annual rate of 2% and their global share of electricity production should increase from 20.1% in 2006 to 22.3% in 2030.
- Due to their simplicity, natural gas power plants are relatively inexpensive and fast to construct, efficient to operate, and easy to maintain.
- Construction of a power plant that generates 1000 megawatts (MW) may take as little as 2 years to complete.
- LNG has a high potential to reduce fuel costs which are the main cost factor of inland barging (up to more than 50% of the total transport costs).
- Reduced air emissions, higher efficiency of a modernized fleet and increased competitiveness will be the basis for economic growth and for the creation of jobs

in the navigation sector as well as a good alternative for the industry sectors suffering from high logistics costs.

Environmental Benefits

Emissions savings associated with natural gas are Well-to-Wheel greenhouse gas reduction of between 11% and 20%, NOx emissions reduced by 80%, Particulate emissions reduced by 75%.

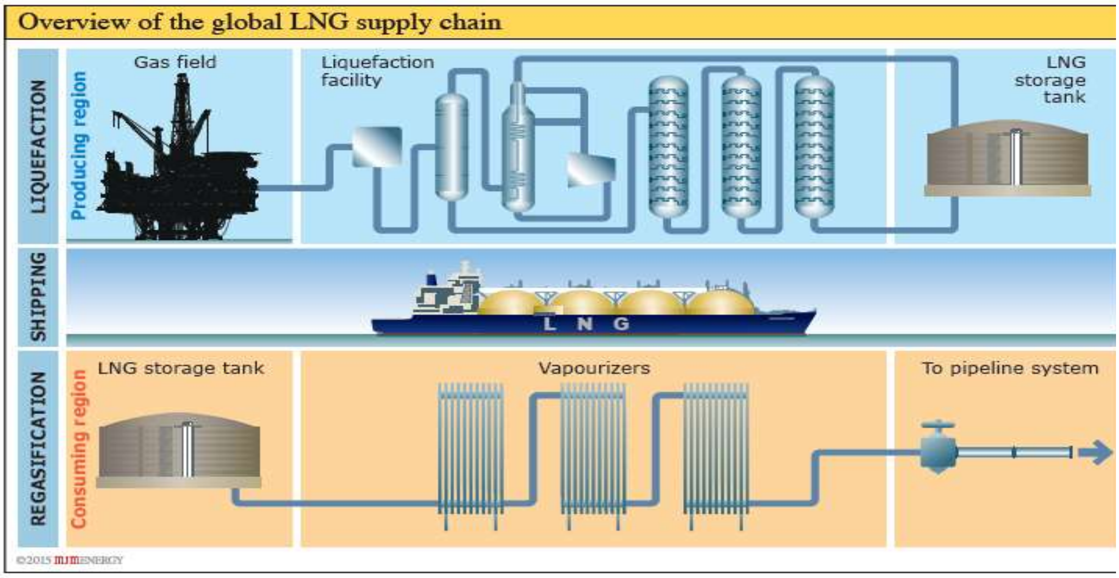
Economic Benefits

The technical innovation in the production of LNG has made LNG to be one of the least expensive transportable fuels.

2.6 Demerits of Liquefied Natural Gas

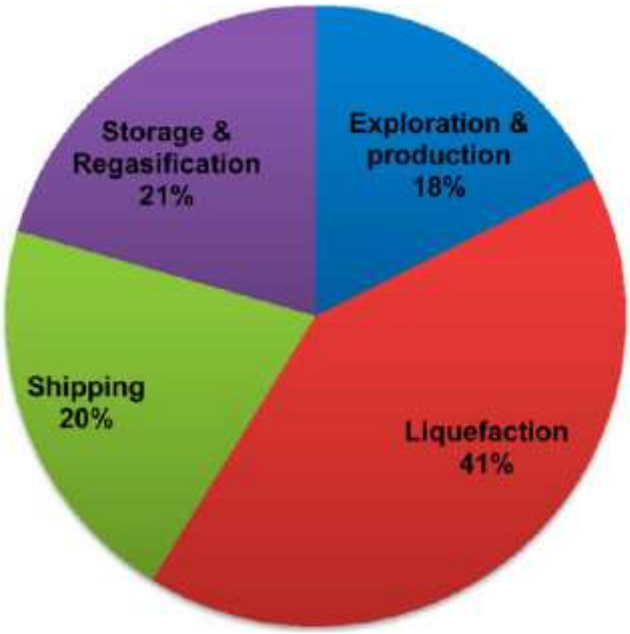
- **Cost Competitiveness:** LNG energy projects are among the most expensive in all energy sectors and are also technically very challenging.
- **Greenhouse Gas Emission:** LNG supply chain emits more greenhouse gases than the supply chain for pipeline gas, primarily because of the extra processing steps needed for LNG shipment.
- **Shipping:** LNG shipping cost is the most favorable cost component in the overall LNG supply chain without which LNG supply would totally lack competitiveness.
- **Security and diversity**: LNG represents 15% of the EU's gas imports and contributes to its energy security and diversity of supply.
- **Affordability**: Affordability will be an important consideration in the EU's fuel-mix decisions concerning LNG.
- **Energy efficiency**: The LNG supply chain tends to be more energy intensive than the supply chain for pipeline gas due to the extra processing steps. The difference is narrower when LNG is compared to remote pipeline deliveries.

3 Technical Analysis of Liquefied Natural Gas (LNG) Liquefaction Plant



(The MJM Energy LNG Supply Handbook 2015−2035)

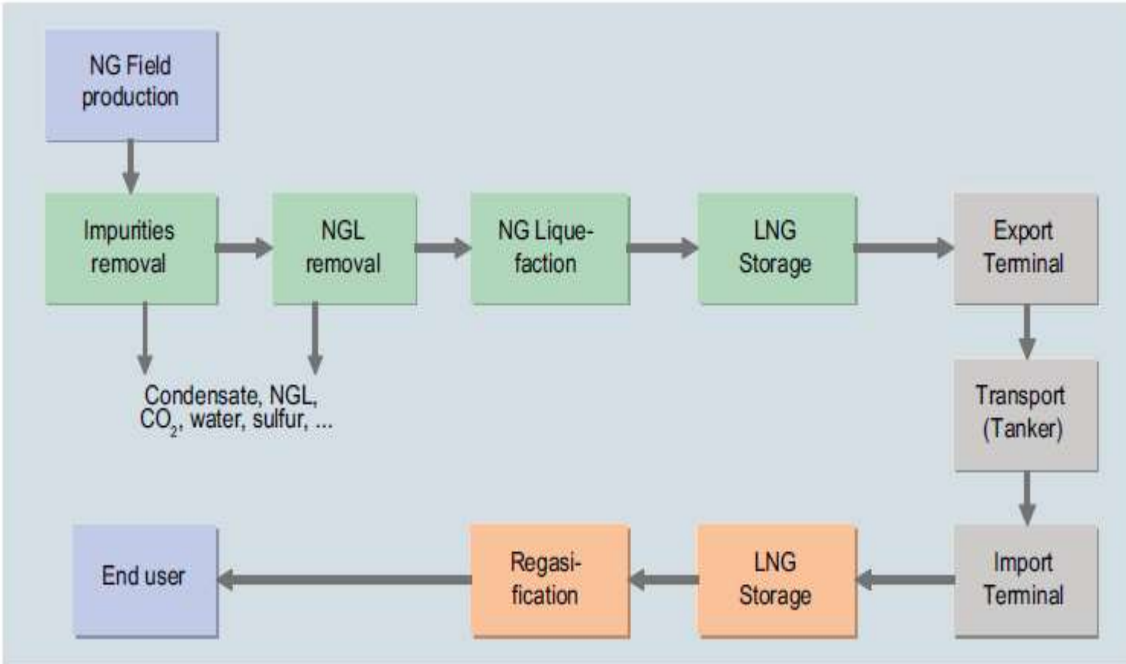
Figure 8. **Overview of the Global LNG Supply Chain**



Lim, W., Choi, K., & Moon, I. (2013)

Figure 9. **Cost breakdown of LNG Supply chain**

The LNG supply chain from gas fields to consumers comprises a number of process and logistic (storage and transportation) steps as shown in Figure 10.



(Improving Natural Gas Liquefaction Plant Performance with Process Analysers. Siemens AG 2014)

Figure 10. **Processes of LNG Value Chain**

3.1 Natural Gas Pre-treatment

The liquefaction process requires all impurities and components that solidify at liquefaction temperatures to be removed from the wellstream prior to liquefaction. When the raw gas reaches the process plant,it consists of three phases: natural gas, condensate and water. They are separated and split into three streams in a unit called slug catcher.

The condensate is heated to remove any residual gas. Pure condensate is stabilized by removing lighter hydrocarbons (NGL, Natural Gas Liquids) such as methane, ethane, propane and butane. Condensate is used as an additive in motor fuel production at refineries and as a feed material at petrochemical plants.

The liquid removed from the bottom of the slug catcher is treated to remove solid particles, salts and most of the water. The water is filtered through a biological treatment system before being discharged.

The Natural Gas is further treated by:

• Passing through an absorption column to remove carbon dioxide using the amine method. This is necessary to prevent the CO2 freezing during liquefaction and cause damages along the process.
• Drying it in dewatering columns to prevent the water turning to ice later in the process.
• Removing very small quantities of mercury that could damage metal equipment in other parts of the process by passing through a separate unit.
Some of the natural gas is diverted from the flow to generate electricity in gas turbines. Exhaust heat from these units is used to warm up the heating medium in the plant.

Natural Gas Liquid Removal

The product specification for liquefied natural gas (LNG) defines the minimum content of propane, butane and other heavier hydrocarbons the gas is allowed to contain, and its calorific value. To meet these requirements, the heavier components (natural gas liquids, NGL) must be removed through a fractionation process by passing the gas through a fractionation column.Methane and ethane are taken off from the top of the column and continue into the gas liquefaction process. NGL products such as propane, butanes and other heavier hydrocarbons are removed from the bottom of the column and sent on to the plant for liquefied petroleum gases (LPG).

Liquefaction

The gas continues to the liquefaction part of the plant ("cold box") for cooling to liquefied natural gas (LNG). This facility consists fundamentally of several heat exchangers.

The gas passes through them for pre-cooling to about -50 °C, beginning of liquefaction at about -80 °C and subcooling at about -160 °C and finally emerges as a liquid.

The gas flows through thin tubes which are constantly bathed in coolant – pure fluids or mixes of nitrogen, methane, ethane and propane. The coolant takes up heat from the gas and evaporates, while the gas is cooled and condenses to liquid.

When it enters the cooling process, the gas may contain too much nitrogen in relation to the specification. This surplus is extracted initially in a nitrogen removal column. The top product of that process is nitrogen and some LNG, which go to a separate two-column removal process. Separated nitrogen is finally released to the air and any LNG returns to the process flow. LNG taken out at the bottom of the nitrogen removal column has a temperature of about -163 °C. It is piped from the cold box to storage tanks.

The global LNG industry has adopted two main liquefaction processes:

- The propane pre-cooled multi-component refrigeration (C3/MR) process, also known as the APCI process and used by the majority (about 80%) of LNG plants.
- The pure refrigerant cascade process.

The LNG plants were based on the cascade process using propane, ethylene, and methane as refrigerants. However, the majority of large LNG projects have been based on the C3/MR process. Various studies have shown that the efficiencies of the two main processes are similar.

Transport and Regasification

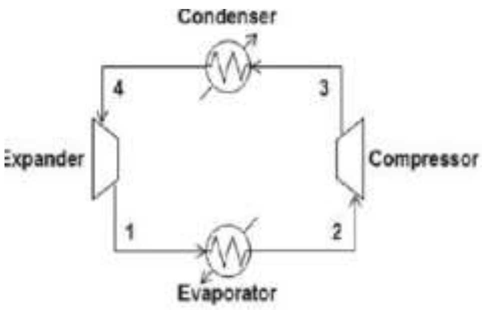
The liquefaction process reduces the volume of natural gas by a factor of 600 allowing it to be shipped by sea. LNG is typically transported by specialized tanker with insulated walls, and is kept in liquid form by autorefrigeration, a process in which the LNG is kept at its boiling point. Upon arrival at its destination, LNG is generally transferred to specially designed and secured storage tanks and then warmed to its gaseous state in evaporators with different design – a process called regasification.Finally it is transported via pipelines to the end user.

Real processes or plants may deviate from the above description depending on varying technologies and product demands.

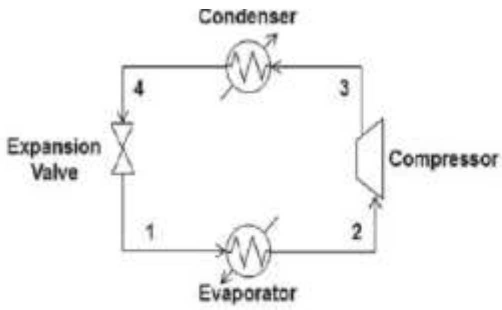
3.2 Fundamental Principles of Natural Gas Liquefaction Process

Liquefaction of natural gas requires the removal of sensible and latent heat over a wide range of temperatures using one or more refrigerants and thus a complicated refrigeration system,either compression refrigeration or absorption refrigeration is required. In LNG plants, a compression refrigeration cycle is generally used.

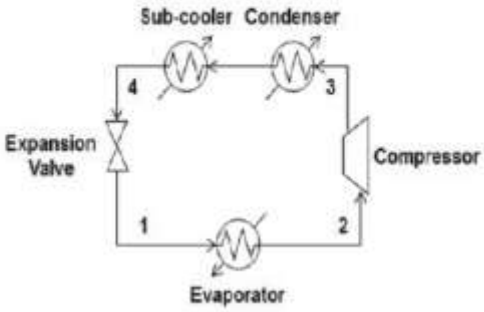
The ideal compression refrigeration cycle is shown below.

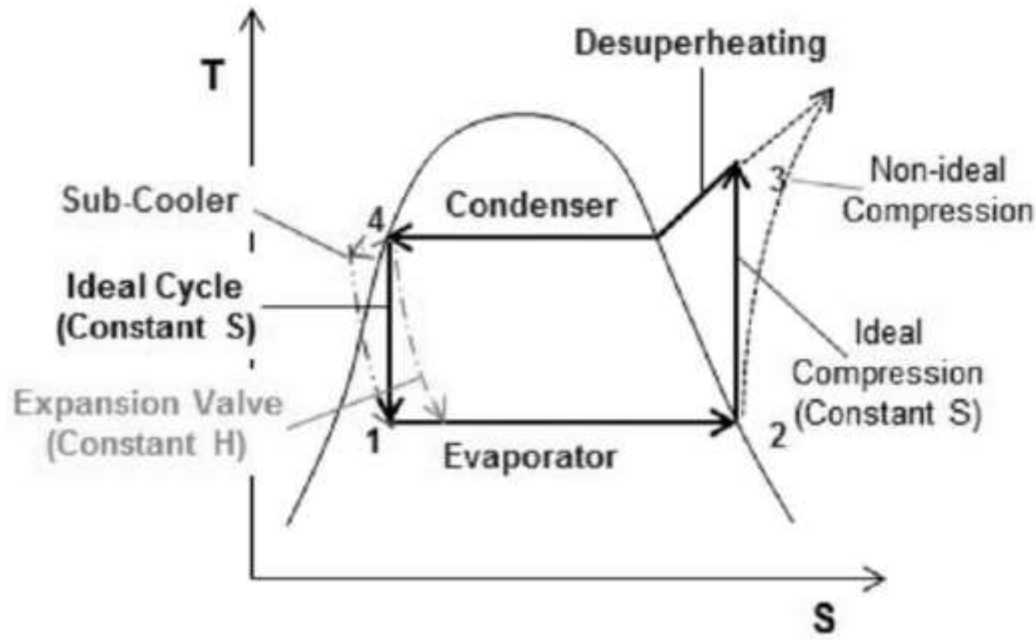


(a) Ideal cycle

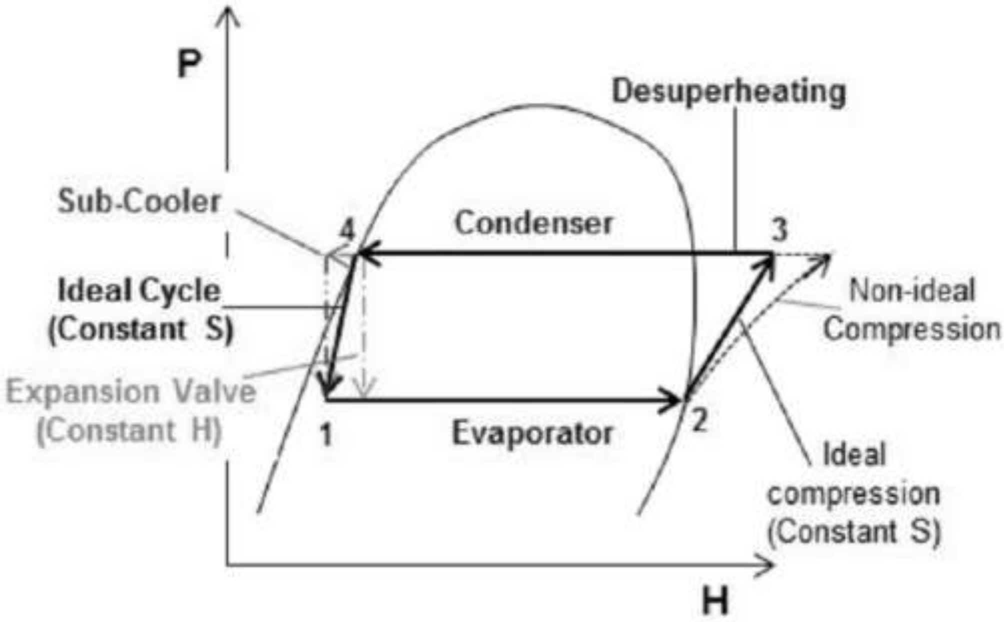


(b) Non-ideal cycle with expansion valve





(d) T-S diagram



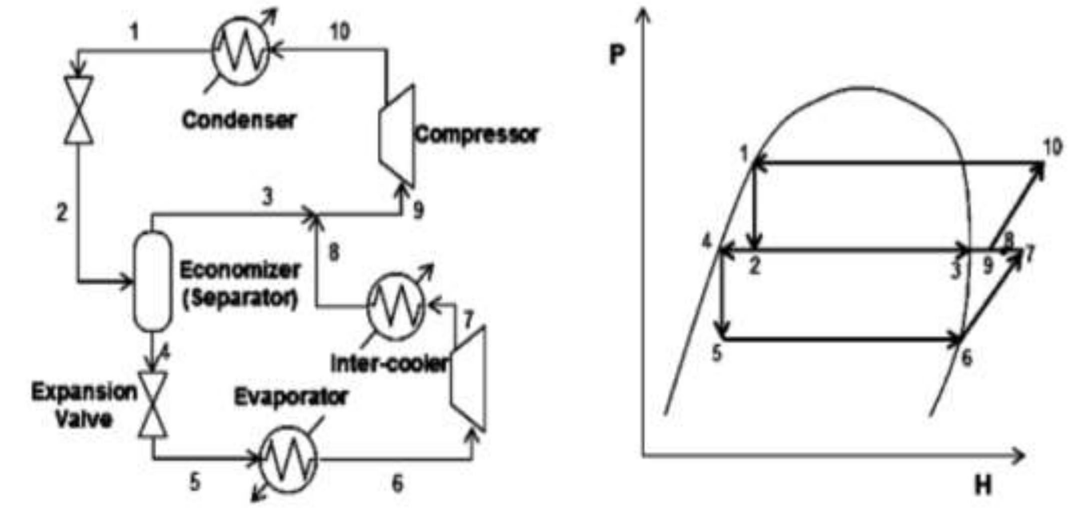
(e) P-H diagram

Lim, W., Choi, K., & Moon, I. (2013)

Figure 11. **Compression refrigeration cycles**

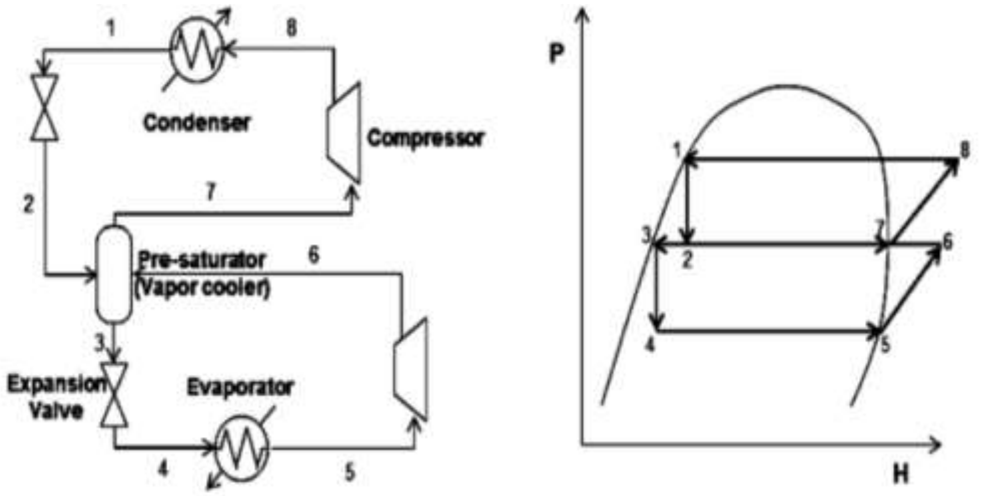
The cycle works as follows. In the first step (1→2), a refrigerant absorbs heat at constant pressure and temperature in an evaporator; in the second step (2→3), pressure is increased at constant entropy in the compressor. In the third step (3→4), desuperheating and condensation, in which enthalpy decreases at a constant pressure, are performed in a condenser. In the last step (3→4), the refrigerant returns to its original pressure at constant entropy in an expander.

Improvements in refrigeration cycle efficiency can be achieved by modifying the cycle configuration. Vaporization of the liquid in the evaporator provides refrigeration. Thus, compression work can be reduced by adding an intermediate level. This intermediate level is added between two temperature levels, with the vapor formed after the first pressure reduction separated from the liquid and fed directly into the high-pressure compressor as shown in Figure below.



(a) Multi-stage compression with economizer and inter-cooler (b) P-H diagram

The intermediate level allows the insertion of an intercooler to reduce the amount of superheat in the compressors. However, it is not feasible to use an intercooler in a lower temperature cycle. In this case,an economizer (phase separator) can be substituted with a presaturator (vapor cooler) to reduce the superheat to zero, as shown in Figure below.

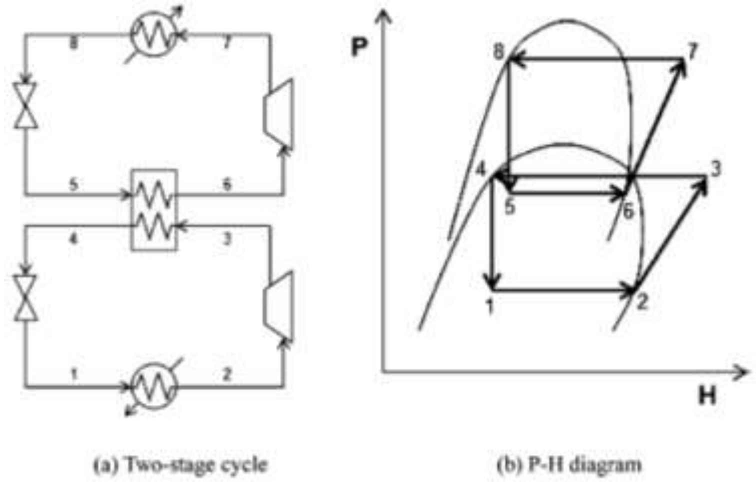


(c) Multi-stage compression with pre-saturator (d) P-H diagram

Lim, W., Choi, K., & Moon, I. (2013)

Figure 12. **Multi-stage Compression Refrigeration Cycles**

The presaturator can reduce the inlet temperature to the next compression level by direct contact with the liquid refrigerant. However, presaturation requires a higher vapor refrigerant flow rate. Two or more cycles with different refrigerants may be operated at the same heat exchanger as shown in Figure below.

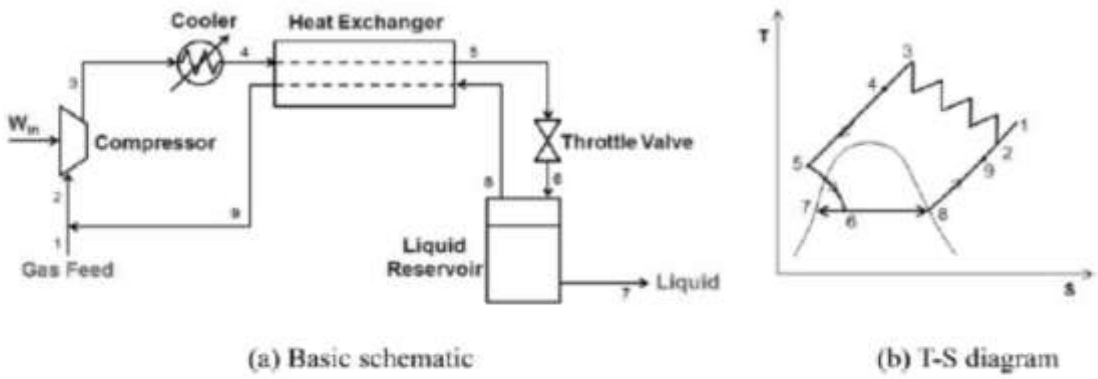


Lim, W., Choi, K., & Moon, I. (2013)

Figure 13. **Cascade refrigeration cycle**

The cascade refrigeration cycle is used to provide very low-temperature refrigeration in cases where a single refrigerant cannot be used for operation due a wide range of operating temperatures.

The liquefaction process is completed when the natural gas is cooled to a temperature in the two-phase region in a simple Linde liquefaction process, which depends solely on throttling expansion as shown below.



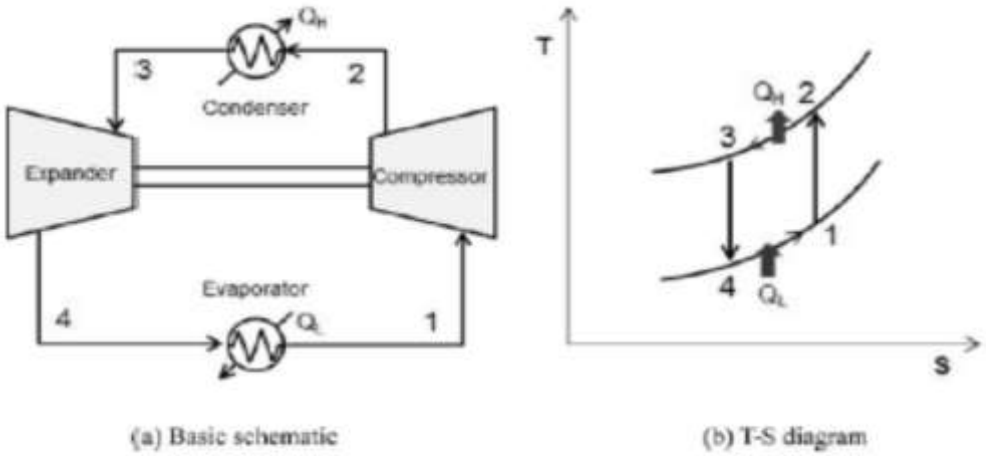
Kanoglu, M.; Dincer, I.; Rosen, (2008)

Figure 14. **Simple Linde Liquefaction process**

Feed gas is mixed with the uncondensed portion of the gas from the previous cycle,and the mixture is compressed by a multistage compressor.

The compressed gas is precooled to ambient temperature and can be cooled even further by refrigeration. The high-pressure gas is cooled by a return gas stream in a heat exchanger and then expanded through a throttle valve, and the outlet stream exists in an equilibrium state of liquid and vapor phases. The outlet stream is flashed in the separator, producing liquefied product at its bottom. Gas from the separator is used to cool the high-pressure gas stream in the heat exchanger above.

The reverse-Brayton cycle, as shown in Figure below

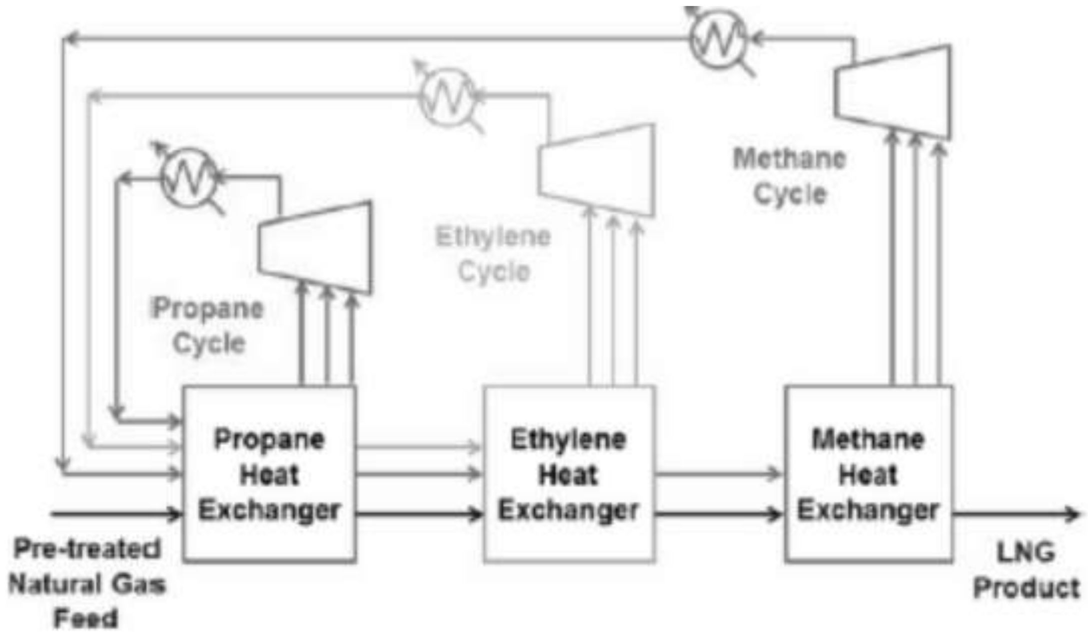


(Chang, H. M.; Chung, M. J.; Lee, S.; Choe, K. H. 2011,278−286)

Figure 15. **Reverse-Brayton cycle**

It uses gas phase refrigerant. This cycle is widely used for cryogenic liquefaction, and it forms the basis of the expander process in natural gas liquefaction.Natural gas liquefaction processes have been developed by combining characteristics of different refrigeration cycles.

3.3 Commercial Natural Gas Liquefaction Processes



Lim, W., Choi, K., & Moon, I. (2013)

Figure 16. **Classic Cascade Process**

Many liquefaction processes have been developed and applied in LNG plants over the last few decades. The processes can be classified into three categories based on the type of refrigeration cycle and equipment used: a cascade process using pure refrigerants, a mixed refrigerant process using refrigerant mixtures, and an expander process using expanders instead of Joule−Thomson (J−T) valves.

3.3.1 Cascade. Technip/Air Liquide Cascade

This process comprises three separate refrigeration cycles as shown above. The three refrigerant cycles are typically operated at three evaporation temperature levels with multistage compression.

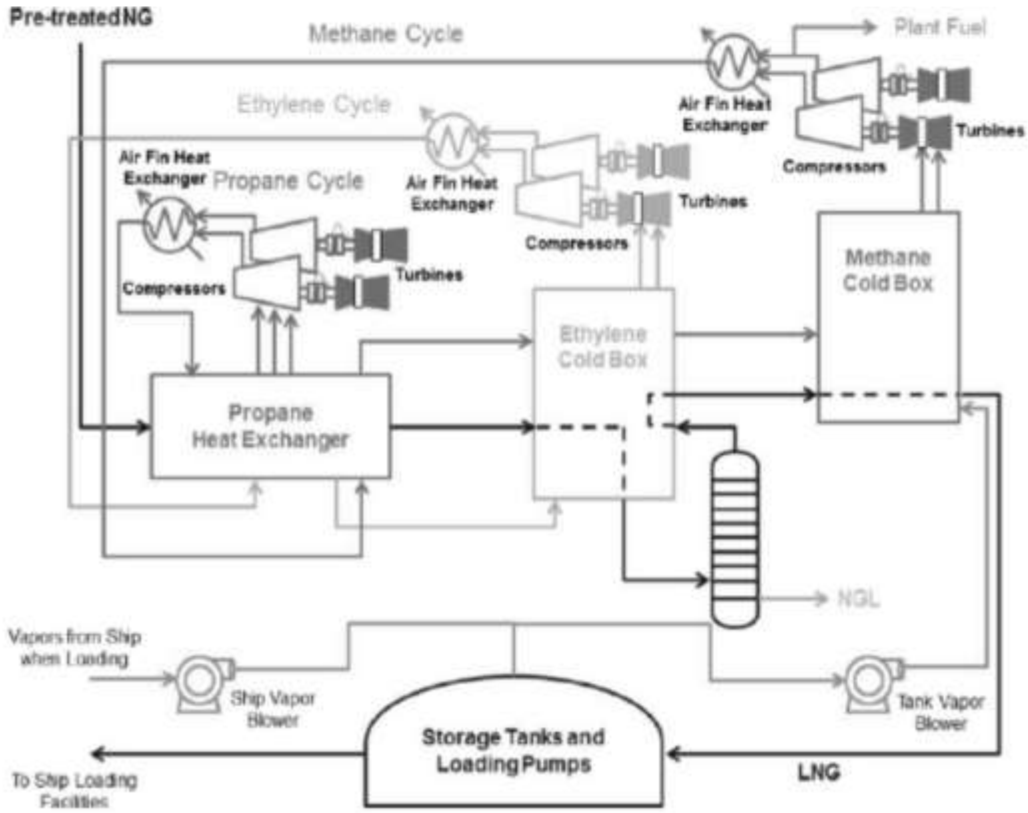
High-pressure propane is condensed by ambient air or cooling water in the multistage compression step. In the propane cycle, the propane is used to cool the natural gas and the other two refrigerants to −30 °C. The ethylene cycle then cools the natural gas and methane to about −100 °C. Finally, the methane is used to produce LNG at −160 °C.

A kettle-type heat exchanger is employed in the propane cycle, and a coil-wound heat exchanger (CWHE) is used in the ethylene and methane cycles. Steam turbines contribute to drive compressors for each refrigerant cycle and condensers uses cooling water as a coolant. The three-train has a capacity of nearly 1.1 MTPA.

3.3.2 Phillips Cascade

This process also uses propane, ethylene, and methane cycles, but the single train capacity is 50% greater than that of the three trains at other plant. This process is considered to be the first that employed gas turbine/compressor sets and a plate-fin heat exchanger (PFHE) in each refrigeration cycle.

3.3.3 Phillips' Optimized Cascade (POC)



(Andress, D. L.1996)

Figure 17. **Phillips Optimized Cascade (POC) Process**

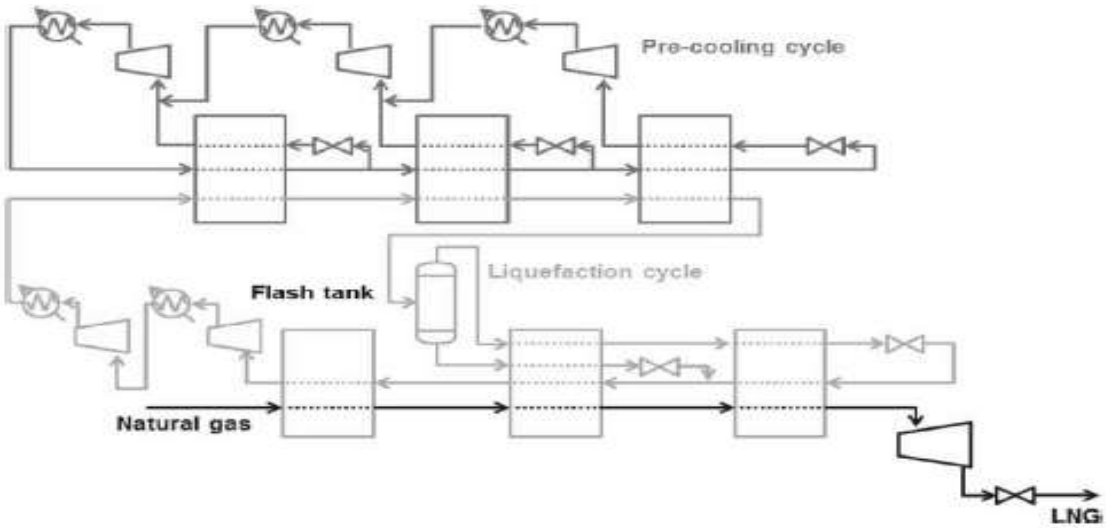
This is a new version of the cascade process and also uses three pure refrigerants (propane, ethylene, and methane), and each cycle is operated separately at multiple pressure levels. The process has evolved from the original cascade process because the methane cycle is now an open cycle or a feed-flash system, rather than a closed cycle. This improvement enables a separate fuel gas compressor to be eliminated, as well as allowing stored vapors and vapors from tanker loading to be used for reliquefaction rather than being routed directly to fuel or flare, thereby increasing LNG production.The parallel arrangement of gas turbine/compressor sets in each refrigerant cycle increases availability and allows easier operation. Further,the process configuration enables the same amount of power to be used in each cycle.

Refrigeration and liquefaction are achieved in a series of PFHEs arranged in vertical cold boxes. Precooling can be carried out in a core-in-kettle type exchanger. The refrigerants are compressed by centrifugal compressors driven by gas turbines.The latest POC process uses highly efficient aero-derivative gas turbines for the liquefaction process.The cascade process requires relatively high capital and maintenance costs due to the amount of equipment needed for the refrigerant cycle, even though the power requirements are relatively low. Therefore, this process is suitable for large capacity trains. The current capacity per train is 5.2 MTPA.

3.3.4 Mixed Refrigerant.APCI Single Mixed Refrigerant(SMR)

The first single mixed refrigerant (SMR) process was developed by APCI and uses a single cycle with a mixture of nitrogen and hydrocarbons (methane, ethane, propane, etc.) as a refrigerant instead of several pure refrigerants as in the cascade process. The condensation and evaporation steps are carried out in a single cycle over a wide range of temperatures to cool the natural gas to about −160 °C.The cycle uses CWHE as the main cryogenic heat exchanger (MCHE). This process was developed to decrease the amount of equipment required compared to the cascade process; however, a relatively greater amount of power is required for this process than the cascade process due to the larger refrigerant flows in the cascade process.

3.3.5 Technip/Air Liquid (TEALARC)



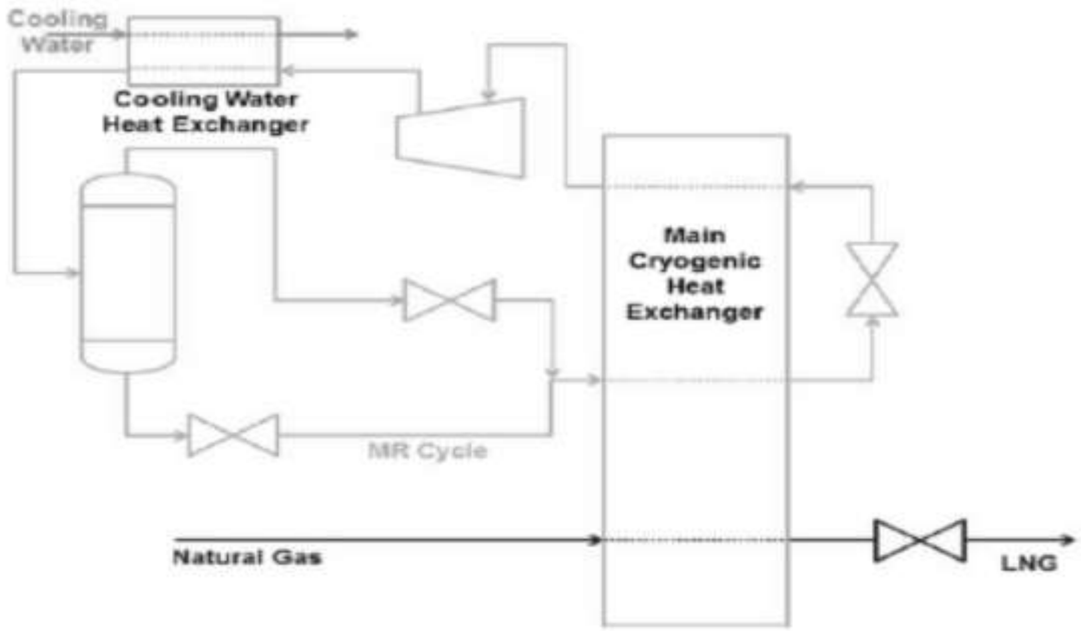
(Andress, D. L.1996)

Figure 18. **TEALARC process**

This two pressure single mixed refrigerant process uses a single mixed refrigerant cycle with a 33% increase in capacity per train. This process It consists of two refrigeration cycles, precooling and liquefaction, as shown above.

In the precooling cycle, the refrigerant used in the liquefaction cycle is precooled and partially condensed by a mixed refrigerant composed mainly of ethane and propane. The liquefaction cycle cools the natural gas by a mixed refrigerant comprising mainly methane and ethane.

3.3.6 PRICO Process



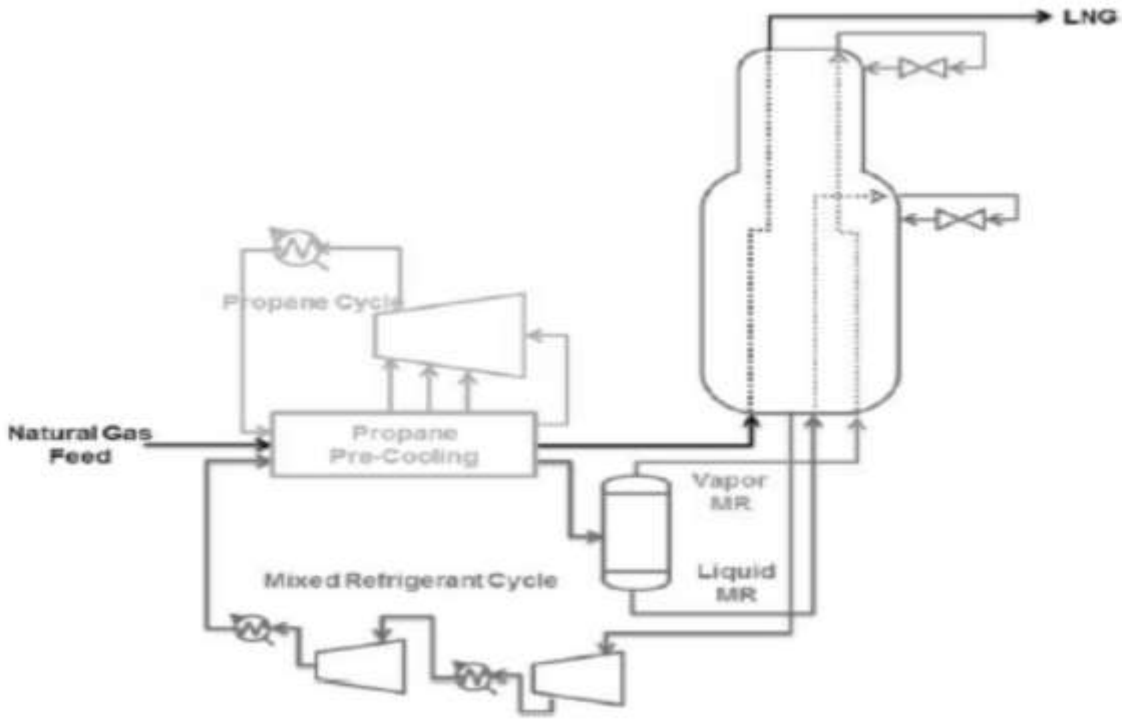
(Stebbing, R.; O'Brien, 1975)

Figure 18. **PRICO process**

The PRICO process is one of the well-known SMR processes and uses a single mixed refrigerant composed of a set of nitrogen and hydrocarbons such as methane, ethane, propane, butane, and pentane.

Cooling and liquefaction steps are performed at several pressure levels. The mixed refrigerant is compressed by a compressor and then condensed in the main heat exchanger. The refrigerant is expanded through a Joule−Thomson (J−T) valve and then evaporated as it returns through the main heat exchanger.This process uses PFHEs in cold boxes. The axial compressors are driven by steam turbines.

3.3.7 APCI Propane Precooled Mixed Refrigerant (C3MR) Process



(Pillarella, M.; Liu, Y.-N.; Petrowski, J.; Bower, R.2007)

Figure 19. **C3MR process**

A basic schematic of the C3MR process, which consists of two main stages which are propane precooling and mixed refrigerant (MR) stages is shown above The precooling cycle cools the natural gas to around −40 °C at three or four different pressure levels using a pure propane refrigerant.This cycle may also be used to cool and partially liquefy the mixed refrigerant. To use propane for cooling the natural gas, the propane is compressed to a high pressure at which it can be condensed by ambient air or cooling water.

In the MR cycle, a mixed refrigerant comprising nitrogen,methane, ethane, propane, and sometimes butane is used in a single MCHE to liquefy and subcool the natural gas from typically −35 °C to between −150 and −162 °C.

The refrigerant that has been processed in the precooling cycle is separated in a high-pressure separator. The liquid and vapor MR streams pass through separate circuits in the MCHE. The liquid MR stream participates in cooling in the warm bundle of the MCHE that cools the natural gas, and is flashed across a J−T valve on the shell-side of the MCHE.

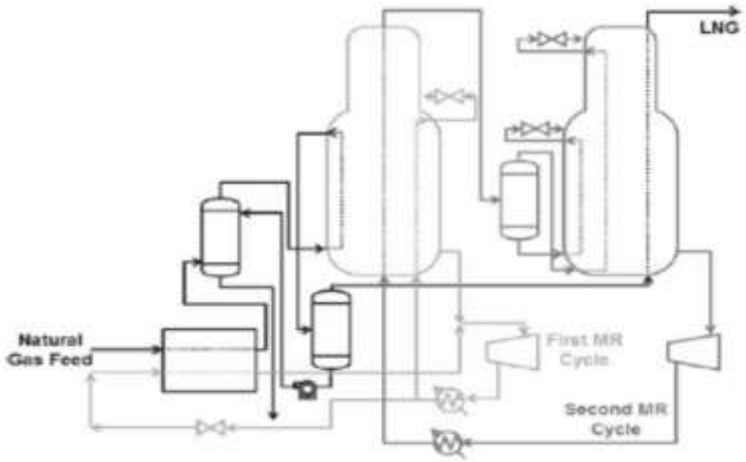
The liquid MR evaporates and flows downward to provide cooling duty for the lower bundle. The vapor MR stream is used to liquefy and subcool the natural gas stream to −162 °C in the cold bundle and is flashed across a J−T valve on the shell-side of the MCHE. This stream flows downward to provide cooling duty for the cold bundle. Then, the vapor and liquid output MR streams are merged to provide partial cooling duty for the lower bundle.

The overall vaporized MR is compressed up to 45−48 bar. It is cooled and partially liquefied, first by ambient air and cooling water, and then by the propane in the precooling cycle. Precooling is achieved in a kettle-type heat exchanger. The MR cycle uses a CWHE as the MCHE. Propane compression is carried out by a centrifugal compressor. In earlier plants, only centrifugal compressors with steam turbine drivers were used for MR compression. However, recently constructed plants use axial compressors for the low-pressure (LP) stage and centrifugal compressors for the high-pressure (HP) stage, together with gas turbine drivers.

In the most recently constructed plants, the SplitMR technology, in which a driver is associated with a set of propane and MR compressors, is used in the C3MR process. This configuration allows full utilization of the gas turbine power,thereby increasing the train capacity for the same number of compressors and drivers.

Since the first LNG plant using the C3MR process was commissioned in 1972, the capacity of a single train has increased from less than 0.5 MTPA to about 5 MTPA.

3.3.8 Dual Mixed Refrigerant (DMR) Process



Pillarella, M.; Liu, Y.-N.; Petrowski, J.; Bower, R.2007)

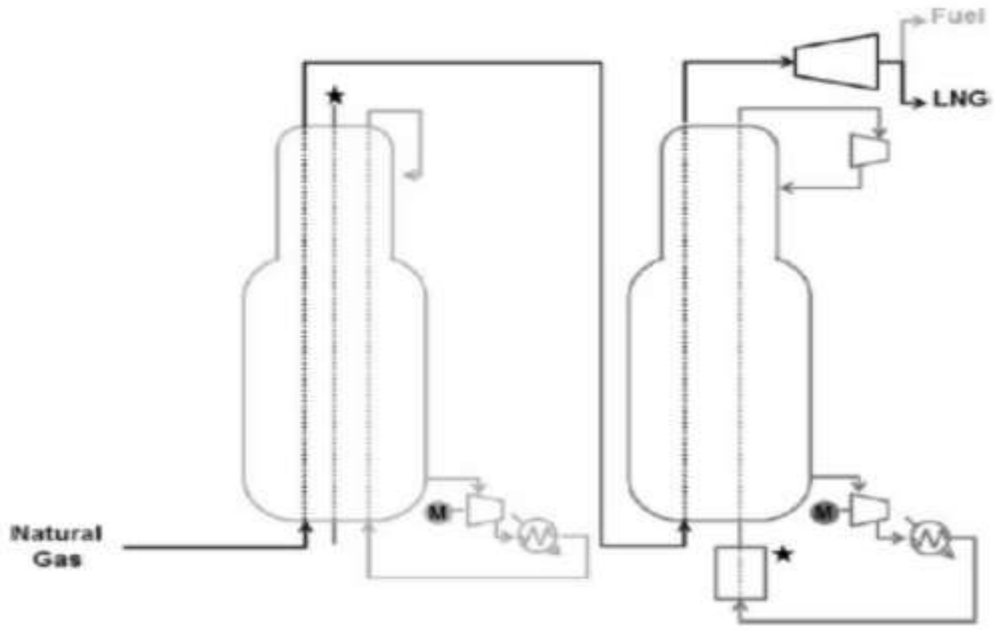
Figure 20. **DMR process**

The dual mixed refrigerant (DMR) process was developed to overcome the inherent limitations of compressor size in using a pure propane refrigerant for the C3MR process.

This process has a configuration similar to the C3MR process, comprising two separate cycles, precooling and liquefaction. Use of a mixed refrigerant (composed mainly of ethane and propane) instead of pure propane in the precooling cycle allows for more flexible design while maintaining the compressor configuration. Natural gas is cooled to about −50 °C in the precooling cycle and then liquefied and subcooled to about −153 °C in the liquefaction cycle using a mixture of nitrogen, methane, ethane, and propane. LNG is produced using a liquid expander and end-flash vessel at its atmospheric boiling temperature of about −161 °C.

This process uses two CWHEs and different amounts of power are required for each cycle and each train was designed for 4.8 MTPA LNG production.

3.3.9 Parallel Mixed Refrigerant (PMR) Process

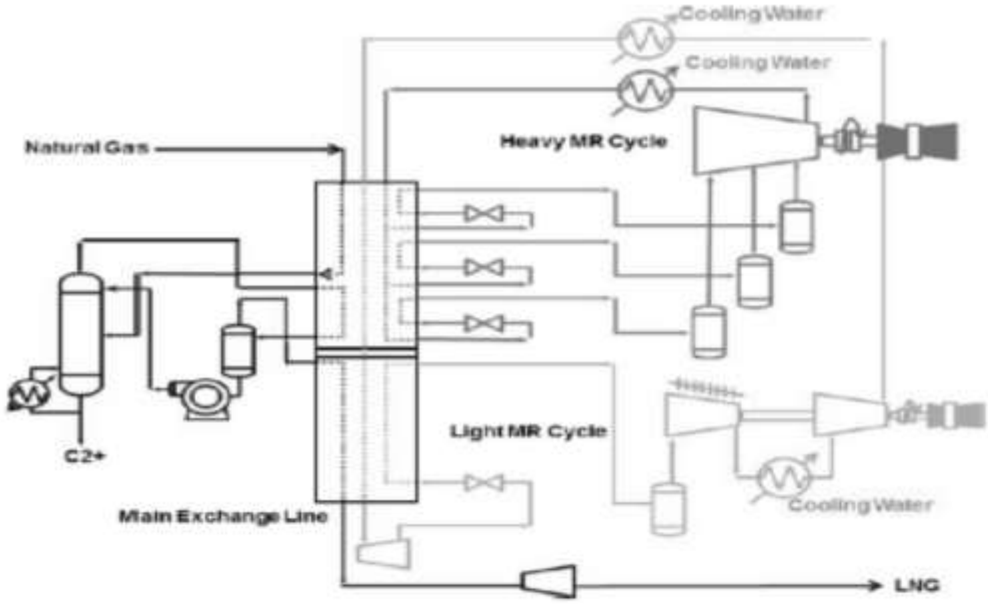


(Terry, L. 1998)

Figure 21. **PMR Process**

The (PMR) process consists of precooling and liquefaction cycles.Either propane or MR can be used as a refrigerant for the precooling cycle. The main feature of the PMR process is that two MR cycles for liquefaction are configured in parallel, which reduces the pressure drop in the system and improves the reliability of the plant, thereby improving process efficiency; the train capacity can reach 8 MTPA using existing compressors.

3.3.10 Liquefin Process

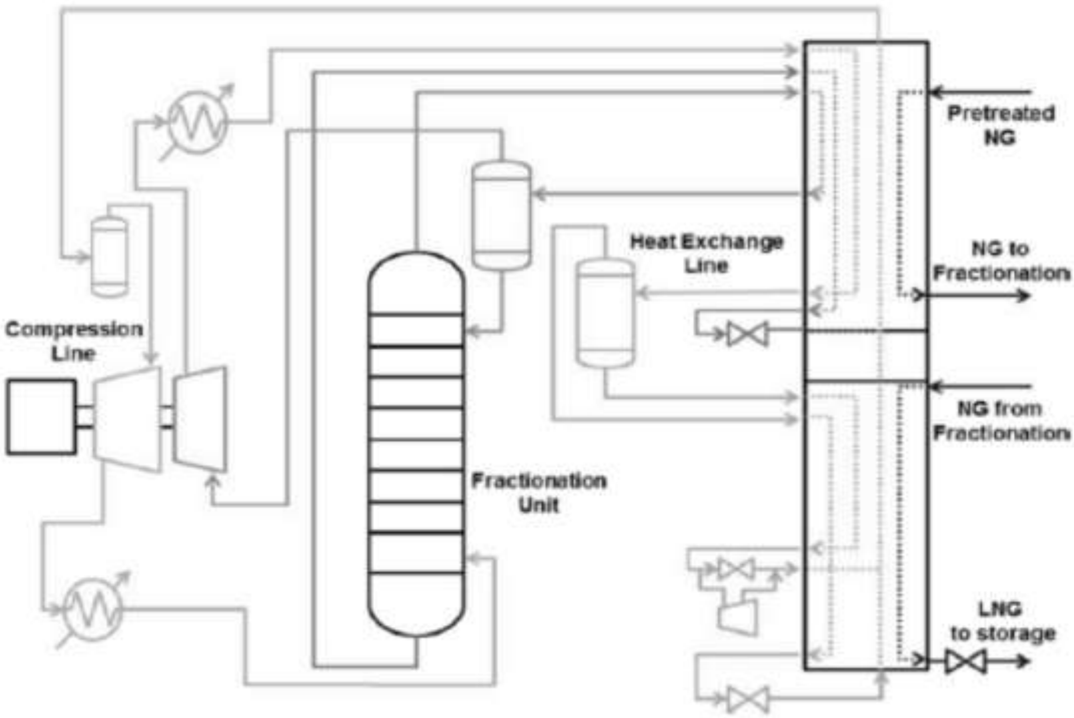


(Hudson, H. M.; Wilkinson, J. D.; Cuellar, K. T.; Pierce, M. C. 2003)

Figure 22. **Liquefin Process**

The Liquefin process uses two mixed refrigerant cycles, precooling and liquefaction cycles.The two refrigerants are composed of methane, ethane, propane, butane, and nitrogen but the compositions differ in each cycle. The heavy MR precooling cycle is used to cool the natural gas, and precool and liquefy the other mixed refrigerant at three different pressure levels. The light MR liquefaction cycle is used to liquefy and subcool the natural gas. Both cycles are carried out in PFHE arranged in a cold box. Each cycle is designed to use the same amount of power so that the same set of drivers can be used for the compressor across different cycles, which translates into significant cost savings. In addition, the relatively lower flow rate of the mixed refrigerant permits a much greater train capacity to be achieved with existing axial compressors.

3.3.11 Integral Incorporated Cascade (CII) Process

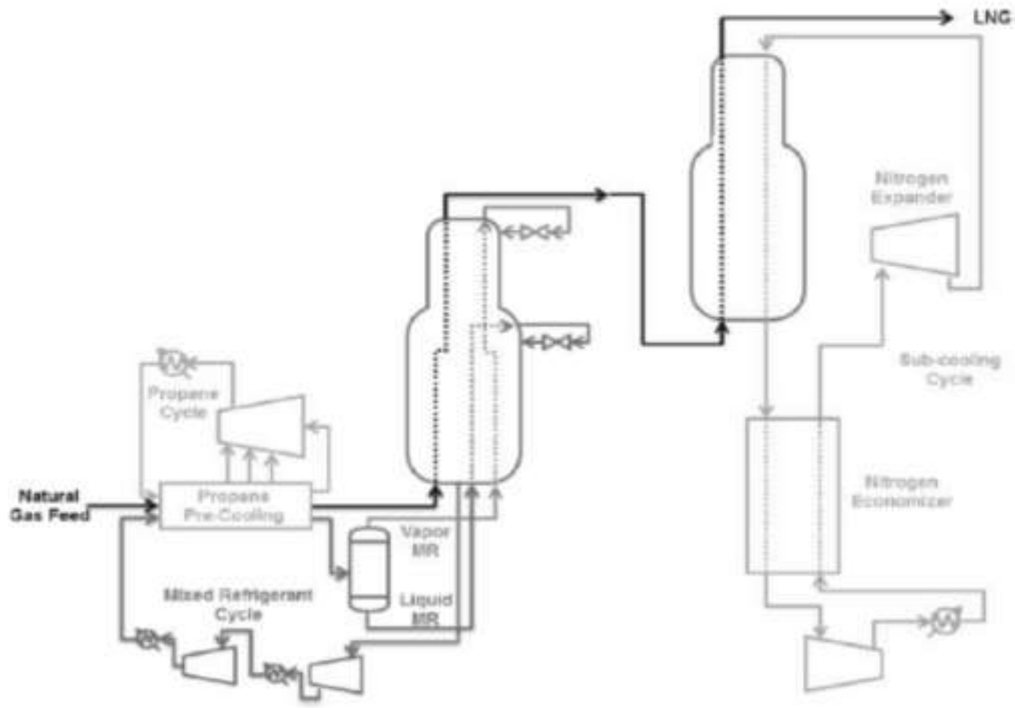


(Flesch, E.; Raillard, J.-C. 1998)

Figure 23**. Integral Incorporated Cascade (CII) Process**

It is a new single cycle process that uses a mixture of nitrogen and hydrocarbons (from methane to propane) as a refrigerant and consists of three subunits: a compression line, a cycle fluid fractionation unit, and a heat-exchange line. The cycle fluid fractionation unit separates the mixed refrigerant into two fluid types: heavy fluid (pentane and butane) and light fluid (nitrogen, methane, and ethane). The heavy fluid is used to precool the natural gas, while the light fluid is used to liquefy and subcool the natural gas. A single heat-exchange line consists of two large cores of PFHEs and comprises two sections: an upper section to precool the natural gas, and a lower section to liquefy and subcool the natural gas. Similar to the single cycle processes, precooling, liquefaction, and subcooling are carried out in the same heat exchanger.

3.3.12 AP−X Process



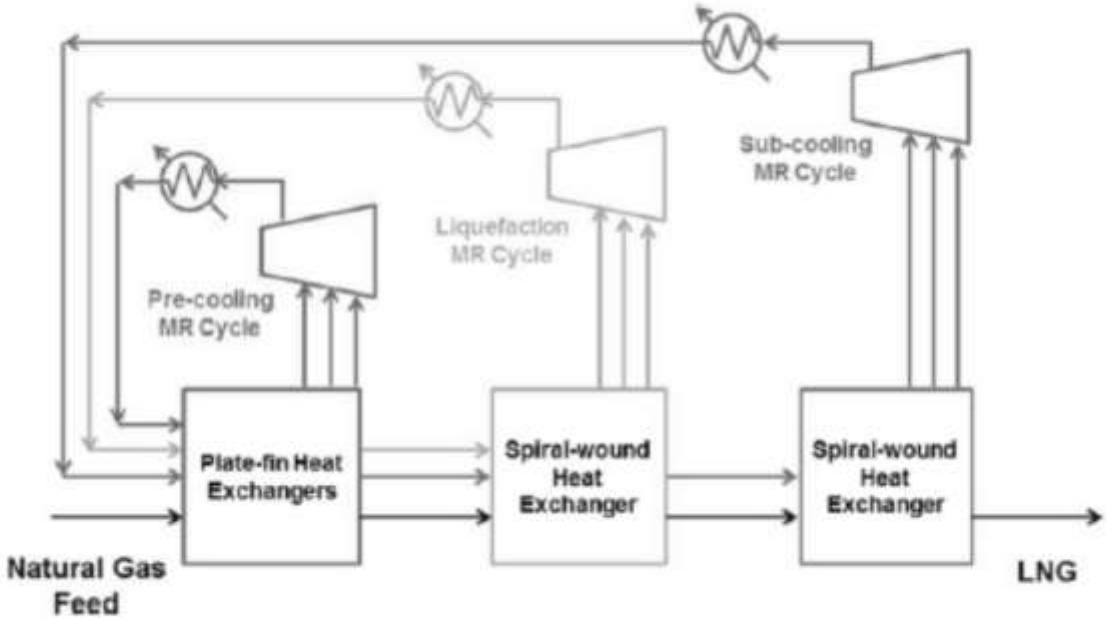
(Berger, E.; Forg, W.; Heiersted, R. S.; Paurola, P.2003)

Figure 24. **AP−X Process**

The AP-X process was developed from the C3MR process by APCI. This process comprises three cycles: a propane precooling cycle, a mixed refrigerant cycle, and a nitrogen subcooling cycle. A unique feature of this process is that the LNG is subcooled using a nitrogen expander cycle rather than a mixed refrigerant cycle. Natural gas precooled to about −30 °C in the propane cycle using kettle-type heat exchangers is cooled and liquefied to about −120 °C in the MCHE with a mixed refrigerant. The LNG is subcooled using cold gaseous nitrogen from the nitrogen expander.

In the nitrogen cycle, nitrogen is compressed to a high pressure and then cooled to near ambient temperature. The highpressure nitrogen is cooled in a nitrogen PFHE-type economizer with low-pressure nitrogen returning to the compressor. The high-pressure nitrogen passing through the nitrogen economizer is expanded to a low pressure to further reduce its temperature in the expander. Compared to the C3MR process, the nitrogen expander subcooling cycle allows the flow of both propane and mixed refrigerant to be reduced without affecting production, enabling much higher capacities of nearly 8 MTPA using existing equipment.40 CWHEs are used for the MR and nitrogen subcooling cycles.

3.3.13 Mixed Fluid Cascade(MFC) Process

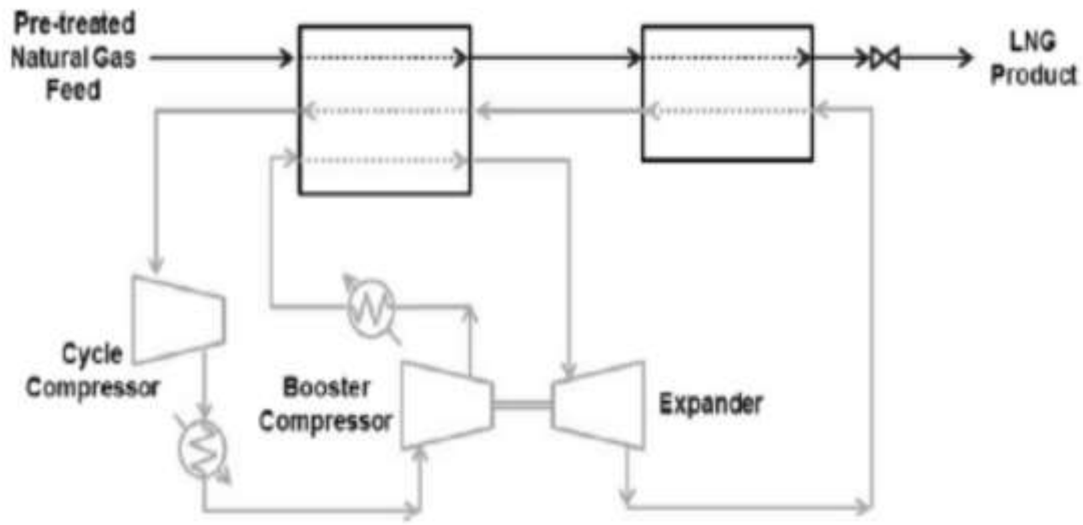


(Berger, E.; Forg, W.; Heiersted, R. S.; Paurola, P.2003)

Figure 25. **Mixed Fluid Cascade (MFC) Process**

The mixed fluid cascade (MFC) process was developed and the capacity of a single train that uses this process is 4 MTPA. This process is similar to the cascade process and also consists of the three cycles of precooling, liquefaction, and subcooling.Compared to the cascade process, the MFC process has higher efficiency as it uses three mixed refrigerants instead of three pure refrigerants. The mixed refrigerants are composed of methane, ethane, propane, and nitrogen, but the compositions differ in each cycle. Another feature is that the power requirements for each cycle are not the same, unlike the POC process. The precooling cycle uses PFHE, while the liquefaction and subcooling cycles use CWHE.

3.3.14 Single Nitrogen Expander Process



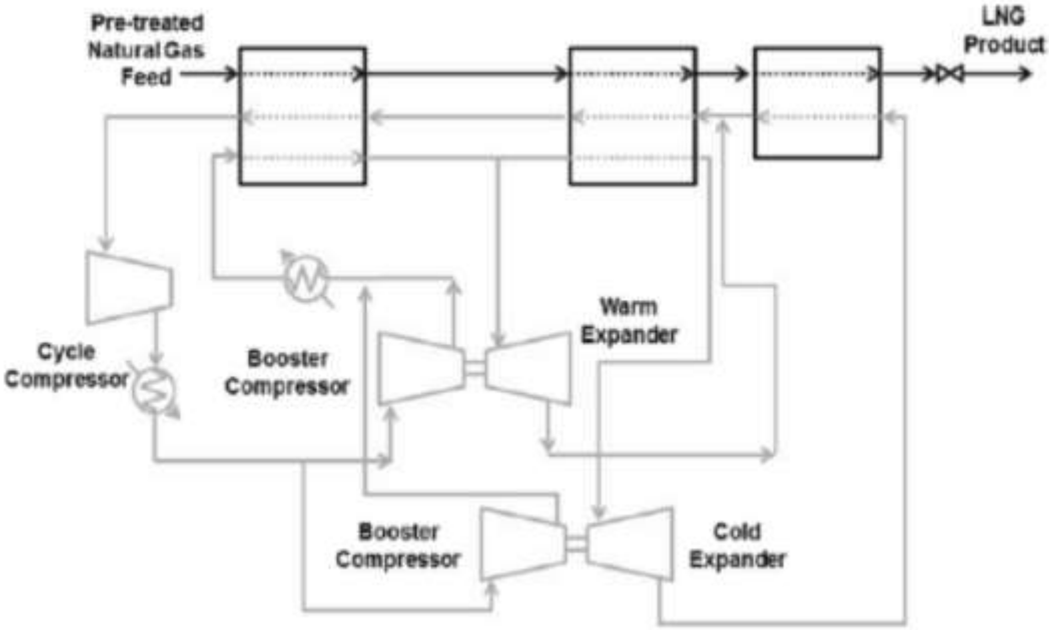
(N.G.Kirillov, 2004)

Figure 26. **Single Nitrogen Expander Process**

Nitrogen expander processes which are based on reverse-Brayton and Claude cycles, are used mostly in offshore and small-scale liquefaction plants. Nitrogen expander processes have been widely used for cryogenic liquefaction, including LNG peakshaving and in industrial gas liquefiers.

A simple single nitrogen expander cycle is shown above.Refrigeration is carried out through compression and work-expansion using nitrogen as the refrigerant. High-pressure nitrogen is cooled in the heat exchangers with low-pressure refrigerant returning to the compressor. The high-pressure nitrogen is then work-expanded in the expander to reduce its temperature. The expander generates simultaneously useful work which is usually supplied to the booster compressor. The low pressure nitrogen from the expander liquefies natural gas and cools the high-pressure nitrogen in heat exchangers. Nitrogen passing through the heat exchangers is compressed by the main cycle compressor and booster-compressor. The process efficiency is relatively low because a pure gas refrigerant is used over a wide temperature range. Therefore, the single nitrogen expander process is only suitable for plants with small capacities.

3.3.15 Double Nitrogen Expander Process

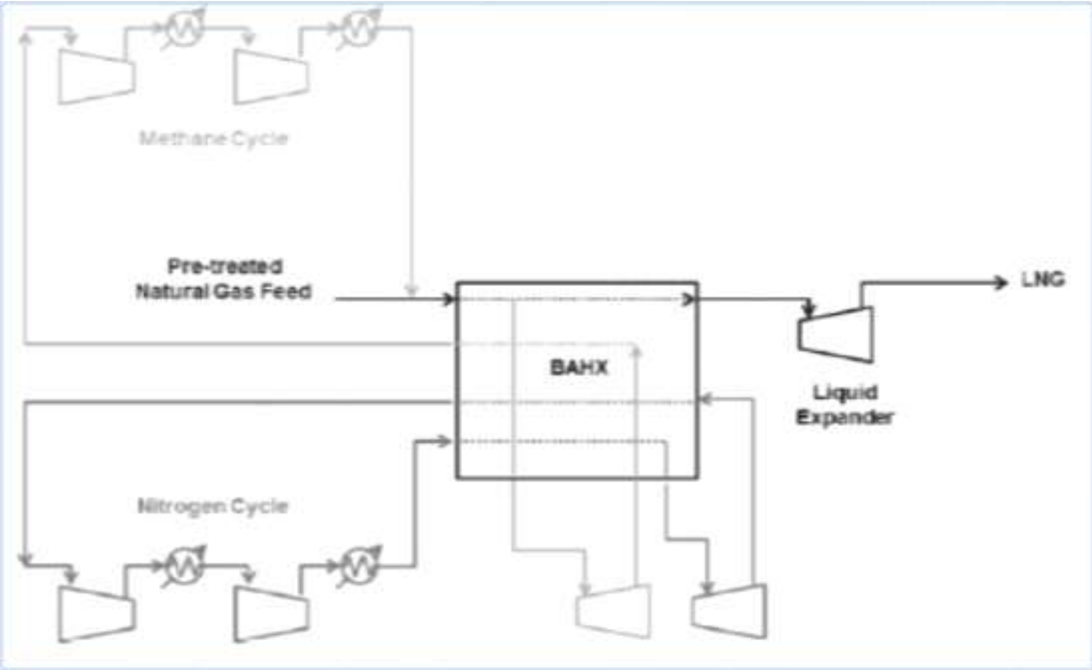


(N.G.Kirillov, 2004)

Figure 27. **Double Nitrogen Expander Process**

The double nitrogen expander process is a modification of the single nitrogen expander process. This process has been widely used to liquefy nitrogen and oxygen for the last few decades.It comprises two expander cycles: warm and cold expander cycles.Both expander cycles enable natural gas to be liquefied and subcooled at small temperature differences reducing the specific power requirements but increasing the size of the heat exchanger required. Nitrogen refrigerant can be substituted with methane refrigerant in the existing process.The methane refrigerant may reduce the specific power for liquefaction, but this is outweighed by the safety implications of using a hydrocarbon refrigerant rather than inert nitrogen.

3.3.16 Dual Independent Expander Process

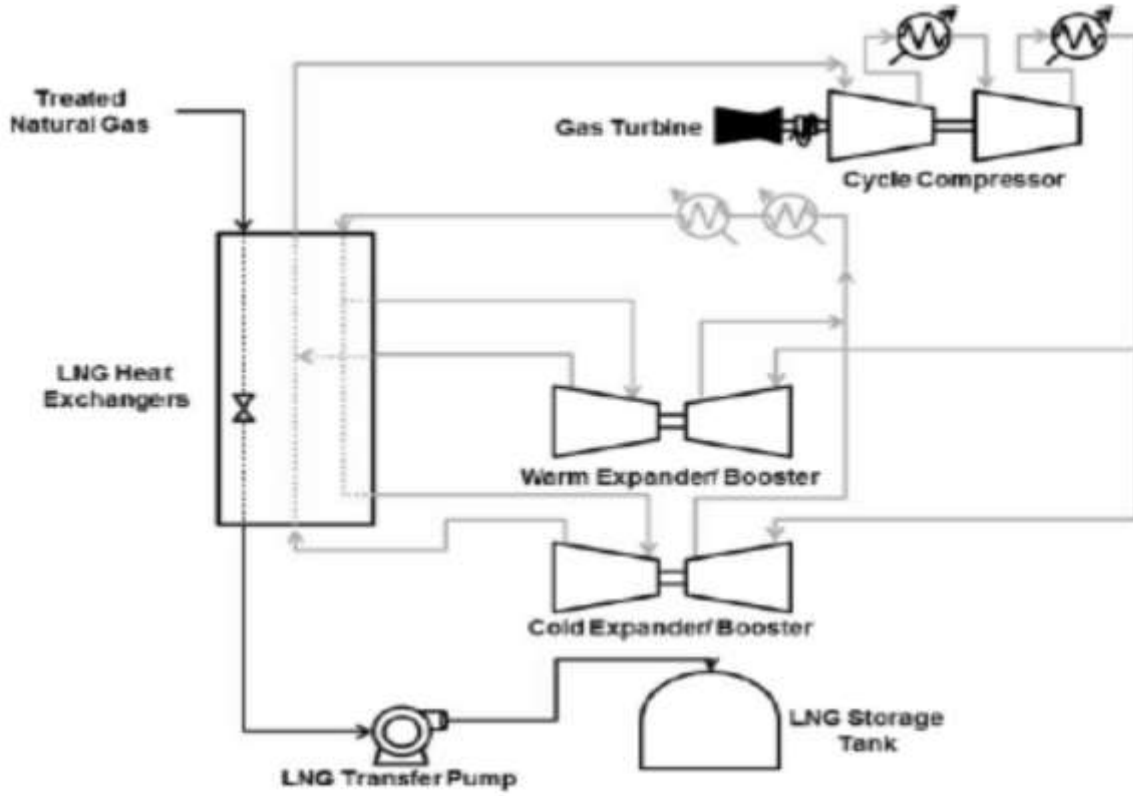


(Lim, W., Choi, K., & Moon, I. 2013)

Figure 28. **Dual Independent Expander Process**

The dual independent expander process uses two separate refrigeration cycles, methane and nitrogen cycles to improve process efficiency by reducing the temperature difference between liquefaction and subcooling. While this process requires a larger heat exchanger than a single expander process, the required specific power can be reduced compared to that required for a single expander process. However, the process safety decreases because of the use of a hydrocarbon refrigerant. The use of methane increases the need to ensure adequate spacing between equipment to prevent jet fires and blast pressure damage.

3.3.17 Compact LNG (cLNG) Expander Process



(Lim, W., Choi, K., & Moon, I. 2013)

Figure 29. **Compact LNG (cLNG) Expander Process**

The compact LNG (cLNG) process similar to the SMR process except that pure nitrogen refrigerant is used.This process is operated under two pressure levels of nitrogen expansion to improve thermodynamic efficiency. To cool the nitrogen to a low-enough temperature to liquefy natural gas, the cLNG process uses both self-cooling and turbo expanders. The power generated from the turbo expander is recovered and used to recompress the refrigerant.

Table 5

Commonly Used LNG Liquefaction Processes

SN	PROCESS	DEVELOPERS	STC (MTPA)
1.	Phillips Optimized Cascade(POC)	Conoco Phillips	4−9
2.	PRICO	Black and Veatch Pritchard	0.1−2.1
3.	APCI Propane Precooled Mixed Refrigerant(C3MR)	APCI	0.5−6.1
4.	Shell and APCI dual Mixed Refrigerant	Shell and APCI	0.5−8.4
5.	IFP/Axens Liquefin	IFP/Axens	N/A
6.	Parallel Mixed Refrigerant(PMR)	Shell	6−9
7.	Gaz de France Integral Incorporated Cascade	Gaz de France	N/A
8.	APCI AP−X	APCI	5.8−9.0
9.	Statoil Linde Mixed Fluid Cascade(MFC)	Linde in collaboration with Statoil	4.0−6.6

(Weems, P. R., & Hwang, M. (2013). jwt016.)

STC: Single Train Capacity

3.4 Criteria For Liquefied Natural Gas (LNG) Process Selection

The success of a LNG project is crucially dependent on the processes selected for natural gas liquefaction. The following are the proposed a set of criteria for selecting appropriate processes, taking technical and economic aspects into consideration.

- Process Efficiency: This is related to the thermodynamic efficiency of the process and the efficiency of the equipment. Improving thermodynamic efficiency leads to a reduction in energy consumption and capital costs.
- Reliability
- Site conditions
- Safety
- Process requirements (NGL or LPG recovery)
- Train Capacity and thermal efficiency
- Hydrocarbon refrigerant storage
- Flexibility,simplicity of operation
- Ease of start up and shut down
- Availability of equipment
- Overall Space requirement
- Total Cost (Capital and Operating costs)

However, the priority of each factor will differ depending on the characteristics of the LNG project. In offshore plant projects, energy efficiency may be less important than safety, operability, and compactness compared to onshore projects.

3.5 LNG Transportation

Figure 30. **LNG Transportation**

- Pipelines are built to safely transport natural gas from well sites to storage, distribution and processing facilities where natural gas can be liquefied for export.
- LNG takes up to 600 times less space than regular natural gas, making it easier to store and transport.
- If spilled, LNG evaporates into the atmosphere, leaving no residue on either soil or water, No environmental clean-up is required.
- Large, specially designed, double hulled ships transport LNG overseas.
- Once it reaches its destination, LNG is unloaded from the ship into a plant that turns it back to natural gas for transportation to customers.
- LNG is used as an energy supply for industry, as fuel for heating, cooking and other domestic purposes, as an alternative fuel for the transportation sector and for a wide range of other purposes.

Figure 31. **LNG Receiving Terminals**

3.6 LNG Receiving Terminals

LNG receiving terminals often referred to as "regasification terminals" receive LNG carriers unload their LNG cargoes and store the LNG in tanks. In conventional receiving terminals facilities either onshore or offshore, the unloaded LNG is stored onshore in large tanks until gas is required by the end consumers.

- Regasification terminals have been operating in populated areas of the world for over 45 years
- Import terminal – Facility that has the capability of accepting and storing LNG from overseas. There are currently 12 terminals operating in the United States and one in Puerto Rico.
- Export terminal – Facility that has the capability to liquefy and store natural gas so it can be loaded on to ships and sent overseas.

3.7 LNG Storage Tanks

Figure 32. **LNG Storage Tanks**

LNG storage tank is a specialized type of storage tanks can be found in ground, above ground or in LNG carriers. The common characteristic of LNG Storage tanks is the ability to store LNG at the very low temperature of -162 °C (-260 °F). LNG storage tanks have double containers, where the inner contains LNG and the outer container contains insulation materials. The most common tank type is the full containment tank. Tanks vary greatly in size, depending on usage.

If LNG vapours are not released in LNG storage tanks, the pressure and temperature within the tank will continue to rise. LNG is a cryogen and is kept in its liquid state at very low temperatures. The temperature within the tank will remain constant if the pressure is kept constant by allowing the boil off gas to escape from the tank.

3.8 LNG Safety

Important factors to consider in LNG Safety include

- Fire Hazard Properties of LNG
- LNG Physical State Reaction
- Concentration in Air
- Low temperature of the LNG Fuel
- High Energy Content of the LNG Tank
- Experience in Handling LNG

There are possible hazards associated with LNG:

- Rapid Phase Transition (RPT): The sudden vaporization or phase transition from liquid to vapour that has occurred upon occasion when LNG has been spilled into water has caused a physical explosion. No injuries have occurred from an RPT of LNG but equipment has been damaged.
- Asphyxiation: For human death to occur from asphyxiation, the LNG vapours must reduce the normal oxygen concentration in the air (about 21%) to less than 6 %.Breathing is impaired when the oxygen level in the air is reduced to less than 15 % and vomiting occurs when the oxygen level is below 10%.
- Fire, deflagration or explosion if in confined space from ignited natural gas vaporising from spilled LNG.
- Vapour dispersion and remote flash fire
- LNG Leakages
- Frostbite from Liquid or cold vapour spills
- Overpressure of transfer systems caused by thermal expansion or vaporization of trapped LNG.
- Boiling Liquid Expanding Vapour Explosion (BLEVE) of a pressurized tank subjected to a fire.
- Tank over pressurization due to rollover effects.

Overall, the LNG industry has an excellent safety record. As of 2013, about 240 million tonnes of LNG were traded around the world and 350 carriers have completed more than 135,000 voyages, travelling more than 240 million kilometres at sea. Vessels are inspected once a year and with a full dry dock inspection every five years.

3.9 Economic Analysis of Large Scale LNG Liquefaction Plant

3.9.1 Typical Nigeria Liquefied Natural Gas (NLNG)

Nigeria LNG Limited was incorporated as a limited liability company on 17 May 1989, to produce LNG and Natural Gas Liquids (NGL) for export. The plant was built by TSKJ consortium, which was led by former Halliburton's subsidiary KBR. Other participants of the consortium were Snamprogetti,Technip and JGC Corporation.The first train came into operation in 1999.

Facilities

- Six LNG processing units (trains) with a total nameplate processing capacity of 22 MTPA.
- Diversified Gas Supply (Associated Gas & Non-Associated Gas) and six main dedicated gas transmission pipelines with four of them on-shore
- Four LNG storage tanks, each with a capacity of 84,200 cubic metres.
- A common fractionation plant to process LPG
- A common condensate stabilisation plant.
- Three Condensate storage tanks, each with a capacity of 36,000 cubic metres.
- Four LPG refrigerated storage tanks, each with a capacity of 65,000 cubic metres (2 each for propane & butane).
- 10 gas turbine electricity generators with a combined capacity of more than 320 MW
- Two LNG export jetties; one of which also exports LPG, and the other also exports Condensate, with a combined capacity of more than 400 loadings per year.
- 23 LNG ships dedicated to the service of NLNG

Shareholders

Nigeria LNG Limited is jointly owned in the following proportions: Nigerian National Petroleum Corporation (NNPC) owns 49%, Shell Gas B.V. owns 25.6%, Total LNG Nigeria Ltd owns 15% and Eni International owns 10.4%.

Operations

Nigeria LNG Limited operates six liquefaction units (LNG trains) producing 22 million metric tonnes of LNG per year (mmtpa).This amounts to roughly 10% of the world's LNG consumption.Trains 1, 2 and 3 have production capacities of 3.2 mmtpa, whilst trains 4, 5 and 6 have capacities of 4.1 mmtpa each.The final investment decision on the train 7 has not yet been made.

Financing

The base project (Trains 1 and 2) which cost US$3.6 billion, was financed by NLNG's shareholders. The third train (expansion project), including additional storage, cost US$1.8 billion and was funded by shareholders as well as reinvested revenue from the base project. The NLNGPlus project (Trains 4 & 5) cost US$2.2 billion and was funded with a combination of internally generated revenue and third party loans amounting to US$1.06 billion. Train 6 (NLNGSix project) cost US$1.748 billion, financing was handled by shareholders. The total cost of building six LNG trains was US$9.348 billion. (http://www.nlng.com/Our-Company/Pages/The Plants.aspx#sthash.oH9xPBhG.dpuf)

4 Methodology

An economic analysis of 6.0 million tonnes per annum (MTPA) LNG Liquefaction plant with an initial investment of $3.0 billion was undertaken using Monte Carlo simulation method in which uncertainties were revealed and respective impacts on economic feasibily and viability defined.A spreadsheet based economic model was utilized in this study to characterize the impact of uncertainties through Sensitivity Analysis as shown in Table 6.

The Monte Carlo simulation generates values of the key parameters such as Royalty, LNG Revenue, Total Operating Expenses, Feed cost, EBITDA, Total depreciation, Operating Earning (FOP Margin), Income Tax and Cash flow from operations corresponding to the economic measures such as Net Present Value (NPV), Internal Rate of Return (IRR), Profitability Index (PI), Present Value Ratio (PVR), Pay Back Time (PBT), Profit to Investment (PIR) under 1,000 simulations.

5 Results

5.1 Executive Summary

An implementation of a new LNG plant with 6.0 Million Tonnes per annum (MTPA) capacity.The financial scenario was planned to be $3.0 billion investment for operations for a period of twenty (20) years.

The LNG Plant projected revenue for 2016 is $1.8 billion from a Total Addressable Market (TAM) of XX.X.This implies to work on XX% of market share.From the 2016 forecast, the projected EBITDA will be $1.194 billion (66.31%) given an operating earnings of $1.044 billion (57.98%) from the revenue.The upcoming P/L impact of this LNG plant looks motivated for a Pull through revenue of additional derivative products under the same LNG Plant.

The financial model provided very optimistic results for the investment.A Net Present Value (NPV) of 6.072 billion dollars with an Internal Rate of Return (IRR) of 32.0% which is much bigger than the considered 10% of cost of capital with a moderate growth of 2% due to a commodity and Pay Back Peirod of 4.3 years seems a viable and healthy technology investment.

Table 6

MTPA LNG Project Financial Analysis

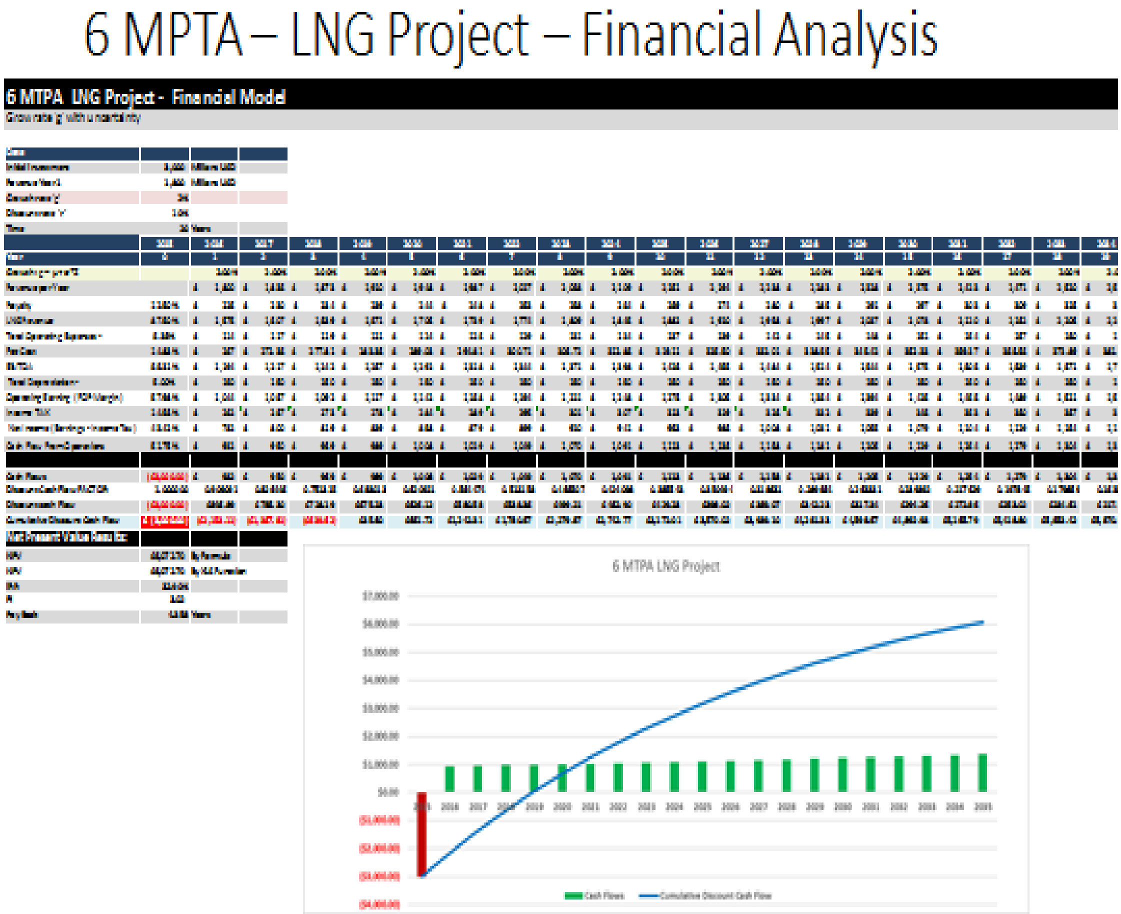


Table 7

Sensitivity Analysis of NPV, IRR and Payback Period (PBP)

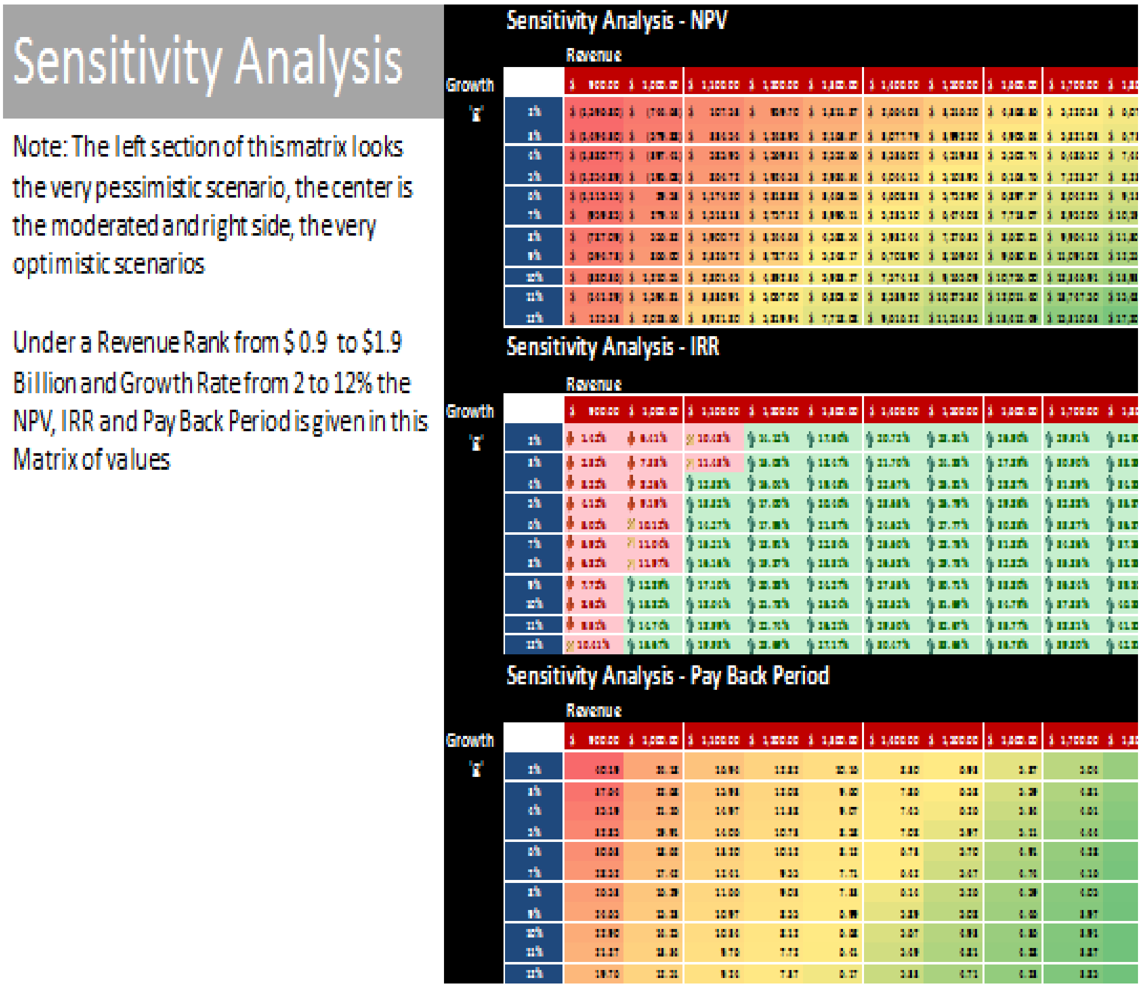


Table 8

Sensitivity Analysis of PVR and PIR

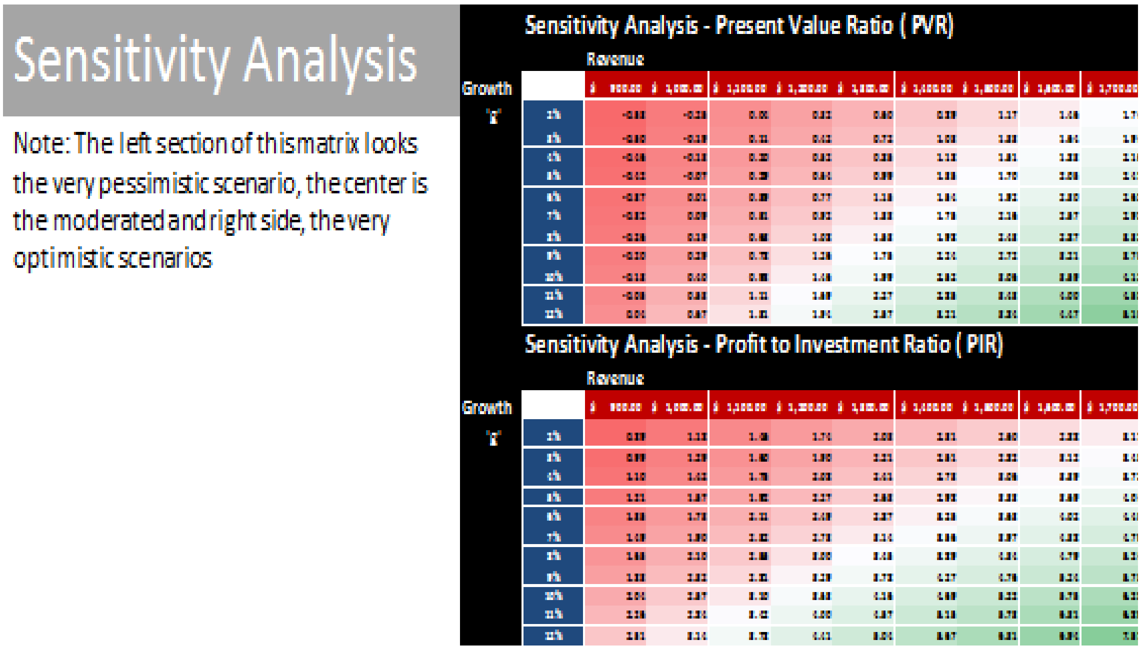


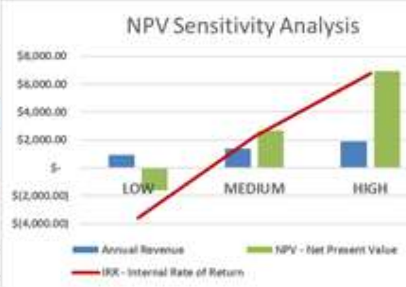
Table 9

Sensitivity Analysis Summary

6 MTPA LNG Project - Summary Table

Data			
Initial Investment	$ 3,000.00	Millions USD	
Revenue Year 1	$ 1,800.00	Millions USD	
Growth rate 'g'	2%		
Discount rate 'r'	10%		
Time	20	Years	
Net Present Value Results:			
NPV - Net Present Value	$6,072.70	Millions USD	
IRR - Internal Rate of Return	32.90%		
PI - Profitability Index	3.02		
Pay Back Period	4.36	Years	
PVR - Present Value Ratio	2.024		
PIR - Profit to Investment Ratio	3.45		

Sensitivity Analysis under 2% Growth	Lower	MEDIUM	Upper
Annual Revenue	$ 900.00	$ 1,400.00	$ 1,900.00
NPV - Net Present Value	($1,596.80)	$ 2,664.03	$ 6,924.86
IRR - Internal Rate of Return	1.42%	20.72%	35.86%
Pay Back Period (Years)	40.19	8.30	3.79
PVR - Present Value ratio	(0.53)	0.89	2.31
PIR - Profit to Investment Ratio	0.893	2.31	3.73



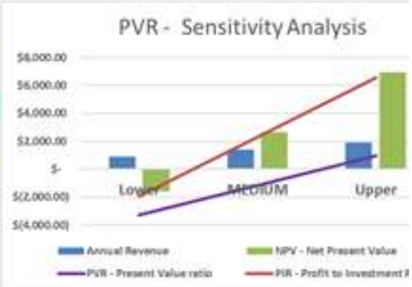


Table 10

Monte Carlo Simulation

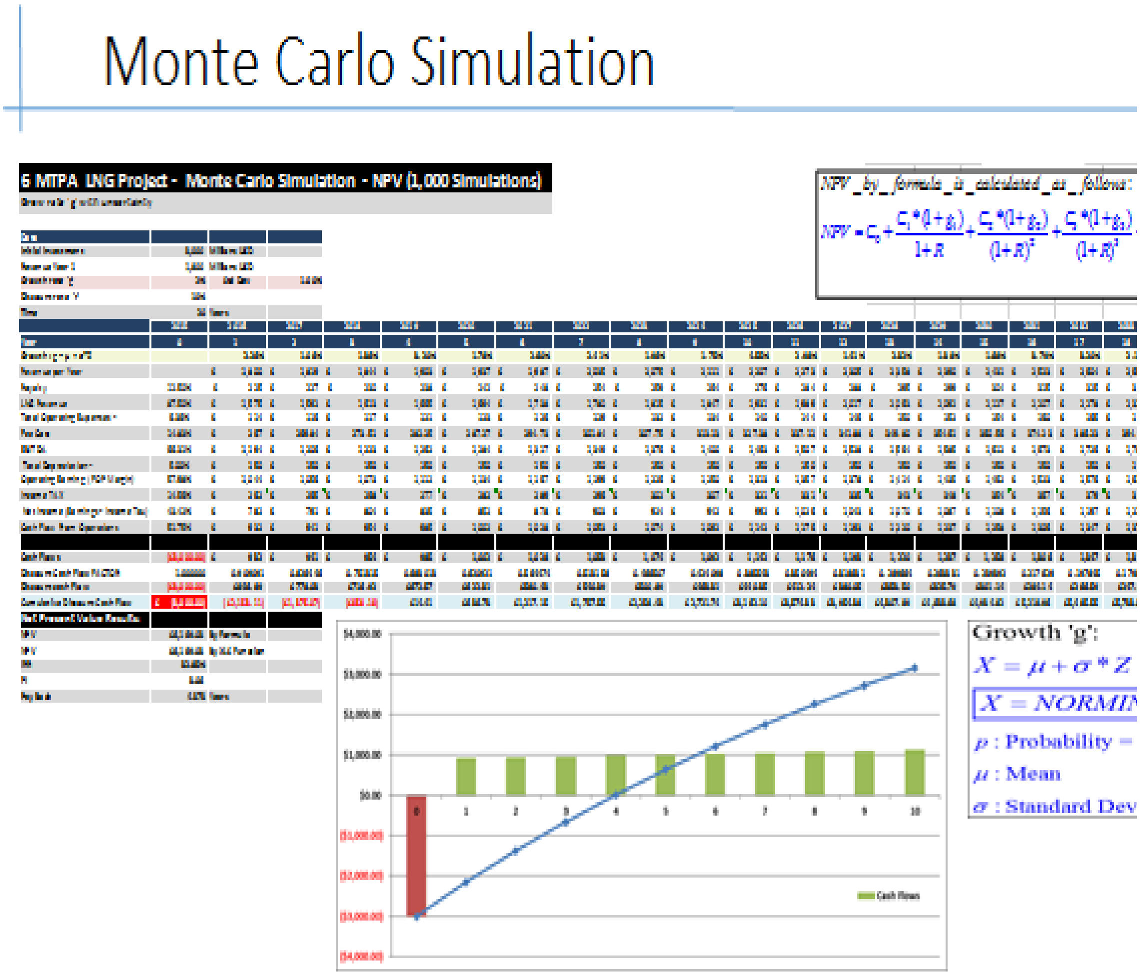
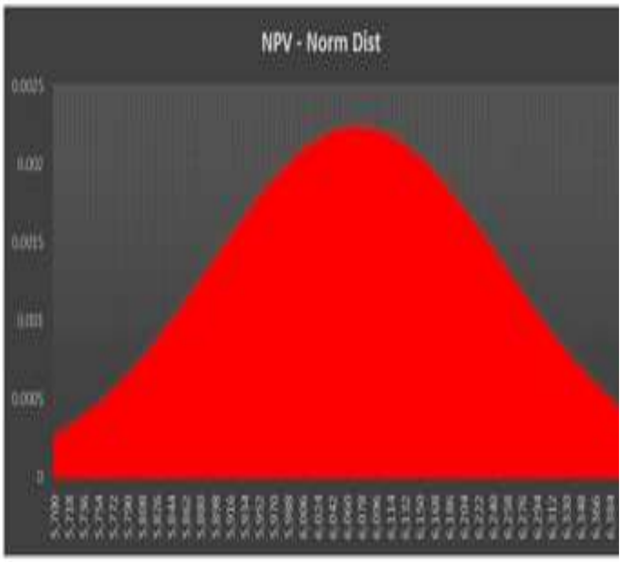


Table 11

Monte Carlo Simulation Results

Monte Carlo Simulation – NPV of the Project

NPV - Monte Carlo Simulation Results			
Number of Samples:		1,000	
NPV Mean	$	6,075.44	Millions
NPV - Standard Deviation	$	176.60	2.91%
Minimum	$	5,556.09	Millions
Maximum	$	6,647.37	Millions
5% Percentile	$	5,765.42	Millions



6 Analysis and Discussion of Result

The Sensitivity Analysis and Monte Carlo Simulation results with respect to the Net Present Value (NPV) and the Internal Rate of Return (IRR) will be considered and evaluated to enhance decision making.

The results in Table 6 shows an initial investment of $3.0 billion with a revenue per year of $1.8 billion at a growth rate (g) 2% and discount rate (r) of 10% within the period of 20 years (2015−2035).

From the 2016 forecast, the projected EBITDA is $1.194 billion (66.31%) given an operating earnings of $1.044 billion (57.98%) from the revenue and a feed cost of $267 million (14.83%) while the LNG revenue remains $1.575 billion (87.50%).

In the next 20 years (2035), the projected EBITDA is $1.739 billion at an operating earnings of $1.589 billion resulting to about 45.64% increment.

Similarly, the Royalty is $225 million (12.50%), LNG value is $1.575 billion (87.50%), total Operating expenses is $114 million (6.36%), cash flow from operations is $932 million (51.75%) while the total depreciation value remains constant for the period of 20 years at $150 million (5.0%).

The financial analysis model in Table 9 provides optimistic values for the planned LNG project investment.A Net Present Value (NPV) of $6.072 billion with an Internal Rate of Return (IRR) of 32.90% which is much bigger than the considered 10% of cost of capital with a moderate growth of 2% and Pay Back Period of 4.36 years coupled with Profitability Index (PI) of 3.02, Present Value Ratio (PVR) of 2.024 and Profit to Investment Ratio (PIR) of 3.45 is a viable, feasible and worthy investment.

Furthermore, The Sensitivity Analysis under 2% growth rate shows a lower, medium, and upper value at an annual revenue of $900.0 million (lower), $1.4 billion (medium) and $1.9 billion(upper).

NPV ($1.596 billion), IRR (1.42%), PBP (years) of 40.19, PVR of (0.53) and Profit to Investment Ratio of 0.893 were obtained at the lower annual revenue of $900.0 million.

Likewise, NPV ($2.664 billion), IRR (20.72%), PBP (years) of 8.30, PVR of (0.89) and PIR (2.31) were the results obtained at medium annual revenue ($1.4 billion).

Lastly, NPV ($6.924 billion), IRR (35.86%), PBP (years) of 3.79, PVR of (2.31) and PIR (3.73) were observed and recorded at the upper annual revenue ($1.9 billion).

The NPV and PVR Sensitivity Analysis graph were shown in Table 9.

The NPV Sensitivity Analysis shows a graph in which the annual revenue is represented by **blue** colour while the Net Present Value (NPV) and Internal Rate of Return (IRR) are represented by **green** and **red** colour respectively.

It should be noted that at the medium level ($1.4 billion), the annual revenue was at about 18% while the NPV was at about 21% with a slight difference of 3% but there was significance increment at the high level ($1.9 billion) with the annual revenue at 20% and the NPV was at about 37% resulting to 17% difference while the Internal Rate of Return (IRR) increases from 20% at the medium level and reached the peak of 37% at the high level.

The PVR Sensitivity Analysis included the Present Value Ratio (PVR) value represented by the **purple** colour on the graph as shown in Table 9 in addition to the AR, NPV and IRR.

At the medium value ($1.4 billion), PVR was 2.52 while the PIR was 4.69 at the discount rate (r) of 10% while the values of PVR and PIR at the high value ($1.9 billion) were 5.18 and 7.34 respectively.

In Table 7, it should be noted that the left section of the matrix looks the very pessimistic scenario in which the centre is of moderate value and the right section is the very optimistic scenario.

Under a revenue rank from $0.9 billion to $1.9 billion and growth rate (g) from 2% to 12%, keeping the discount rate (r) at 10%, the NPV, IRR and Pay Back Period values are shown.

Similarly, Table 8 shows the PVR and PIR values in which the left section of the matrix looks the very pessimistic scenario in which the centre is of moderate value and the right section is the very optimistic scenario.

Table 10 shows the results of the Monte Carlo Simulation under 1,000 interactions with the initial investment of $3.0 billion and projected revenue per year of $1.8 billion at a growth rate (g) 2% and discount rate (r) of 10% for operations for the period of 20 years (2015−2035),taking the standard deviation to be 1.00%,the NPV value is $6.169 billion by formula and XLS function,the IRR value of 32.85% was obtained while the Profitability Index (PI) is 3.06 and the Pay Back Period (PBP) is 4.373 years.

Under 1,000 simulations, the model came up with a Net Present Value (NPV) value of $6.075 billion from 20 years investment with a standard deviation of 2.91% or $0.176 billion which is a very stable and safe investment.

Table 11 shows the value of the NPV mean ($6.075 billion), NPV ($176.60 million) at standard deviation (2.91%), minimum ($5.556 billion), maximum ($6.647 billion) and ($5.765 billion) was obtained at the 5% percentile.

The following factors should be noted.

- $1.0 billion is equivalent to $1,000 million.
- Internal Rate of Return (IRR) that is higher than the cost of capital is fine.
- Pay Back Period (PBP) is the length of time required to recover the cost of an investment.
- Present Value Ratio (PVR) is the ratio of the NPV to the Present Value of Cost.

  While NPV fails to deliver a measure of capital efficiency, the PVR index calculates a measure of investment efficiency that is very useful in projects with significant capital investment. It is the ratio of the discounted (usually after tax) net cash generated by a project to the discounted pre−tax cash outlays or investment.
- Profit to Investment Ratio (PIR) is the ratio of the Net Operating Income to the cost of an investment.
- Net Income is the difference between the operating earnings and the Income Tax.

The cash flow spread sheet as shown in Table 6 model result for 6.0 MTPA LNG plant and Table 9 shows the computation of the economic measures (NPV, IRR, PI, PBP, PVR and PIR).The cash flow model result showed positive and encouraging outcomes about the profitability of the LNG project.

It resulted in a positive and large NPV after tax of $6.072 billion at a discount rate of 10%.The decision rule is to accept all projects with positive NPV values.

The discount factor is assumed to take care of inflation and some uncertainty in the time value of money. The undiscounted cumulative profit to investment ratio is 3.45.This implies that the profit is 3.45 times as huge as the initial investment and it is a good ratio for an investment without considering the time value of money.

The Present Value Ratio (PVR) evaluates the effects of inflation rate and other uncertainty in the investment. It also helps to quantify the size of the investment. The decision rule is to accept investment with positive PVR.

As shown in Table 9, the value of PVR is 2.024 at a discount factor of 10%.

Similarly, an Internal Rate of Return of 32.90% was obtained which is quite impressive as it is above the standard hurdle rate for investors in Nigeria.

Internal Rate of Return (IRR) takes care of factor such as high volatility of currency and exchange rate. This connotes that inflation rate will hardly affect the profitability of the venture.

7 Conclusion

Liquefied natural gas (LNG) is attracting great interest as a clean energy alternative to other fossil fuels due to its ease of transportation and low carbon dioxide emissions which contributes to air pollution and global warming. Liquefied Natural Gas liquefaction plants have been constructed on a global scale to meet the incessant demand for LNG.

Besides, to achieve greater capacity, more complex refrigeration cycle designs that combine two or more different conventional single refrigeration cycles are being developed to obtain higher yield effects in the liquefaction process to maximize efficiency and achieve greater capacity and single train capacity has been increased to strengthen price demand. Likewise,studies are aimed on designing efficient processes for offshore and small-scale plants to improve profitability. LNG plants are recognized to be energy efficient and cost effective as they require a large amount of power for the processes of compression and refrigeration, and need special equipment such as cryogenic heat exchangers, compressors, and drivers. Therefore, the major challenges in the LNG industry is to improve the efficiency of the current natural gas liquefaction processes in combination with cost savings.

A positive Net Present Value (NPV), Profitability Index (PI) greater than 1 and good IRR values that is greater than the cost of capital and Payback period of less than 5 years showed that LNG Liquefaction is profitable and good investment in Nigeria.

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