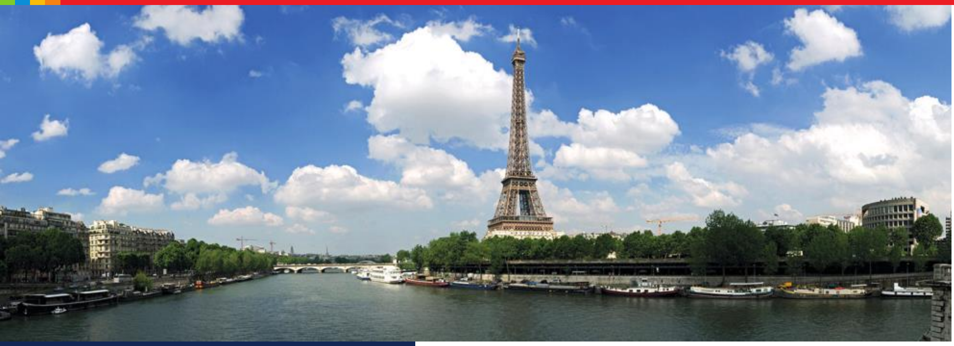
2012-2015 Triennium Work Reports

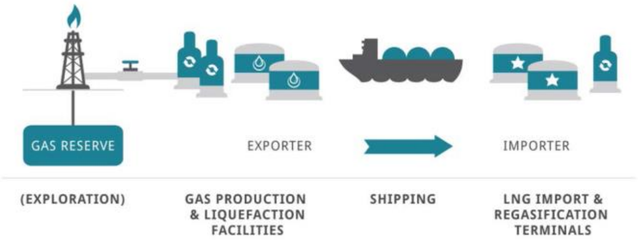


Life Cycle Assessment of LNG

International Gas Union

Programme Committee D Study Group 4

June 2015



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Executive Summary

This report supports the Four Pillars of Natural Gas articulated for the 2012-2015 IGU Triennium:

- Pillar 1: Human resources for the future
- Pillar 2: Natural Gas available everywhere
- Pillar 3: Natural Gas for a sustainable development
- Pillar 4: Combination with renewables and Electricity.

This work, and IGU's emphasis on LNG generally, are particularly supportive of Pillars 2, 3, and 4. LNG has a long history in the world energy picture beginning in the 1960s. Today, the world players in the international market comprised of a diverse set of national oil companies (NOCs), multinational major and "supermajor" oil and gas companies, and consortia of companies including producers and large consumers of natural gas. The international industry is composed of upstream, midstream, and downstream business segments supported by a strong services infrastructure. The LNG value chain, in its traditional form, includes liquefaction, marine transport, regasification, and natural gas distribution and consumption, with particular focus on power generation.

LNG exhibits comparative economic advantages to pipeline supplies of natural gas over long distances and comparative environmental advantages relative to competing power generation primary fuels such as coal. Throughout its history, LNG has demonstrated an exemplary safety record and continually strives to maintain the highest levels of safety in operations.

Life cycle assessment (LCA) is formally defined within the set of International Standards Organization (ISO) standards as follows:

> "LCA studies the environmental impacts and potential impacts throughout a product's life (i.e., cradle to grave) from raw material acquisition through production, use, and disposal. The general categories of environmental impacts needing consideration include resource use, human health, and ecological consequences."[1]

The benefits of LCA are to better understand the environmental impact of a product and its effect in each step of the value chain and to be able to show the competitive advantages of a specified product system over another, competing or substitute product system. Several key LCAs have been developed in recent years covering the general LNG value chain. A recently-completed study by Pace Global (a Siemens Company) under sponsorship from the Center for LNG (CLNG) provides valuable insights in comparing various configurations of the LNG value chain to coal when the two primary energy forms compete in supplying the power generation market. This study provides a detailed summary of this recent analysis.

A more general need for continuing LCA studies covering LNG is the requirement for broad and detailed data covering these various configurations of LNG projects. Development of ISO-compliant life cycle inventory (LCI) data for analysis and ultimate use in LCAs is a key objective of this study and should remain a focus for the immediate future. This study's

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[1] International Standards Organization, "Environmental Management – Life Cycle Assessment – Principles and Framework," ISO 14040, 1997.

efforts are characterised in terms of the ISO objectives and scope requirements covering range of application, interest of realisation, target groups, accessibility for public use, and technical system boundaries.

The objective of this study is to develop LCI data useful for supporting analysis and LCAs covering major "modular" operations of the medium- to large-scale international trade in LNG from receipt of natural gas at liquefaction facilities, gas pre-treatment and liquefaction, shipment of LNG via marine carrier and receipt at regasification ("regas") receiving terminal facilities, regasification at those facilities, and delivery to the natural gas pipeline system leaving the liquefaction facility. The technical approach covers four modules for liquefaction processes, five power generation for compression serving liquefaction, four marine carrier designs, and five receiving terminal technologies.

LCI data is presented in detailed data tables in an appendix to the report. An illustrative example of these tables is provided in Part Two of the report. Conclusions and recommendations arising from the study are provided, emphasizing the need for further data development on emissions and greater transparency of emissions characteristics for alternative technologies available to projects. From these conclusions and recommendations, alternative energy forms can be compared with LNG, and technology development pathways for improved environmental performance within the LNG chain can be targeted.

1. Introduction

This report presents the work of International Gas Union (IGU) Study Group D.4, “Life Cycle Assessment of Liquefied Natural Gas (LNG) for the 2012-2015 IGU Triennium. The report is divided into two main sections:

- Part One covers background information on LNG, life cycle assessment (LCA), and related topics.
- Part Two covers specific work of the Study Group, including development of life cycle inventory (LCI) data as a tool for supporting LCA for medium- to large-scale LNG trade operations and markets.

Detailed LCI data is provided in Appendix A of the report and is published for general use of practitioners, IGU members, and others to support LNG chain- and trade-specific LCA studies.

2. Acknowledgements

The Study Group wishes to thank several individuals and organizations for their substantial contributions to the overall study and sections of this report. To William Cooper, past Executive Director of the Center for LNG (CLNG) and Paul Sibal of Exxon/Mobil and chairman of the CLNG Technical Committee, the Study Group extends its thanks for supporting the efforts of Pace Global (a Siemens Company) for its development of detailed data and analysis in parallel and cooperation with the Study Group’s efforts. CLNG’s willingness to support the work of Pace Global and coordinate its technical scope of work with the “modular” LNG chain approach described in this study has been instrumental in the completion of the Study Group work.

To the Pace Global team of Dr. Jay Balasubramanian, Bijan Patala, Joanna Martin, and Robert Linden, the Study Group extends its thanks for their high-quality and timely technical analysis under its contract with CLNG and for making extraordinary efforts to coordinate its work with those of the Study Group. The Pace Global work, published separately from this report, serves as an extremely valuable resource for comparisons of LNG life cycle impacts with those of competing forms of primary energy.

The Study Group would also like to extend its gratitude to Dr. Knut Maråk of Statoil who provided calculations of LNG chain air emissions compatible with this study’s modular approach and consistent with the Pace Global study approach. His willingness to take on this analytical work greatly contributed to the data development for this study and benefits IGU by expanding the technical contributions to the subject of LNG LCA generally.

The Study Group would also like to recognize three contributing authors of the Part One report sections, Bayan Taha, Fawaz Al-Mejlad, and Fatma Al-Naimi of Qatargas. Their contributions late in the project were extremely valuable in completing the report.

Finally, the Study Group would like to acknowledge the contributions of Calogero Migliore of Repsol, Jupiter Ramirez of Anadarko, and Rob Klein Nagelvoort, LNG Technical Consultant who had to leave the Study Group due to assignment of other responsibilities but who contributed to the project development and report review.

3. Part One: Background

a. IGU and the Four Pillars of Natural Gas

The main role of IGU (International Gas Union) is to advocate for Natural Gas as an integral part of a sustainable global energy system. This is done through promoting all the Natural Gas related developments in the energy sector.

As part of IGU's efforts in advocating for Gas, 4 pillars have been identified to focus on:

- Human resources for the future
- Natural gas available everywhere
- Natural gas for a sustainable development
- Combination with renewables and electricity.

i. Natural gas available everywhere

Pillar 2 focuses on ensuring access to natural gas everywhere, which includes a focus on LNG as an effective, reliable, and clean means of delivering energy to remote consuming areas. The main advantages of the use of LNG are:

- Ability of gas monetization from remote areas
- The possibility of supply to for from regions where pipeline transportation is impossible or ineffective
- The effectiveness of transport over long distances
- Flexibility of destination and volumes of gas supplies.

ii. Natural gas for a sustainable development

Pillar 3 focuses on the contribution of Natural Gas to a more sustainable world. With its low carbon emissions compared to other available fossil fuels, Natural Gas provides a solution to the world's economic and environmental challenges in a secure and sustainable manner.
It is the fuel of choice for energy efficiency, and is the cleanest of all hydrocarbons:

- When burnt for heating homes or for industrial uses, it releases 25-30% less CO2 than oil and 40-50% less than coal per unit of energy produced.
- When burnt to generate electricity, it releases around 60% less than coal for every kWh sent out.
- Natural gas also produces small amounts of nitrogen oxides, sulphur dioxide or particulates.

However, with a broadening of the resource base and the development of unconventional sources such as shale, etc. the sustainability of Natural Gas is again being questioned, which makes such studies more relevant than ever.

iii. Combination with renewables and electricity

Pillar 4 focuses on how natural gas enables renewable energy sources (RES) due to its flexibility. Natural gas generation can be switched on and off relatively quickly, making natural gas-fired generation the fuel of choice to accommodate sudden changes in electricity demand or supply. This is especially important in countries with wind and solar energy as major components of their energy mix, which are intermittent renewable sources.

b. Liquefied Natural Gas (LNG) and Its Role in World Energy

i. The Origins of LNG

The term LNG refers to Liquefied Natural Gas, which is Natural Gas that cooled down and converted into a liquid state. This is done to facilitate the process of transportation, and to be able to deliver larger quantities.

The foundations of today's LNG industry lie well in the past. The discovery of LNG was initiated by experiments done by a British scientist named Michael Faraday early in the 19th century, and the first practical compressor refrigeration machine was built in 1873 by a German engineer named Karl Von Linde, in Munich. In 1912. The first LNG plant was built in West Virginia in the U. S. and started operating in 1917. The first commercial liquefaction plant was built in Cleveland, Ohio in 1941, and In 1959, the world's first LNG tanker, "Methane Pioneer" delivered a cargo from Lake Charles, Louisiana, to Canvey Island, U.K.

A plant in Arzew, Algeria as the first to make commercial shipments, sending LNG to the U.K. in 1964. The plant at Arzew had a total nameplate capacity of around 0.89 million tonnes of LNG per annum (MTPA). Today, LNG facilities are up to 30 times larger, supported by improvements in technologies and infrastructure.

From 1969 until today, Japan has been the largest LNG market. Japan's first LNG cargoes were supplied from the Kenai, Alaska plant in the U.S.

The demand for LNG has grown rapidly since the 1980's, mainly due to:

- Flexibility of destination and volumes of gas supplies
- Supply to regions where pipeline supply is inefficient or impossible
- Environmental advantages over other fossil fuels, and
- Price competitiveness and efficiency.

Since 2008, Qatar has been the largest LNG exporter in the world with a total of LNG production of 77 MTPA.

ii. The World LNG Players

Global LNG supply dynamics are changing rapidly with the evolvement of the industry. This partly is because of technological advances that the latest LNG trains production units within an LNG plant are nearly 30 times the size of the first ones, constructed in the 1960s in Algeria. LNG ship size is also increasing, generating additional economies of scale. Many of the technological increases have occurred in Qatar, which has made the most eye catching additions to global LNG supply, rapidly building its capacity to a world leading 77 million tonnes a year in 2011.

In the future, all of the LNG liquefaction projects that are currently under construction in Australia are expected to be completed and, therefore, Qatar may be overtaken by Australia as the largest exporting country. Further supply growth can materialize from a few other countries such as Mozambique and Tanzania in east Africa and the U.S. and Canada in North America.

According to the International Energy Agency, global gas liquefaction capacity amounts are over 280 million tonnes a year, about a third more than five years ago, when it was 208 million tonnes a year.

According to BP Energy Outlook 2035 share of gas in primary energy consumption will increase. Moreover the flexibility and integration of the global gas market continues to increase due to rapidly growing LNG trade: LNG's share of traded gas rises to above 46% by 2035.

Taking into account these projections, as well as the further development of LNG technologies we can conclude on potential reduction emissions and the impact on the environment.

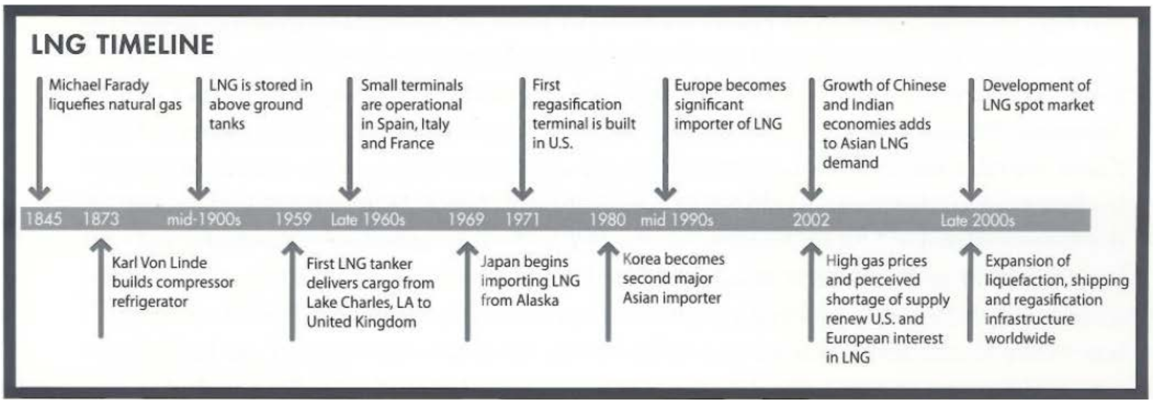


Figure 1 - LNG Industry Timeline

Traditional International LNG trade is mainly trades done through long term sales and purchase agreements. This is to ensure security of outlet and revenue to LNG producers who are looking to make an investment in a liquefaction plant. There are different types of LNG producers/exporters including national oil companies (NOCs), international oil companies (IOCs), and joint ventures.

Other types of trade include spot and short term trades that come from uncommitted volumes or optimized long term contracts. Recently, reloads has picked up mainly in Europe due to excess supply in the region.

In terms of pricing, long term volumes prices are typically oil linked and when applicable a hub indexation is applied (i.e.: the U.K. market). However, recently we have been seeing some hybrid formulas that include oil and hub indexation at the same time.

iii. LNG Industry Schematics

The LNG industry operates through a supply chain that comprises of three main components; Upstream, Midstream, and Downstream. An additional attribute that contributes to the flow of the LNG supply chain are services offered by third parties to facilitate the process.

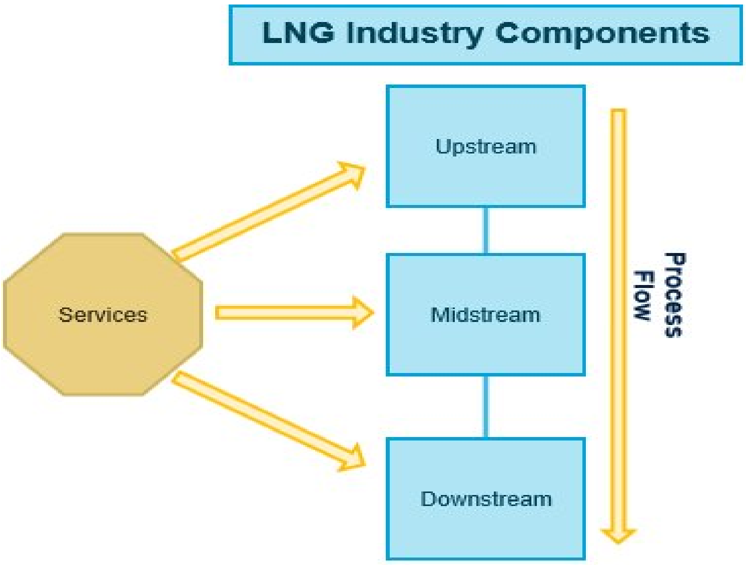


Figure 2 - Overview of LNG Value Chain Segments

Upstream

Upstream activities comprise of the exploration and production of Natural Gas to feed the liquefaction process. The discovery and drilling for Natural Gas are done by major international players in the energy sector who can also subcontract to service companies.

Midstream (sometimes included in Downstream)

LNG shipping and logistics of delivery are administrated in this stage. The main method of LNG transportation method at this level is LNG vessels that come in different classes with different volumes capacity (conventional, Q-Flex, and Q-Max carriers). Depending on the type of LNG agreement, LNG delivery can either be Free on Board (FOB) shipping method, where the seller's responsibility to deliver terminates at their premises once the vessel is loaded or delivery ex-ship (DES) where the seller is responsible to deliver to the buyer's regasification Terminal.

Downstream

Once the LNG is delivered to the buyer, it has reached the downstream level. At this stage the LNG is regasified at the receiving terminal to its original state and then distributed to customers that will distribute it to the end-users.

Services

During the lifecycle of LNG production and distribution, certain services are required to ensure that the process runs smoothly. These services include support to the process (e.g., products, machinery), maintenance and technology support, which contributes to the reliability and sustainability of the process.

iv. The LNG Value Chain

The supply chain includes all the facility and equipment involved in extracting natural gas from underground reservoir, liquefying it, and transporting it to the end user. The supply chain is typically long in terms of distance and expensive in terms of the capital cost of equipment and facility involved. The components of the supply chain typically include:

- Gas field production infrastructure
- Feed gas pipeline to the gas processing plant
- A large scale refrigeration plant involving heat exchangers to liquefy the feed gas
- LNG storage and port loading facilities (everything must kept cold)
- LNG marine tankers
- LNG receiving terminal including port loading, LNG storage, regasification, and gas send out compression facilities
- Connection to Natural Gas transmission and distribution network to deliver gas to customers
- Sometimes, distribution of LNG by truck to small, remote off grid gas customers.

The LNG value chain starts with the liquefaction process of Natural Gas, followed by shipping it to different markets using an LNG carrier. Once the LNG reaches the target market, it is regasified back to the original state and consumed in the power industry, or distributed as Natural Gas.

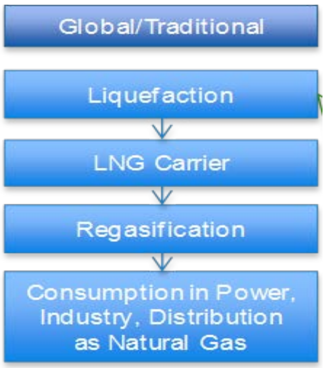


Figure 3 - The LNG Value Chain for Globally Traded LNG
Source: International Gas Union

Liquefaction

Land based liquefaction facilities are the most common in the LNG industry. They are onshore facilities that liquefy natural gas (feed gas) produced either onshore or offshore (transmitted through pipelines to the onshore facility in the case of offshore production). Locating the LNG production facilities offshore provides the liquefaction "onsite" at offshore production fields of natural gas, gives the possibility of economic development of smaller natural gas fields and fields remote to pipeline infrastructure (i.e., "stranded gas"), potential monetization of associated gas previously flared or reinjected, and may address onshore restrictions of land use for onshore facilities.

Transport

The process of transporting Natural Gas has become more efficient throughout the years. Qatar, with the help of Samsung, Hyundai, and Daewoo advanced technologies, managed to obtain a fleet of larger LNG volume carriers, known as Q-Fleet vessels. The conventional carrier size today has increased substantially to 145,000 cubic meters (m^3) of LNG cargo capacity as compared to the first Algerian commercial LNG carrier in 1964, with a capacity of just 27,400 m^3. With the creation of Q-Flex and Q-Max vessels, the maximum vessel capacity was again raised to a range of 210,000 to 260,000 m^3. The Q-Max is 80% larger than a conventional vessel and consumes 40% less energy per cargo-ton mile (see table below).

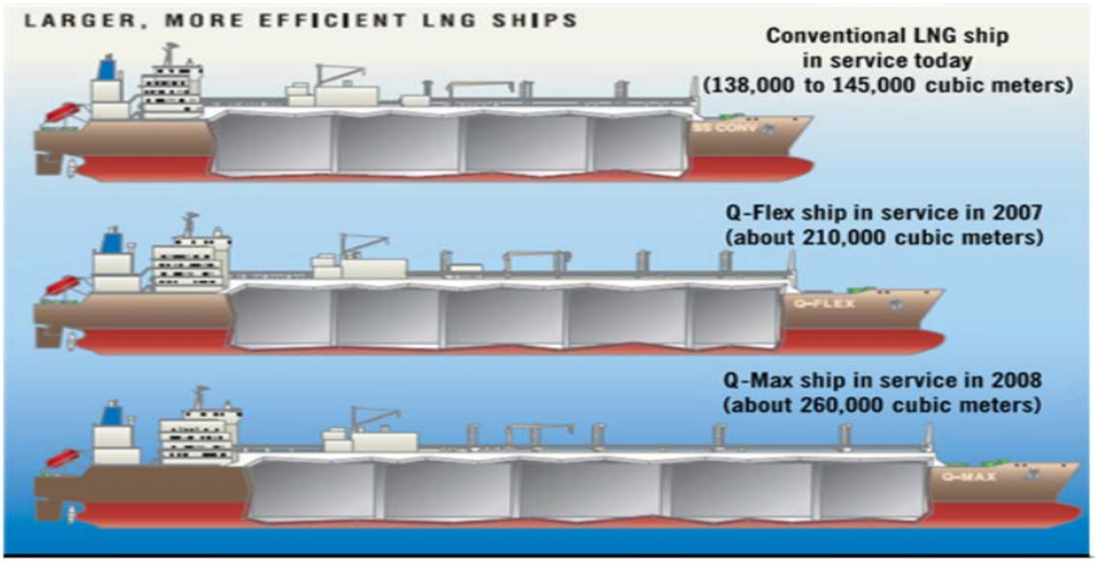
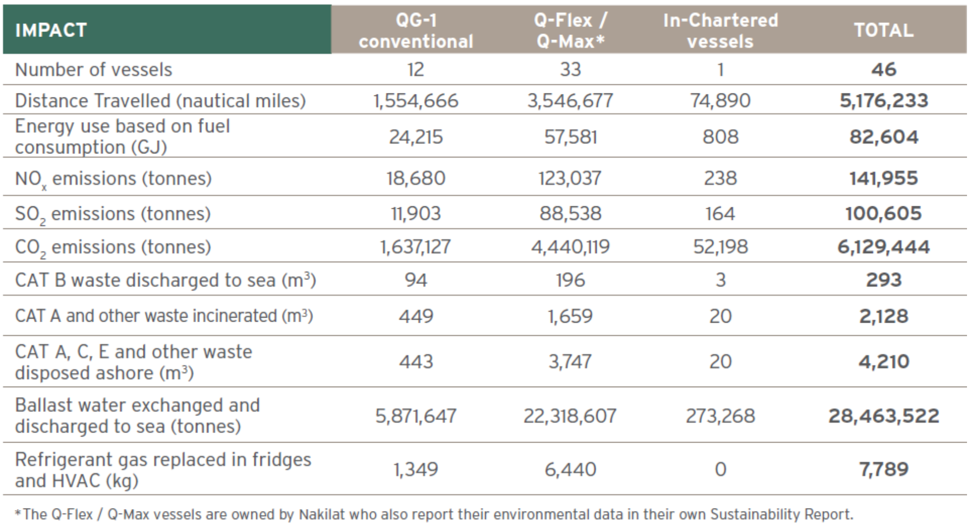


Figure 4 - LNG Marine Carriers
Source: International Human Resources Development Corporation

Table 1 - LNG Carrier Activity



IMPACT	QG-1 conventional	Q-Flex / Q-Max*	In-Chartered vessels	TOTAL
Number of vessels	12	33	1	**46**
Distance Travelled (nautical miles)	1,554,666	3,546,677	74,890	**5,176,233**
Energy use based on fuel consumption (GJ)	24,215	57,581	808	**82,604**
NO_x emissions (tonnes)	18,680	123,037	238	**141,955**
SO_2 emissions (tonnes)	11,903	88,538	164	**100,605**
CO_2 emissions (tonnes)	1,637,127	4,440,119	52,198	**6,129,444**
CAT B waste discharged to sea (m^3)	94	196	3	**293**
CAT A and other waste incinerated (m^3)	449	1,659	20	**2,128**
CAT A, C, E and other waste disposed ashore (m^3)	443	3,747	20	**4,210**
Ballast water exchanged and discharged to sea (tonnes)	5,871,647	22,318,607	273,268	**28,463,522**
Refrigerant gas replaced in fridges and HVAC (kg)	1,349	6,440	0	**7,789**

*The Q-Flex / Q-Max vessels are owned by Nakilat who also report their environmental data in their own Sustainability Report.

Source: Qatargas

The improvement in LNG shipping safety standards was recently recognized by the Green award foundation, which recently launched a certification scheme for LNG carriers worldwide. The Green Award for LNG carriers comes from the Green Award scheme, established in 1994, in order to promote quality shipping amongst sea-going vessels. All over the world the Green Award certifies ships, ship managers and oil companies that prove their dedication to high quality, safety and environmental standards.

Regasification

Regasification plants are typically located at the offloading terminals where LNG is pressurized back into its gaseous state for distribution into the send-out pipelines.
There are four types of regasification technologies (vaporizers) that will be discussed in detail in Part Two of this paper:

1- Submerged Combustion
2- Open Rack-Seawater
3- Air heater, closed loop glycol/water
4- Air Heater, open loop water.

v. LNG and Its Comparative Economic Advantages

LNG is quickly gaining market share at the expense of other hydrocarbon resources, while coal fights back, renewable fuels support the change of energy mix, and nuclear shows signs of life. Expectations for the potential of renewable fuels associated technologies are often overstated, and reducing coal's environmental impact is not small undertaking.

Growing interest for LNG supply is caused by increased energy demand and the need for diversification and security of supply. LNG provides flexibility in procurement similar to traded oil because buyers can, individually or jointly, contract, buy, and transport LNG from several suppliers. In addition, LNG is more attractive because LNG prices are more competitive than natural gas transported by pipeline. The LNG industry allowed the process of transporting natural gas to become more efficient. As the graph below shows, at a certain distance, using an LNG carrier is more efficient than a pipeline.

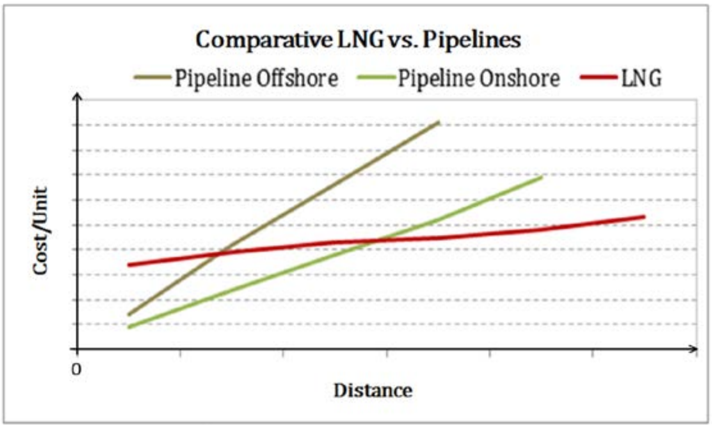
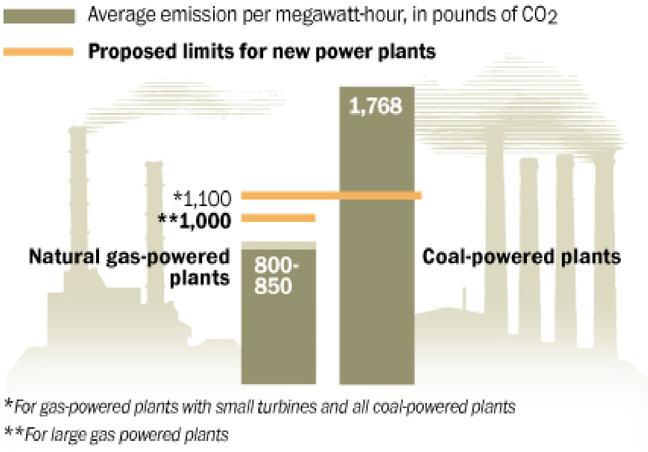


Figure 5 - Comparison of LNG versus Pipeline Transport of Natural Gas
Source: Institute of Gas Technology.

vi. LNG and Its Comparative Environmental Advantages

The demand for LNG has grown rapidly since the 1980’s, mainly because of its environmental advantages over other fossil fuels, in addition to its price competitiveness, and efficiency. In power generation, Coal has been always the traditional source due to its availability, cost, and simplicity for use. With the emergence of oil, suppliers and buyers favor oil because of its natural state. Oil, being liquid form under ambient temperatures and pressures, helps users and suppliers to ship it and store it easily. With the discovery of Natural Gas, it became a highly demanded source of energy because it is considered relatively cheaper and cleaner than other fossil fuels. According to The U.S. Energy Information Administration (EIA), power plants in 2002 needed 10,314 British thermal units (Btu) from coal or 10,641 from petroleum to generate 1 kilowatt-hour (kWh) of energy. In terms of Natural Gas, in the past, power plants needed 9,533 Btu to generate a kWh. However, with the rapid technology developments the LNG industry, power plants were able to increase their efficiency by using 8,039 Btu to generate 1 kWh in 2012. On the other hand, petroleum and coal plants are becoming less efficient, using 10,991 and 10,498 Btu to generate 1 kWh. (source: http://www.eia.gov/electricity/annual/html/epa_08_01.html)



*For gas-powered plants with small turbines and all coal-powered plants
**For large gas powered plants

Figure 6 - Comparison of Carbon Dioxide Emissions, Coal vs Natural Gas in Power Plants
Source: The Washington Post

Compared with other fossil fuels, LNG is considered the cleanest and most environmentally friendly fuel, with less emissions of carbon dioxide (CO_2), sulphur dioxide (SO_2), methane (CH_4), and nitrogen dioxide (N_2O) emissions as shown in the tables below.

Table 2 - Comparison of Overall Greenhouse Gas Emissions: Coal versus Natural Gas in Power Plants

Greenhouse Gases Emissions

lbs/MWh	Coal	Natural Gas	Δ of Emission
CO2	2200	861.1	61%
CH4	0.2523	0.0168	93%
SO2	18.75	0.0043	100%
N2O	0.0367	0.0017	95%

Source: Energy Information Administration, U. S. Department of Energy.

vii. LNG Safety

The LNG industry has an excellent safety record, as a result of several factors. First the industry has been developed to ensure safe and secure operations, from engineering to technical competency of personnel. Second, the physical; and chemical properties of LNG are well understood and the plants designs are well proven through many years of operation. Third, the standards, codes, and regulations that have been developed for the LNG industry ensure safety and are continuously evolving and improving.

LNG facilities can be located above ground. Operators and owners have many more opportunities for locating LNG facilities in comparison with traditional underground gas storage alternatives that depends on underground geological conditions such as depleted tanks, aquifers, and salt caverns.

LNG has an excellent safety record, due to strict industrial safety standards applied worldwide. Up to 2012 there have been some 50,000 LNG carrier trips, without a significant accident or safety problem, either at port or on the high seas.

c. Life Cycle Assessment (LCA) and LNG

i. LCA Defined:

Formally defined by the International Standards Organization (ISO), life cycle assessment is the "compilation and evaluation of inputs, outputs and the potential environmental impacts of a product system throughout its life cycle."[2] A more complete definition is provided in an earlier version of the governing standard (ISO 14040):

> "LCA studies the environmental impacts and potential impacts throughout a product's life (i.e., cradle to grave) from raw material acquisition through production, use, and disposal. The general categories of environmental impacts needing consideration include resource use, human health, and ecological consequences."[3]

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[2] International Standards Organization, "Environmental Management – Life Cycle Assessment – Principles and Framework," ISO 14040, 2006, p. 4.

[3] International Standards Organization, "Environmental Management – Life Cycle Assessment – Principles and Framework," ISO 14040, 1997.

Current international standardization of LCA methods is documented in several ISO standards. The following are the principal ISO standards documents applicable to LCA development and use:

- "Environmental Management – Life Cycle Assessment – Principles and Framework," ISO 14040 (2006)
- "Environmental Management – Life Cycle Assessment – Requirements and Guidelines," ISO 14044 (2006)
- "Environmental Management – Life Cycle Assessment – Illustrative Example on How to Apply ISO 14040 to Impact Assessment Situations," ISO 14047 (2012)
- "Environmental Management – Life Cycle Assessment – Data Documentation Format," ISO 14048 (2002)
- "Environmental Management – Life Cycle Assessment – Illustrative Examples on How to Apply ISO 14044 to Goal and Scope Definition and Inventory Analysis," ISO 14049 (2012).

Additionally, a number of valuable resources supporting LCA development and use are available publicly. One such source that is referred to throughout development of the Study Group report is the following text: "Life Cycle Assessment: A Guide to Best Practice."[4] This source addresses a broad spectrum of issues of LCA, including goal and scope definition, life cycle inventory analysis, life cycle impact assessment, life cycle interpretation, reporting, and critical review, and transition from LCA to sustainability assessment. The reader who would want to see more background on general LCA issues should consult this text or another text covering these general subjects.

iv. Benefits of LCA

The benefits of Life cycle assessment is to better understand the environmental impact of a product and its effect in each step of the chain, and be able to show the competitive advantage of a certain product over another, by showing its impact on the environment.
The results of LCA include technical details of processes and recommendations to update major market players what can be applied to improve a cycle performance environmentally. With these results, suppliers, logistics, and buyers are able to determine the hot spots of the life cycle processes and practices that aggressively emit greenhouse gases. From that point, major players can improve or adapt more developed practices. Also, they can invest in research and efficient new technologies to minimize fuel combustions and venting in certain processes. For example, Qatargas has invested $1 billion (U.S.) in the Jetty Boil-Off Gas Recovery project to reduce flaring during the loading of LNG carriers. With this project, Qatargas recovers the equivalent of about 600 thousand tonnes of LNG per annum. This recovery helped them to save volumes and reduce carbon dioxide to 1.6 million tonnes per annum.

For LNG receiving terminals and gas markets, LCA can point to synergies that reduce overall environmental impact by sharing infrastructure assets and using side products and services (such as cold utilization) to reduce cumulative environmental impact to the region.

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[4] Klopffer, Walter and Brigit Grahl, Life Cycle Assessment (LCA): A Guide to Best Practice, Wiley VGH, Weinheim, Germany, 2014.

The life cycle assessment has been used to assess the LNG supply chain, showing the environmental impact of it as compared with other fossil fuels. This has played a major role in advocating for LNG as a cleaner source of energy. With lower greenhouse gases and other emissions, and increased energy efficiency, LNG is becoming the fuel of choice in an industry that is moving towards improving environmental awareness.

Recent work sponsored by the American Petroleum Institute (API) in the U.S. have included development of consistent LCA method for assessing greenhouse gas emissions (mainly CO2, CH4, and NOx) from LNG operations.[5] This effort should facilitate greater uniformity in LCA development and use.

v. LCA Studies of the LNG Chain

Several prominent LCA studies have focused on environmental impacts of the LNG chain and impacts associated with competing fuels. Most address air pollutant emissions, including greenhouse gases, as the principal outputs of concern. Also, most address the entire natural gas value chain (from natural gas production and end use in combustion systems or other application) and in which LNG plays a role as a storage and transport means of natural gas delivery. The following is a partial list of recent studies:

- Power Systems Life Cycle Analysis Tool (Power LCAT) for USAEE, by Drennen, 2011. This study explains the basic methodology used to calculate production costs and to estimate environmental performance.

- Life Cycle Analysis, by Tim Skone, Joe Marriott,PhD, James Littlefield, July 2013. This study develops an inventory of emissions results, and calculates life cycle costs for the plant with and without CCS.

- Natural Gas Technology Assessment, by Timothy J. Skone, June 30, 2012. This study discusses the role of Natural Gas power in meeting the energy needs of the United States.

- From Unit Processes to Completed LCAs_ NETL Life Cycle Analysis, by netl.doe.gov/energy-analyses, 2012. This study explains the methodology includes the critical analysis of scope, assumptions, level of detail, data quality, interpretation of results.

As will be discussed further in Part Two of this report, this IGU study addresses only air pollutant emissions for the LNG chain. This focus is emphasized to develop breadth of data for various configurations of LNG projects, conceived of as an assembly of “modules,” in order to capture the broadest diversity of projects. Also, this study focuses only on natural gas (in the form of LNG), leaving aside issues of comparative air emissions in order to emphasize data development for the LNG chain. It is envisioned that users who want to proceed with comparative fuel LCAs will perform a similar data development approach for the competing fuel of interest.

vi. Case Study of LCA Applied to LNG Trade: Natural Gas versus Coal for Power Generation

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[5] American Petroleum Institute/Asia Pacific Partnership on Clean Development and Climate, Cleaner Fossil Energy Task Force, “Consistent Methodology for Estimating Greenhouse Gas Emissions from Liquefied Natural Gas Operations,” Prepared by the Levon Group, LLC, Final Draft, July 2012.

One of the most useful applications of LCA is in comparing environmental impacts over energy lifecycles for competing primary energy sources. As discussed later in this report, comparisons of natural gas and coal as a power generation fuel have been conducted using LCA to compare air emissions of greenhouse gases (GHGs) and other pollutants. Most recently, the U. S. Center for LNG (CLNG) sponsored an LCA for greenhouse gas emissions covering primary energy production (natural gas and coal), conversion and transport including LNG for natural gas, and end use as a power generation fuel in various configurations of generation assets.[6] As of the printing of this IGU report, it is anticipated that the full CLNG study will be published on its website (source: http://www.lngfacts.org).

The competing natural gas and coal chains covered by the CLNG study included coverage of LNG liquefaction, transport and regasification within the natural gas value chain to competing production, transport and end use of coal in central power stations. LNG chain module data reported in the LCI in Part Two of this report were compiled by the CLNG contractor, Pace Global, and used to represent the LNG chain segments of this case study. LNG chain modules covered include natural gas pre-treatment for liquefaction, major liquefaction technologies served by various compression drive systems and electric power approaches, major LNG marine carrier designs and propulsion systems, and major regas technologies served by electric power approaches. The following liquefaction technologies were addressed by the study and represented by independent modules:

- ConocoPhillips Optimized Cascade
- Air Products Single Mixed Refrigerant (SMR)
- Air Products Propane-Precooled Mixed Refrigerant (C3MR)
- Air Products Dual Mixed Refrigerant (DMR).

Power generation and drivers for refrigerant compression included:

- Two GE Frame 7EA gas turbines per train, without waste heat recovery
- Two GE Frame 7EA gas turbines per train, with waste heat recovery to provide process heat requirements
- Five GE LM2500+ G4 aero-derivative gas turbines per train, without waste heat recovery
- Five GE LM2500+ G4 aero-derivative gas turbines per train, with waste heat recovery to provide process heat requirements
- Electric motor drives.

Sources of calculated GHG emissions from LNG shipping include ship loading, the laden voyage, ship offloading, the ballast voyage, and support vessels needed while approaching and in port. The ship design types analysed in the CLNG analysis were as follows:

- 145,000 cubic meter conventional steam propulsion Moss/Membrane ships using LNG boil-off gas (laden) and boil-off/bunker fuel (ballast)

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[6] Center for LNG, “LNG Full Life Cycle Assessment of Greenhouse Gas Emissions,” Draft Report prepared by Pace Gobal, May 2015.

- 165,000 cubic meter Dual Fuel Diesel Electric membrane ship using LNG boil-off gas (laden) and boil-off/bunker fuel (ballast)

- 216,000 cubic meter Q-Flex membrane ship using bunker fuel (laden and ballast) with shipboard boil-off gas reliquefaction

- 266,000 cubic meter Q-Max membrane ship using bunker fuel (laden and ballast) with shipboard boil-off gas reliquefaction.

Emissions from the laden and ballast voyages shall be provided on a per nautical mile basis to allow adaptation of the analysis to any combination of liquefaction plant and receiving terminal locations. LNG life cycle emissions were estimated for China, India, Western Europe (represented as Germany), Japan, and South Korea.

Emissions from LNG regasification and receiving terminal operations assume an onshore terminal location. Boil-off gas generated from a ship unloading operation is assumed to be recovered. The regasification segment analysis considers several regasification system designs:

- Seawater-heated open rack vaporizers

- Submerged combustion vaporizers

- Air-heated vaporization using a closed loop glycol / water system heated by air

- Air-heated vaporization using and an open loop air-heated water system

- LNG vaporization via waste heat from a co-located power plant.

The gas-fired power generation segment includes an analysis of combined-cycle and simple-cycle power plants. Segment emissions from natural gas and LNG cases were calculated and summed in terms of "adjusted metric tonnes (tonnes) of carbon dioxide equivalent (CO_2-e) per MWh." Pace Global adjusted the GHG emissions at each segment of the supply chain in order to accurately reflect the emissions resulting from 1 MWh of electricity generation.[7]

The modular approach used in the CLNG study is consistent with the modular representation of emissions data documented in Part Two of this IGU report. Consistency for these LNG modules was agreed to between CLNG and the IGU Study Group prior to either group embarking upon its work. It should be noted that since the IGU results only focus on emission rates and are intended to be independent of LNG trade, the destinations of LNG and transport of competing coal discussed in the CLNG report is not addressed in this IGU report. For detail on the methodology used for estimating coal-related emissions from the mine mouth to consumption in power generation, the reader should consult the CLNG study report. Also, conclusions related below comparing regional differences associated with transhipment of LNG and coal are those of CLNG and are beyond the scope of the IGU Study Group activity.

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[7] According to Pace Global, "An emission factor in the production segment, for example, was adjusted by a certain percentage to reflect the fact that a given portion of the produced gas would be combusted during the life cycle and thus would not be available for combustion in the power plant. While a unit of gas at the production segment would produce a certain amount of emissions per MWh at the power plant, a fraction would be combusted before it gets to the power plant."

In addition and since the comparison covered the full primary energy life cycle, upstream emissions generated by energy development and delivery to the LNG chains and downstream energy delivery and combustion in power generation were covered. GHG emission performance for the natural gas chain (and individual LNG chain alternatives) were compared with total coal chain emissions up to and including power generation.

Emissions coverage in the CLNG study included estimates of total life cycle GHG emissions (in metric tonnes of CO_2-equivalent per megawatt hour) for each segment of the LNG supply chain from the wellhead, to the liquefaction plant, aboard a tanker for export, at the LNG receiving terminal, and as end-use for power generation. Emissions estimates were compiled for each segment of the value chain as well as for the total life cycle. The coal chains of the LCA were similarly analysed to calculate estimated emissions throughout the life cycle process of coal extraction, transportation, and end-use combustion for power generation.

Results and conclusions in this discussion of the CLNG analysis represent the views of the analysis team and not those of the IGU Study Group. Much of this discussion is reproduced from the Executive Summary of the CLNG study report of maintain consistency and avoid errors in reinterpretation of the CLNG findings.

As emphasized by Pace Global in the CLNG report, its results of the LNG and coal life cycle emissions assessments are dependent on a wide array of assumptions and outcome uncertainty is inherent due to the myriad data and analytical inputs used throughout the analysis supporting this report. Admittedly, the analysis is particularly sensitive to GHG emission factors, emission rates, and Global Warming Potential (GWP) factors. Actual GHG emissions for both the LNG and coal life cycle analyses can vary substantially depending on the specific local conditions and process technologies employed.

Nevertheless, the LCA results highlight important differences between the emissions generated from LNG and coal for power generation, including the following:

- Existing coal technology was found to produce approximately 163 percent more emissions on a life cycle basis than the *low* case for LNG (an average of 1.309 tonnes CO_2-e/MWH for the installed power plant case across five countries/regions compared to 0.497 tonnes CO_2-e/MWH for the low LNG case).

- Emissions from an existing coal-fired power plant were determined to be approximately 132 percent greater on a life cycle basis than the *high* case for LNG (1.309 tonnes CO_2-e/MWH compared to 0.564 tonnes CO_2-e/MWH for the high LNG case).

- The analysis indicated that an efficient new-build coal-fired power plant would emit 109 percent more emissions from a life cycle perspective than the *low* case for LNG (an average of 1.041 tonnes CO_2-e/MWH for the installed power plant case versus 0.497 tonnes CO_2-e/MWH for LNG case).

- Compared to the high case for LNG, an efficient new-build coal-fired power plant would emit 85 percent more emissions on a life cycle basis (1.041 tonnes CO_2-e/MWH versus 0.564 tonnes CO_2-e/MWH for LNG).

- The majority of emissions for both coal and LNG are emitted during the combustion (power generation) process. 65-76 percent (representing the low and high case) of emissions from natural gas are generated during the combustion cycle, versus an average of 78.7 percent for an existing coal-fired plant and 77.4 percent for a typical new-build.

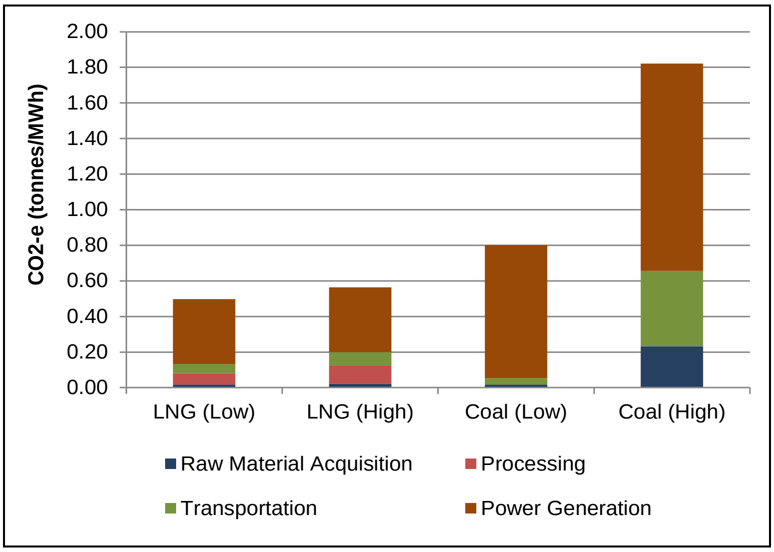
- For all coal cases, combustion emissions were greater than for LNG. Emissions from raw material acquisition were also generally higher for coal than for LNG. However, processing segment emissions were greater for LNG due to incremental processing requirements such as liquefaction, regasification, and pipeline transport.

Table 3 presents the total emissions for each stage of the life cycle for power generation from coal and LNG. The data are presented as a range of potential estimated emissions for each segment of the LNG and coal scenarios.

Table 3 - Comparison of LCA Results for Primary Energy Production and Delivery (Coal and LNG) from the CLNG Study

	Low GHG Case		High GHG Case	
LNG LCA	**CO_2-e (tonnes/MWh)**	**% of Total**	**CO_2-e (tonnes/MWh)**	**% of Total**
Raw Material Acquisition	0.017	3.4%	0.021	3.7%
Processing	0.064	12.9%	0.104	18.4%
Transportation	0.051	10.3%	0.074	13.1%
Power Generation	0.365	73.4%	0.365	64.7%
Total:	0.497	100.0%	0.564	100.0%

	Installed Power Plant (Range, All Countries)	New-Build Power Plant (Range, All Countries)
Coal LCA	**CO_2-e (tonnes/MWh)**	**CO_2-e (tonnes/MWh)**
Raw Material Acquisition	0.018-0.232	0.017-0.191
Processing	----	----
Transportation	0.036-0.424	0.036-0.352
Power Generation	0.909-1.166	0.748-0.884
Total:	1.071-1.499	0.870-1.158



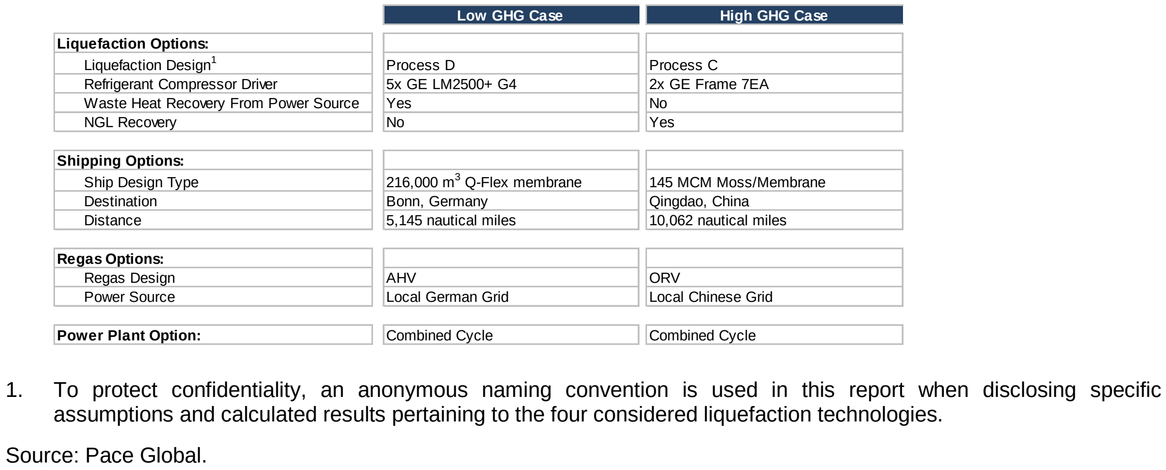
Source: Pace Global based on referenced sources.

Notes:
1. Raw material acquisition includes all segments in the LCA that involve extracting the natural resource from the earth.
2. Processing includes all segments in the LCA that involve changing the resource's molecular makeup or its state of matter. For LNG, this includes all processing steps prior to initial pipeline distribution, liquefaction, and regasification.
3. Transportation includes all segments in the LCA that involve transporting the natural resource. This comprises pipeline transportation, both to the liquefaction plant and also to the power generation plant; and LNG shipping.
4. Power Generation represents the final segment in the LCA where the natural resource is combusted for electricity production.
5. "Coal (Low)" and "Coal (High)" in the above chart refer to the lowest-emitting option (whether country/region or existing/new build plant) and the highest-emitting option, respectively.

Source: Center for LNG, "LNG Full Life Cycle Assessment of Greenhouse Gas Emissions," prepared by Pace Global, May 2015. Reprinted with Permission of Center for LNG.

The LNG life cycle analysis resulted in a low GHG case and high GHG case in order to present a range of possible life cycle GHG emissions. The liquefaction, shipping, and regasification segments were analysed using several distinct options to provide a more inclusive representation of possible emissions. To present life cycle GHG emissions from each segment on a per-unit of MWh-produced basis, each possible scenario created from the module options were analysed independently. Due to the sheer amount of possible scenario iterations (28,000 specific to the LNG analysis), CLNG found that it was not possible to present LCA results for all scenarios. The purpose of the low and high GHG cases was to present a range of estimated and possible life cycle GHG emissions that can be generated. Table 4 provides an overview of the specific options that comprise both cases and as presented in the CLNG report.

Table 4 - Overview of Low and High GHG Cases for LNG Segments from the CLNG Study



	Low GHG Case	High GHG Case
Liquefaction Options:		
Liquefaction Design[1]	Process D	Process C
Refrigerant Compressor Driver	5x GE LM2500+ G4	2x GE Frame 7EA
Waste Heat Recovery From Power Source	Yes	No
NGL Recovery	No	Yes
Shipping Options:		
Ship Design Type	216,000 m^3 Q-Flex membrane	145 MCM Moss/Membrane
Destination	Bonn, Germany	Qingdao, China
Distance	5,145 nautical miles	10,062 nautical miles
Regas Options:		
Regas Design	AHV	ORV
Power Source	Local German Grid	Local Chinese Grid
Power Plant Option:	Combined Cycle	Combined Cycle

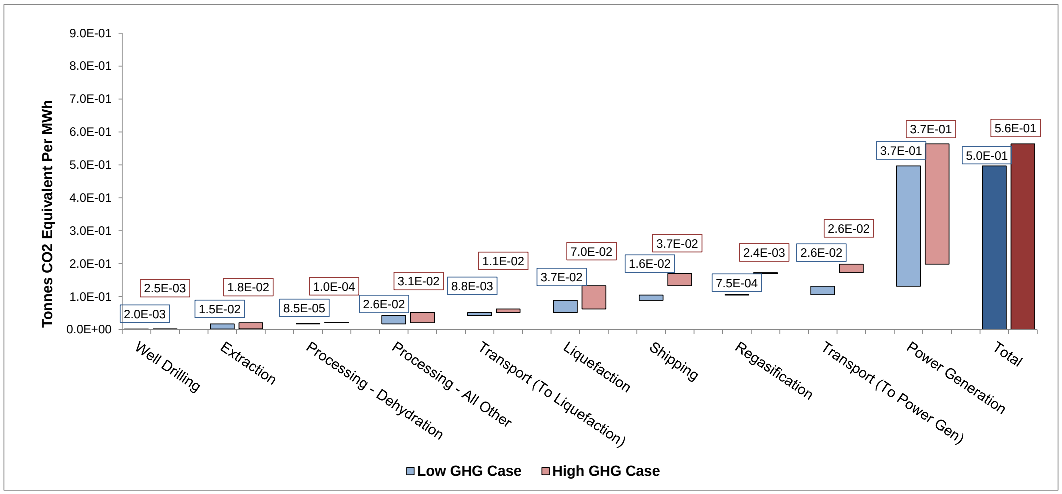
1. To protect confidentiality, an anonymous naming convention is used in this report when disclosing specific assumptions and calculated results pertaining to the four considered liquefaction technologies.

Source: Pace Global.

Source: Center for LNG, “LNG Full Life Cycle Assessment of Greenhouse Gas Emissions,” prepared by Pace Global, May 2015. Reprinted with Permission of Center for LNG.

The life cycle GHG emissions for each segment of the LNG analysis are presented in Table 5. For both cases, power generation accounted for the most GHG emissions of any segment, representing 73.5 percent for the low GHG case and 64.7 percent for the high GHG case. After power generation, the segments that contribute the most life cycle GHG emissions included processing post-dehydration, liquefaction, and pipeline transport to the power generation gate. These four segments accounted for 21.2 percent to 29.2 percent for the low and high GHG cases, respectively. The remaining segments accounted for 5.4 percent to 6.0 percent for the low and high GHG cases, respectively. In total, CLNG analysis determined that life cycle GHG emissions from the LNG analysis were 4.97E-01 kg of CO_2-e per MWh produced for the low GHG case and 5.64E-01 kg of CO_2-e per MWh produced for the high GHG case. Alternatively, the high GHG case generated life cycle GHG emissions that were 13.4 percent higher than the low GHG case.

Table 5 - Summary of LNG LCA Analysis from the CLNG Study



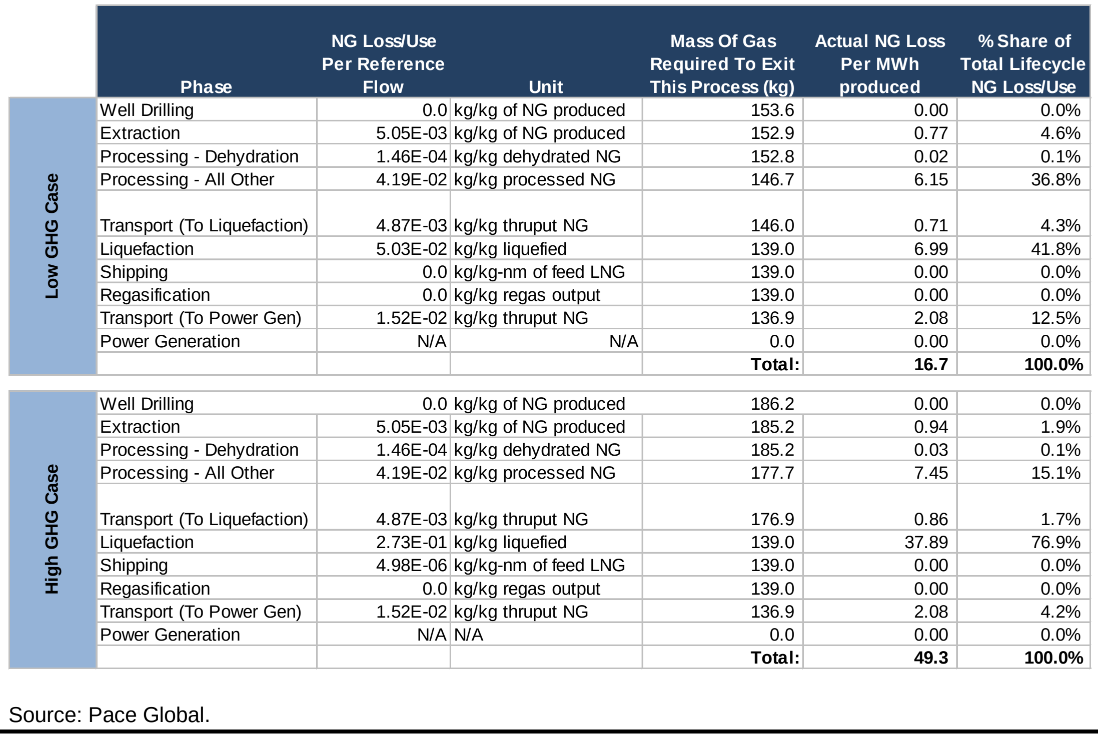
	Low GHG Case		High GHG Case	
Phase of LCA	**CO_2-e (tonnes/MWh)**	**% Of Total**	**CO_2-e (tonnes/MWh)**	**% Of Total**
Well Drilling	2.05E-03	0.4%	2.48E-03	0.4%
Extraction	1.51E-02	3.0%	1.83E-02	3.2%
Processing - Dehydration	8.51E-05	0.0%	1.03E-04	0.0%
Processing - All Other	2.57E-02	5.2%	3.12E-02	5.5%
Transport (To Liquefaction)	8.83E-03	1.8%	1.07E-02	1.9%
Liquefaction	3.73E-02	7.5%	7.04E-02	12.5%
Shipping	1.61E-02	3.2%	3.72E-02	6.6%
Regasification	7.49E-04	0.2%	2.38E-03	0.4%
Transport (To Power Gen)	2.61E-02	5.2%	2.61E-02	4.6%
Power Generation	3.65E-01	73.5%	3.65E-01	64.7%
Total:	**4.97E-01**	**100.0%**	**5.64E-01**	**100.0%**

Source: Pace Global.

Source: Center for LNG, "LNG Full Life Cycle Assessment of Greenhouse Gas Emissions," prepared by Pace Global, May 2015. Reprinted with Permission of Center for LNG.

As pointed out by Pace Global, integrating each segment of the life cycle analysis was critical to determine the amount of gas loss or use for each segment. Gas loss occurs from vented emissions during routine processes or unplanned fugitive emissions inherent in several stages of the LNG analysis. Gas use occurs from using natural gas as fuel to power the operations of various categories of equipment. Table 6 below presents the results of natural gas loss and use over the entire life cycle analysis for the low and high GHG cases. The exhibit also shows the mass of gas required to exit each process before entering the gate of the subsequent segment in order for one MWh to be produced.

Table 6 - Summary of Natural Gas Loss and Use Within the LNG Life Cycle from the CLNG Study



	Phase	NG Loss/Use Per Reference Flow	Unit	Mass Of Gas Required To Exit This Process (kg)	Actual NG Loss Per MWh produced	% Share of Total Lifecycle NG Loss/Use
Low GHG Case	Well Drilling	0.0	kg/kg of NG produced	153.6	0.00	0.0%
	Extraction	5.05E-03	kg/kg of NG produced	152.9	0.77	4.6%
	Processing - Dehydration	1.46E-04	kg/kg dehydrated NG	152.8	0.02	0.1%
	Processing - All Other	4.19E-02	kg/kg processed NG	146.7	6.15	36.8%
	Transport (To Liquefaction)	4.87E-03	kg/kg thruput NG	146.0	0.71	4.3%
	Liquefaction	5.03E-02	kg/kg liquefied	139.0	6.99	41.8%
	Shipping	0.0	kg/kg-nm of feed LNG	139.0	0.00	0.0%
	Regasification	0.0	kg/kg regas output	139.0	0.00	0.0%
	Transport (To Power Gen)	1.52E-02	kg/kg thruput NG	136.9	2.08	12.5%
	Power Generation	N/A	N/A	0.0	0.00	0.0%
				Total:	**16.7**	**100.0%**
High GHG Case	Well Drilling	0.0	kg/kg of NG produced	186.2	0.00	0.0%
	Extraction	5.05E-03	kg/kg of NG produced	185.2	0.94	1.9%
	Processing - Dehydration	1.46E-04	kg/kg dehydrated NG	185.2	0.03	0.1%
	Processing - All Other	4.19E-02	kg/kg processed NG	177.7	7.45	15.1%
	Transport (To Liquefaction)	4.87E-03	kg/kg thruput NG	176.9	0.86	1.7%
	Liquefaction	2.73E-01	kg/kg liquefied	139.0	37.89	76.9%
	Shipping	4.98E-06	kg/kg-nm of feed LNG	139.0	0.00	0.0%
	Regasification	0.0	kg/kg regas output	139.0	0.00	0.0%
	Transport (To Power Gen)	1.52E-02	kg/kg thruput NG	136.9	2.08	4.2%
	Power Generation	N/A	N/A	0.0	0.00	0.0%
				Total:	**49.3**	**100.0%**

Source: Pace Global.

Source: Center for LNG, "LNG Full Life Cycle Assessment of Greenhouse Gas Emissions," prepared by Pace Global, May 2015. Reprinted with Permission of Center for LNG.

Ultimately, both the low and high GHG cases were estimated to require 136.9 kg of natural gas to reach the power plant gate to produce one MWh of electricity. For the low GHG case, over the course of the life cycle boundaries, 153.6 kg of gas was the estimated resource requirement that needed to be extracted from the well because the steps involved in delivering electrical power via the LNG value chain resulted in an estimated total of 16.7 kg of natural gas loss or use per MWh produced. Since both the low and high GHG cases both used the same assumptions for a combined cycle power plant, the high GHG case also required 136.9 kg of natural gas to reach the power plant gate to produce one MWh of electricity. Over the course of the life cycle boundaries, 186.2 kg of gas was the estimated resource requirement that needed to be extracted from the well because the steps involved in the LNG value chain resulted in an estimated total of 49.3 kg of natural gas loss or use per MWh produced.

This analysis assumed a combined cycle power plant is being utilized in both the low and high GHG cases because these types of power plants will represent the majority of capacity of future gas-fired generation facilities. However, an analysis for simple cycle gas-fired power plants was also presented. Simple cycle power plants were calculated to require 211.2 kg of natural gas to produce one MWh of electricity, representative of a 54.2 percent increase in fuel consumption rate calculated for combined cycle power plants. This is a substantial difference, and its effects cascade throughout the life cycle analysis as each segment prior to power generation will require substantially more natural gas throughput, thus increasing GHG emissions from every segment in the life cycle. The increase in fuel consumption rate alone would result in 14.4 percent increase in life cycle GHG emissions for the low GHG case, highlighting the importance of power plant efficiency at the end of the life cycle analysis. This illustrates the importance that natural gas loss or use has on total life cycle GHG emissions. The more gas loss or use from any segment necessitates more gas in each previous segment.

Simple cycle gas-fired power generation plants were not included in the presentation of the high GHG case because there is a low likelihood that exported LNG from the U.S. will ultimately be consumed in a simple cycle plant and thus would not produce a likely representative estimated GHG emission range.

The results of the coal LCA showed that power generation produces the majority of GHG emissions from the coal life cycle, averaging 78.7 percent among the five countries/regions analysed for the ‘average’ installed plant and 77.4 percent for the new-build option. Emissions from power generation as a percentage of the country/regional total were the highest for Western Europe and India, with emissions of 1.005 CO2-e/MWh (94 percent of the total) and 1.166 CO2-e/MWh (91 percent of the total), respectively, for the existing plant option. Emissions from coal transport varied significantly among the countries, due to the different distances travelled and the various transport modes employed. South Korea and Japan had the highest emissions from transportation for both power plant options, averaging 0.401 tonnes CO2-e/MWh for the installed plant and 0.349 tonnes CO_2-e/MWh for the new-build option. Emissions from coal extraction and mining, which include fugitive emissions from both mining and post-mining operations, ranged from approximately 1.4 – 1.5 percent of the total for Japan and South Korea (which source their coal primarily from Australia) to 15.5 – 16.5 percent for domestically sourced Chinese coal.

The CLNG study represents an important illustration of the application of LCA for comparative analysis of energy value chains and, through the LCA methodology, environmental advantages of natural gas through the LNG value change. However, this study demonstrates additional power of the modular approach to LCA analysis by showing the robustness of conclusions through its representation of a variety of chain options and configurations. This approach represents a significant advancement in the practical use of LCA for broader discussions of energy policies related to atmospheric emissions and helps bypass criticisms of selective choices on how energy chains are represented.

4. Part Two: IGU Life Cycle Inventory (LCI) Development

The IGU Study Group has emphasized development of an ISO-compliant life cycle inventory for conducting air pollutant emissions (including greenhouse gases) for various configurations of the LNG chain and to support more general LCA methodologies including comparisons to competing fuels. The sections that follow through Section 3.6 address ISO-required topics for characterizing LCA activities and documentation.

a. Goals of IGU LCI Activity for LNG

i. Range of Application

The goals of LCAs conducted using this study are intended to characterize air emissions from LNG operations comprising the value chain from receipt of natural gas for liquefaction to delivery of regasified (“regas”) LNG for pipeline distribution as natural gas or liquid delivery of LNG directly to end use applications. Air emissions covered include point source and area source emissions of conventionally-regulated air quality pollutants (including particulates, carbon monoxide, oxides of nitrogen) and major “greenhouse gases” (including carbon dioxide and methane). Emissions-related LNG activities addressed include steady state operations, energy transfer operations, storage operations, and onsite and offsite point source power supply operations supporting the LNG chain.

ii. Interest of Realisation

LNG chain emissions characterization data is intended to provide the basis for comparison of LNG value change emissions to other competing energy forms and to provide the basis for improved performance in air emissions reductions achievable through new technology applications, operational changes, and other LNG chain modifications.

iii. Target Groups

LCAs conducted using this study may be conducted by industry participants and associations, governmental authorities, non-governmental organizations (NGOs), or individuals.

iv. Publication or Other Accessibility for the Public

LCAs conducted using this study may be made publicly available for review and use or retained for private and proprietary use. However, the data developed for LNG chain characterization in this study will be freely available for public use through IGU in report and digital form.

b. The Role of LCI Development Within LNG LCA

Life cycle inventory analysis is defined as the following:

> "…a phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its entire life cycle."[8]

However, before LCI analysis can proceed and ultimately support broader LCAs, the inventory of inputs and outputs must be compiled within the LCI proper. The goal of this IGU work is to develop the initial LCI for more general use in LCI analysis initially and LCAs serving a number of IGU objectives over the long term. It is anticipated that this work will be updated and used by other IGU study group projects under the headings of sustainability, social license, and general environmental impact analysis.

c. Objectives of LCI Development Under This Study

The specific objective of the study during the last 3 years (2012-2015) was to develop International Standards Organization (ISO)-compliant life cycle inventory (LCI) data to support independent LCAs. The ISO Standard 14040, "Environmental Management – Life Cycle Assessment – Principles and Framework" and Standard 14044 "Environmental Management – Life Cycle Assessment – Requirements and Guidelines" provide the essential requirements for compiling LCI data. LCAs conducted using this study's LCI data would characterise air emissions from LNG operations comprising the LNG value chain. This includes beginning with the receipt of natural gas for liquefaction to delivery of regas for pipeline distribution as natural gas, direct end use, or liquid delivery of LNG directly to end use applications. Air emissions covered include point source and area source emissions of conventionally-regulated air quality pollutants (including particulates, carbon monoxide, oxides of nitrogen) and major GHGs (CO_2, CH_4, and others). Emissions-related LNG activities addressed include steady-state liquefaction and regasification operations, energy transfer operations, storage operations, and onsite and offsite point source electrical and mechanical power supply operations supporting the LNG chain.

LNG chain emissions data is intended to provide the basis for comparison to emissions from other competing energy forms. Value chain emissions characterisations also help to identify opportunities for improved performance in air emissions reductions achievable through new technology applications, operational changes and other LNG chain modifications.

LCAs conducted using this study's LCI data may be conducted by industry participants and associations, governmental authorities, non-governmental organisations (NGOs), or individuals.

Also, LCAs ultimately conducted using this study's results may be made publicly available for review and use or retained for private and proprietary use. However, the data developed for LNG chain characterisation in this study is freely available for public use through the IGU report. Digital presentation of the data is ultimately envisioned.

d. Study Approach

Since all LCAs on LNG are fundamentally limited by definitions of the LNG chains, this project uses a "modular approach" for LCI data development and archive. This approach helps support a range of individual LCAs to serve the broadest definitions of the industry. Independent assembly of LNG LCA modules by independent investigators allows users to

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[8] International Standards Organization, "Environmental Management – Life Cycle Assessment – Principles and Framework," ISO 14040, 2006, p. 2.

represent chains that are directly relevant to their projects and LCA concerns. In the full IGU report, chain coverage has been limited to the following segments and chain modules:

- Liquefaction, beginning with received feedstock
  - Optimized Cascade
  - Single Mixed Refrigerant (SMR)
  - Propane-Precooled Mixed Refrigerant (C3MR)
  - Dual Mixed Refrigerant (DMR).

- Power generation/drives serving compression and other plant requirements
  - Frame 7EA Gas Turbines, No Waste Heat Recovery
  - Frame 7EA Gas Turbines, Waste Heat Recovery
  - LM2500+ Aero-Derivative Gas Turbines, No Waste Heat Recovery
  - LM2500+ Aero-Derivative Gas Turbines, Waste Heat Recovery
  - Electric motor drives.

- LNG transport, focusing on marine carriers
  - 145,000 Cubic Meter Conventional Steam Propulsion Moss/Membrane Containment, LNG Boil-Off Gas Used as Fuel (Laden) and Boil-Off/Bunker Fuel (Ballast)
  - 165,000 Cubic Meter Dual Fuel Diesel Electric Membrane Containment, LNG Boil-Off Gas Used as Fuel (Laden) and Boil-Off/Bunker Fuel (Ballast)
  - 216,000 Cubic Meter Membrane Containment (Q-Flex Class), Bunker Fuel (Laden and Ballast), Shipboard Boil-Off Gas Reliquefaction
  - 266,000 Cubic Meter Membrane Ship (Q-Max Class), Bunker Fuel (Laden and Ballast), Shipboard Boil-Off Gas Reliquefaction.

- Regas, terminating with plant send out.
  - Seawater-Heated Open Rack Vaporizer System
  - Submerged Combustion Vaporizer System
  - Air-Heated Vaporization, Air-Heated Closed Loop Glycol/Water System
  - Air-Heated Vaporization, Water-Heated Open Loop System
  - Power Plant Waste Heat Vaporization System.

The basic structure of individual modules for air emissions characterization follows the example shown in Figure 7 below.

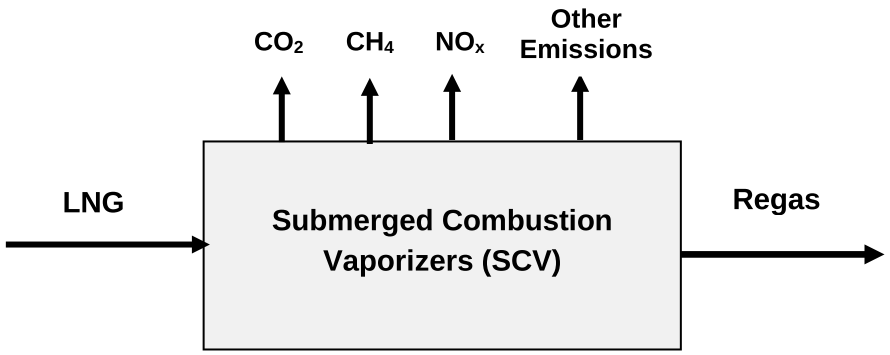

Figure 7 – Example of Module Product Inputs and Product\ and Emissions (point and area source) Outputs.

Figure 8 presents the full list of modules addressed by this study and in the LCI data presented in Appendix A. The various possible combinations of modules potentially representing actual LNG value chains are represented in the figure by interconnections.

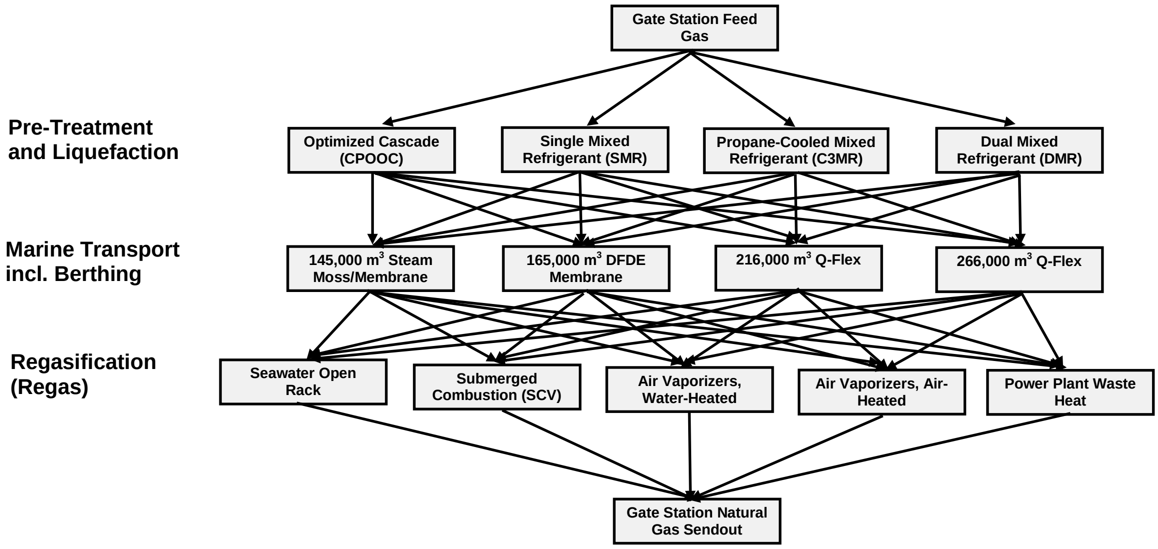

Figure 8 – Possible LNG Module Combinations (excluding power generation options for simplification).

Upstream gas supply and downstream natural gas and LNG end uses are not covered because of the complexities of these segments and their coverage in other LCAs to explore specific policy objectives. The consensus of the IGU Study Group is that LNG LCA emissions with respect to liquefaction, LNG transport and regasification need to be captured in a reliable, robust and transparent way (that is, “get the LNG chain right” for representing the broader natural gas value chain). Additionally, many other studies have and continue to address upstream and downstream emissions issues, but characterisation of air emissions from the LNG chain elements remains an understudied focus.

Only onshore facilities for liquefaction and regasification in large-scale, traded LNG operations are represented. “Retail LNG” such as LNG transfers as vehicle fuel and floating LNG are not addressed. The “product system” for LCA purposes is limited to production, transportation and delivery of primary energy in the form of natural gas in its compositional form (principally as methane). In addition, emissions from primary energy inputs to LNG production, transportation and regasification, such as fossil fuel use for onsite and offsite power supply supporting these LNG operations is included. It does not address secondary energy products or co-products of LNG operations that feasibly could be included within LNG facilities and operations.

e. The Product System

LNG chains addressed by this study include large-scale LNG trade operations involving marine transfer of produced LNG, originating at the receipt of natural gas at liquefaction facilities and terminating at the point of regas send out to a natural gas pipeline system or delivery of received LNG directly to end use customers via land transportation. The product system is limited to production, transportation, and delivery of primary energy in the form of natural gas in its composite form (principally as methane) and does not address secondary energy products or co-products of LNG operations that feasibly could be included within LNG facilities and operations.

f. Technical System Boundaries

Product system boundaries (natural gas receipt for liquefaction to delivery of natural gas to pipelines or LNG to end use customers) comprise the linear system boundaries of the LNG chains covered. Upstream natural gas production, gas processing, or other operations as well as downstream natural gas transport and end uses are not within the system boundaries. Emissions associated with product modules are covered, and point source power generation emissions (onsite and offsite) are included. Emissions covered include point source and area source emissions of conventionally-regulated air pollutants and greenhouse gases discussed above. Emissions from production, transport, construction, commissioning, repair and maintenance, and decommissioning of LNG chain technologies and facilities are outside the system boundaries and are not covered. Emissions from module start up, shutdown for major maintenance, and retirement are outside the system boundaries and are not covered. Module operations ongoing between these events are within the system boundaries and are relevant throughout the operating life of the module.

The product system boundaries (natural gas receipt for liquefaction to delivery of natural gas to pipelines or LNG to end use customers) comprise the linear system boundaries of the LNG chains covered. Emissions from production, transport, construction, commissioning, repair and maintenance, and decommissioning of LNG chain technologies and facilities are outside the system boundaries and are not covered. Emissions from module start-up, shut-down for major maintenance and retirement are outside the system boundaries.

g. Limitations of This Study

It should be noted that this study emphasizes LCA issues subject to its definition of the product system, the technical system boundaries, and the study’s scope. A variety of more expansive definitions of the study might be envisioned in the future, such as full coverage of the natural gas value chain including LNG, coverage on land and water resource usage, project development, start-up, and retirement, production of coproducts, and impacts associated with module design, construction, and retirement. However, owing to the current international concern over air emissions, especially for greenhouse gases, the near-term utility of the study to address those environmental concerns deserved the highest priority for Study Group attention.

h. LCI Data Presentation

Data is presented in Appendix A and is shown in tabular form following the requirements of ISO Technical Specification ISO 14048[9] and in conformance with the general standard for LCA, ISO Standard 14040.[10] Table 7 provides an illustration of data presentation for one module, Optimized Cascade liquefaction.

Table 7 – Example of LCI Data Reporting – Optimized Cascade Liquefaction

1	**Process: Optimized Cascade Liquefaction**	
1.1	**Process description**	Progressive refrigeration cycles using refrigerants vaporizing at different but constant temperatures.
1.1.1	**Name**	Optimized Cascade Liquefaction
1.1.2	**Class**	
1.1.2.1	**Name**	Conoco/Phillips Optimized Cascade
1.1.2.2	**Reference to nomenclature**	Commercial
1.1.3	**Quantitative reference**	
1.1.3.1	**Type**	LNG produced
1.1.3.2	**Name**	Mass
1.1.3.3	**Unit**	Tonnes per year
1.1.3.4	**Amount**	1
1.1.4	**Technical scope**	Gas pretreatment to storage
1.1.5	**Aggregation type**	Liquefaction train
1.1.6	**Technology**	
1.1.6.1	**Short technology descriptor**	Optimized Cascade
1.1.6.2	**Technical content and functionality**	Typical configurations use three stages using different refrigerants to desuperheat feed gas, condense gas, and subcooled condensed liquid through successive loops
1.1.6.3	**Technology picture**	[see Mokhatab, et. al., p. 224]
1.1.6.4	**Process contents**	
1.1.6.4.1	**Included processes**	*^Including methyl diethanol amine CO2 removal to 50 ppm. NGL removal included where identified with emission factors. Molecular removal of water.
1.1.6.4.2	**Intermediate product flows**	*^Removal of 100% of propane and butane and 90% of ethane where NGL removal process is identified. NGL residual gas compressor discharge is air cooled, reducing gas discharge temperature to 32^{o}C at ambient temperature 21^{o}C.
1.1.6.4.2.1	**Source process**	[unlabelled] Boundary – natural gas pipeline gate station
1.1.6.4.2.2	**Input and output source**	[unlabelled] Natural gas pipeline gate station.
1.1.6.4.2.3	**Input and output destination**	[unlabelled] Liquefaction plant storage.
1.1.6.4.2.4	**Destination process**	[unlabelled] Marine carrier.

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[9] International Standards Organization, "Environmental Management – Life Cycle Assessment – Data Documentation Format," ISO/TS 14048. 2002.

[10] International Standards Organization, "Environmental Management – Life Cycle Assessment – Principles and Framework," ISO 14040, 2006.

Table 7 (Continued)

1.1.6.5	**Operating conditions**	*^Feed gas: 88% methane, 1% nitrogen, 2% carbon dioxide, 6% ethane; 2% propane, 0.5% isobutene, 0.5% n-butane. Operating conditions: 60 bar @ 21ºC and ambient air cooling and 21ºC ambient air.
1.1.6.6	**Mathematical model**	^Statoil: SCEET-LNG proprietary model. *Pace Global: Feed gas pretreatment process heat requirements provided by BASF, molecular sieve process heat requirements provided by Exxon/Mobil, power generation emissions modelled with Thermoflow/GT Pro.
1.1.7	**Valid time span**	
1.1.7.1	**Start date**	-
1.1.7.2	**End date**	-
1.1.7.3	**Time-span description**	-
1.1.8	**Valid geography**	
1.1.8.1	**Area name**	-
1.1.8.2	**Area description**	-
1.1.8.3	**Sites**	-
1.1.8.4	**GIS reference**	-
1.1.9	**Data acquisition**	Undocumented
1.1.9.1	**Sampling procedure**	-
1.1.9.2	**Sampling sites**	-
1.1.9.3	**Number of sites**	-
1.1.9.4	**Sample volume**	-
1.1.9.4.1	**Absolute**	-
1.1.9.4.2	**Relative**	-
1.2	**Input/Output**	
1.2.1	**Identification number**	[unlabelled]
1.2.2	**Direction**	Output
1.2.3	**Group**	Air emissions
1.2.4	**Receiving environment**	Ambient air
1.2.5	**Receiving environment specification**	[unlabelled]
1.2.6	**Environment condition**	Ambient conditions; 21oC, 1 bar
1.2.7	**Geographical location**	[unspecified]
1.2.8	**Related external system**	Origin: Feed gas (1.1.6.5) from NGL recovery at intermediate product flow conditions (1.1.5.4.2) or from molecular sieve process (1.1.6.4.1).
1.2.9	**Internal location**	Gas delivered to liquefaction train; liquid delivered to storage.
1.2.10	**Name**	CO_2: CH_4: NO_x CO_2e:
1.2.11	**Property**	kg/tonne LNG produced
1.2.12	**Amount**	**2 FRAME 7EA GAS TURBINES; NO NGL RECOVERY; NO WASTE HEAT RECOVERY:*** CO_2: 1.75E-04 to 1.94E-04, plus 1.33E-04 (flaring)* CH_4: 0.0, plus 4.80E-07 (flaring)* NO_x: 0.0* CO_2e: 1.75E-04 to 1.94E-04, plus 1.48E-04 (flaring)* **2 FRAME 7EA GAS TURBINES; NGL RECOVERY; NO WASTE HEAT RECOVERY:*** CO_2: 2.00E-04 to 2.19E-04, plus 1.62E-04 (flaring)* CH_4: 0.0, plus 5.82-07 (flaring)* NO_x: 0.0* CO_2e: 2.00E-04 to 2.19E-04, plus 1.48E-04 (flaring)* **2 FRAME 7EA GAS TURBINES; NO NGL RECOVERY; WASTE HEAT RECOVERY:*** CO_2: 1.13E-04 to 1.25E-04, plus 1.33E-04 (flaring)* CH_4: 0.0, plus 4.80E-07 (flaring)* NO_x: 0.0*

		CO_2e: 1.13E-04 to 1.25E-04, plus 1.48E-04 (flaring)* **2 FRAME 7EA GAS TURBINES; NGL RECOVERY; WASTE HEAT RECOVERY:*** CO_2: 1.29E-04 to 1.41E-04, plus 1.62E-04 (flaring)* CH_4: 0.0, plus 5.82E-07 (flaring)* NO_x: 0.0* CO_2e: 1.29E-04 to 1.41E-04, plus 1.79E-04 (flaring)* **5 LM2500+G4 GAS TURBINES; NO NGL RECOVERY; NO WASTE HEAT RECOVERY:*** CO_2: 1.58E-04 to 1.77E-04, plus 1.33E-04 (flaring)* CH_4: 0.0, plus 4.80E-07 (flaring)* NO_x: 0.0* CO_2e: 1.58E-04 to 1.77E-04, plus 1.48E-04 (flaring)* **5 LM2500+G4 GAS TURBINES; NGL RECOVERY; NO WASTE HEAT RECOVERY:*** CO_2: 1.80E-04 to 2.00E-04, plus 1.62E-04 (flaring)* CH_4: 0.0, plus 5.82E-07 (flaring)* NO_x: 0.0* CO_2e: 1.80E-04 to 2.00E-04, plus 1.79E-04 (flaring)* **5 LM2500+G4 GAS TURBINES; NO NGL RECOVERY; WASTE HEAT RECOVERY:*** CO_2: 1.08E-04 to 1.21E-04, plus 1.33E-04 (flaring)* CH_4: 0.0, plus 4.80E-07 (flaring)* NO_x: 0.0* CO_2e: 1.08E-04 to 1.21E-04, plus 1.48E-04 (flaring)* **5 LM2500+G4 GAS TURBINES; NGL RECOVERY; WASTE HEAT RECOVERY:*** CO_2: 1.23E-04 to 1.68E-04, plus 1.62E-04 (flaring)* CH_4: 0.0, plus 5.82-07 (flaring)* NO_x: 0.0* CO_2e: 1.23E-04 to 1.68E-04, plus 1.48E-04 (flaring)* **ELECTRIC MOTORS; NO NGL RECOVERY:*** CO_2: 1.59E-04 to 1.76E-04, plus 1.33E-04 (flaring)* CH_4: 0.0, plus 4.80-07 (flaring)* NO_x: 0.0* CO_2e: 1.59E-04 to 1.76E-04, plus 1.48E-04 (flaring)* **ELECTRIC MOTORS; NGL RECOVERY:*** CO_2: 1.83E-04 to 1.99E-04, plus 1.62E-04 (flaring)* CH_4: 0.0, plus 5.82-07 (flaring)* NO_x: 0.0* CO_2e: 1.83E-04 to 1.99E-04, plus 1.79E-04 (flaring)* ***Pace Global**
1.2.13	**Mathematical relations**	Formulae*
1.2.14	**Documentation**	Modelled Emissions; Reported April 2015*

While this structure is familiar to LCA practitioners following the iSO specifications, it may not be familiar to the general reader. ISO 14048 provides general background on the development and use of this format and should be consulted for more information on approach to applying this information to LCAs. Those who wish to explore the specifications in detail might first refer to Annex B of ISO 14048, which provides a specific example for implementation of this data documentation approach.

ISO 14048 outline three areas of data documentation for performing life cycle inventory assessment:

- Process description and inputs and outputs quantification
- LCI modelling and analysis documentation
- LCI administrative information.

The data provided in this report addresses process description and inputs and outputs quantification only. LCI modelling was not performed in the course of this study. Also, since no commitment has been made to manage LCI information beyond this study at this time, LCI administrative information is beyond the scope of this study.

Over the course of this study, only two LCI data sources were identified that simultaneously covered the breadth of the LNG chain modules targeted by the Study Group and the granularity of data with respect to specific unit processes, side processes, and operating conditions that were deemed to be essential to characterizing atmospheric emissions in a reasonable and reliable way. These two studies include recently completed Pace Global study sponsored by Center of LNG[11] and specialized modelling provided by Statoil using its Statoil Carbon Emission Estimation Tool for LNG (SCEET-LNG model).[12][13] While many other sources address LNG emissions generally, process specifics and operating conditions are lacking in the presentation of the data, placing the reliability and validity of emissions data under uncertainty. For economy, both the Pace Global and Statoil emission factors are presented together in the ISO 14048 formatted tables. This also allows for easier and more direct comparisons across these two data sources. It is envisioned that additional data development on this topic would call for breaking out these various data sources into independent tables as strict adherence to the ISO approach would call for.

The tables In Appendix A present data documentation developed over the course of the study. Data provided is subject to the product system, scope, and technical system boundaries specified for this study and as descripted in earlier report sections. Importantly, only data sources where the chain modules identified for this study could be unambiguously identified and emissions quantified are shown in the tables below. This level of documentation “granularity” was targeted at the onset of the study, and while a number of LCA studies have been performed on courser data and undocumented data sources, these studies were not deemed directly relevant to this study.

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[11] Center for LNG, “LNG Full Life Cycle Assessment of Greenhouse Gas Emissions,” prepared by Pace Gobal, May 2015. Reprinted with Permission of Center for LNG.

[12] Neeraas, Bengt and Knut Maråk, “Energy Efficiency and CO2 Emissions in the LNG Chains,” Second Trondheim Gas Technology Conference, 2-3 November, 2011.

[13] Maråk, Knut. SCEET-LNG model calculations tailored to IGU Study Group modules and operating conditions.

5. Conclusions and Recommendations for Continuing LCA Work

Several salient conclusions are made based on the Study Group work, including the following:

- Without qualification, further development of data for LCA of the LNG chain requires greater primary data documentation and, in some important cases, disclosure of proprietary data. The usefulness of detailed LCA as a technique for characterizing air emissions from LNG operations will remain limited under current data documentation and disclosure practices. This limitation is particularly important for comparisons of LNG chain options for environmental performance and identification of project technology options for improved performance and technology development.

- Practical application of the LCI data within full LCAs is the principal means of accruing benefits of this study. It is envisioned that continuing IGU studies under the “Sustainability” focus of PGC A may employ this data to its full extent. However, public availability of the data to the broader LCA community can assist IGU in contributing to more broadly addressing environmental and sustainability objectives.

- Documentation of LCI data highlights the need for broader primary data development for air emissions from the LNG value chain and the need to extend data development beyond steady-state LNG operations.

- Full implementation of LCA requires going beyond primary air emissions, which has been the focus of most LCAs covering LNG to date, and addressing water, solid waste, and land use issues.

- Focus on maintaining maximum transparency and objectivity is highlighted by the ISO standards reporting and documentation approach. Only through the use of such tools and their essential requirements can consensus on emissions from the LNG value chain be achieved.

- LCI data, including its use in complete LCAs, can be used for “technology roadmap” development for reducing emissions within LNG chains and should be employed to that end.

- Competing energy forms need to be similarly quantified and documented for reasonable and justifiable comparisons of energy chains to natural gas generally and LNG specifically. It is envisioned that this study will prompt similar efforts to competing fuels so that consistent comparisons of life cycle impacts can be conducted.

6. References

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National Energy Technology Laboratory (U.S.), “From Unit Processes to Completed LCAs: NETL Life Cycle Analysis, Laboratory,” 2012,

Neeraas, Bengt and Knut Maråk, “Energy Efficiency and CO_2 Emissions in the LNG Chains,” Second Trondheim Gas Technology Conference, 2-3 November, 2011.

Skone, Timothy, “Natural Gas Technology Assessment,” National Energy Technology Laboratory, 2012.

Skone, Timothy, Joe Marriott, James Littlefield, “Life Cycle Analysis,” July 2013.

6. Appendix A: LCI Data Tables

[FULL PERMISSIONS TO REPRINT KEY PROPRIETARY DATA AND CALCULATIONS WERE NOT RECEIVED BY THE IGU DEADLINE FOR SUBMITTING THE STUDY GROUP REPORT. THEREFORE, THESE MATERIALS ARE NOT PROVIDED HERE. SUBSEQUENT TO RECEIVING THE REQUIRED PERMISSIONS, THE LCI DATA TABLES WILL BE INCORPORTED IN THE REPORT AND ARCHIVED AT IGU.]

Appendix B: Units and Conversion Factors

IGU Conversion Factors[14]

← ***Multiply by*** →

	Tonnes LNG	**cm LNG**	**cm gas**	**cf gas**	**mmBtu**	**boe**
Tonnes LNG		2.222	1,300	45,909	53.38	9.203
cm LNG	0.450		585	20,659	24.02	4.141
cm gas	7.692×10^{-4}	0.0017		35.31	0.0411	0.0071
cf gas	2.178×10^{-5}	4.8×10^{-5}	0.0283		0.0012	2.005×10^{-4}
mmBtu	0.0187	0.0416	24.36	860.1		0.1724
boe	0.1087	0.2415	141.3	4,989	5.8	

Pace Global Study Global Warming Potentials (GWP) for Greenhouse Conversion Factors[15]

Description	**Value**	**Unit**	**Source**
CO_2	1	lbs CO_2-e/lb CO_2	(IPCC, Fifth Assessment Report, 2013)
CH_4	30	lbs CO_2-e/lb CH_4	(IPCC, Fifth Assessment Report, 2013)
N_2O	265	lbs CO_2-e/lb N_2O	(IPCC, Fifth Assessment Report, 2013

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[14] International Gas Union, “Natural Gas Conversion Guide,” IGU Office of the Secretary General, Oslo, Norway, 2012.

[15] Center for LNG, “LNG Full Life Cycle Assessment of Greenhouse Gas Emissions,” Draft Report prepared by Pace Gobal, May 2015.

Appendix C: Contributors

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