CENTRE FOR CONTINUING EDUCATION

APPENDIX – I (Title Page)

Technology role for Natural Gas Valorization

BY

NILESH DAREKAR
SAP ID : 500065858

Guided By

Dr. Avinash Khopkar
Sr. Team Lead
Reliance Research and Development Centre

A DISSERTATION REPORT SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENT OF
MBA (OIL AND GAS MANAGEMENT)
OF
CENTRE FOR CONTINUOUS EDUCATION
UNIVERSITY OF PETROLEUM & ENERGY STUDIES, DEHRADUN

© Centre for Continuing Education, UPES, Dehradun

APPENDIX – II

ACKNOWLEDGEMENT

This is to acknowledge with thanks the help, guidance and support that I have received during the Dissertation.

I have no words to express a deep sense of gratitude to the management of **University of Petroleum & Energy Studies** for giving me an opportunity to pursue my Dissertation, and in particular **Dr. Avinash Kopkhar**, for his able guidance and support.

I must also thanks to all my teachers and the faculty of University of Petroleum & Energy Studies for their valuable support.

NRDarekar.

Nilesh Darekar
323, Sadashiv Peth,
Near Tilak Road,
+91-9881383814
e-mail: nileshdarekar04@gmail.com
Date:15th Nov 2019
Place: Pune

CENTRE FOR CONTINUING EDUCATION

APPENDIX – III

A Declaration by the Guide

This is to certify that the **Mr Nilesh Darekar**, a student of (MBA oil & Gas Program), SAP ID **500065858** of UPES has successfully completed this dissertation report on "Technology role for Natural Gas Valorization" under my supervision.
Further, I certify that the work is based on the investigation made, data collected and analyzed by him and it has not been submitted in any other University or Institution for award of any degree. In my opinion it is fully adequate, in scope and utility, as a dissertation towards partial fulfillment for the award of degree of MBA.

Dr. Avinash Kopkhar (Sr. Team Leader)
Reliance Research and Development Centre
e-mail: avinash.khopkar@ril.com
Date: 30th Nov 2019
Place: Mumbai

CENTRE FOR CONTINUING EDUCATION

APPENDIX - IV

Table of Contents

© Centre for Continuing Education, UPES, Dehradun

Abbreviations

Abbreviation	Meaning
LDVs	Light-duty vehicles
CNG	Compressed natural gas
LNG	Liquified natural gas
AFVs	Alternative fuel vehicles
FCEVs	Fuel cell electric vehicles
AFDC	Alternate fuel data center
BEV	Battery electric vehicle
PEMs	Polymer electrolyte membranes
NGVs	Natural gas vehicles
CBG	Compressed Bio-Gas
tcm	Trillian cubic meter
ICE	Internal combustion engine
NOx	Nitrogen Oxide
NMHC	National Muli-Housing council
GHG	Green House Gas
PLC	Project life cycle

List of Tables and Illustrations

Table of Figures

Executive Summary / Abstract

Energy consumption is loosely correlated with gross national product and climate, but there is a large difference even between the most highly developed countries, such as Japan and Germany with an energy consumption rate of 6 kW per person and the United States with an energy consumption rate of 11.4 kW per person. In developing countries, particularly those that are sub-tropical or tropical such as India, the per person energy use rate is closer to 0.7 kW. Bangladesh has the lowest consumption rate with 0.2 kW per person.

Global warming emissions resulting from energy production are an environmental problem. Efforts to resolve this include the Kyoto Protocol (1997) and the Paris Agreement (2015), international governmental agreements aiming to reduce harmful climate impacts, which a number of nations have signed. Limiting global temperature increase to 2 degrees Celsius, thought to be a risk by the SEI, is now doubtful.

To limit global temperature to a hypothetical 2 degrees Celsius rise would demand a 75% decline in carbon emissions in industrial countries by 2050, if the population is 10 billion in 2050. Across 40 years, this averages to a 2% decrease every year. In 2011, the emissions of energy production continued rising regardless of the consensus of the basic problem.

Greenhouse gases are not the only emissions of energy production and consumption. Large amounts of pollutants such as sulphurous oxides (SOx), nitrous oxides (NOx), and particulate matter (PM) are produced from the combustion of fossil fuels and biomass; the World Health Organization estimates that 7 million premature deaths are caused each year by air pollution. Biomass combustion is a major contributor. In addition to producing air pollution like fossil fuel combustion, most biomass has high CO2 emissions.

The rapid increase of energy demand, the high oil and gas prices, and the strategic drive of coal-rich countries to reduce their dependence on imported crude oil have led to reconsider coal as a primary feedstock for the production of chemicals.

Countries with large coal reserves, such as China, are very active in the research, development, and implementation of coal-based projects such as the transformation of syngas to olefins via methanol synthesis (MTO) or via dimethyl ether or SDTO process (syngas via dimethyl ether to olefins). However, there are some challenges in the great potential of the coal-to-olefins industry.

Coal gasification generates excess CO2 that has to be removed from the synthesis gas and discharged from the plant. The environmental pressure to reduce CO2 emissions may bring about CO2 sequestration technologies that have to be implemented before coal-based processes are established worldwide.

At proven world oil resources of 156.7 billion tons (2003) and their constant current consumption of 4.265 billion tons in 2005, oil will be sufficient for ~37 years. Similarly, natural gas will be sufficient for 68 years at its proven world resources of 175.77 trillion Nm3 (2003) and constant consumption at a level of 2.6 trillion Nm3 in 2005. Russian reserves account for up to 40% of natural gas and no more than 10% of oil and gas condensate resources. Gas is much cheaper than oil.

In view of this fact, the problem of replacing the oil products used as feedstocks for the synthesis of lower olefins to natural gas under Russian conditions is urgent and seems worthy of detailed consideration.

The main industrial method for the synthesis of lower olefins is the pyrolysis of liquid oil distillates and lower saturated hydrocarbons in tubular furnaces at 800–950°C. In Western Europe, 90% of lower olefins are synthesized via the pyrolysis of gasoline; in the United States, nearly 30% of lower olefins are obtained via the pyrolysis of liquid oil products; among them, 42% are synthesized from ethane and 29% from liquefied gases.

- Technologies for the Synthesis of Ethylene and Propylene from Natural Gas

Biomass gasification has potential as a source for hydrocarbon products in view of feedstock flexibility and the possibilities to reduce net CO2 emissions. The use of biomass for the production of lower olefins might benefit from low feedstock costs and tax incentives. However, the potential for cost reduction in light olefins production is limited by the cost of collection and transportation of biomass in large-scale applications and the production of synthesis gas.

The syngas obtained from biomass is CO-rich and in general contains several impurities, as is the case for coal-based syngas. The syngas derived from these sources requires extensive purification to remove contaminants, such as sulfur, that are detrimental for the catalysts used in syngas transformation processes. For most conversion processes, the H2/CO ratio needs to be adjusted by means of the water gas shift reaction (WGS). After purification and tuning the H2/CO ratio, syngas can be used for the production of chemicals and fuels.

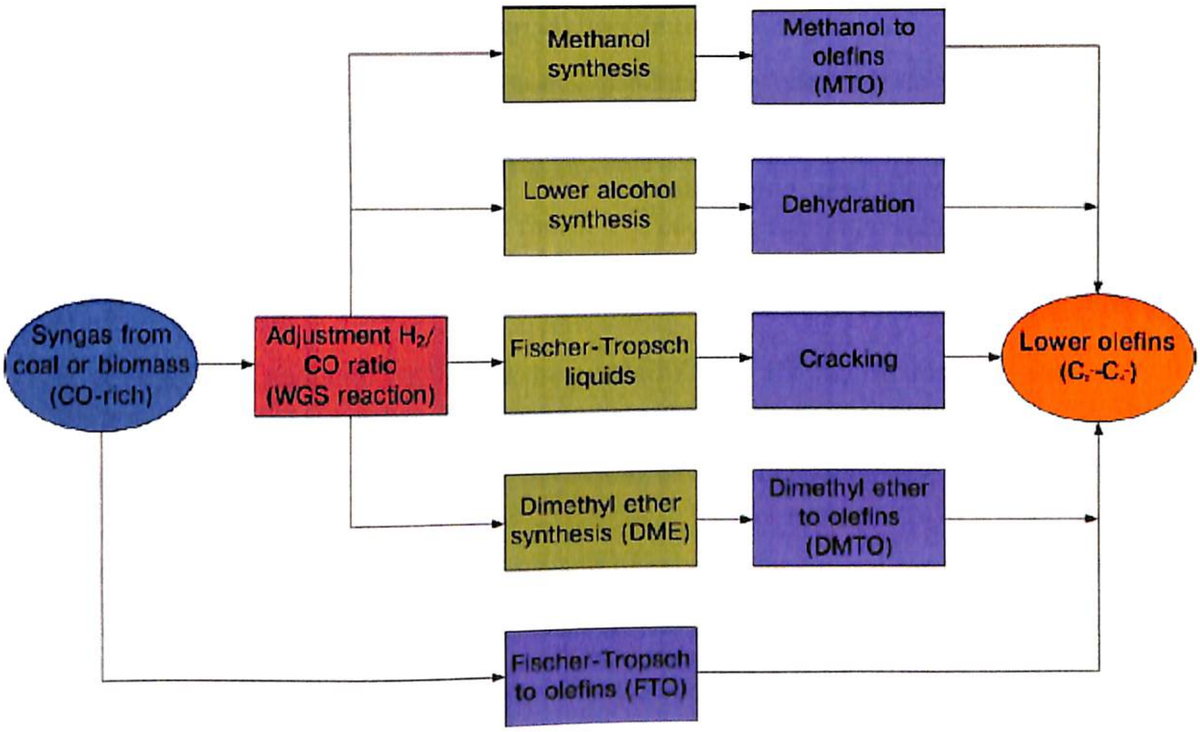


Figure 1: Process for the transformation of CO-rich synthesis gas into lower olefins. [11]

With the recent discovery of large shale gas reserves in the U.S., new possibilities are open for the transformation of natural gas to olefins. Wet shale gas can be directly fed to ethane crackers to produce ethylene, while dry shale gas can be used for the production of syngas and thus be transformed directly or indirectly to lower olefins.

The increased availability of natural gas from shale deposits has produced a major shift in the feedstocks used for the production of ethylene in U.S., and consequently it has affected the propylene and butadiene markets. The use of ethane as feedstock for the crackers instead of naphtha results in a tighter supply of C3 and C4 olefins, and it might increase the prices for those chemicals in the future. These issues have also opened opportunities for alternative processes for the production of propylene and butylenes.

Large shale gas reserves have been found not only in U.S. but also in other countries such as China, which holds the largest technically recoverable reserves. The exploitation of shale gas for energy purposes and for the production of lower olefins is expected to increase dramatically in the years to come in spite of some environmental concerns related to its extraction and the high costs involved in the production of shale gas.

Petroleum Minister launches 'STAT' initiative to promote the use of alternative fuels.

Bio-gas is produced naturally through a process of anaerobic decomposition from waste / bio-mass sources like agriculture residue, cattle dung, sugarcane press mud, municipal solid waste, sewage treatment plant waste, etc. After purification, it is compressed and called CBG, which has pure methane content of over 95%. Compressed Bio-Gas is exactly similar to the commercially available natural gas in its composition and energy potential. With calorific value (~52,000 KJ/kg) and other properties similar to CNG, Compressed Bio-Gas can be used as an alternative, renewable automotive fuel. Given the abundance of biomass in the country, Compressed Bio-Gas has the potential to replace CNG in automotive, industrial and commercial uses in the coming years.

The government will buy compressed biogas produced in local plants and use it as fuel for vehicles. This will provide another source to increase the income of farmers. Petroleum Ministry, about 15 million tons of gas will be received annually from a total of 5000 compressed biogas stations, which is about 40 percent of the CNG currently being used. Currently, about 4.4 million tons of CNG is used annually as a vehicle fuel in the country. The government will invest about Rs 1.7 lakh crore in this scheme and it will provide employment to about 75,000 people.

Benefits of the scheme:

- It is hoped that this step will boost the availability of affordable transport fuel and will also help in the disposal of waste materials in the state.
- Through this scheme, you will be invited to set up a capacity compressed biogas plant in urban and rural areas.
- The government will buy the compressed biogas produced in these plants and use it as fuel for vehicles.
- Through this scheme, the government will provide cheaper vehicle fuel as well as agricultural residues will be used properly, and animal feces and urban waste will also be used.
- It will provide another source to increase farmers' income.
- Support to national commitments in achieving climate change goals
- Reduction in import of natural gas and crude oil
- Buffer against crude oil/gas price fluctuations

Compressed bio-gas networks can be integrated with city gas distribution (CGD) networks to boost supply to domestic and retail users in existing and upcoming markets. In addition to retailing from OMC fuel stations, compressed bio-gas can be injected into CGD pipelines at a later date for efficient delivery and optimized access to cleaner and more economical fuels.

- 'STAT' initiative to promote the use of alternative fuels.

Economic Factors Linking Natural Gas and Crude Oil Prices:

Increases in oil prices may affect the natural gas market in several ways.

Demand:
An increase in crude oil prices motivates consumers to substitute natural gas for petroleum products in consumption, which increases natural gas demand and hence prices.

Supply:

- Increases in crude oil prices resulting from an increase in crude oil demand may increase natural gas produced as a co-product of oil, which would tend to decrease natural gas prices.
- An increase in crude oil prices resulting from an increase in crude oil demand may lead to increased costs of natural gas production and development, putting upward pressure on natural gas prices.
- An increase in crude oil prices resulting from an increase in crude oil demand may lead to more drilling and development of natural gas projects, which would tend to increase production and decrease natural gas prices

Finally, another factor linking the natural gas and crude oil markets is liquified natural gas (LNG), which permits the transformation of natural gas from remote gas producing countries to large gas consuming areas. A "world market" of natural gas likely would reinforce the linkages between natural gas and crude oil prices.

- Arno de Klerk – Department of Chemical and Materials Engineering University of Alberta, Canada arpa-e.energy.gov

1 Introduction

1.1 Overview

World energy consumption is the total energy produced and used by the entire human civilization.

Electricity generation:

The total amount of electricity consumed worldwide was 19,504 TWh in 2013, 16,503 TWh in 2008, 15,105 TWh in 2005, and 12,116 TWh in 2000. By the end of 2014, the total installed electricity generating capacity worldwide was nearly 6.142 TW (million MW) which only includes generation connected to local electricity grids. In addition there is an unknown amount of heat and electricity consumed off-grid by isolated villages and industries. In 2014, the share of world energy consumption for electricity generation by source was coal at 41%, natural gas at 22%, nuclear at 11%, hydro at 16%, other sources (solar, wind, geothermal, biomass, etc.) at 6% and oil at 4%. Coal and natural gas were the most used energy fuels for generating electricity. The world's electricity consumption was 18,608 TWh in 2012. This figure is about 18% smaller than the generated electricity, due to grid losses, storage losses, and self-consumption from power plants.

In 2016 the total world energy came from 80% fossil fuels, 10% biofuels, 5% nuclear and 5% renewable (hydro, wind, solar, geothermal). Only 18% of that total world energy was in the form of electricity. Most of the other 82% was used for heat and transportation.

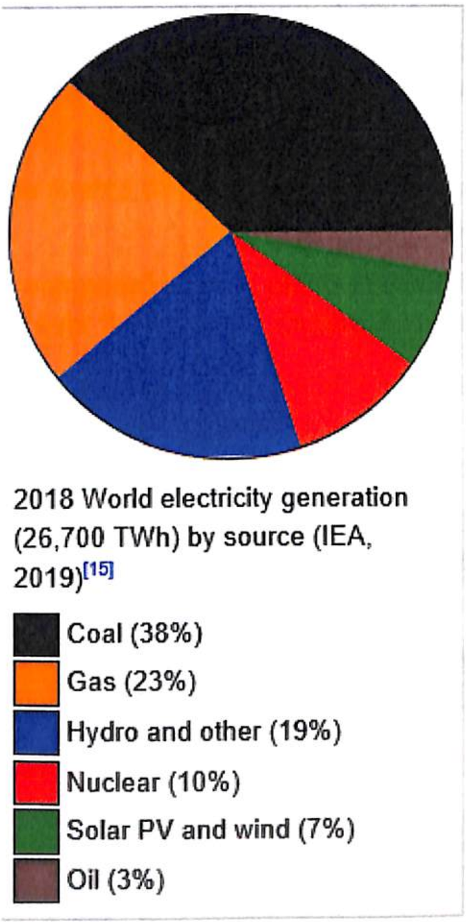


Figure 2: Worldwide Electricity generation [7]

Fossil fuels:

The twentieth century saw a rapid twenty-fold increase in the use of fossil fuels. Between 1980 and 2006, the worldwide annual growth rate was 2%. According to the US Energy Information Administration's 2006 estimate, the estimated 471.8 EJ total consumption in 2004, with fossil fuels supplying 86% of the world's energy.

Coal:

In 2000, China accounted for 28% of world coal consumption, other Asia consumed 19%, North America 25% and the EU 14%. The single greatest coal-consuming country is China. Its share of the world coal production was 28% in 2000 and rose to 48% in 2009. In contrast to China's ~70% increase in coal consumption, world coal use increased 48% from 2000 to 2009. In practice, the majority of this growth occurred in China and the rest in other Asia. China's energy consumption is mostly driven by the industry sector, the majority of which comes from coal consumption.

Coal is the largest source of carbon dioxide emissions in the world. According to James Hansen the single most important action needed to tackle the climate crisis is to reduce CO2 emissions from coal.

Oil:

Coal fueled the industrial revolution in the 18th and 19th century. With the advent of the automobile, aeroplanes and the spreading use of electricity, oil became the dominant fuel during the twentieth century. The growth of oil as the largest fossil fuel was further enabled by steadily dropping prices from 1920 until 1973. After the oil shocks of 1973 and 1979, during which the price of oil increased from 5 to 45 US dollars per barrel, there was a shift away from oil. Coal, natural gas, and nuclear became the fuels of choice for electricity generation and conservation measures increased energy efficiency.

At present, Crude oil is the main source of transportation fuels and demand on crude oil increases year on year.

Oil is a fossil fuel, meaning it is composed of dead plants and animal that lived hundreds of millions of years ago. After decomposing over the eons, the chemical compounds of the remains broke down and formed what we now call oil.

History tells us that:

1) Crude oil demand exceeds crude oil supply.
2) If crude oil supply is the constraints, then technology is adopted to gradually replace the crude oil as feed. Gas to liquid conversion enables the production of similar products as are presently produced from crude oil.

Crude oil and natural gas are both energy commodities. When one gets more expensive on a historical basis, consumers have the option of switching to the other, particularly when it comes to heating.

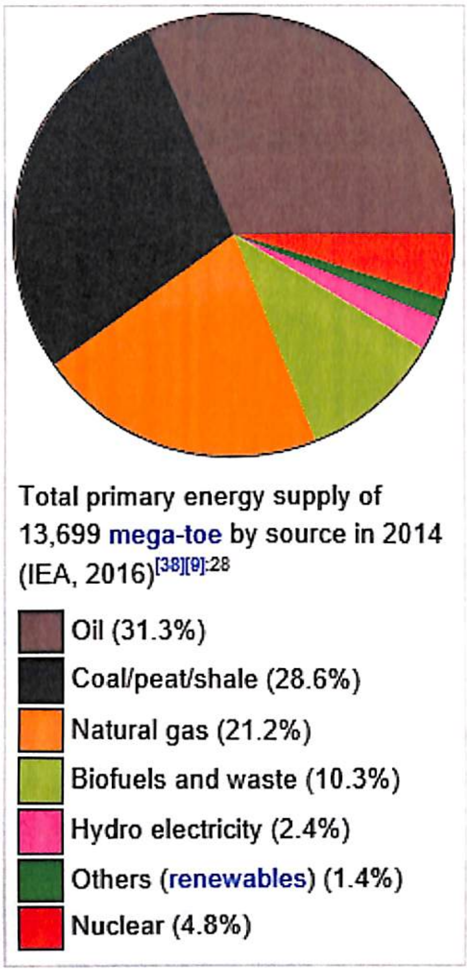


Figure 3: Fossil fuels distribution [7]

Natural Gas:

In 2009, the world use of natural gas grew 31% compared to 2000. 66% of this growth was outside EU, North America, Latin America, and Russia. Others include the Middle East, Asia, and Africa.

Natural gas is growing in importance worldwide and is now making up a larger portion of oil companies' reserves. This trend is driven by discoveries of large gas volumes internationally along with the US shale gas revolution. In parallel to these changes in gas production and demand, oil prices have been increasing steadily over the past 2 yr and have more than doubled since 1Q 2016. As crude prices rise, petroleum product prices rise in tandem. Under normal circumstances, with higher product prices and relatively cheap, plentiful natural gas supplies, announcement of new GTL projects would be expected.

Natural gas in 2012 represented 23.9% of global primary energy consumption and was used mainly in space heating, power generation, industry and transport. While pipeline gas and LNG represent the more familiar routes to market.

Renewable Energy:

Renewable energy is generally defined as energy that comes from resources that are not significantly depleted by their use, such as sunlight, wind, rain, tides, waves and geothermal heat. Renewable energy is gradually replacing conventional fuels in four distinct areas: electricity generation, hot water/space heating, motor fuels, and rural (off-grid) energy services.

Based on REN21's 2014 report, renewables contributed 19 percent to our energy consumption and 22 percent to our electricity generation in 2012 and 2013, respectively. This energy consumption is divided as 9% coming from traditional biomass, 4.2% as heat energy (non-biomass), 3.8% hydroelectricity and 2% electricity from wind, solar, geothermal, and biomass.

World Total Energy Consumption:

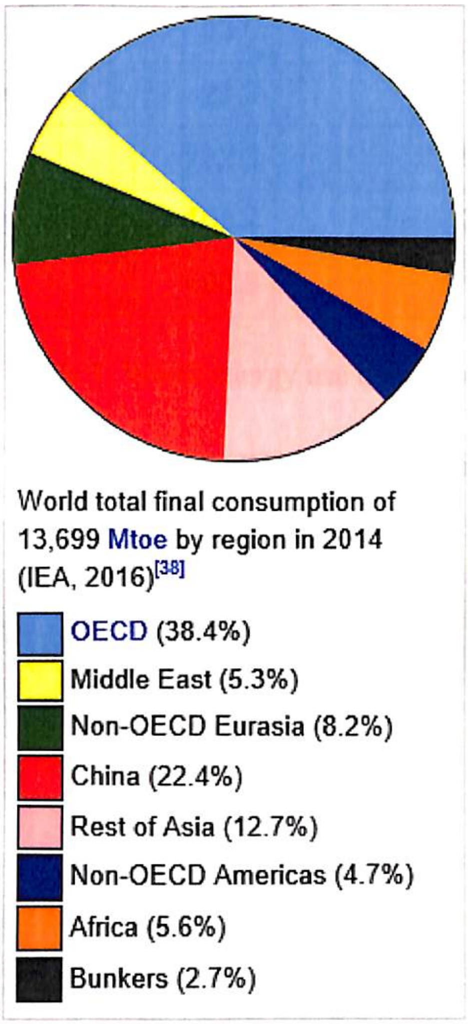

World total final consumption of 13,699 Mtoe by region in 2014 (IEA, 2016)[38]

Figure 4: World total energy consumption [7]

The amounts of energy consumed worldwide in 2012 by four sectors, according to the Energy Information Administration of the US Department of Energy:

- Residential (heating, lighting, and appliances)
- Commercial (lighting, heating and cooling of commercial buildings, and provision of water and sewer services)
- Industrial users (agriculture, mining, manufacturing, and construction)
- Transportation (passenger, freight, and pipeline)

Of the total 120 PWh (120×1015 Wh) consumed, 19.4 were in the form of electricity, but this electricity required 61.7 PWh to produce. Thus the total energy consumption was around 160 PWh (ca 550×1015 Btu). The efficiency of a typical existing power plant is around 38%. The new generation of gas-fired plants reaches a substantially higher efficiency of 55%. Coal is the most common fuel for the world's electricity plants.

World energy use by sector, 2012[89]

Sector	10^{15}Btu	Petawatt-hours	%
Residential	53.0	15.5	13
Commercial	29.3	8.6	7
Industrial	222.3	65.1	54
Transportation	104.2	30.5	26
Total*	**408.9**	**119.8**	**100**

Table 1: World energy use by sector [7]

- World Energy consumption, Wikipedia

1.2 Background

GTL is the conversion of natural gas into liquid products via reforming, synthesis and upgrading processes. The typical GTL product mix focuses on transportation fuels, primarily kerosene and diesel.

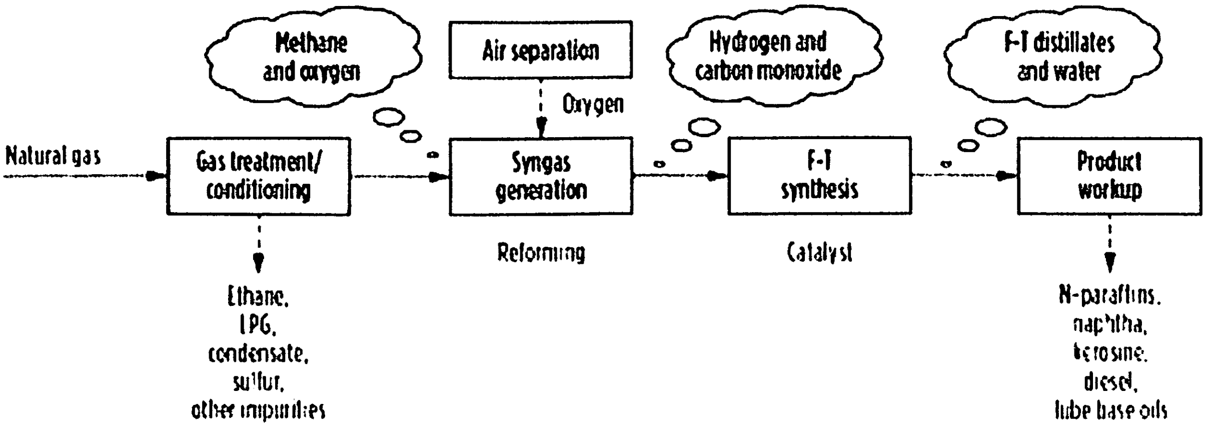


Figure 5: Schematic of GTL production process [10]

- Gas is a very abundant energy resource and will play a primary role in the future energy market.
- Next key technology step for the gas valorization will be related to logistics and transportation.
- The size of gas reserves, distance to market, and supply volatility determine the optimal technology for each development.
- Eni has a long history in gas valorization and is a world's leading vertically integrated natural gas company. Eni owns a complete technological portfolio that include proprietary processes for GTL to enter what is expected to be the "golden age of gas".

GTL technology has four main components:

1. Feedstock preparation

    - Natural gas treatment
    - Air separation to supply oxygen, although some plants make syngas ($CO + H_2$) without oxygen

2. Syngas production using catalytic reactors
3. Fischer-Tropsch (F-T) catalytic process to convert syngas into liquids
4. Liquid refining and separation.

The GTL plant has two main catalytic processes:

- Syngas generation, which can be from coal (e.g., Sasol's coal-to-liquids plant in South Africa), but more commonly uses natural gas as the feedstock to make syngas
- The F-T process, originally developed in Germany in the early part of the 20th century to convert coal and lignite to liquid petroleum products.

- **Production of liquid fuel from SYNGAS by the Fischer-Tropsch method with further pyrolysis of fuel to lower Olefins.**

Since most of ethylene is produced in the world via the pyrolysis of naphtha, and the Fischer–Tropsch method is used in world practice predominantly for the synthesis of liquid fuel, it also was of interest to consider the variant of the synthesis of lower olefins via the pyrolysis of liquid fuel obtained from syngas by the Fischer–Tropsch method. The sequence of reactions is actually the same as in the MTO process, but methanol is replaced by gasoline,
i.e., methane → syngas → gasoline → lower olefins

$$nCO + (2n + 1)H_2 \rightarrow C_nH_{2n+2} + nH_2O + n146.5\ \text{kJ/mol.}$$

They are operated at a pressure of 2.7 MPa and a temperature of 230°C. The capacity of each reactor is nearly 21 000 t/year.

The Fischer–Tropsch process has been implemented in industry predominantly in the fuel variant. The distribution of expenditures on its creation is the following: syngas production, 60%; Fischer–Tropsch synthesis, 25–30%; separation and upgrading, 10–15%.

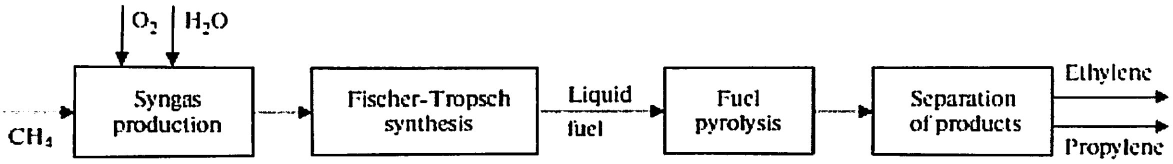


Figure 6: Production of lower Olefins via the Fischer-Tropsch synthesis [10]

- Technologies for the Synthesis of Ethylene and Propylene from Natural Gas

GTL products from a typical large-scale GTL plant are:

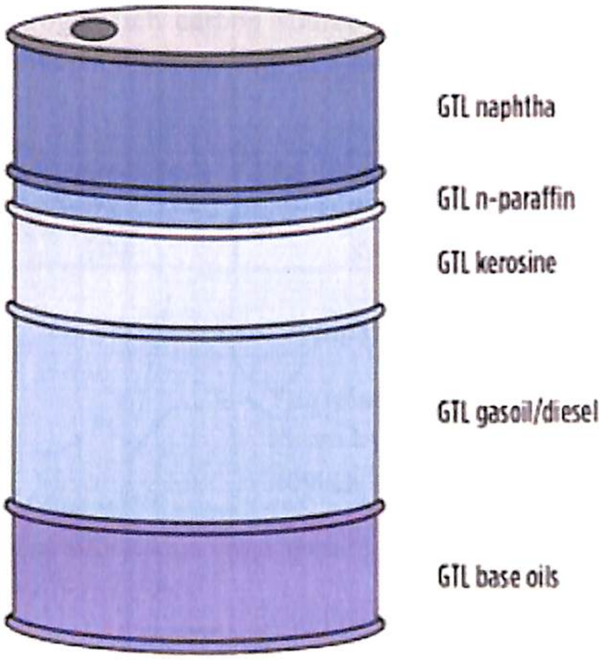


Figure 7: GTL Products from GTL production process [6]

Since the trough in oil prices in 1Q 2016, both crude and petroleum product prices have gone up in value, while natural gas prices have remained fairly low, average of \$2.74/MMBtu over the period.

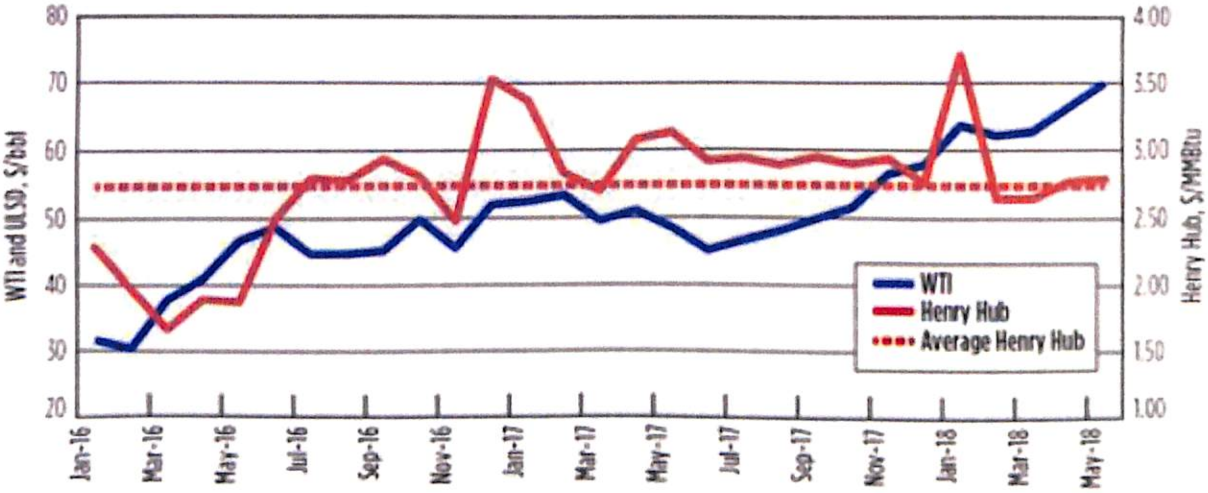


Figure 8: Rise in Crude oil prices vs. Henry Hub gas prices [6]

- Gas processing & LNG, Challenges facing GTL: Rethinking project economics in 2018 and beyond

Up until 2009, the average price relationship between natural gas and crude oil was around the 10:1 level. Oil trades in barrels while natural gas in millions of Btu's (British thermal units or MMBtu).

The ratio translates to 10mmbtu's of natural gas per one barrel of oil. If the price of crude oil is $40 per barrel of around $4 per MMBtu of natural gas.

Natural gas is the most Hydrogen-rich carbon source available on earth. There is an economic incentive for gas to liquid conversion when there is a meaningful price difference between natural gas and crude oil.

Feed material	Feed cost ($/bbl)	Efficiency (%)	Effective cost ($/bbl)
Natural Gas	28	75	37
Crude Oil	100	89	113

Table 2: Cost comparison [3]

- The relation between Crude Oil and Natural Gas Prices by Jose A. Villar, Natural gas Division, Energy Information Administration

Global primary natural gas demand will increase from 3.1 tcm to 5.1 tcm in 2035, with an average rate of increase being close to 2% per year.

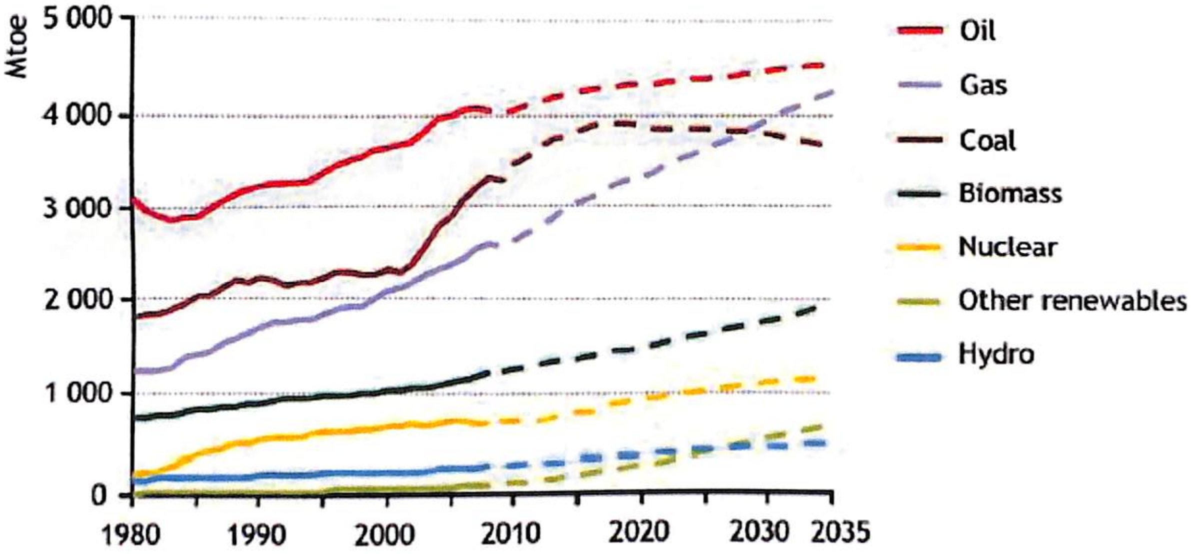


Figure 9: Natural Gas future demand [1]

- Technology role for Natural Gas Valorization, Eni report

Pipeline transport and LNG frequently have logistical constraints due to the geography (and sometimes geopolitics) of the main gas pipelines routes and the restriction to coastal locations for LNG regasification facilities. The demand for these channels of gas transportation and monetization is also subject to future uncertainties.

Qatar, which after Russia and Iran is the third largest natural gas reserves holder in the world, has successfully implemented a diversified global LNG marketing strategy. In 2006 and 2011 Qatar also brought into commercial operation two FTGTL production plants: Oryx GTL and Pearl GTL based on Sasol and Shell technologies.

There are a variety of processes which produce synthetic liquid hydrocarbons from other hydrocarbon or biomass feedstocks. These include Gas to Liquid (GTL); Coal to Liquid (CTL); Biomass or Biogas to Liquid – biofuels (BTL).

- The Oxford Institute for Energy Studies, Olga Glebova, NG-80

GTL dilemma:

Pros	Cons
• Gains access to abundant gas reserves	• High Capex
• Possible value chain opportunities and synergies (upstream and chemicals)	• Low energy efficiency
• Global growth in liquid fuels demand	• Price spread gas – oil uncertainty
• Legislation mandating low Sulphur, lighter, clean-burning fuels	• Limited industrial references

Gas to Liquid (GTL) is a refinery process to convert natural gas to other gaseous hydrocarbons into longer chain hydrocarbons, such as gasoline or diesel fuel. The motivation for GTL is to produce liquid fuels, which are more readily transported than methane.

The status of the Natural Gas Valorization Technologies:

Mature Technologies:

Energy Market:
- LNG
- Large Scale Methanol
- Industrial Power Project
- Pipeline

Chemical Market:
- Methanol
- Ammonia, Urea

New Technologies: (limited application)

Energy Market:
- Small-Medium Energy
    - ➢ On-shore application for local market
    - ➢ Access to regional or international gas markets
    - ➢ Suitable for small-medium reserves (typical train capacity: 50ktpa upto 2 mtpa)
- Floating LNG
    - ➢ Typical LNG train capacity for floating application: from 1 up to 3.6 mtpa

Fuel Market:
- GTL
- DME (Di-Methyl Ether)

Technology under development (R&D)

Energy Market:
- Marine CNG (composite)
    - Transportation of compressed gas at 200-250 bar
    - Suitable for regional market (max 3000km) and small medium reserves
- NGH (Natural Gas Hydrate)

Fuel Market:
- Floating GTL
- Breakthrough technologies for direct conversion

New Technologies (no application)

Energy Market:
- Marine CNG

Fuel Market:
- Small Scale GTL

- Technology role for Natural Gas Valorization

We will begin by reviewing the historic development of the industrial-scale production

Malaysia

The Bintulu GTL plant in Malaysia is situated on Sarawak Island in Bintulu and since 1993 has produced the following products: liquefied petroleum gas (up to 5%), naphtha (up to 30%), diesel fraction (up to 60%) and paraffin (up to 5-10%). Natural gas from the fields offshore Sarawak is used as the syngas feedstock.

New Zealand

In 1985 ExxonMobil brought onstream a plant producing gasoline from methanol (Methanol to Gasoline technology (MTG) or "Mobil-process") in New Zealand (New Plymouth city) with a capacity of about 14,500 b/d of synthetic gasoline.

The Republic of South Africa

In 2002 the partnership "GTL.F1AG" was created to construct a pilot GTL plant at the Mossgas plant complex in Mossel-Bay. Its shareholders became: Statoil (Norway) -37.5%; PetroSA (Republic of South Africa)-37.5%, Lurgi (Germany) -25%). Technology developed by Statoil is used at the plant for manufacturing GTL.

Qatar Petroleum/Sasol

Qatar has built and commissioned significant GTL production capacity during the period from 2006 to 2012. Given its emergence in the same period as the world's largest LNG producer while at the same time developing its domestic industrial sector based on gas feedstock, it is reasonable to ask why Qatar also undertook the construction of the world's largest GTL facilities at this time.

Qatar Petroleum/Shell

In 2006 the QSGTL partnership (Qatar Petroleum-75% and Shell -25%) was established for the construction and operation of the Pearl GTL project. It is located 75 km from the capital of Qatar in Ras Laffan city. Shell was responsible for providing the capital investment 26.
Unlike Oryx GTL, Pearl GTL is a completely integrated project "from offshore well to GTL products". It includes gas production, processing of gas and FTGTL production. The plant feedstock is 1.6 bcf/d (or 45.3 mmcm/d.) of natural gas from the gas-condensate North Field.

- The Oxford Institute for Energy Studies, Olga Glebova, NG-80

1.3 Purpose of the study

The growth of the demand for lower olefins will inevitably increase the demand for the feedstocks required in the petrochemical industry. With the recent high oil prices, research has been directed to the development of processes based on alternative feedstocks for the production of lower olefins.

Apart from high oil prices, there are some other drivers in the search for alternative routes and feedstocks:

- The production of lower olefins via steam cracking is one of the ten most energy-consuming processes of the chemical and petrochemical industry.
- There is a growing awareness of the depletion of conventional oil reserves. Some analysts suggest that oil consumption will surpass the discovery of new reserves followed by the depletion of known reserves.
- The oil contained in unconventional reserves is heavy oil in the case of so-called oil sands. The extraction and upgrading of unconventional oil currently may involve higher costs and higher CO2 emissions in comparison with conventional oil.
- There is a pressing necessity to decrease CO2 emissions. Feedstocks such as biomass have lower net CO2 contribution.
- Many countries, among them Japan, China, and Brazil, are searching for alternatives to reduce their reliance on imported crude oil and refined products.

Several processes have been developed in an attempt to solve one or more of the challenges encountered by the lower olefins industry. These processes are based on alternative feedstock such as coal, natural gas, or biomass.

Increasing urban air pollution, greenhouse gases, and declining fossil energy sources are the three major problems of transportation sector which drive the use of alternative vehicular fuels to prevent energy shortage, reduce oil dependency and decrease tailpipe emissions including air pollutants and greenhouse gas emissions. This dissertation focused on life cycle analysis of HCNG heavy-duty vehicle in which 15% gaseous hydrogen blended with compressed natural gas has been investigated in terms of net energy ratio, GHG value, and cost-effectiveness over a scale of 'per MJ energy output' in two fuel options, i.e. 0%HCNG and 15%HCNG for an entire well-to-wheel cycle. An engineering economic approach has been used to evaluate cost-effectiveness ratio of CNG and 15%HCNG pathways derived from fuel economy improvement.

- The well-to-wheel analysis of hydrogen enriched compressed natural gas for heavy duty vehicles using life cycle approach to a fuel cell

1.4 Research Hypotheses

In today's modern world, where new technologies are being introduced, use of transportation energy is increasing rapidly. Fossil fuel, particularly petroleum fuel, is the major contributor to energy production. Fossil fuel consumption is continuously rising as result of population growth in addition to improvements in the standard of living. Increased energy demand requires increased fuel production, thus draining current fossil fuel reserve levels at a faster rate. This has resulted in fluctuating oil prices and supply disruptions. Rapidly depleting reserves of petroleum and decreasing air quality raise questions about the future. Alternative fuels such as CNG, HCNG, LPG, LNG, bio-diesel, biogas, hydrogen, ethanol, methanol and di-methyl ether have been tried worldwide. The use of hydrogen as a future fuel for internal combustion (IC) engines is also being considered.

India is one of the few developing countries actively working on the research and development of hydrogen-based transportation. Under the Ministry of New and Renewable Energy's National Hydrogen Energy Roadmap, various research institutes and vehicle manufacturers have been conducting research on developing competitive and safe methods for production, storage and transportation of hydrogen since 2003. Currently, 96% of hydrogen is produced from natural gas, other fossil fuels and biomass. Hydrogen produced from natural gas could reduce CO2 emissions by 40-65% compared to petrol. Vehicles were also successfully modified and demonstrated to support hydrogen fuel.

Earlier this year, Tata Motors developed a hydrogen fuel-cell bus. However, a complete transformation to hydrogen is difficult, especially for developing countries like India, because of economic and infrastructure challenges. The present price of hydrogen in India at the delivery point is estimated to be Rs 876/kg (equivalent petrol price is Rs 175). With the cleanest method of hydrogen production, electrolysis of water, the price would nearly double.

Hydrogen as a fuel for transportation will have huge global traction in the near future. Shifting to hydrogen vehicles will, doubtless, reduce emissions. However, rigorous research is required to reduce the cost of production and transportation of hydrogen in India. The cost of hydrogen vehicles has dropped worldwide by 80% since 2002. Car manufacturers are targeting to reduce their cost by a further 75% by 2030. This would make hydrogen vehicles more affordable in India.

Main drivers for introducing Hydrogen Enriched Compressed Natural Gas Blended Fuel for automobiles are to increase IC engine performance and reduction of both local pollutants and emission gases from environments. Air pollution is fast becoming a serious global problem with increasing population and its subsequent demands. This has resulted in increased usage of hydrogen as fuel for internal combustion engines. Hydrogen resources are vast, and it is considered as one of the most promising fuel for automotive sector.

Hydrogen as an energy source is widely touted to be the future transportation fuel. In this context, the Supreme Court of India advised the Delhi government and the Environment Pollution (Prevention & Control) Authority (EPCA) to analyse the feasibility of hydrogen in the transportation sector and the reduction in GST for hydrogen vehicles.

The energy content of hydrogen is 130 megajoules/kg, much higher than that of fossil fuels (45 and 46 MJ/kg for diesel and petrol, respectively). Moreover, water is the only byproduct of its combustion.

- Review on Opportunities and Difficulties with HCNG as a future fuel for IC engine

Worldwide adoption of hydrogen has been rising steadily. Currently, hydrogen vehicles are operated in the US, Japan, Denmark, Germany, China, France, and South Korea. Car manufacturers such as Toyota, Hyundai and Honda are selling hydrogen-fueled cars that can provide fuel economy of upto 28 km/litre of petrol equivalent (~2-3 times of petrol). Hydrogen-fuelled buses have a higher range (around 300-450 km) than EV buses (upto 249 km). The fuel-filling time for hydrogen is comparable to that of petrol and diesel and much better than for charging EVs (4-6 hours). This makes it suitable for adoption in medium-to-heavy vehicles.

However, infrastructure development will remain the major constraint. As a starting point to this transition, HCNG fuel (with 18-23% H_2 blended with compressed natural gas) can be used in existing CNG vehicles with minor modifications. Recently, EPCA has suggested shifting from CNG to HCNG in public buses in Delhi, by utilising the current infrastructure, instead of deploying electric buses. This will help in developing the infrastructure for hydrogen production, supply and storage.

The Delhi government has collaborated with Indian Oil Corporation to deploy 50 HCNG buses and a fuelling station next year. This would reduce greenhouse gas (GHG) emissions from CNG vehicles by 15-20%, carbon monoxide (CO) emissions by 70%, and hydrocarbon emissions by 15%. This will also improve fuel economy. In fact, HCNG can easily meet new BS-VI emission standards, with some emission controls for nitrogen oxides (NOx), such as SCR converters. EPCA has estimated that the fuel cost for HCNG is estimated to increase by Rs 0.75/km compared to CNG, nearly 4.5% of the current CNG price in Delhi. This is marginal compared to the usual annual price hike in CNG.

Other cities in the NCR and in states with a good CNG supply (such as Gujarat and Maharashtra) should also consider a transition towards HCNG. Using HCNG has the potential to reduce GHG emissions by 0.67–1.42 million tons annually in India.

The total requirement of HCNG for a complete transition in all vehicles in India is estimated to be around 6,600 tons a day. This needs an initial ballpark investment of Rs 5,445 crore, estimated based on EPCA's assessment specific for Delhi. This amount is in the same range as that of the subsidy corpus allocated for EVs for five years. Allocating a budgetary amount for HCNG infrastructure for the next five years would help in transitioning to a cleaner, hydrogen-based economy. Road tax waivers and government subsidies for installing fuelling stations could also help bring about a notable transition to hydrogen-fuelled vehicles.

- Hydrogen: towards cleaner and sustainable transport

The concept of using hydrogen enhanced compressed natural gas fuel for HDVs has been well understood by many researchers and scientists. Although HCNG® is comparatively more advantageous than conventional CNG in terms of performance and cleaner emissions, the large scale application has not been achieved till now. One of the major barriers to large scale marketization of HCNG is immaturity of 'hydrogen economy' which encompasses hydrogen production, storage, T&D and HCNG fuelling infrastructure. Therefore, to get the deep insight to HCNG technology, life cycle analysis is an effective choice.

- The well-to-wheel analysis of hydrogen enriched compressed natural gas for heavy duty vehicles using life cycle approach to a fuel cell

Tremendous works have been done to achieve performance and emission evaluation of HCNG vehicles since past few decades. Interestingly, most of the scientific research works have claimed numerous advantages of hydrogen addition to compressed natural gas fuel at optimized engine's operating conditions. The 20% hydrogen enrichment (HCNG®) requires no severe engine's modifications apart from slight adjustments in the fuel supply system and operating conditions. It is also obvious to find out a slight reduction in brake specific fuel consumption and exponentially decreased air pollutants and tailpipe emissions. However, it has not achieved commercialization phase till now and one thing that hinders its promotion is the 'hydrogen economy' itself. The purpose of this investigation was to perform a simplified version of life cycle analysis for demonstration project which presents the full picture of environmental impacts of HCNG® aimed for light-duty vehicle usage and has been compared with counterpart baseline CNG vehicle. Hydrogen is not a primary energy source, rather it is an energy carrier. Henceforth, the feedstock for hydrogen production plays a vital role in the realization of cleaner and efficient HCNG vehicle technology. The stringent emission and fuel economy requirements for light-duty vehicle operations demand the use of clean-burning alternative fuels such as compressed natural gas. The ultimate goal of this work was to find the amount of energy (MJ/km) required 'per vehicle km' and grams of CO2, equivalent (GWP) per vehicle km (g/km). Results give the understanding of two perspectives; qualitative and quantitative. Generally speaking, researchers proved that the 20-30% HCNG overpasses the dominance of CNG in three major tiers: reduction on fuel consumption, air pollutants, and as greenhouse gas emissions depending upon the accuracy of operating conditions.

In 2007, suggested that China surpassed the USA as the world's largest contributor to CO2 emissions. The rapid increase in economic growth rate, urbanization, and industrialization over the past few decades (in particular for last 10 years) in China has resulted in the tremendous booming of transportation services and automobile markets. Currently, China is the world's largest automobile market and among one of the fastest growing nations in the global automobile market. Compared to conventional buses, AFVs offer better performance and reduced GHG emission. However, only half of the AFVs analyzed proved to be fulfilling dual benefits (energy saving & lower GHGs). According to Anadolu Agency, China is currently leading with the most natural gas vehicles. It has been pointed out that China has the largest population of natural gas vehicles globally followed by Iran and India at the end of 2017, according to the current statistics of NGV Global.

Hydrogen is a zero-emitter fuel with a very fast laminar burning speed and wide range of flammability which confirms it as one of the superlative energy carrier to enhance the slow burning rate of CNG at lean burn and constitute tremendous possibilities to empower the present generation internal combustion engines together with compressed natural gas which sounds promising at the current era of transition to a greener future transportation [12]. NOx, CO, NMHC, CH4 emissions, and BSFC decreases by 51%, 36%, 47%, and 7%, respectively whereas the maximum power remains the same with HCNG® (20% HCNG) as compared to baseline CNG engine.

- Life cycle analysis of HCNG light duty vehicle demonstration project

2 Literature Review

Natural gas is a major source of electricity generation through the use of cogeneration, gas turbines and steam turbines. For transportation, burning natural gas produces about 30% less carbon dioxide than burning petroleum. It can also be use for production of refinery products and petrochemicals etc.

Combined Cycle Plant for Power Generation: Introduction

The process for converting the energy in a fuel into electric power involves the creation of mechanical work, which is then transformed into electric power by a generator. Depending on the fuel type and thermodynamic process, the overall efficiency of this conversion can be as low as 30 percent. This means that two-thirds of the latent energy of the fuel ends up wasted. For example, steam electric power plants which utilize boilers to combust a fossil fuel average 33 percent efficiency. Simple cycle gas turbine (GTs) plants average just under 30 percent efficiency on natural gas, and around 25 percent on fuel oil. Much of this wasted energy ends up as thermal energy in the hot exhaust gases from the combustion process.

To increase the overall efficiency of electric power plants, multiple processes can be combined to recover and utilize the residual heat energy in hot exhaust gases. In combined cycle mode, power plants can achieve electrical efficiencies up to 60 percent. The term "combined cycle" refers to the combining of multiple thermodynamic cycles to generate power. Combined cycle operation employs a heat recovery steam generator (HRSG) that captures heat from high temperature exhaust gases to produce steam, which is then supplied to a steam turbine to generate additional electric power. The process for creating steam to produce work using a steam turbine is based on the Rankine cycle. The most common type of combined cycle power plant utilizes gas turbines and is called a combined cycle gas turbine (CCGT) plant.

There are different alternative routes to produce the refinery products, Petrochemicals etc. other than the traditional route of crude oil.

- The simplest ethylene synthesis method is the oxidative condensation (or dimerization) of methane (OCM process), but the implementation of this method is discouraged by a low ethylene yield.
- Among the relatively simple methods for the synthesis of ethylene (together with acetylene)
- immediately from methane are thermooxidative pyrolysis (TOP process) and pyrolysis in the presence of chlorine (Benson process), whose disadvantages are a high temperature and a great number of byproducts.
- A wide range of processes for the synthesis of ethylene and propylene with a small amount of butylenes are based on the intermediate synthesis of syngas from methane and its further use for the direct synthesis of lower olefins or products for subsequent catalytic pyrolysis to lower olefins, such as methanol (methanol_to_olefins (MTO) and methanol_to_propylene (MTP) processes), dimethyl ether, and liquid fuel (Fischer–Tropsch method).
- The methyl chloride_to_olefins (MCTO) process consisting of the synthesis of methyl chloride via the oxidative chlorination of methane and the catalytic pyrolysis of methyl chloride differ from these three stage processes in the absence of the syngas production stage.
- Production of liquid fuel from SYNGAS by the Fischer-Tropsch method with further pyrolysis of fuel to lower Olefins.
- Production of lower olefins from Syngas from Coal.
- Production of lower olefins from Syngas from biomass.

- GTL Fuels: Shell GTL Fuel is an alternative fuel for use in diesel engines, which can lower local emissions (e.g. particulate matter, NOx, hydrocarbons and carbon monoxide). It can be used in existing heavy-duty diesel vehicles without modifications, allowing for easy switchover from diesel fuel with no infrastructure investment required. Shell GTL Fuel is already in daily use with commercial fleets in Germany and the Netherlands.
- GTL Kerosene: GTL Kerosene is a synthetic product made from natural gas rather than crude oil, which can be used in aviation and other applications. Compared with conventional oil-based kerosene, GTL Kerosene produces virtually zero sulphur dioxide emissions and lower particulate emissions. This means that once blended with conventional jet fuel to create GTL Jet Fuel, it can be attractive to airlines and airport authorities keen to improve local air quality at busy airports by reducing local emissions.
- GTL Normal Paraffins: GTL Normal Paraffin is an alternative feedstock for detergent production replacing normal paraffins from oil-based kerosene. Also known as light detergent feedstock (LDF) and heavy detergent feedstock (HDF), these products are used in making washing up liquids and PVC plasticisers.
- GTL Base Oil: GTL Base Oils represent an entirely new way of producing synthetic base oils – the main component of lubricants – from natural gas. We market our gas-to-liquid process in the lubricants industry as Shell PurePlus Technology. It converts natural gas into crystal-clear base oils with virtually none of the impurities found in crude oil.
- GTL Naphtha: GTL Naphtha is an alternative high-quality feedstock for chemical manufacturing that makes the building blocks for plastics. It offers superior yields of ethylene and propylene over conventional naphtha.
- Biogas to use as alternative fuels.
- HCNG as a future fuel for Internal combustion engine.
- Hydrogen as a future fuel for Internal combustion engine.

- Technologies for the Synthesis of Ethylene and Propylene from Natural Gas

C2 to C4 olefins are traditionally produced from steam cracking of naphtha. The necessity for alternative production routes for these major commodity chemicals via non-oil-based processes has driven research in past times during the oil crises. Currently, there is a renewed interest in producing lower olefins from alternative feedstocks such as coal, natural gas, or biomass, in view of high oil prices, environmental regulations, and strategies to gain independence from oil imports. This review describes the major routes for the production of lower olefins from synthesis gas with an emphasis on a direct or single step process, the so-called FTO or Fischer–Tropsch to olefins process. The different catalysts for FTO are outlined and compared, and the key issues and requirements for future developments are highlighted. Iron-based catalysts are prevailing for FTO, and reproducible lower olefin selectivities of 50 wt % of hydrocarbons produced have been realized at CO conversions higher than 70% for 60 to 1000 h on stream. Remarkably the high selectivity to lower olefins has been achieved over a broad range of process conditions (P, T, H2/CO ratio, GHSV). A major challenge for further development and application of FTO catalysts is the suppression of carbon lay-down to enhance catalyst lifetime and to preserve their physical integrity under demanding reaction conditions.

- Catalyst for Production of lower Olefins from Synthesis Gas: A Review

The method of producing liquid fuel through the oxychlorination of methane was more profitable than others. The results of comparative analysis of the capital cost for processing natural gas to liquid hydrocarbons.

	Oxidative condensation	Partial oxidation	Oxychlorination of methane	MTG*, fixed bed	MTG, fluidized bed	Fischer–Tropsch process
Processing equipment	273.2	346.9	218.4	261.1	220.5	240.0
Utilities, infrastructure, and offsites	208.2	273.5	204.8	208.3	203.6	216.9
Miscellaneous expenses	202.1	223.6	173.8	213.3	197.4	189.9
Total	683.5	844.0	597.0	682.7	621.5	646.8

*MTG, methanol-to-gasoline conversion.

Table 3: A comparative analysis of capital costs of the processing of natural gas into liquid hydrocarbons (million U.S. dollars at a capacity of 14500 bar/d) [10]

The engineering and economic evaluation OCM process was performed for its implementation both in a gas producing region and at a chemical enterprise which consumes ethylene for further processing and incurs a deficit of it. The calculations were performed for an industrial unit with a capacity of 200 000 t of ethylene per year.

Yield of products	Gaseous hydrocarbon feedstocks, wt %			Liquid hydrocarbon feedstocks, wt %	
	ethane	propane	butanes	naphtha	gasoil
Hydrogen and methane	13	28	24	26	23
Ethylene	**80**	**45**	**37**	**30**	**25**
Propylene	**1.11**	**14.0**	**16.4**	**14.1**	**14.4**
Butadiene	1.4	2	2	4.5	5
Mixture of butylenes	1.6	1	6.4	8	6

Table 4: Yield of products in the steam cracking of different hydrocarbon feedstocks [10]

Ethylene, propylene, and butylenes are key building blocks in the chemical industry. Throughout this review we refer to C2–C4 olefins as lower or light olefins. These base chemicals are among the organic chemicals with the largest production volumes worldwide. Their broad spectrum of derivatives result in a very diverse end market ranging from packing materials and synthetic textiles to antifreezing agents, solvents, and coatings.

	U.S.A.	Asia[a]	China	Europe
ethylene	23975	18237	14188	19968
propylene	14085	14295	na[b]	14758
ethylene dichloride	8810	3222[c]	na	1323
benzene	6862[d]	10889	5530	5107
ethyl benzene	4240	na	na	1226
cumene	3478	na	na	na
ethylene oxide	2664	845[c]	na	2619
butadiene	1580[e]	2715	na	2020
methanol	na	na	15740	na

Table 5: Production of Organic Chemicals in 2010 in Thousands of Metric Tons [11]

Ethylene is the largest-volume petrochemical produced worldwide. It is used to produce intermediate chemicals of high importance in industry such as ethyl benzene, ethylene oxide, and ethylene Dichloride etc.

Ethylene is mainly used by the plastics industry. In 2010, approximately 61% of the total consumption of ethylene was for production of polyethylene in the Western European countries.
Ethylene is also used in the production of other plastics such as polystyrene (PS), polyethylene terephthalate (PET), and polyvinyl chloride (PVC), which are widely used in the packaging, textile, and construction industries.

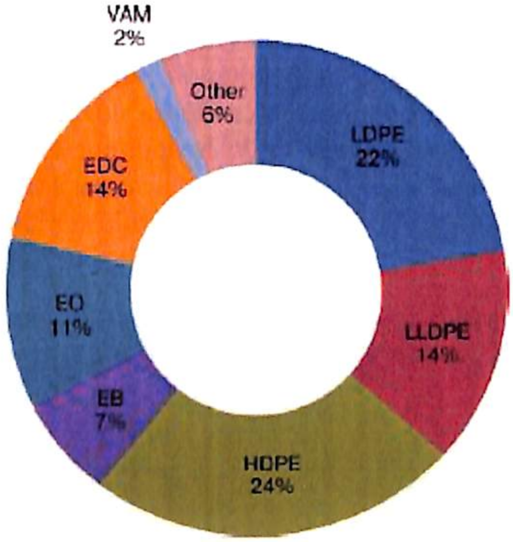


Figure 10: Ethylene consumption over different products in the Western European countries [11]

Commercial ethylene production is mainly based on steam cracking of a broad range of hydrocarbon feedstocks. In Europe and Asia, ethylene is obtained mainly from cracking of naphtha, gas oil, and condensates, while in the U.S., Canada, and the Middle East ethylene is produced by cracking of ethane and propane. Naphtha cracking is the major source of ethylene worldwide; however, gas cracking has been gaining importance in recent years.

Propylene is a versatile petrochemical which has even more derivatives than ethylene. However, the tremendous growth of polypropylene consumption over the past 15 years has been the main driver of the large increase of the demand of propylene. In 2010, more than 55% of propylene consumption was dedicated to the production of polypropylene in the Western European countries. Approximately 13% of the propylene was used in the production of propylene oxide, which is a chemical precursor for the synthesis of propylene glycol and polyols. The rest of the production was used in the synthesis of cumene (about 8%), acrylonitrile, isopropyl alcohol, and many other industrially relevant chemicals.

The C4 olefins fraction is composed of butadiene, isobutylene, and n-butenes which are used in fuel and chemical applications. Butadiene is mainly used as raw material for the production of different types of synthetic rubber (SBR, polybutadiene rubber, etc.). These synthetic rubbers are in high demand all over the world, especially in Asia, for the manufacture of finished goods in the electronics and automotive sectors. Butadiene is also used for the production of ABS (acrylonitrile–butadiene–styrene), SB (styrene–butadiene) copolymer latex and block copolymers, and nitrile rubbers (NBR). One of the most important applications of butylenes is in the fuel industry, accounting for approximately 85% of butylenes' world production.

- Catalyst of Production of Lower Olefins from Synthesis Gas: A Review

According to expert estimates, the approximate relative cost of olefins obtained by different methods has proven to be minimal for the lower olefins synthesized from ethane.

Expert estimates cannot always be true, as it is difficult to take into account all the expenditures and complexities of technologies. For example, the separation of ethane requires laborious natural gas purification and drying stages and then the separation of ethane under pressure and a temperature below −100°C. A high ethylene yield is usually observed in the pyrolysis of ethane. However, other products, including such a valuable component as propylene, are hardly formed in this case. At nearly equal prices on straight run gasoline, ethane, and liquefied gases, a decrease in the unit consumption of feedstocks and a number of other items of expenditures upon the transition from gasoline fractions to gaseous fractions is accompanied by a nearly equal decrease in the value of byproducts. For this reason, there is almost no decrease in the prime cost in comparison with the use of gasoline.

Moreover, ethane separated from all the natural gas produced in the world under the assumption that its content is 3% on average will provide only one third of the world demand for ethylene.

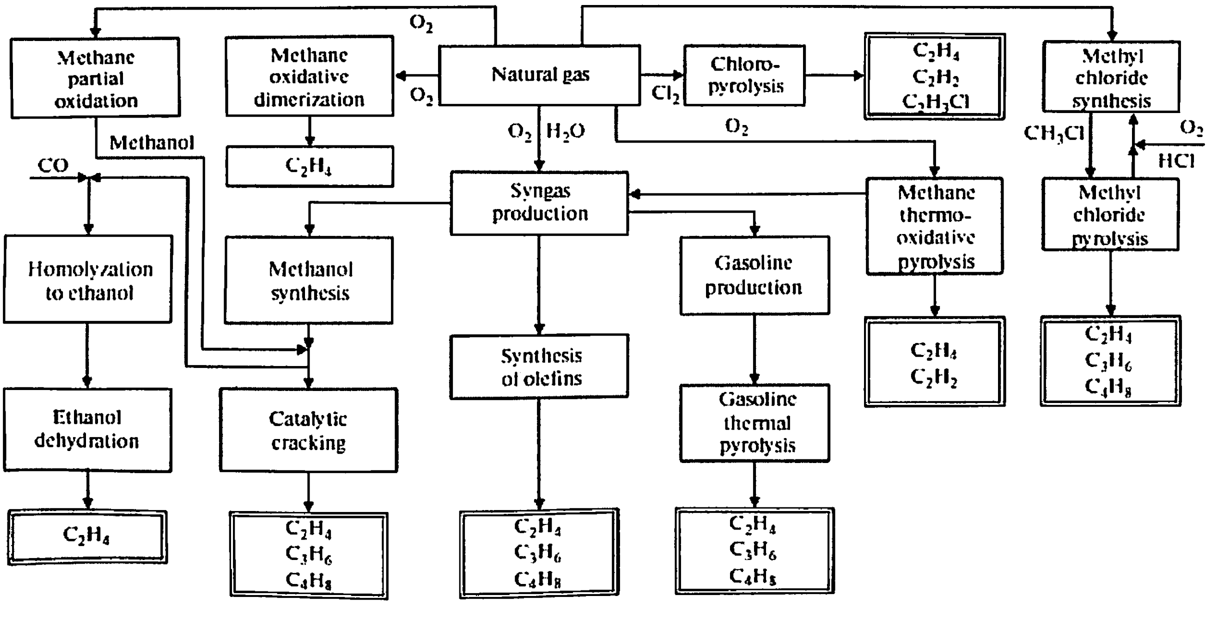


Figure 11: Different variants for the production of Olefins from natural gas [10]

- Technologies for the Synthesis of Ethylene and Propylene from Natural Gas

2.1 Review Area Broad

Exploring the Intersection of Hydrogen fuel cell and Natural gas vehicles

Topic will explore the infrastructure requirements, regional trends, and tradeoffs and opportunities at the intersection of hydrogen fuel cell and natural gas use for on road transportation.

2.1.1 Natural Gas vehicles

Natural gas, composed primary of methane, is extracted from oil and gas wells via drilling as well from shale formations via hydraulic fracturing. The natural gas is then separated and processed to meet quality standards for water content, hydrocarbon dewpoint, heating value, and hydrogen sulphide content.

As a domestic resource, natural gas is attractive for reducing oil imports, and as a fossil fuel it is attractive because of its low carbon: hydrogen ratio and high thermal efficiency in combustion. Natural gas vehicles (NGVs) have cleaner tailpipe emissions profiles relative to conventional gasoline and diesel vehicles. For light duty vehicles (LDVs) , the total CO_2 emission are approximately 25% less per mile traveled than a gasoline engine. Medium and heavy duty vehicles (HDVs) running on natural gas also have lower emissions of particulates, NOx, CO_2, and hydrocarbons.

Since natural gas is a gaseous fuel at atmospheric conditions, it occupies a large volume relative to liquid fuels. It is thus stored on vehicles at high pressure as compressed natural gas (CNG) or as a cooled liquid as a liquified natural gas (LNG), which increases a cost and weight of NGVs relative to gasoline or diesel. It takes 3.8 gallons of LNG to equal the energy contents of a gallon of diesel.

Despite the additional vehicle cost and weight, the lower fuel prices can make NGVs attractive for many applications. Over the past several years, CNG has been about 50-70% and LNG has been 80-90% the price of an energy equivalent amount of diesel. The Energy information Administration projects that natural gas will offer a significant fuel cost savings over gasoline and diesel through at least 2040. Moreover, the Potential Gas Committee's most recent assessment estimated that as of 2012, the US possesses a technically recoverable resources base of 2,384 trillion cubic feet, the highest estimate ever. This is enough gas for decades, if not a century of use, even if NGVs became more common place. For example, if 10% of all US LDVs in 2035 were NGVs, it would represent a 2.8% increase in total US natural gas demand for that year.

Current state of technology and development

A CNG fuel system lowers high-pressure gas from the storage tank to the operating pressure of the engine. The gas is then injected into the engine similar to the way gasoline is injected into a gasoline engine. The driving experience, engine and powertrain are thus largely identical to a gasoline model. This is in contrast to other alternative fuel vehicles (AFVs), such as electric vehicles (EVs) or fuel cell electric vehicles (FCEVs) and makes NGV easily accessible.

Even in these forms, the storage requirements are still greater than gasoline or diesel, thus NGVs typically have increased weight and purchase costs and slightly lower fuel economy and range.
Natural gas storage costs are the primary contributor to NGV purchase premiums. CNG tanks are typically made out of solid steel, to maintain an internal pressure of 3600 psi, while also being safe enough to withstand damage from a collision.

Infrastructure:

According to DOE AFDC, there are 743 public CNG stations and over 1400 including private installations in the US. The large number of private stations reflects CNGs adoption among fleet owners conducting regional operations; centralized refueling of CNG powered vehicles can take advantage of lower cost slow-fill technologies.

Natural gas infrastructure for transportation is significantly added by the fact that the natural gas transmission pipelines already exist for electric power, industrial, commercial, and residential purposes. While NGV stakeholders will likely not have to fund significant new natural gas transmission pipelines, the cost of installing CNG or LNG dispensers can still be daunting.

CNG refueling stations can be time-fill or fast-fill (DOE AFDC). Time-fill stations take fuel from a utility line and use a compressor to raise the gas to high pressure. Fast-fill stations use a high powered compressors. The CNG is stored in and dispensed from a series of storage tanks at high pressure (4,300 psi), which enables a fill time comparable to gasoline fueling. The CNG compressors are noise and consumed significant electricity. Combined with the storage requirements needed for fast-fill, stations require significantly more space than gasoline or diesel fueling infrastructure.

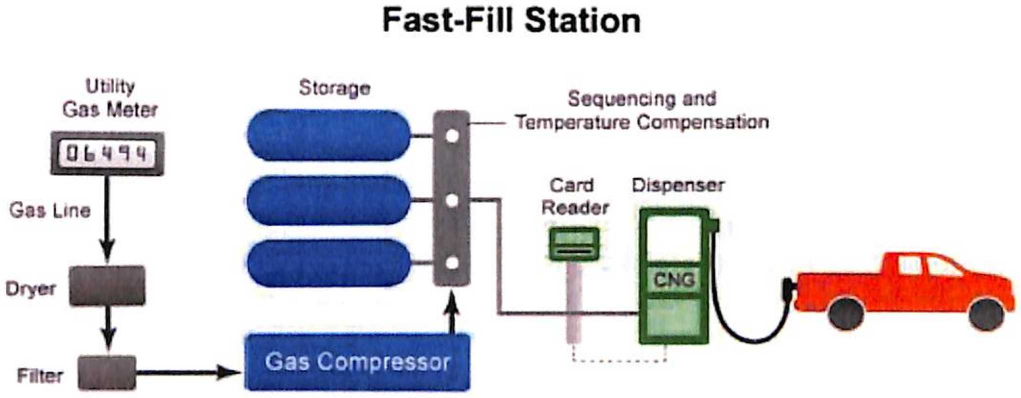


Figure 12: CNG fast-fill station configuration [13]

LNG uses dispensers that are more similar to gasoline or diesel. It is a liquid fuel dispensed at 30-120 psi (DOE AFDC). LNG stations have additional complications, such as tank truck offloading, cryogenic fuel storage, vapor management, and venting minimization. Liquefaction of natural gas requires cooling of temperatures of -260 degF and filtering to remove impurities, and is therefore most efficiently done in a dedicated, centralized facility and is normally delivered by truck to fueling stations.

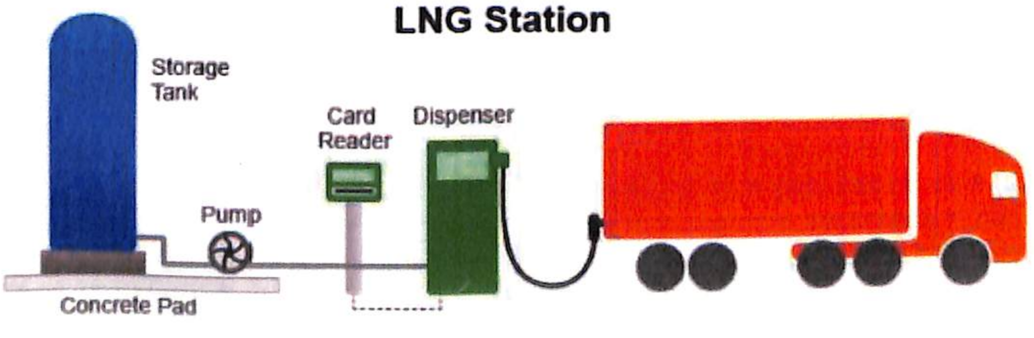


Figure 13: LNG station configuration [13]

Opportunities and challenges

Cost

The general industry prospective is that trucks travelling less than 200-300 miles between fueling are better suited to CNG and longer distance are better suited to LNG, relative fuel price and the "weight-sensitivity" of the operation.

Moreover, the weight-sensitivity operations may need to compensate for using CNG or LNG by making additional trips – thus a greater discount rate relative to diesel is needed to make natural gas cost competitive.

Efficiency

NGVs are typically less efficient than the gasoline or diesel vehicles they replace. For LDVs, natural gas is typically used in spark-ignited engines that are designed to perform optimally with gasoline.

For HDVs, spark-ignited NGVs replace compression-ignited diesel vehicles. This efficiency deficit is more pronounced than for LDVs because compression-ignited engines can achive higher compression ratios and higher thermal efficiencies. Another source of efficiency loss for heavy duty LNG vehicles is burnoff, essentially the evaporations of LNG that escapes the fuel tank. This is one reason LNG is best suited for long haul trucks since many hours of continuous driving minimizes the burnoff losses per tank.

Safety

The safety challenges in an NGV stem from the high pressure storage of gas and/or the combustion risk of natural gas. The greatest risk is the puncturing of a CNG tank during an accident. Since natural gas is lighter than air, it would dissipate quickly if it escaped from the storage tank, and the placement of the tank away from the engine keeps the fumes away from high temperatures (natural gas ignition temperature is higher than gasoline).

Environmental consideration

The benefits of the lower emission profile of NGVs should not be understated for HDVs operating in controlled air quality district. However, while natural gas burns more cleanly and has lower tailpipe emissions relative to gasoline and diesel, analyses suggest methane leakage across the natural gas supply chain may mitigate these benefits.

- Transitioning the transportation sector: Exploring the Intersection of Hydrogen fuel cell and Natural gas vehicles

2.1.2 Hydrogen Fuel Cell Vehicles

What is a hydrogen fuel cell vehicle, and why consider hydrogen for transportation?

Hydrogen is one of the most abundant elements on earth. It is a gas, except at extremely cold temperature (20K), and is colorless, odorless, tasteless, and monotoxic. Hydrogen is not an intrinsic energy source but a secondary energy carrier similar to electricity. Consequently, the advantages of using hydrogen as fuel on security of supply or greenhouse gas emissions depend upon how the hydrogen is produced. Over 95% of hydrogen produced in the US is made from natural gas via steam methane reforming. In this process natural gas is broken down in a reaction with high temperature steam in the presence of the catalyst to produce a hydrogen-rich gas. A kilogram of hydrogen gas contains the energy equivalent of a gallon of gasoline.

A fuel cell is an electrochemical device that converts chemical energy from a fuel to electric energy with no combustion involved. The hydrogen fuel cell electric vehicle (FCEV) is an all-electric vehicle similar to a battery electric vehicle (BEV) except that the electric power comes from a fuel cell system with on-board hydrogen storage. Thus, the vehicle's power and the amount of stored energy can be controlled separately rather than being tied to battery size (DOE AFDC). Polymer electrolyte membranes (PEMs) are the most common type of fuel cell for vehicles.

The fuel cell stack operates like a battery pack with the anodes fueled by hydrogen gas and the cathodes fueled by oxygen from the air. Hydrogen is broken into protons and electrons through an electrochemical reactions in the fuel cell catalyst, and protons travel through the membrane to the cathode. FCEVs are fueled with hydrogen at a fueling station, much like gasoline fueling, and hydrogen is stored on the vehicle at high pressure as a compressed gas.

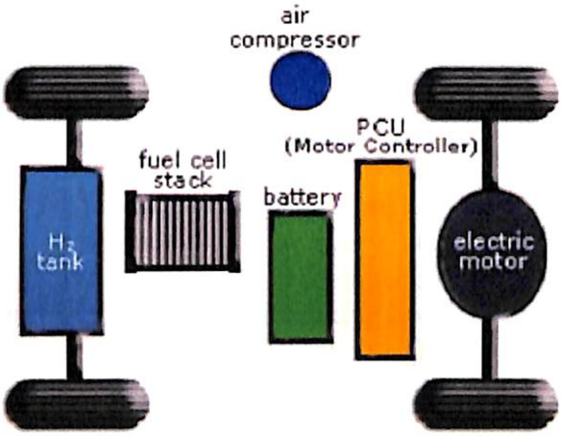


Figure 14: Fuel cell vehicle schematic [13]

Hydrogen could be used directly in an internal combustion engine, instead of a fuel cell, but would then offer no efficiency benefit over traditional gasoline engines. Alternatively, other fuel cell types exist which do not require hydrogen as fuel, and thus fuel cells could enter the market independently of hydrogen production or infrastructure development. However, fuel cells powered by hydrogen have the highest conversion efficiency and thus are viewed as making the most sense for transportation applications. Moreover, the byproduct of fuel cells is just water, so there are no tailpipe emissions stemming from vehicle operations.

The attractiveness of FCEVs is similar to the benefits of BEVs. FCEVs offer zero tailpipe emission, an alternative to petroleum and a pathway to renewable and sustainable transportation. By using an electric drive, FCEVs offer excellent acceleration, constant torque availability, quiet operation, and low level of vibration. Both BEVs and FCEVs could be renewable fueled, depending on the electricity or hydrogen production feedstock. However, unlike BEVs which are generally limited by battery range to small vehicles, FCEVs generally have driving ranges comparable to ICEs and are suitable to all vehicle sizes. Moreover, refueling time is similar to that of gasoline vehicles and the refueling experience is also cleaner than the traditional gasoline experience. Full recharges require several hours, and existing direct current fast charging technologies can provide 80% charge in less than 30 minutes.

Current state of technology and deployment

Vehicles

Fuel cell stacks currently used in automotive applications use a proton exchange membrane with precious metal (primarily platinum) catalysts to promote the hydrogen-oxygen reaction. Today, the efficiency of fuel cell system for passenger cars is around twice that of a gasoline internal combustion engine. Compressed gas at 5000 psi or 10000 psi has emerged as the primary technology path for the introduction of FCEVs. Hyundai recently became the first automaker to commercially release a FCEV. The Tucson Fuel cell has a driving range of up to 265 miles and is offered for a 36 month lease at $499/month, including fuel and maintenance. Several other companies have announced plans to introduce FCEVs commercially starting in 2015, but mainly in regions where governments are coordinating efforts to build hydrogen infrastructure.

According to the 2013 DOE Fuel Cell Technology Office program accomplishments, over 180 demonstrations FCEVs have been in operations with a typical range of 250 miles and up to 430 miles of range. They have demonstrated 2500 hours of durability in real world conditions. This is relative to 950 hours of durability reported for 2006. DEO also reports that there have been advances in manufacturing methods and materials that have reduced the cost of gas diffusion layers in particular by 50% since 2008, and overall cost reductions of over 35% in a similar time frame.

Water is the byproduct of the chemical reaction in the fuel cell stack, and water product that remains in the stack will freeze during cold parking. For every FCEVs, this meant that in cold weather operation, the stack had difficulty starting and freezing damage could rapidly degrade the stack. FCEVs use a small battery for both regenerative braking and cold start operation. FCEVs deployed in cold weather regions have validated this progress, and they have performed through several winters of demonstration and validation testing.

Infrastructure and Hydrogen production

In the US, there are 12 hydrogen stations currently registered with DOE and California has announced plans to build 25 more to support the deployment of FCEVs, The United Kingdom, Japan, Germany, and South Korea have signaled their intentions to move towards commercial introduction of hydrogen fueled vehicles and infrastructure in the near future, with government providing coordination and funding support for early movers in industry. These developments are motivated by environmental, economic and energy security concerns.

For example, the UK H2mobility program sites four potential benefits for hydrogen vehicles:

- Decarbonizing road transport to support an overall goal of 80% reduction of carbon emission by 2050.
- Creating new economic opportunities
- Diversifying energy supplies
- Reducing local environmental impacts

Until a large number of FCEVs are in use, the cost of hydrogen as a fuel will be high due to upfront infrastructure costs. There are two paradigms for hydrogen infrastructure to support FCEVs. The first paradigm involves the centralized production of hydrogen at a dedicated facility and distribution to refueling stations. Centralized production, while costly, represents how hydrogen is produced today for industrial applications and thus would be easiest to transition to a fledging transportation infrastructure. The second paradigm involves the distributed production of hydrogen at the refueling locations. There is some disagreement in the literature about which paradigm is best suited for nascent infrastructure. The National Academies and National Petroleum Council both suggest centralized production will be used initially and then gradually transition to distributed production. Large hydrogen production facilities exist in most states and some excess capacity exist that could be dedicated to transportation.

After production at a large centralized facility, hydrogen can be compressed and distributed in gaseous state through pipelines, distributed in gaseous state by truck or liquified by cooling and delivered by truck. Pipeline have the lowest operational cost, but have a steep capital cost that is exacerbated by the need to use non porous stainless steel to avoid hydrogen embrittlement of standard metals.

Since hydrogen is stored on the vehicle in gaseous form, this is the anticipated state of distribution as well. On-road hydrogen deliveries are traditionally made by tankers that carry up to 250kg of gaseous hydrogen at 2500 psi in steel cylinders and are made at $1.25 - $2.25 per kg. Distribution technologies introduced in 2010 increase capacity per truck and allow for storage at pressure at or above the pressure needed at the refueling locations (up to 7250 psi), thereby alleviating on-site compression needs and reducing cost. However, frequent delivery to a retail fueling location adds logistical complexity and is generally perceived as costlier in the near term, but may scale more readily to support higher hydrogen demand.

Opportunities and challenges

Cost

Meeting range, longevity, and fuel cell efficiency targets has been shown to be technically feasible, but the cost of FCEVs are still far from being cost competitive with conventional internal combustion engine vehicles. Addressing the research challenges in hydrogen storage, the use of platinum as catalyst, and manufacturing complexities would reduce the cost of FCEV consumers.

Storage technologies

The compressed gas storage capacity, and hence the vehicle driving range, is limited by the volume and cost of tanks that can be packaged in vehicles. While hydrogen has a high energy density by mass, it has poor volumetric energy density. To achieve driving ranges over 300 miles, carbon fiber reinforced composite tanks are used to balance sufficient strength versus manageable weight.

Durability

Increased longevity of fuel cell stacks is needed for commercial success. The electrolyte membrane is sensitive to stress, harmful chemical exposure or high current hot spots. Membrane failure plagued early FCEVs but improvements have been demonstrated and catastrophic failure have not been observed in the latest demonstration efforts.

Safety

The safety challenges for FCEVs and at refueling stations stem from high voltage electrical equipment, high pressure gas storage, and combustion risk of hydrogen. The safety of high voltage electric power is managed on FCEVs similarly to EVs, where safety requirements have resulted in on-road safety statistics comparable to that of traditional internal combustion vehicles.
Comparable safety criteria and engineering standards have been applied to FCEVs, with adaptation of safety provisions for differences between properties of natural gas and hydrogen. While fire risk is somewhat mitigated because hydrogen dissipates much faster than gasoline fumes (due to its low density), hydrogen is far more easily ignited than natural gas or gasoline and burns with a flame that is nearly invisible in daylight.

Environmental considerations

For hydrogen produced via steam methane reforming, the final products are hydrogen and CO2, which is typically released into the atmosphere. Hydrogen produced by water electrolysis uses electricity to split water molecules into oxygen and hydrogen. Electrolysis typically has a lower efficiency than SMR (55-75%), but unlike SMR, efficiency is best at low output levels.

Increased adoption of FCEVs can contribute to substantial reduction in urban pollution from soot, NOx, and SOx. However, the likely leakage rate of hydrogen and the subsequent consequences are somewhat uncertain. Just as methane leakage rates from natural gas operation are an active area of debate, hydrogen leakage rates are also difficult to ascertain.

- Transitioning the transportation sector: Exploring the Intersection of Hydrogen fuel cell and Natural gas vehicles

2.1.3 Hydrogen – blended natural gas (HCNG)

Hydrogen-blended compressed natural gas (HCNG) as a fuel for stationary and mobile applications has already been the subject of several research projects. These mixtures of natural gas and hydrogen are commonly known as Hythane®, which is a registered trademark of Brehon Energy PLC. According to Teztlaff (2001) and Biogas Väst (2005), small fractions of hydrogen in natural gas (5–10% by volume) can be transported in natural gas pipelines without affecting their function. But also compression, storage and fuelling of HCNG is possible to some extent without adjustments of the equipment.

Vehicle application

Due to the normally small proportions of hydrogen in the fuel mixture (up to some 5% hydrogen by mass and 30% by volume, respectively) the physical properties of the mixture are close to those of natural gas and do not have any significant impact on components designed for natural gas. Therefore, an NGV fuel system is generally compatible with HCNG, and only small modifications of a natural gas engine are needed to run on HCNG.

Furthermore, a study carried out by Beckmann et al. (2005) revealed that a stable operation of a small uncharged four-stroke SI natural gas engine on blends of natural gas and up to 55% hydrogen by volume is possible without design-engineering modifications of the carburation and ignition system as well as of the combustion chamber.

From a technical point of view, HCNG is particularly interesting for the use in lean-burn natural gas engines, since the supplement of hydrogen to natural gas with its unique burning characteristics improves the lean-burn capability of the fuel. Therefore, many research projects are focused on this issue with regard to the heavy-duty vehicle sector. Lean-burn operation provides a measure for increasing the engine efficiency while regulating the NOx emissions to very low levels. Under part-load conditions, however, the combustion stability of lean-burn natural gas engines becomes poor, which is often met by increasing the charge. As a result, the efficiency decreases while NOx emissions increase. Adding hydrogen to natural gas can avoid this measure by improving the part-load properties of the fuel.

Performance and efficiency

Without performing engine modifications, blending hydrogen with natural gas reduces the power output of the engine as a result of the lower volumetric energy density of hydrogen in relation to natural gas.

Due to the significantly higher flame speed of hydrogen compared to natural gas and other hydrocarbon fuels, however, adding hydrogen to natural gas consequently increases the flame speed of the charge, which leads to an increased burn rate as well as an improved combustion stability. On the one hand, the increased burn rate and, hence, the reduced combustion duration allows retarded ignition timing, which decreases heat losses and results in a higher cycle efficiency η_i. Furthermore, the gain of stability can be used to extend the lean limit of a natural gas engine.

Emission

Hydrogen addition in natural gas engines was found to decrease carbon-based emissions like CO2, CO and HC, mainly due to the direct carbon replacement. Furthermore, the higher flame speed and burn rate of hydrogen, respectively, leads to a higher combustion pressure, temperature and, hence, higher oxidation rates, which also contribute to a reduction of HC emissions.

Fuel and Vehicle study

A survey of research papers on the utilisation of different HCNG blends in ICEs, and evaluated the results from an environmental, technical and economical point of view. The addition of hydrogen to natural gas reduces HC, CO and CO2 emissions while having a tendency to increase NOx emissions. Furthermore, the efficiency can be increased and the fuel consumption decreases with increasing hydrogen. The survey shows that 20–30% hydrogen enrichment of natural gas by volume gives the most favourable engine operation. Higher hydrogen contents undermine the knock resistance characteristics of natural gas, lower power output of the engine and increase the fuel cost. Lower hydrogen contents do not make enough use of the performance enhancement potential of hydrogen.

A literature review as well and analysed HCNG fuel properties with regard to the utilisation in a heavy-duty turbocharged lean-burn SI engines. The results of the study also indicate that 20–30% hydrogen by volume in an HCNG mixture provides the desired benefits in terms of emission reduction without unduly affecting engine performance and efficiency, whereas hydrogen contents beyond 30% by volume are associated with a penalty in terms of engine performance, hardware limitations as well as fuel storage and cost.

Operating data of a dedicated NGV is used that was tested on CNG and HCNG with 15% hydrogen by volume and without any modifications of the engine. The testing of the HCNG fuel blend revealed lower HC, CO and CO2 emissions, whereas NOx emissions considerably increased by 91% compared to CNG operation. However, the NOx emissions were still below the emissions of the gasoline counterpart. The efficiency was somewhat higher for the operation on HCNG.

In contrast, operating data of a dedicated NGV is also consulted in this study that was operated on CNG and HCNG with 15 and 30% hydrogen by volume. This time, however, the vehicle was modified to run on the 30% HCNG fuel blend. The modifications include supercharging for higher power output as well as exhaust gas recirculation (EGR) for lower combustion temperatures in order to decrease NOx emissions. As a result, NOx emissions only slightly increased by maximum 15% when switching from CNG to HCNG while marginally increased HC emissions had to be accepted. CO and CO2 emissions, again, decreased substantially, and the efficiency was slightly higher for the operation on HCNG, whereas the performance somewhat decreased.

Summary

NGVs can normally be operated on common HCNG blends without any ‘direct’ modifications of the natural gas engine.10 In general, HCNG fuel blends with a hydrogen proportion of 20–30% by volume are considered to give the most favorable engine operation in terms of emission reduction, performance maintenance and fuel costs. HC, CO and CO2 emissions generally decrease with an increasing proportion of hydrogen in the fuel, while NOx emissions tend to increase substantially without further modifications. Furthermore, efficiency increase, whereas the performance is somewhat lower for an NGV operated on HCNG.

- Life Cycle Assessment: Vehicle use of Hydrogen – Blended Natural Gas

2.2 Review Area Narrow

2.2.1 Technological change

Technology provides humans with the capability of transforming their natural environment locally, regionally and, more recently, globally. Therefore, technology plays a significant role as both a source and a remedy of global environmental change like global warming. It relates to all major drivers of global environmental change such as population growth, economic development and resource use. Moreover, technology is also central in monitoring environmental impacts and implementing response strategies.

Technology consists of both hardware and software. While hardware stands for technology in terms of artefacts, software represents the disembodied nature of technology like knowledge and skills required to produce and use technological hardware. In this regard, knowledge is often distinguished between public knowledge that can be acquired by anyone, proprietary knowledge that is protected by patents and access is limited through licensing agreements as well as tacit knowledge that is unrecorded and passed on at first hand.

Institutions, including legislation, companies and capital markets as well as social norms and attitudes, are important determinants for the emergence and functionality of systems for producing and using technological hardware. They determine the development of particular combinations of hardware, their final success or rejection and, if successful, the pace of their integration in economy and society. Therefore, technology cannot be separated from the socio-economic context out of which it evolves and which is responsible for its production and its use. In turn, the socio-economic environment is shaped by technologies that are produced and used. Therefore, it turns out to be a difficult task to incorporate the numerous interrelationships among technology, economy, society, and environment in theory, models, and policy.

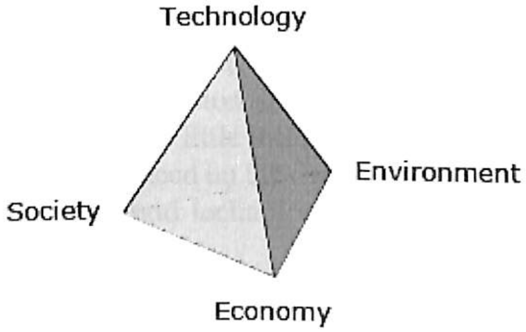


Figure 15: Technological interrelationships [14]

The essential feature of technology is change. In the beginning, a new technology is immature, costly and limited in its applications. Niche market applications are the first touchstone for an emerging technology, where it has to prove its performance rather than its profitability. If it prevails, subsequent improvements and cost reductions can lead to wider applications.

Technologies change all the time individually and in their aggregate, typically by substituting older technologies. However, technological change is neither simple nor linear. In the beginning, uncertainty governs technological change. Moreover, it is dynamic (continuous introduction of new varieties, subsequent improvements and modifications) and cumulative (build-up on previous experience and knowledge). Last but not least, technological evolution is systemic. It is almost impossible to manage change through attention to just a few key technologies since technologies, in general, increasingly depend on one another for both production and use and, in particular, increasingly depend on infrastructures of transport, energy and communication.

All the above mentioned interdependences of technology cause enormous difficulties in implementing large-scale and radical changes. With regard to a radical change of energy and transport technology, considerable time will be needed since many stakeholders are involved and habits, institutions as well as technological networks are adapted to the use of fossil fuels. But these interdependences are also what causes technological changes to have such pervasive and extensive impacts once they are implemented—last but not least since they also set the prerequisites for new technologies. Thus, the challenge associated with the transition toward a sustainable energy and transport system is not only to start up diffusion of new technology immediately, but also to guide technology development with a long-term perspective in order to prevent the implementation of dead-end technology.

2.2.2 Technology Life Cycle

Technology obtain significance only through its application (innovation) and subsequent widespread adoption (diffusion). Understanding diffusion is crucial since it is the basis for technologies to exert any noticeable impact on economic growth, socio-economic transformations and on the environment. As indicated above, however, technological growth cannot be analysed by focusing on technology itself. The essence of technological diffusion is the interaction of technology with its environment, including other technologies.

Research into technological change has shown that the diffusion of technologies tends to follow an S-shaped curve as shown in figure. The thereof derived conceptual model of a technology life cycle can be divided into three phases: formation (introduction), growth (diffusion) and saturation (maturity).

The formative period is mainly governed by uncertainty since there are always various competing technologies that allow to perform a particular task. Due to the high costs of emerging technologies, their often-inferior performance compared to that of existing technologies as well as possible infrastructure incompatibilities, market diffusion is slow. Moreover, principal supporters of new technologies are often unorganised and have little influence, which in turn slows down the diffusion process. During this period, emphasis is placed on the demonstration of technical viability rather than on cost reduction with learning effects and technology improvements from experimentation and development.

In the growth phase, technical viability is established and further efforts lead to positive returns. Growth is stimulated by a number of positive feedback mechanisms such as economies of scale (in production and consumption), economies of scope (co-evolution of complementary technologies), learning by doing and learning by using. Unlike the large variety of technical options in the formative period, these mechanisms tend to reduce variety and create a dominant design, which further decrease uncertainty and increase the possibility to reduce costs through learning and scale economies.

Saturation sets in as diffusion slows down due to saturated markets and diminishing returns of further improvements. In this phase, competition is based almost entirely on cost reduction and externalities like environmental issues may become visible that also constrain a further diffusion.

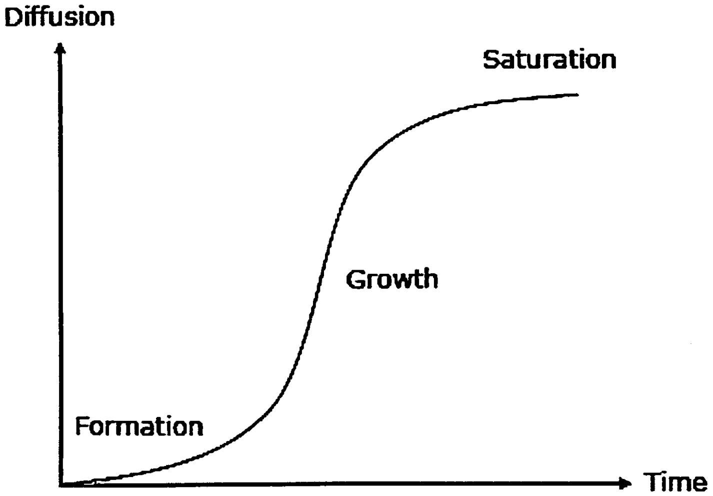


Figure 16: Conceptual model of a technology life cycle [14]

Besides economic issues, three important aspects determine the pace of technological diffusion: (i) compatibility, i.e. requirements for additional infrastructures or the existence of standards facilitating interchanges (network externalities), (ii) complexity with regard to learning and knowledge requirements for producing and using new technology and (iii) testability, i.e. the possibility to try out new technology, to easily obtain innovations and to gain experience and information from users. However, as indicated in the beginning, it is difficult for radically new technologies to obtain significance in a market that is adapted to mature and prevailing technologies.

- Life Cycle Assessment: Vehicle use of Hydrogen – Blended Natural Gas

2.2.3 Project Management services

Project management services can be applied to "LCA Studies Project" to increase the possibilities of obtaining better results.

A project is different from the rest of the operations taking place in organizations, because every project has a defined end point (temporary feature) and is not equal to similar products or services (uniqueness property). Project management is achieved through "application and integration of project management processes of initiation, planning, implementation, monitoring and control, and closing". The knowledge to manage projects includes nine interrelated areas i.e. Integration, Definition and Scope, Time, Cost, Quality, Human Resources, Communication, Risk and Procurement, which apply during the project life cycle (PLC). The PLC is defined to facilitate the management of a project. In Figure 17, outlines the time and effort invested in the PLC from the conception until the end of the project.

It should be mentioned that when talking to the PLC, we refer directly to the Project, not the "methodological phases" of LCA, or stages of life cycle of a system (product or service) in the study.

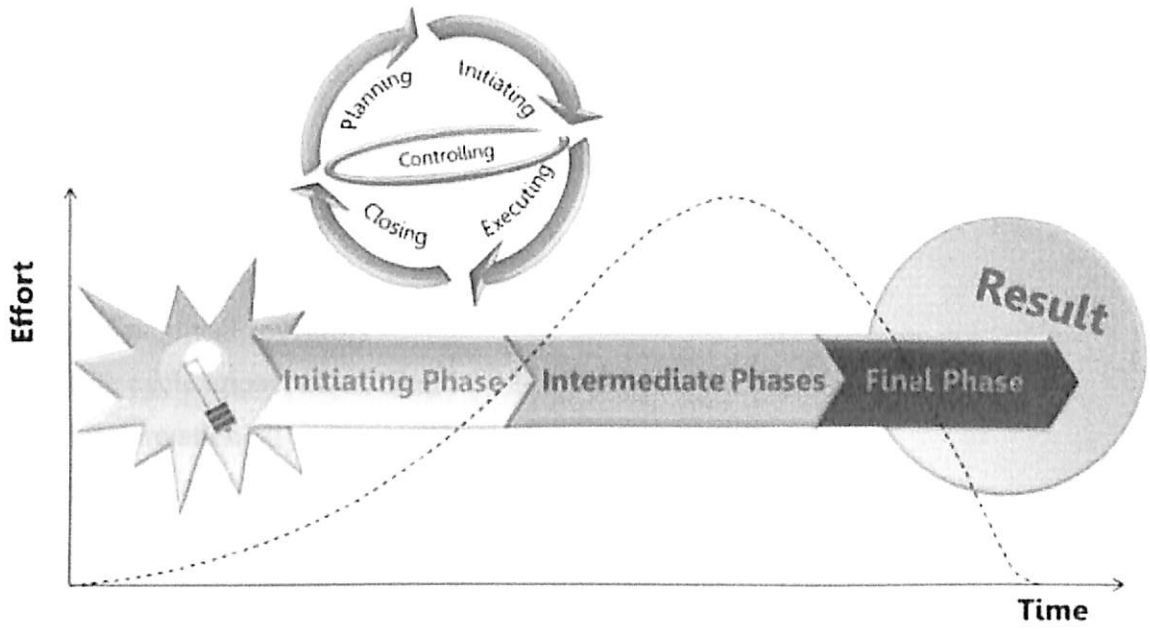


Figure 17: Project life cycle and Project management Process Groups [21]

In Figure 18, shows a matrix to outline the transversal relationship between LCA Phases of an LCA study and Processes Group of any project.

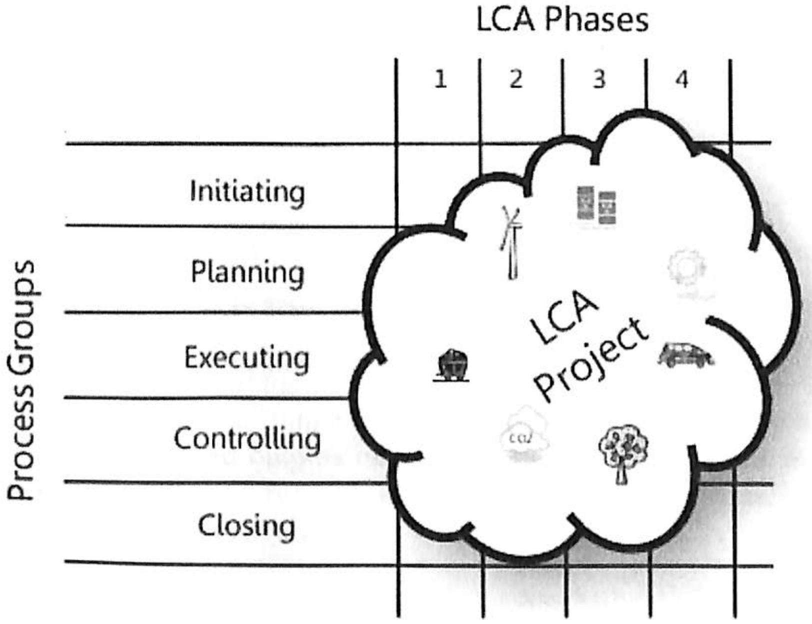


Figure 18: Project life cycle and Project management Process Groups [21]

Project Methodology for LCA

- Initiating project Group
    1. Approach the system
    2. Project Charter of the LCA Project

- Planning Process Groups
    1. LCA Project Proposal
    2. Contract
    3. Objective and Scope of LCA
    4. Project Management Plan
- Executing Process Group
    1. Development Inventory
    2. Life cycle impact assessment
    3. Interpretation
- Group process Monitoring and control
- Closing Process Group
    1. LCA Study report
    2. Critical Review
    3. Contract Closure

- Life Cycle Assessment projects by process groups

2.2.4 Engineering services

Life-cycle assessment (LCA, also known as life-cycle analysis, Eco balance, and cradle-to-grave analysis) is a technique to assess environmental impacts associated with all the stages of a product's life from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling. Designers use this process to help critique their products. LCAs can help avoid a narrow outlook on environmental concerns by:

- Compiling an inventory of relevant energy and material inputs and environmental releases;
- Evaluating the potential impacts associated with identified inputs and releases;
- Interpreting the results to help in making a more informed decision.

The goal of LCA is to compare the full range of environmental effects assignable to products and services by quantifying all inputs and outputs of material flows and assessing how these material flows affect the environment. This information is used to improve processes, support policy and provide a sound basis for informed decisions.

- Life Cycle Assessment - Wikipedia

This dissertation provides engineering services to implement the Life cycle assessment (LCA) for vehicle use of HCNG:

- Method
    1. Goal Definition
        - Purpose
        - Intended application and Audience

2. Scope definition
    - Functional Unit
    - System Boundaries
    - Data quality
    - Impact assessment method
    - Assumption and Limitations

- Results
    1. Energy Use
    2. Global warning potential
    3. Nitrogen Oxide
- Discussion
    1. Sensitivity analysis
    2. Fleet results for vehicle demonstration
- Conclusion

- Life Cycle Assessment: Vehicle use of Hydrogen – Blended Natural Gas

2.3 Life Cycle Assessment (LCA) for Vehicle use of HCNG

In the ISO 14040 series, Life Cycle Assessment (LCA) is defined as the "compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle" (ISO 14040 1997). The life cycle approach means that a product is followed from its "raw material extraction", through the production of preliminary products and the product itself, further along its use phase to its "disposal". Inputs (resource use) and outputs (emissions) of each process along this life cycle are quantified, and the potential impacts on the environment are assessed.

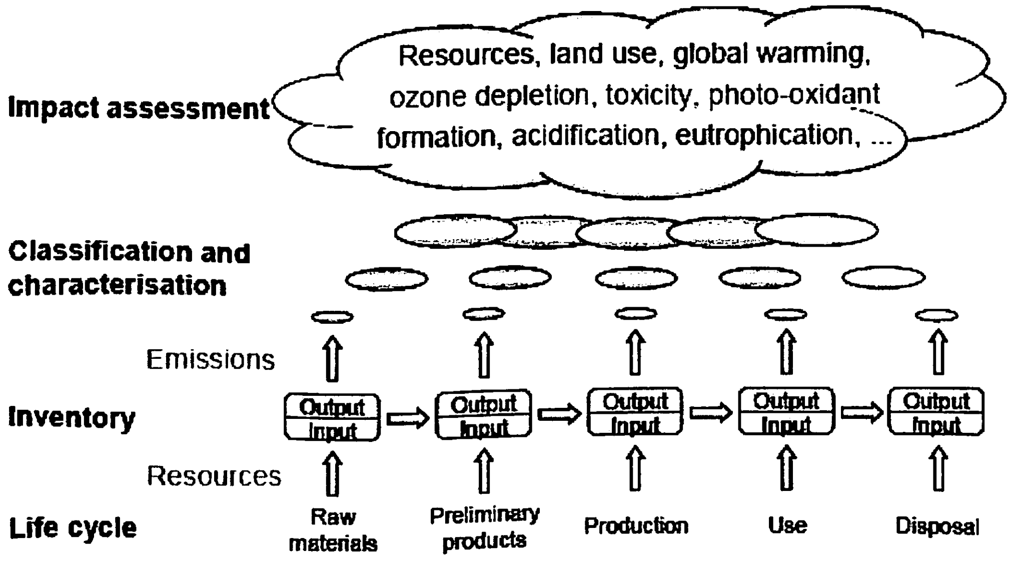


Figure 19: Life cycle approach [14]

LCA can be further described as a procedure for how such studies are carried out (figure 19). The first step is the goal and scope definition, in which the product to study and the purpose of the LCA are specified. Based on these specifications, a life cycle model is constructed, and the resources used as well as the emissions produced are calculated in the Life Cycle Inventory (LCI). The environmental consequences of the life cycle can be described in a subsequent step called Life Cycle Impact Assessment (LCIA). This is usually done by aggregating the inventory results in environmental impact categories through the act of classification and characterisation. Finally, the results are presented and interpreted either on the inventory or impact assessment level, or both, consistent with the defined goal and scope of the LCA.

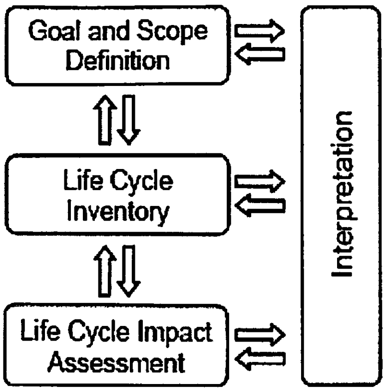


Figure 20: LCA Framework [14]

LCA is a comprehensive method for the analysis of the potential environmental impact of product systems. It provides a clear life cycle logic with a methodology for describing, comparing and evaluating complex system chains with diverse environmental impacts. The holistic approach reveals 'hot spots' in the life cycle of a product and, thus, helps to avoid sub-optimisations that may be the result if only a few processes are focused on. However, the significance of an LCA highly depends on the stated purpose of the study as well as on the methodological choices that are made.

2.3.1 Purpose

The purpose of this LCA study is to quantify and analyse the environmental aspects of using different blends of natural gas and hydrogen as vehicle fuels in ICEs.

- Life Cycle Assessment: Vehicle use of Hydrogen – Blended Natural Gas

2.3.2 Scope definition

2.3.2.1 Functional Limit

LCA results are related to a specific function of the studied product, which is also a basis for comparisons of different alternatives. This implies a technical analysis of possible product functions as well as the specification of the function that is decisive in terms of the stated goal of the study. This function is described in a quantitative manner by the functional unit that corresponds to a reference flow in the life cycle model, and to which all other flows are related.

The decisive function of the compared fuel blends is the powering of a vehicle by the conversion of the fuel energy in an internal combustion engine. The functional unit is defined as **1 vehicle km.** The comparison of different fuel blends on basis of the functional unit implies the comparability of the studied vehicles in terms of size, power and other vehicle attributes.

2.3.2.2 System Boundaries

The system boundaries are illustrated in figure 19. They comprise the following processes:

- Natural gas supply,
- Hydrogen supply,
- Electricity production,
- Filling station operation and
- Vehicle use.

This basically defined system is the same for the supply of the different fuel blends. Therefore, the system model in detail only includes those parts of the life cycle that are affected by changes of the fuel composition. The industrial process in figure 19, from which hydrogen is gained as a by-product, is shadowed since it is not affected by any system changes

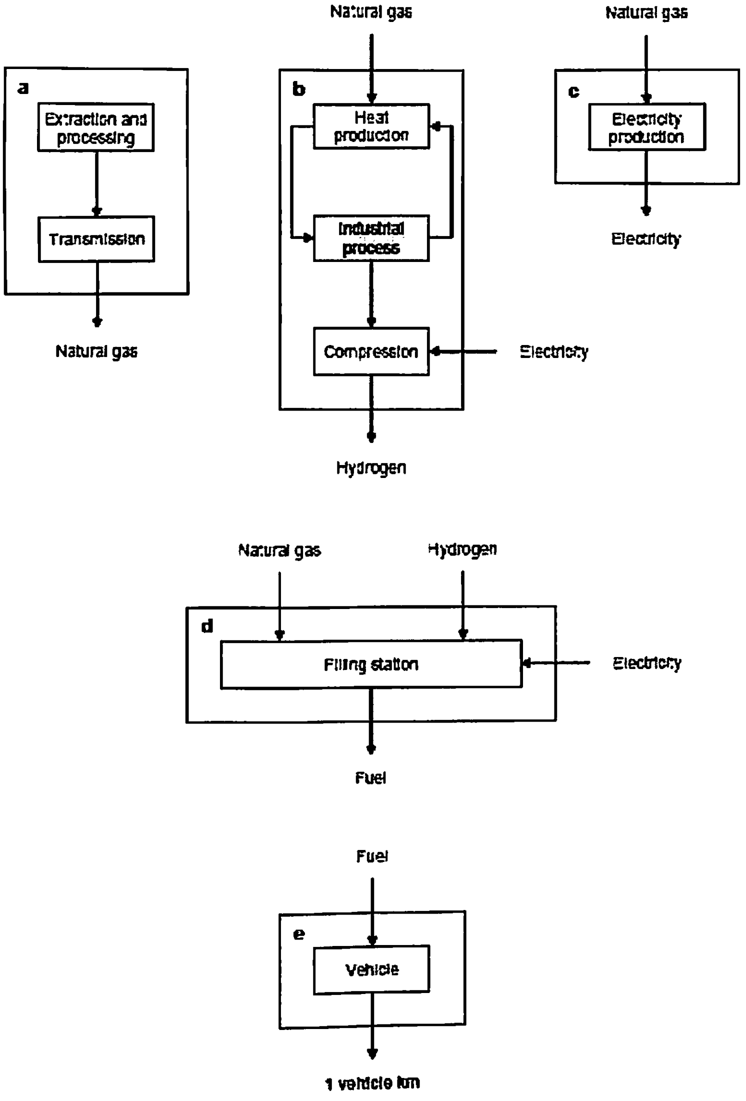


Figure 21: System boundaries for (a) natural gas supply, (b) hydrogen supply, (c) electricity production, (d) filling station operation and (e) vehicle use [14]

2.3.2.3 Data Quality

Assessing and reporting data quality is essential if the results of an LCA are to be properly interpreted and communicated. For this reason, a comprehensive documentation of the collected data can be found together with the LCI data for each process.
Data was mainly collected by literature research and interviews with project partners, operators of the facilities and their suppliers. Data gaps (missing data and data inconsistencies) were filled with estimates and assumptions based on the same sources. Average data was collected for the natural gas supply, heat production and electricity production. Other data is site-specific.

2.3.2.4 Impact assessment method

As indicated above, the LCI results can be presented and interpreted either on the inventory or impact assessment level, or both. LCIA is a mandatory step in an LCA study, which aims at describing the potential environmental impact of the environmental loads quantified in the inventory analysis.

In this study, the inventory results are presented and interpreted on both the inventory and impact assessment level according to the most important tailpipe emissions from vehicles operated on CNG and hydrogen. These are emissions to air of carbon dioxide (CO2) and methane (CH4), expressed on the impact assessment level as global warming potential (GWP), as well as nitrogen oxides (NOx). In addition, energy use is described in terms of the primary energy that is used for the supply of natural gas to the system. The impact assessment method applied in this study is illustrated in figure 22.

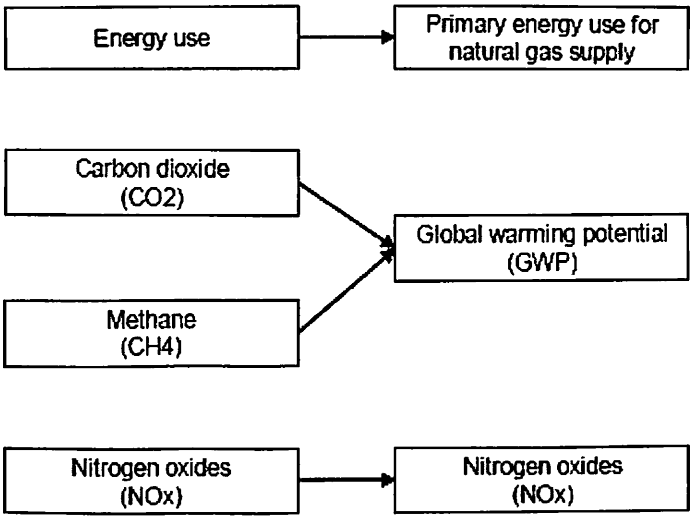


Figure 22: Impact assessment method [14]

Energy Use

In an LCI, energy use is always accounted for. It is an inventory parameter that is easy to communicate and often understood as an indicator for energy-related environmental impact, even though energy use as such does not cause environmental impact.

Since the modelled system depends on natural gas as its only input, the total amount of natural gas that is consumed by the system is considered as an indicator for energy use. In the following, this indicator is represented by the primary energy use for the supply of natural gas to the system.

Global warming potential

In this study, the LCIA considers the inventory results for CO_2 and CH_4. CO_2 is chosen since it is the most important greenhouse gas (GHG) regarding its worldwide emissions to air in connection with the energy conversion of carbon-based fuels. CH_4 is another important GHG and, moreover, it accounts for the bulk of the total emissions of unburned hydrocarbons to air when using natural gas as a vehicle fuel.

The potential contribution of CO2 and CH4 to global warming, i.e. their capacity to absorb infrared radiation and thereby heat the atmosphere, is expressed as their global warming potential (GWP).

Nitrogen Oxides

NOx emissions to air can be considered as the main pollutant of concern when hydrogen is used solely or as a fuel additive in ICEs.

Furthermore, NOx emissions contribute to a number of impact categories, such as acidification, eutrophication, photo-oxidant formation and human toxicity.

2.3.2.5 Assumptions and limitations

A major assumption and, hence, limitation of the study goes along with the heat production and system expansion, respectively. As indicated above, hydrogen that is used for the demonstration project has to be taken out of the heat production process and, consequently, replaced by natural gas as alternative fuel. It is supposed that the emissions might considerably vary with the share of hydrogen in the fuel. Especially the NOx emissions are assumed to be lower with a decreasing share of hydrogen, whereas the emissions of unburned hydrocarbons could be higher.

With the available data, however, it is not possible to properly estimate the hydrogen-related emissions since the effects of different hydrogen supplements on the combustion characteristics are unknown. The same applies for the adjustment of operating parameters to the fuel composition. Furthermore, a linear approximation might not be applicable. Instead, the calculations are based on constant emission factors for the heat production from natural gas, which are not further adjusted to the share of hydrogen in the fuel. However, this is assumed to be a valid approximation since maximum 5 kg/hr out of 380 kg/hr hydrogen will be used for the demonstration project, which equals about 0.17 MW that have to be replaced by natural gas in a 57 MW steam boiler.

A sensitivity analysis was performed in order to assess the possible effects on the results and the conclusions of the study, if hydrogen-related emissions would be considered. The same was done for estimated data in connection with minor assumptions, regarding the supply of natural gas, the compression of natural gas and hydrogen as well as the operation of the hydrogen vehicle.

- Life Cycle Assessment: Vehicle use of Hydrogen – Blended Natural Gas

2.3.3 Results

The results are presented in two groups for each category. The first group (including two bars) represents the unmodified vehicle operated on CNG and HCNG-15. The second group (including four bars) represents the modified vehicle operated on CNG, HCNG-15, HCNG-30 and hydrogen. It should be noted, however, that it is about a differently modified vehicle in the case of hydrogen but based on the same vehicle type.

	CNG	HCNG-15	HCNG-30	Hydrogen
Share of hydrogen				
by volume	0.00%	15.00%	30.00%	100.00%
by mass	0.00%	1.85%	4.38%	100.00%
by energy	0.00%	4.54%	10.36%	100.00%
Density [kg/Nm^3]	0.84	0.73	0.61	0.09
Heating value [MJ/Nm^3]	40.00	35.62	31.23	10.78

Table 6: Fuel properties of CNG, HCNG and hydrogen [14]

	Nm^3/100 km	MJ/km
Unmodified vehicle		
CNG	16.81	6.72
HCNG-15	18.20	6.48
Modified vehicle		
CNG	13.69	5.48
HCNG-15	15.83	5.64
HCNG-30	17.37	5.43
Hydrogen	40.63	4.38

Table 7: Fuel economy of unmodified and modified vehicle [14]

From the figures in table 7, we can see that the efficiency tends to increase when switching from CNG to hydrogen-blended fuels and hydrogen, respectively. However, we can also see that the efficiency of the modified vehicle first decreases when switching from CNG to HCNG-15, and that the gain of efficiency for HCNG-30 is only marginal. This is connected with the modifications of the vehicle. On the one hand, the modifications aim at lowering the combustion temperature in order to decrease the NOx emissions. On the other hand, the vehicle is modified to run on HCNG-30, which might explain the lower efficiency for the vehicle operation on HCNG-15.

The different magnitudes of fuel consumption between the unmodified and the modified vehicle can be explained by the different vehicle types. The same characteristics are also reflected in the fuel economy of their gasoline counterparts with a consumption of roughly 20 l/100 km and 16 l/100 km, respectively. In general, the studied vehicles are characterised by a high fuel consumption, which is not representative for common European light-duty vehicles. For comparison, the European well-to-wheel (WTW) analyses carried out, calculate with a fuel consumption in the dimension of 2.3 MJ/km for dedicated NGVs.

2.3.3.1 Energy use

With regard to 1 MJ of supplied fuel at the filling station, the total natural gas consumption and, hence, the primary energy use for the supply of natural gas to the system increases towards higher shares of hydrogen in the fuel as shown in table 4-3. This is due to the additional demand for natural gas in order to produce heat and electricity within the scope of the hydrogen supply.

	Energy use [MJ/MJ fuel]
Vehicle fuel	
CNG	1.10
HCNG-15	1.13
HCNG-30	1.16
Hydrogen	1.68

Table 8: Natural gas energy use for fuel supply [14]

Figure 23 shows the results for the natural gas energy use and, as additional information, figure 24 shows the on-site electricity consumption for the compression of natural gas and hydrogen. Both figures are related to the functional unit of 1 vehicle km.

From figure 23 we can see that the energy use decreases for the unmodified vehicle, which can be explained by the considerable increase of the vehicle efficiency compared to a slight increase only of the energy use per MJ fuel. In contrast, the energy use increases for the modified vehicle when switching from CNG to HCNG-15 since both, the energy-related fuel consumption and the energy use per MJ fuel, increase. For HCNG-30 and hydrogen, the energy use is higher than for CNG since both times the increase of the energy use per MJ fuel is substantially higher than the increase of the vehicle efficiency.

As shown figure 24, the on-site electricity consumption rises with an increasing share of hydrogen in the fuel for both the modified and unmodified vehicle since additional electricity is needed for the compression of hydrogen.

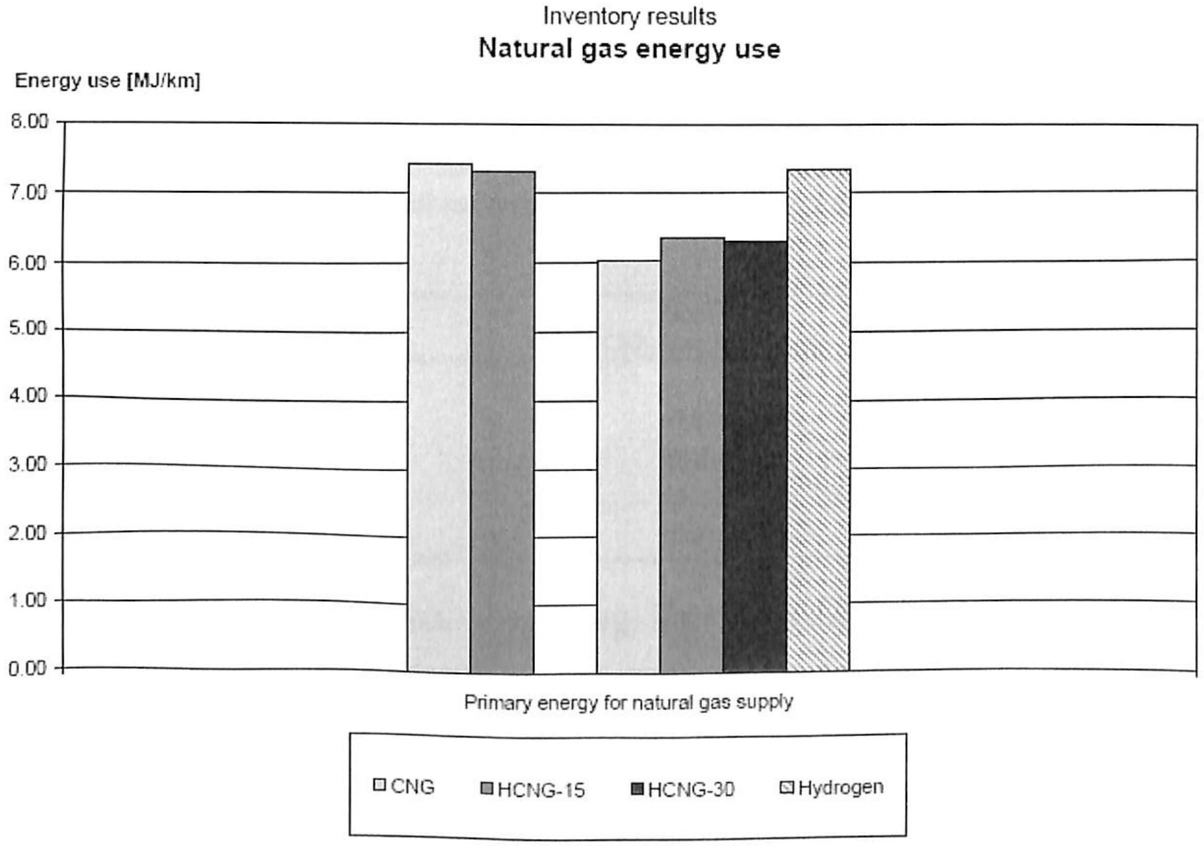


Figure 23: LCA results for Natural gas energy use [14]

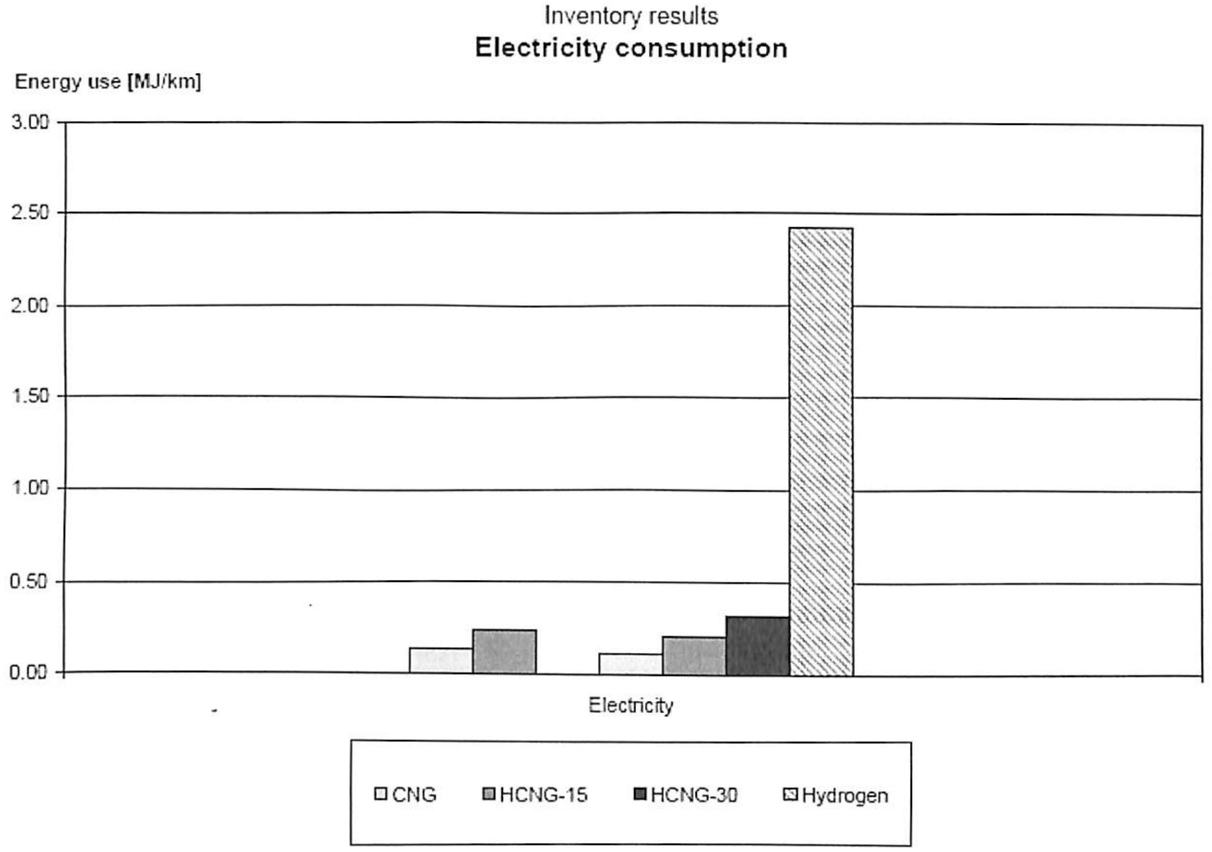


Figure 24: LCA results for Electricity consumption [14]

2.3.3.2 Global warming potential

From table 9, which shows the global warming potential with regard to 1 MJ of supplied fuel at the filling station, we can see a progressive increase of GWP towards higher shares of hydrogen in the fuel. This is mainly due to the increasing heat and electricity production in order to supply hydrogen to the filling station. The associated natural gas supply has only a marginal influence on this GWP increase.

	GWP [g CO_2 eqv./MJ fuel]
Vehicle fuel	
CNG	6.50
HCNG-15	10.52
HCNG-30	15.67
Hydrogen	95.05

Table 9: Natural gas energy use for fuel supply [14]

In figure 25, we can see the results for the global warming potential of the different system processes as well as the total GWP of the entire system, all related to the functional unit of 1 vehicle km. The CO2 emissions are about 400 up to some 4,000 times higher than the CH4 emissions and, thus, CO2 is actually the only relevant GHG in this study with regard to GWP.15 More precisely, the CH4 emissions account for about 5% of the total GWP of the natural gas supply and decrease to roughly 0.5% for the supply of hydrogen. Furthermore, the natural gas supply and the vehicle use almost solely contribute to the total emissions of CH4 in almost equal shares, except for the hydrogen vehicle. With regard to CO2, the emissions from the vehicle use-phase are up to almost an order of magnitude higher than those from the corresponding fuel supply chains, again except for the hydrogen vehicle.

In case of the vehicle use, we see, on the one hand, a general decrease of the GWP along increasing shares of hydrogen in the fuel, mainly due to the direct carbon replacement. On the other hand, the decrease for the unmodified vehicle is much stronger than for the modified vehicle, which again can be referred to the reduced combustion temperature in the modified vehicle. There are naturally no GHG emissions from the vehicle that is operated on pure hydrogen.

Altogether, we see that for CNG and HCNG the main impacts come from the vehicle use-phase, whereas the GWP of the hydrogen vehicle originates almost completely from the emissions associated with the heat and electricity production. However, we can also see that the emissions from the heat and electricity production have a noticeable effect on the total results for the HCNG-operated vehicles relative to the CNG case, i.e. for the unmodified vehicle there is still a benefit left from the vehicle use-phase, whereas the smaller benefit from the operation of the modified vehicle is foiled by the emissions from the heat and electricity production processes.

It should be noted that the CH4 emissions from the vehicle use illustrate the trade-off described in the theory chapter (see section 2.1.3). For the unmodified vehicle, an emission reduction of nearly 34% can be achieved when using HCNG-15 instead of CNG, which results in a total CH4 reduction of about 22% for the whole system. In contrast, the emissions from the modified vehicle slightly increase by some 3% and 8% when switching from CNG to HCNG-15 and HCNG-30, respectively. The latter can be explained by the lowered combustion temperatures due to the modifications that aim at reducing the NOx emissions.

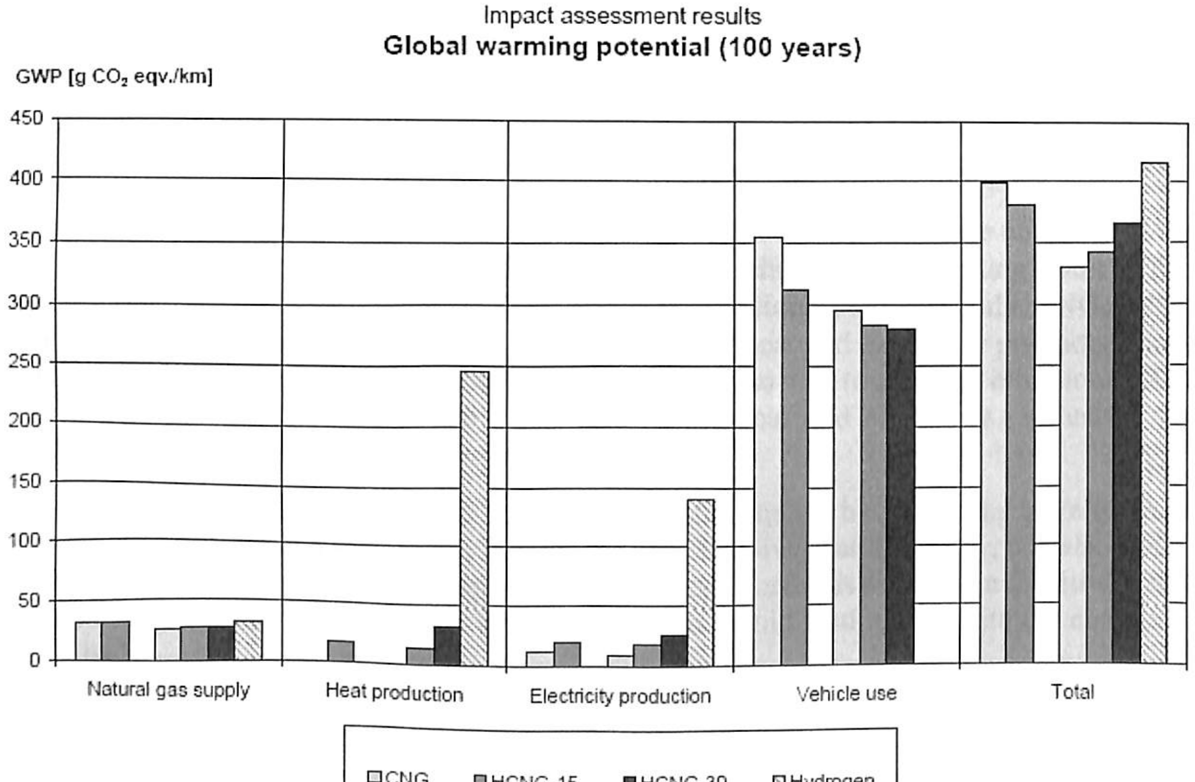


Figure 25: LCA results for global warming potential [14]

2.3.3.3 Nitrogen oxides

From table 10, which shows the emissions of nitrogen oxides to air with regard to 1 MJ of supplied fuel at the filling station, we can see a progressive increase of NOx emissions towards higher shares of hydrogen in the fuel. This again is mainly due to the increasing heat and electricity production in order to supply hydrogen to the filling station. The associated natural gas supply has a minor influence on this emission increase.

	NO_x [10^{-2} g/MJ fuel]
Vehicle fuel	
CNG	2.25
HCNG-15	2.65
HCNG-30	3.16
Hydrogen	11.04

Table 10: Emission of nitrogen oxides to air from fuel supply [14]

Figure 26, shows the emissions of nitrogen oxides to air from the different system processes as well as the total NOx emissions from the entire system, all related to the functional unit of 1 vehicle km. Like in case of the GWP results, the emissions from the heat and electricity production show a progressive increase towards higher shares of hydrogen in the fuel.

The NOx emissions from the vehicle use point out an inverse trend compared to the GWP progression, i.e. we can see a considerable increase of NOx emissions from the unmodified vehicle compared to a slight increase only for the modified vehicle with higher shares of hydrogen in the fuel. Here we can clearly see the effects of the vehicle modifications and the combustion temperature, respectively, on the NOx formation. Furthermore, there are very low NOx emissions from the operation of the hydrogen vehicle, which are, as already mentioned, the only fuel-related tailpipe emissions when using hydrogen in an ICE except for water vapor.

As a result, we can see a considerable increase of the total NOx emissions for the unmodified vehicle and a lower but still noticeable increase for the modified vehicle. An interesting point is that the vehicle use is not the dominating source of the total NOx emissions. For CNG and HCNG, the impact from the natural gas supply is even higher. Furthermore, the heat and electricity production together with the natural gas supply almost completely contribute to the total NOx emissions from the hydrogen use. Like in the case of the GWP results, the heat and electricity production have a noticeable influence on the relative NOx results.

It is assumed that NOx emissions from the heat production might be lower the more hydrogen is taken out of this process and replaced by natural gas as alternative fuel. However, it is also stated that only a small amount of the hydrogen surplus is used. Furthermore, it is shown in a sensitivity analysis that there are no reasonable figures for a NOx credit that would lead to a qualitative change of the total results.

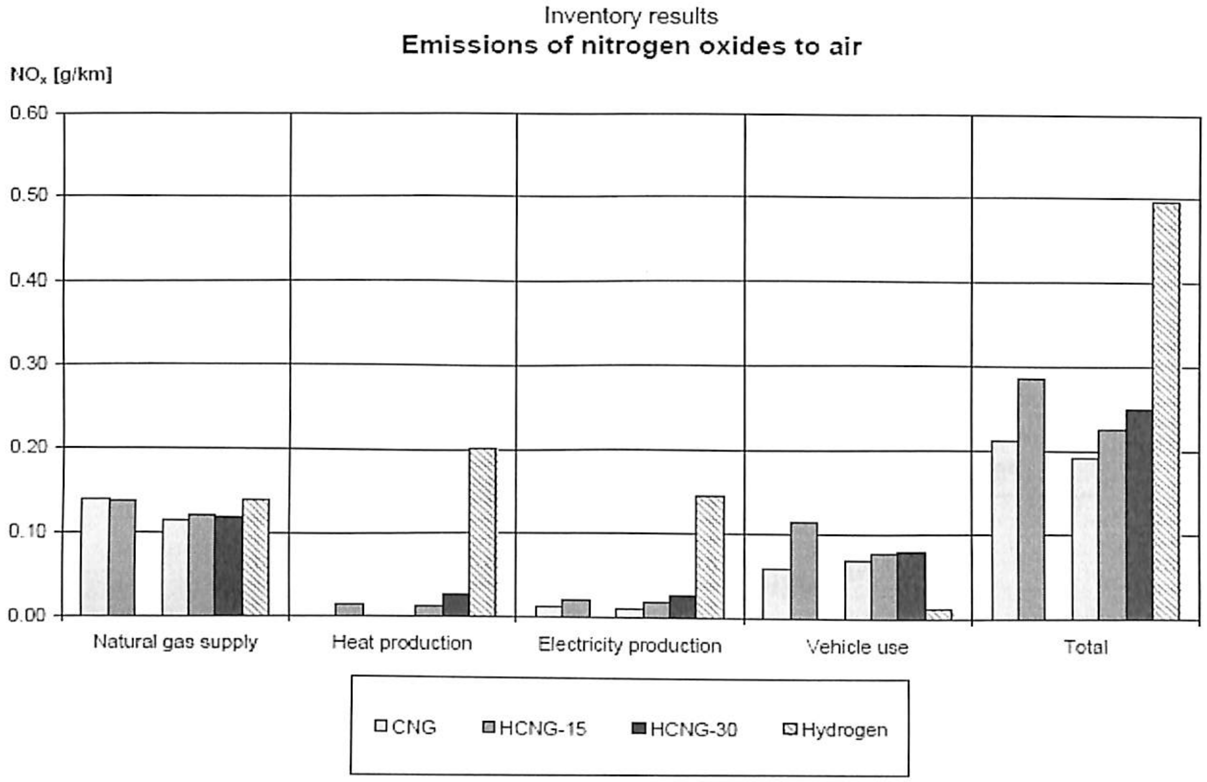


Figure 26: LCA results for emissions of nitrogen oxide to air [14]

- Life Cycle Assessment: Vehicle use of Hydrogen – Blended Natural Gas

2.3.4 Discussion

2.3.4.1 Sensitivity analysis

With the variation of the base case assumptions for the above mentioned processes, a best case and a worst case scenario were analysed in order to quantify the maximum uncertainty. Hence, the best case scenario comprises data for Norwegian natural gas and a lower electricity consumption for the compression of hydrogen. In contrast, the worst case scenario deals with Russian natural gas, a higher electricity consumption for the compression of natural gas as well as higher NOx emissions from the hydrogen vehicle. The relative results compared to the base case are shown in table 11 and table 12.

	Energy use	GWP	NO$_x$
Unmodified vehicle			
CNG	-3.1%	-3.3%	-51.8%
HCNG-15	-4.5%	-4.9%	-39.8%
Modified vehicle			
CNG	-3.1%	-3.3%	-46.4%
HCNG-15	-4.5%	-4.8%	-43.7%
HCNG-30	-6.1%	-6.0%	-41.7%
Hydrogen	-23.3%	-23.3%	-39.8%

Table 11: Best case scenario analysis [14]

In the best-case scenario, as shown in table 11, we can see considerable changes of the NOx emissions as well as of the energy use and the GWP in the hydrogen case.

	Energy use	GWP	NO$_x$
Unmodified vehicle			
CNG	+9.7%	+13.9%	+3.9%
HCNG-15	+9.5%	+14.2%	+2.6%
Modified vehicle			
CNG	+9.7%	+13.6%	+3.5%
HCNG-15	+9.5%	+13.8%	+2.9%
HCNG-30	+9.4%	+12.6%	+2.4%
Hydrogen	+8.0%	+11.5%	+6.3%

Table 12: Worst case scenario analysis [14]

From table 12 we can see that in the worst-case scenario the results for all impact indicators differ by maximally 14.2%. Comparing the total results from the base case with those from the best and worst case scenarios, there are no qualitative changes in the NOx results noticeable, i.e. the progression along the different vehicle and fuel cases remains the same. The same applies for energy use and GWP with regard to the unmodified vehicle. Regarding the modified vehicle, however, we see that the energy use and GWP for hydrogen in the best case is lower than for CNG and HCNG, which is contrary to the base and the worst case. This can be explained by the lower electricity consumption for the compression of hydrogen in the best case scenario, which totally amounts to 0.420 kWh/Nm^3 hydrogen compared to 0.987 kWh/Nm^3 hydrogen in the base case.

The latter issue raises the question, how low the total electricity consumption for the compression of hydrogen must be in order to result in a lower environmental impact from the hydrogen case compared to the other fuel cases. Therefore, a break-even analysis was performed to investigate the trade-offs of energy use and GWP that are related to the corresponding total electricity consumption of the hydrogen compression. The results are given in table 13 for energy use, and in table 14 for GWP.

	CNG	HCNG-15	HCNG-30
Hydrogen compression			
Electricity [kWh/Nm^3 hydrogen]	0.501	0.599	0.543

Table 13: Break-even results for energy use [14]

From table 13 we can see that the electricity consumption for the trade-off in case of CNG is the lowest, followed by HCNG-30 and HCNG-15, which consequentially goes along with the progression of the energy use.

	CNG	HCNG-15	HCNG-30
Hydrogen compression			
Electricity [kWh/Nm^3 hydrogen]	0.429	0.470	0.603

Table 14: Break-even results for GWP [14]

From table 14, we can see again that the electricity consumption for the trade-off in case of CNG is the lowest and increases along higher shares of hydrogen in the fuel according to the GWP trend.

	CNG	HCNG-15	HCNG-30
Heat production			
NO_x credit [g/MJ hydrogen]	0.0695	0.0654	0.0645

Table 15: Break-even results for NOx emission [14]

The NOx emissions from the vehicle operation on hydrogen are always higher compared to the vehicle operation on the other fuels.

2.3.4.2 Fleet results for vehicle demonstration

If hydrogen should be used for a vehicle demonstration, the question remains what kind of hydrogen fuel should be used. An answer might be given by looking at LCA results for certain vehicle fleets. The idea is that with the availability of a certain amount of hydrogen a corresponding number of vehicles can be refueled.

	H_2 consumption [MJ/km]	Scaling factor [-]
Modified vehicle		
HCNG-15	0.29	25.43
HCNG-30	0.65	11.25
Hydrogen	7.35	1.00

Table 16: Hydrogen consumption and scaling factors [14]

For the further assessment, the CNG-related fleet results are calculated by applying the above scaling factors on the differences between the LCA results for the CNG case and the other fuel cases. This time, however, the functional unit is 1 km of the corresponding vehicle fleet. The results are shown in table 17.

	Energy use [MJ/km]	GWP [g/km]	NO_x [g/km]
Modified vehicle			
HCNG-15	+10.68	+274.10	+0.89
HCNG-30	+5.34	+382.78	+0.65
Hydrogen	+3.62	+85.23	+0.30

Table 17: Hydrogen consumption and scaling factors [14]

From table 17, we can see that all results are higher compared to the CNG case. Furthermore, the results show that the hydrogen fleet would have the best environmental performance.

- Life Cycle Assessment: Vehicle use of Hydrogen – Blended Natural Gas

2.3.5 Conclusion

Considering a certain amount of hydrogen that is available for vehicle demonstration, the corresponding fleet of hydrogen vehicles would have the best environmental performance compared to fleets of the modified vehicles running on HCNG-15 and HCNG-30. However, there are no overall benefits connected to the use of any of these fuels compared to the use of CNG. The latter also applies to fleet considerations for the unmodified vehicle.

However, it has been shown that the supply of surplus hydrogen is environmentally preferable compared to the supply of hydrogen via natural gas steam reforming. Furthermore, it has been shown that differences in energy use and GWP between the hydrogen case and the other fuel cases can be offset by a lower electricity consumption for the compression of hydrogen.

In general, the results reveal that the potential environmental impact from the fuel supply chain considerably increases towards a hydrogen share of 100% in the fuel. Hence, characteristic trends of the total results for different fuel cases mainly depend on the efficiency and emission characteristics of the considered vehicles.

We can also see from the results that the fuel supply processes—the natural gas supply and, in particular, the heat and electricity production—are decisive for the total environmental impact associated with the use of pure hydrogen. In contrast, the vehicle use-phase dominates the total results when using CNG and HCNG, except for NOx, which is also influenced by the natural gas supply.

However, the heat and electricity production considerably affect the results and, therefore, can be considered as decisive system processes with regard to the differences between the potential environmental impacts from the different fuel cases. In this respect, producing heat and power in an CHP plant might have a considerable effect on the total results with lower emissions from the life cycle of HCNG and hydrogen.

On the one hand, technological change is more radical when using pure hydrogen. On the other hand, more vehicles and possibly more actors are involved when using HCNG.

The demonstration of HCNG might have a greater potential since it offers the opportunity for a broader public to get in touch with hydrogen and, in particular, to gain experience with its application as an alternative fuel. Hence, it might be easier to open up a market for HCNG than for more complex and radical hydrogen technology due to a better accessibility and an increased customer awareness. Furthermore, the introduction of HCNG might pave the way for related technologies and, in the long-run, for hydrogen technology.

- Life Cycle Assessment: Vehicle use of Hydrogen – Blended Natural Gas

2.4 Factors critical to success of study

Challenges in gas to liquid conversion:

- **Technical complexity is high**

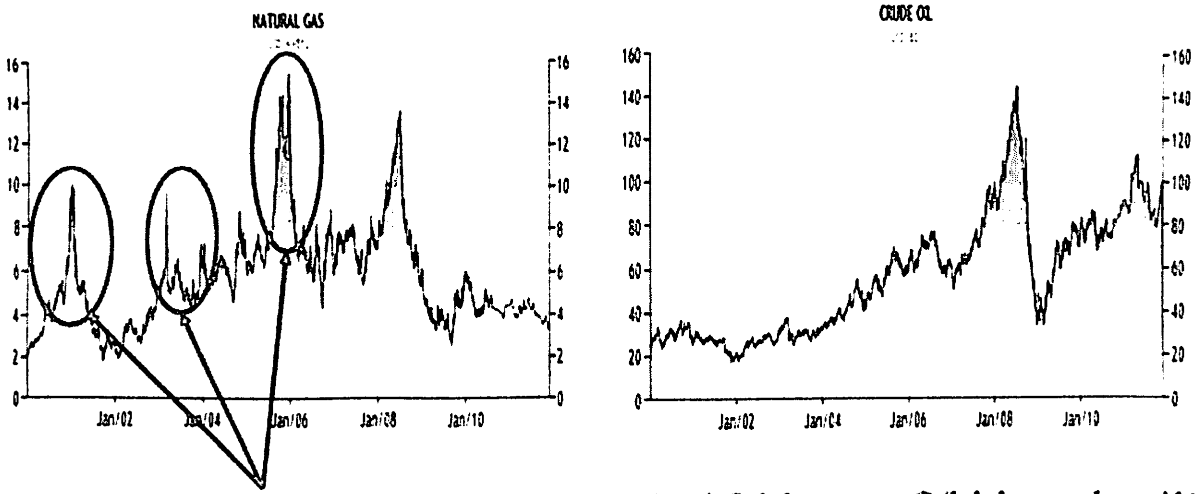
  The company with most production experience in GTL, reported serious technical difficulties during and after commissioning.

- **High Capital Cost:**

  In the early 2000's, the capital cost for GTL facilities that was often quoted, was \$20000-\$30000/bpd (barrel per day)
  After 10 years, much higher actual capital costs were reported for GTL facilities:
  a) Pearl GTL (Shell) - ~\$ 110000/bpd
  b) Escravos GTL (Sasol-Chevron) - ~\$ 180000/bpd
  c) Sasol 1 GTL expansion (Sasol) - ~\$ 200000/bpd
  d) Eni estimate - ~\$ 120000/bpd

- **Risk:**

  The financial risk due to complexity and high capital cost is exacerbated by natural gas and crude oil price volatility.



Price of natural gas in $\$/\text{bbl}_{\text{equiv}} > \$/\text{bbl}$ crude oil!

Figure 27: Oil and Natural Gas price volatility [1]

- Significant gas volumes are needed: 0.5 Bft3d of gas for a 50-Mbpd GTL plant.
- Limited number of players in the GTL technology business.
- GTL plants have proven to be operationally complex.
- Few EPC contractors can handle projects of this size, resulting in a lack of competition.

  - Technology role for Natural Gas Valorization, Eni report

Another challenge in adopting hydrogen is the safety concerns among the public as hydrogen is highly inflammable. Hydrogen is safer than petrol and, till date, no hydrogen vehicle explosion has been reported. Nationwide awareness programmes and vehicle demonstrations in collaboration with vehicle manufacturers and research institutes could allay people's concerns to some extent. Developing safety regulations and codes for hydrogen storage, transportation and fuelling is another area that requires considerable attention.

With proper coordination among research institutes, vehicle manufacturers, safety regulatory authority and state and central governments, extensive commercialisation of hydrogen vehicles is very much possible by the mid-21st century.

- Hydrogen: towards cleaner and sustainable transport

One of the biggest challenges using HCNG as a fuel for engines is determining the most optimized hydrogen/natural gas ratio. When the hydrogen fraction increases above certain limit, abnormal combustion such as pre-ignition, knock and backfire, will occur unless the spark timing and air-fuel ratio are adequately adjusted. As the percentage of hydrogen increased, the lean operation limit extends and the maximum brake torque (MBT) decreases, which means that there are relation among hydrogen fraction, ignition timing and excess air ratio. Therefore finding the optimal combination of hydrogen fraction, ignition timing and excess air ratio along with the other parameters is certainly a large hurdle.

The emissions levels of fuels are probably the most important factor in determining whether the fuel is suitable as an alternative fuel or not. Although the NO_X emissions for CNG are already extremely low compared to traditional fuels, the addition of hydrogen causes increased NO_X emissions. The addition of hydrogen has the opposite effect on the hydrocarbon emissions, so it is necessary to compromise at a hydrogen ratio for which the NO_X and hydrocarbon emissions are equally low. Probably most evident challenge for wide-spread use of the new fuel is the current lack of infrastructure. Similar to other gaseous fuels, natural gas and hydrogen are both lighter than air, therefore if there is a leak it will quickly disperse into air with adequate ventilation. Lastly, the currently cost of hydrogen is higher than the cost of natural gas resulting in HCNG being more expensive than CNG.

- Review on Opportunities and Difficulties with HCNG as a future fuel for Internal combustion engine.

2.5 Summary

The increased use of gasoline and diesel fuels in internal combustion engines causes air pollution and contributes to the greenhouse effect. Many studies have attempted to find solutions for these problems. It has been reported that the share of methane as an alternative fuel would increase gradually due to the growing interest in low emission vehicles and development of alternative fuels for public transportation.

Methane fuel is relatively cheaper than diesel and gasoline, and it can be applied to the existing conventional engines without modification. Methane's octane number, which is higher than gasoline's, is 120, thereby increasing the compression ratio and anti-knocking.

In addition, methane operates with higher thermal efficiency and power output than diesel and gasoline engines. Methane powered vehicles emit less NMHC and NO_X compared to diesel powered vehicles in general.

The addition of hydrogen increases the H/C ratio of hydrogen-methane (HCNG) fuel. A higher H/C ratio results in less CO2 per unit of energy produced, thereby reducing greenhouse gas (GHG) emissions. Improvements in thermal efficiency could also help reduce GHG emissions. However, vehicles using methane have a disadvantage due to slow flame speed. The laminar burning speed for methane is approximately 0.4 m/s, whereas hydrogen has a flame speed about six times higher. Therefore, hydrogen mitigates the limitations of methane. Also, HCNG vehicles emit almost no emission gases because hydrogen is a clean fuel and does not contain carbon atoms.

- Combustion and emission characteristics of HCNG in a constant volume chamber

HCNG has many advantages when it comes to performance. Research has shown that the brake effective thermal efficiency increases with an increased percentage of hydrogen. Another effect of the addition of hydrogen is that the brake specific fuel consumption is reduced, the cycle by cycle variations are also reduced, and the thermal efficiency is increased. Foremost advantage, HCNG is safer than hydrogen due to its lower energy content from hydrogen.

It is evident from literature that emissions can also be improved with the addition of hydrogen. Compared to natural gas, HCNG reduces the HC emissions, which is in part due to the increased combustion stability that comes with the addition of hydrogen. Increased in NO_X emissions are observed due to the increased combustion duration and temperature which is accompanied by addition of hydrogen. The biggest challenge with the commercialization of the fuel comes with developing an infrastructure to support this promising alternative fuel. Although there is currently a large amount of research taking place regarding the HCNG fuel, there are requirement of many steps to take before wide-spread implementation can occur.

- Review on Opportunities and Difficulties with HCNG as a future fuel for Internal combustion engine.

3 Research Design, Methodology and Plan

Research Case Study - The role of natural gas in Brazil's energy mix

Currently, natural gas in Brazil represents around 12.9% of the primary energy supply, with consistent annual growth during the last decade. However, Brazil is entering a time of uncertainty regarding future gas supply, mainly as import from Bolivia is being renegotiated. As such, diversification of gas supply sources and routes need to be considered. Energy systems and infrastructure models are essential tools in assisting energy planning decisions and policy programmes at regional and international levels.

Modelled projections suggest that regional gas demand would increase from 38.8 mcm/day in 2015 to 104.3 mcm/day by 2050, mainly driven by the increasing demand in the industry and power sectors. Therefore, existing regional gas infrastructure would be insufficient to cover future demands. Three different renegotiation scenarios between Brazil and Bolivia were modelled, obtaining distinct cost-optimal infrastructure expansion pathways. Depending on the scenario, the model expects gas demand to be covered by other supply options, such as an increase in pre-salt production, LNG imports and imports from a new Argentinian pipeline.

3.1 Data Sources

The World Energy Council (WEC) Trilemma Report considers energy security, energy equity, and environmental sustainability as main features to define energy sustainability. Achieving high performance in all three dimensions requires to tackle of complex interactions and trade-offs between society, institutions and the environment.

Brazil, which is the world eighth largest energy user with a consumption of around 10.9 EJ/year, is ranked 53rd out of 125 countries in terms of its energy system sustainability. In recent years, the country has been able to scale positions thanks to a decrease in energy exports and an increase in local oil and gas production.

Currently, natural gas has a participation of 12.9% in the Brazilian primary energy mix. The historical daily average gas demand by sector as well as the historical gas-based power generation installed capacity.

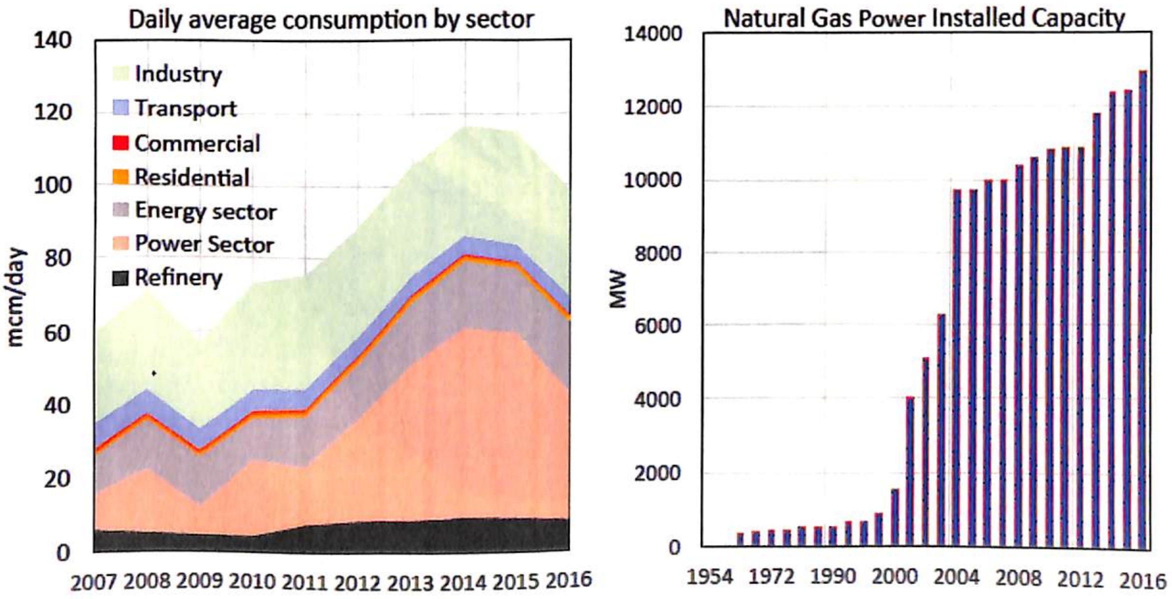


Figure 28: Brazil historical gas demand and gas-fired power generation installed capacity [9]

Natural gas has gained importance due to its lower carbon emissions and competitive prices compared to alternative fossil-fuel energy sources. It is estimated that Brazil has around 369 billion cubic meters (bcm) of proven natural gas reserves.

Between 1990 and 2013, natural gas reached 3 million users, covering 440 of the country 5,570 municipalities. This increase has occurred mainly due to the following measures:

- An increase in local production and imports from the Bolivian pipeline and investments in expanding the national pipeline network (> 15,000 km).
- Privatization of natural gas distribution companies and the expansion of the distribution network.
- The thermoelectric priority programme introduced by the Ministry of Mines and Energy (MME).
- An increase in vehicle natural gas demand.

3.2 Research Design

According to the National Agency of Petroleum, Natural Gas and Biofuels, local natural gas production in 2018 was 73.1 mcm/day (27.7 bcm/year). In terms of imports, the country received on average 29.2 mcm/day (10.7 bcm/year), with intakes from the Bolivian pipeline responsible for 83.5% of the total, while the rest was covered by liquefied natural gas (LNG) imports, mainly coming from Nigeria, the United Sates and Angola.

The Brazilian Energy Planning Company (EPE), the entity responsible for forecasting long-term energy demand and organizing auctions for power capacity and availability, projects that gas demand could grow to 108 mcm/day (39.4 bcm/year) by 2026, with a maximum supply capacity of 120 mcm/day (43.8 bcm/year).

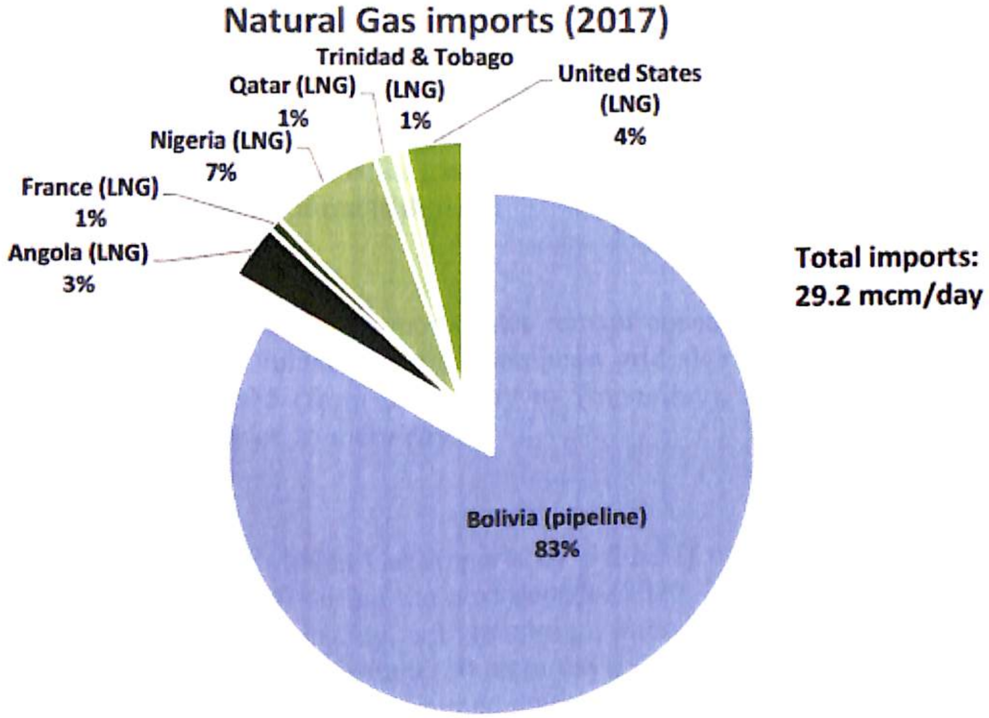


Figure 29: Brazil natural gas imports in 2017 [9]

The purpose of research to forecast regional gas demand (based on socio-economic parameters and technology competition) and to provide cost-effective gas supply chain infrastructure from 2015 through 2050.

3.3 Survey Questions

A questionnaire will be created which will subjected to 10 people to know whether the questionnaire is suitable.

- What grade pipe will be used for the project? Will it be consistent and the strongest available along the entire pipeline path?
- What efforts did you make to co-locate this project with an existing pipeline or other existing right-of-way?
- Who pays for the damage and clean up when something goes wrong?
- Has the company taken into consideration the danger of building a pipeline?
- Exactly what kind of revenue is the township expected to obtain, and when does any revenue stream begin and what it is based on?
- How many acres of public lands are you targeting with this project?
- Are you planning on executing eminent domain?
- How far does a home have to be from the pipeline to be safe if there were an explosion? Is 25 feet enough? 30 feet? 40 feet? Would you feel save if your family and kids lived that close?
- Have you follow the federal pipeline safety regulations: Public Awareness Programs?

- Sample Questions to ask of pipeline companies proposal new or expanding pipeline projects for your community.

3.4 Data Analysis Procedures

For the specific case of regional natural gas demand, a single demand has been calculated. the Gas to Grow Programme is a major government plan that is expected to be implemented in the upcoming years. Thus, three different scenarios for gas infrastructure are explored assuming different imports projections based on future governmental plans:

Scenario 1:

Considers that current Bolivian gas imports rates remain constant throughout the analyzed period (2015–2050), while national intakes from the southeast grid also remain constant. The Argentinian pipeline is expanded in 2035 (from 3mcm/day to 7mcm/day), and expanded fivefold by 2040, reaching a maximum inflow of 15 mcm/day.

Scenario 2:

Considers the reduction of Bolivian Gas imports by a third (from 30 to 20 mcm/day according to Petrobras and EPE projections) during the next decade (2020–2030). Later, imports are reduced to half of the base year's current capacity, with maximum imports of 15 mcm/day. On the other hand, the southeast grid intakes remain constant (10 mcm/day), while the Argentinian pipeline expands its capacity sooner than in Scenario 1. It is assumed that in 2025 it reaches 11 mcm/day, and a maximum flow of 15 mcm/day by 2040.

Scenario 3:

Considers a case where Bolivian imports suffer a gradual reduction until being removed from the market. First, capacity gets reduced by a third in 2025 (20 mcm/day), and then by two thirds in 2030 (10 mcm/day). Finally, after 2030, import flows from Bolivia are completely stopped. In this case, the maximum imports from the southeast branch are expanded by one third in 2030 (reaching 18 mcm/day), while the Argentinian pipeline follows the same infrastructure expansion as in Scenario 2.

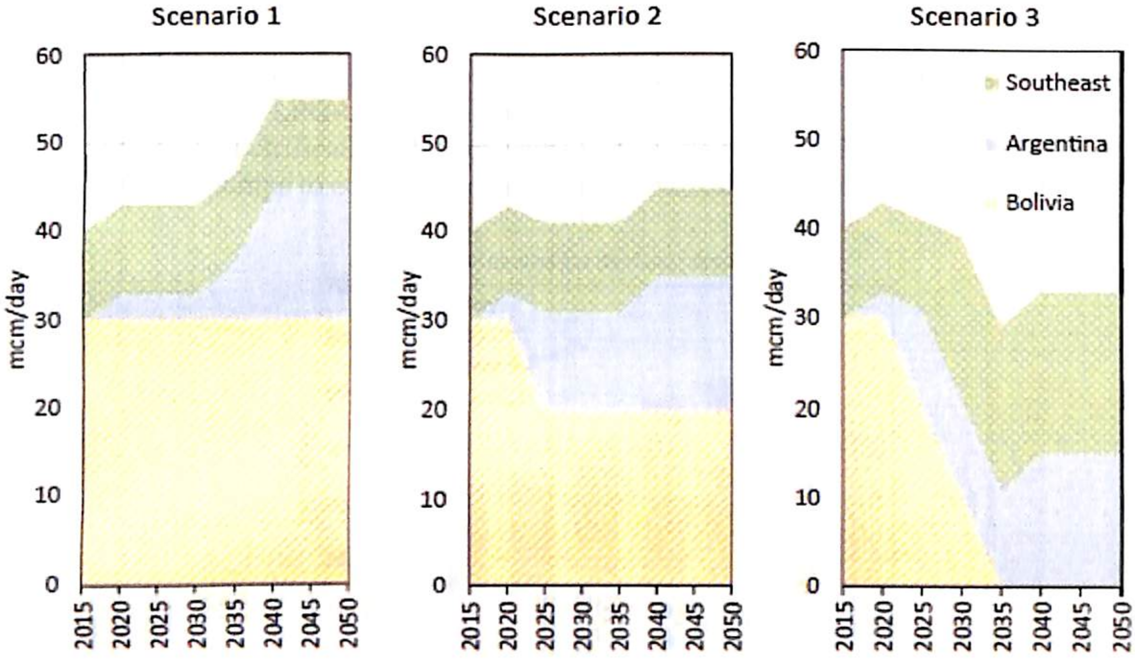


Figure 30: Maximum natural gas import flow rates assumed from Bolivia, Argentina and the Southeast grid [9]

- Study of cost-effective pathways for natural gas infrastructure: A southern Brazil case study

4 Finding and Analysis

4.1 Gas Demand forecast

Results show an expected average annual growth rate of 2.1% between 2015 and 2030, and 1.9% between 2030 and 2050, increasing from 30.8 mcm/day (11.2 bcm/year) to 61.2 mcm/day (22.3 bcm/year). Most of the increase would be driven by the industry sector (+19.8 mcm/day), responsible for 65% of the increase, followed by residential (+9.0 mcm/day or 30%), transport (1.5 mcm/day or 5%), and commercial (-0.02mcm/day, −0.1%).

Most of the new gas demand in the industry sector is expected to come from the steel and fertilizer subsectors. For the residential sector, the increase is due to the installation of gas-based cooking and water heating replacing LPG-based equipment. On the other hand, the small increase in transport is due to the sector's electrification in later years, while the commercial sector expects a wide range installation of heat pumps to cover both cooling demand and water heating requirements.

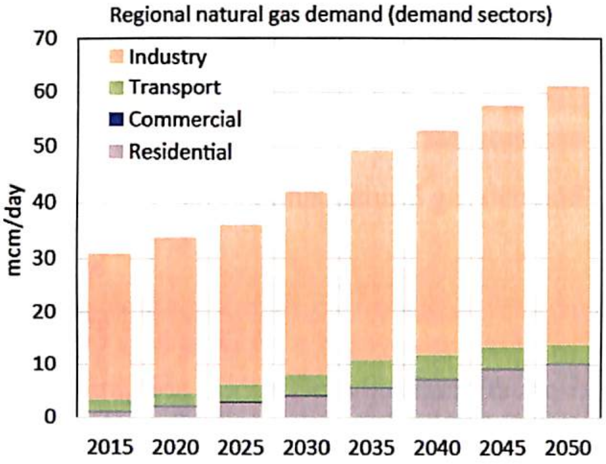


Figure 31: Sectoral future gas demand in the region [9]

Electricity demand is expected to grow at an average annual rate of 2.5%, increasing from 214 TWh/year to 473 TWh/year by 2050. Regarding the specific case of gas, by 2030, a maximum addition of 6 GW of new gas-based combined cycle plants can be expected, and by 2050, total gas capacity could reach 21 GW.

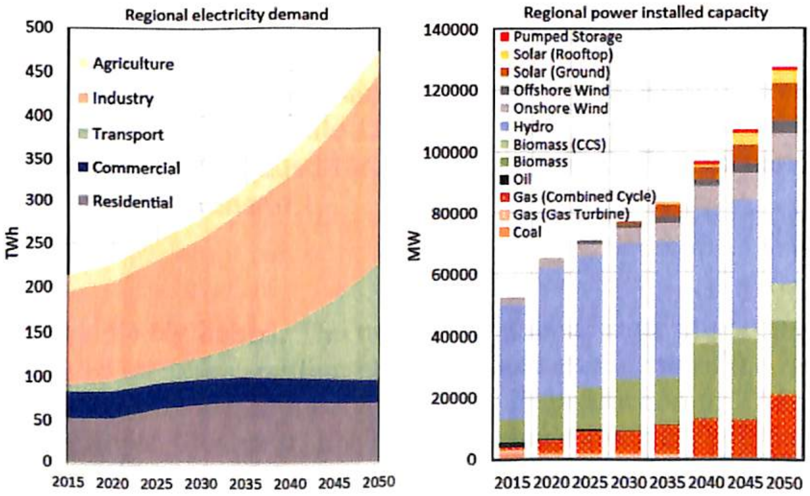


Figure 32: Sectoral electricity demand (left) and power installed capacity (right) for the analyzed region. [9]

The model forecasts a total increase of 65.6 mcm/day by 2050, reaching average consumption rates of 104.3 mcm/day. This value is similar to the current national natural gas demand of 105 mcm/day

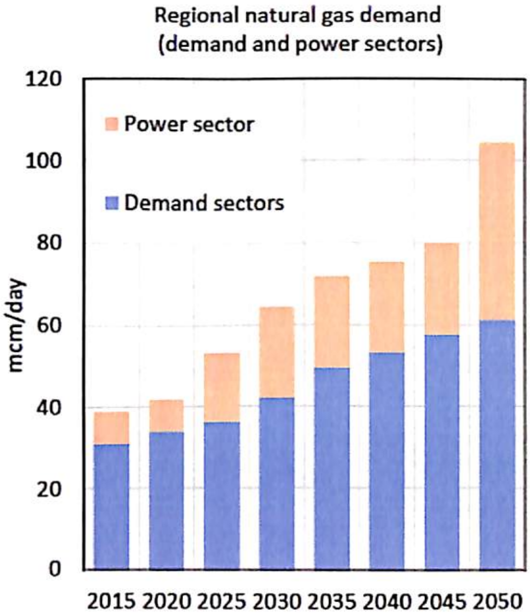


Figure 33: Total regional natural gas demand [9]

4.2 Natural gas infrastructure

Scenario 1:

As in this scenario the main assumption is that Bolivian imports are maintained as per the time of writing (around 30 mcm/day) to cover the future demand, additional imports would be required from Argentina (15 mcm/day) combined with consistent imports in the order of 12 mcm/day from the southeast stream. Also, the pre-salt production would have to increase from 15 mcm/day to 21 mcm/day. However, the main infrastructure addition to the system is due to the extra 31 mcm/day from LNG imports, requiring new large regasification terminals across the coastal regions. Finally, as there would be a surplus of around 5 mcm/day, it should be exported as LNG due to price competitiveness.

Scenario 2:

Bolivian imports are halved by 2050. The main differences with Scenario 2 are the need to increase pre-salt production to 25.6 mcm/day, while LNG imports reach 43.7 mcm/day. Therefore, larger regasification terminals would be required throughout the region. This scenario has an increase in total costs by 15% compared to Scenario 1.

Scenario 3:

Bolivian imports are completely halted. The model suggests a larger import participation form the southeast grid, reaching 18 mcm/day, putting major pressure on the rest of the Brazilian gas system. Additionally, the pre-salt region would have to increase its production to 27.5 mcm/day, requiring larger gas processing facilities. Moreover, LNG imports would reach a maximum of 48.8 mcm/day. The total cost of this scenario is approximately 36% and 18% more than for Scenario 1 and Scenario 2, respectively.

Samples for natural gas projections from 2015 to 2050 in 5-years periods. Different Scenarios are consider are as follows:

Natural Gas source	Scenario 1 Consumption (mcm/day)	Scenario 2 Consumption (mcm/day)	Scenario 3 Consumption (mcm/day)
Bolivian Import	30	15	0
Argentina import	15	15	15
Southeast stream Import	12	12	18
Pre-Salt Production	21	25.6	27.5
LNG Import	31	43.7	48.8
Surplus	5	5	5
Total Demand	114	116.3	114.3
Natural Gas Infrastructure cost	X1	X2 = 1.15*X1	X3 = 1.36*X1 / 1.18*X1

Table 18: Comparison between different Scenario [9]

4.3 Correlation / Regression Analyses

The uncertainty generated by the ongoing contract negotiations between Brazil and Bolivia for the renewal of gas imports has motivated this study. Study has investigated cost-effective infrastructure pathways under different assumptions for the southern states in Brazil. It has provided the opportunity to understand complex dynamics between the different gas producing and consuming sectors. This study has confirmed how additionally to direct gas consumption in the demand sector (especially in the industry and residential sector), electrification in transport would put pressure on a power system, mainly dominated by hydro generation. As a matter of fact, these additional electricity demand derives is supplied by the installation of gas power plants.

Regardless of the analyzed gas supply scenario, it is envisioned that the region would diversify natural gas sources. Both, LNG imports and pre-salt production would have to increase their market share. However, for the country not to diminish its energy security, it needs to be cautious in depending too much on LNG imports, as shown in Scenario 2 and 3. The rearrangement of flows obtained in Scenario 3 is also a major infrastructure decision that needs to be carefully considered. Results suggest that Bolivian gas needs to remain as part of the gas supply to lower future infrastructure cost and provide operational flexibility.

Additionally, the results from the South Brazil case study highlighted an important trade-off between long-term energy security and short-term revenue from exports. Due to the implementation of a time horizon and no incentive to maintain reserves, the model produces as much as possible in order to maximize export revenue.

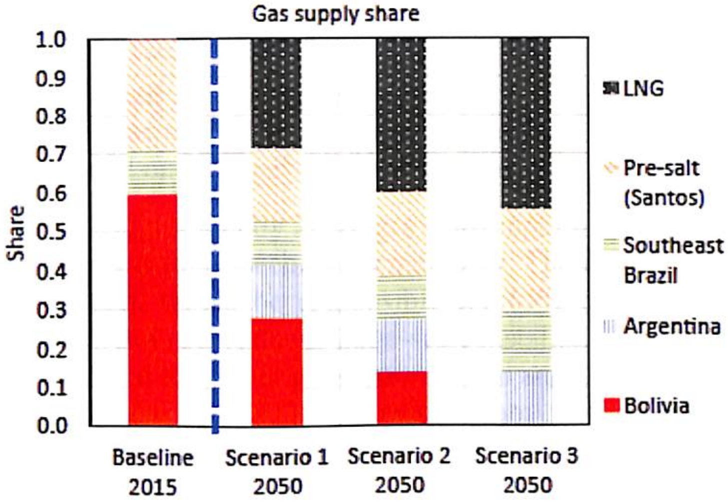


Figure 34: Gas supply share comparison [9]

The role of programmes such as the Gas to Grow will increase the competitiveness of natural gas within the national energy matrix. These outputs are critical to provide support for planning and evaluation at different stages in the supply chain, providing decision makers and other government bodies with tools to evaluate options for capacity expansion in the region.

- Study of cost-effective pathways for natural gas infrastructure: A southern Brazil case study

5 Interpretation of Results

The importance of gas in Brazil and the uncertainty in supply sources bring challenges for future energy security. The focus was to explore the potential new infrastructure required in the region, considering future gas demand under a carbon constrained energy system.

The results from this study suggest that by 2050, gas consumption in the demand sectors of the five-state region would increase two-fold, reaching 60 mcm/day. The industrial sector, mainly driven by steel and fertilizer production, would be responsible for 65% of the new regional gas demand, followed by the residential sector (30%) due to large-scale installation of gas-based cooking and water heating equipment. Gas demand for power generation would add an extra 40 mcm/day, driven by the increase of electricity demand of 221%, growing from 214 TWh to 478 TWh. Due to decommissioning and increasing demand, by 2050 the region would require 21 GW of new installed gas capacity.

At present, although the Bolivia-Brazil gas pipeline (GASBOL) is an important infrastructure asset, due to constraints capacities and prospects for future gas demand in the region, a diversification in gas suppliers is expected to maintain the system's cost as low as possible while ensuring long-term energy security and even short-term revenues from potential exports. However, as demonstrated by the analyzed scenarios, keeping current levels of Bolivian gas intakes could minimise the total system's cost as much as 36%, providing greater operational flexibility compared to a scenario where Bolivian gas intakes are completely ceased. Depending on the scenario, infrastructure pathways suggest a total deployment of a gas transmission network with new additions of regasification terminals across the coast, as imports between 31.2 mcm/day (Scenario 1) and 48.8 mcm/day (Scenario 3) are obtained.

Nevertheless, a careful planning is necessary to avoid stranded gas infrastructure assets as it could complicate the achievement of future carbon mitigation targets in the national energy system. In this sense, the utilisation of integrated models, such as the one presented in this study, could provide crucial information for decision and policy makers to conduct robust analysis and support comprehensive natural gas infrastructure planning and policies.

For future work, the study will be expanded to account for updated values of the natural gas reserves regarding production rates in the context of depletion, as well as more sources of biomethane production. Additionally, an improved technoeconomic assessment of gas assets is
needed as well as a more granular temporal characterisation to account for seasonal fluctuation of different energy sources and its impact on gas supply. Future work includes a multi-objective optimisation with the additional objective of minimising greenhouse gas emissions.

- Study of cost-effective pathways for natural gas infrastructure: A southern Brazil case study

6 Conclusion and Scope for Future Work

A combined cycle power plant is an assembly of heat engines that work in tandem from the same source of heat, converting it into mechanical energy. On land, when used to make electricity the most common type is called a Combined Cycle Gas Turbine (CCGT) plant. By generating power from multiple streams of work, the overall efficiency of the system can be increased by 50–60%. That is, from an overall efficiency of say 34% (for a simple cycle), to as much as 64% (for a combined cycle).[1] This is more than 84% of the theoretical efficiency of a Carnot cycle. This can be done because heat engines can only use part of the energy from their fuel (usually less than 50%). In an ordinary (non-combined cycle) heat engine the remaining heat (i.e., hot exhaust gas) from combustion is wasted.

- Combined cycle power plant – Wikipedia

There is a great necessity of life cycle analysis of HCNG® in order to achieve marketization and promote large scale commercial use. It is evident that 20%hydrogen enhancement optimizes the performance and emission of a conventional CNG vehicle. But, it is very important to consider the downsides of adding 20% hydrogen and get an insight to 'hydrogen economy'. The pathways of hydrogen have a tremendous impact on environment as well as economics. So, it is recommended to perform life cycle analysis and life cycle cost analysis to obtain a detailed and comprehensive cluster of remarks. However, in this research, using data from literature, a simplified but an effective approach has been chosen to perform well-to-wheel analysis of HCNG HDV. The general conclusion can be made as renewable hydrogen pathways can be the best choice of HCNG pathways. It is evident that if in future, these renewable hydrogen pathways get cheaper, technically advanced and energy efficient, 20%HCNG vehicles can get a booming market in a near-term future especially for heavy duty applications such as passenger buses. One of the greatest challenges associated with HCNG vehicular technology is lack of sufficient infrastructure e.g. refuelling stations, high costs of hydrogen generation, and choice of highly carbon-intensive fossil-based hydrogen pathways because of comparatively better maturity and energy efficiency. Additionally, in future, shale gas can be one of the best replacements of conventional compressed natural gas even compared with 20%HCNG pathways.

- The well-to-wheel analysis of hydrogen enriched compressed natural gas for heavy duty vehicles using life cycle approach to a fuel cell

Hydrogen has been considered as green fuel for futuristic transportation as an alternative to the petrol / diesel oil without / with reduced environmental concerns like emission of harmful gases and global warming effect. The modes of transportation may be hydrogen fuelled vehicles based on IC engine / fuel cell technologies. Such vehicles have attracted more attention by the automakers, Governments and the customers despite the limitations (i) Safety regulations are to be followed during handling hydrogen (its transportation, storage and use as gaseous fuel) since hydrogen being flammable and explosive gas (ii) hydrogen being produced from the sources other than primary fuel sources is expensive, (iii) fuel cells having higher efficiencies but presently too expensive and (iv) absence of infrastructure that delivers / dispenses hydrogen or its precursors. Fuel cell vehicles can't be commercialized till they become cost-wise competitive in the market and infrastructure for dispensing hydrogen is established.

- Report on transportation through hydrogen fueled vehicles in India

Increases in crude oil prices have certainly helped GTL economics, but this may not be sufficient for the approval of large-scale projects, given the complex dynamics involved. A significant drop in project CAPEX, sustained low gas prices and further appreciation in crude prices are needed to turn the tide. In response, the industry has taken steps to reduce project CAPEX and improve the yield of high-value products. Despite these changes, the relatively high CAPEX requirement for large-scale GTL projects means that mini-GTL projects are more likely to be sanctioned in the near future.

- The relation between Crude Oil and Natural Gas Prices by Jose A. Villar, Natural gas Division, Energy Information Administration

FTGTL is a process which converts natural gas into liquid hydrocarbons. Major new FTGTL plants were brought online in Qatar in 2006 (Oryx GTL) and 2012 (Pearl GTL) with productive capacities of 32.4 and 140 thousand b/d respectively. During FTGTL synthesis the following set of products is produced: liquefied petroleum gas (LPG), naphtha, kerosene and diesel fractions. The FTGTL kerosene and diesel fractions do not conform to international standards on a number of qualitative characteristics, most importantly density and greasing ability, so there is a necessity to process the fuels further. The utilization of these two final products is possible only after altering the quality characteristics of the fraction to the required standards.

- The Oxford Institute for Energy Studies, Olga Glebova, NG-80

Coal or biomass-based syngas contains sulfur and other contaminants that act as strong poisons for the catalysts used in the synthesis of methanol and DME. This implies that stringent, and costly, gas cleanup procedures should be used for the conditioning of CO-rich syngas intended to be used in the methanol synthesis process. Also, research is needed to improve the activity, selectivity, and stability of MTO and DMTO catalysts as most of them exhibit fast deactivation due to the formation of carbon deposits.

- Catalyst for Production of lower Olefins from Synthesis Gas: A Review

Bibliography

1. Technology role for Natural Gas Valorization, Eni report
2. The Oxford Institute for Energy Studies, Olga Glebova, NG-80
3. The relation between Crude Oil and Natural Gas Prices by Jose A. Villar, Natural gas Division, Energy Information Administration
4. 'STAT' initiative to promote the use of alternative fuels.
5. Arno de Klerk – Department of Chemical and Materials Engineering University of Alberta, Canada arpa-e.energy.gov
6. Gas processing & LNG, Challenges facing GTL: Rethinking project economics in 2018 and beyond
7. World Energy consumption, Wikipedia
8. Life Cycle Assessment, Wikipedia
9. Study of cost-effective pathways for natural gas infrastructure: A southern Brazil case study
10. Technologies for the Synthesis of Ethylene and Propylene from Natural Gas
11. Catalyst for Production of lower Olefins from Synthesis Gas: A Review
12. Review on Opportunities and Difficulties with HCNG as a future fuel for IC engine
13. Transitioning the transportation sector: Exploring the Intersection of Hydrogen fuel cell and Natural gas vehicles
14. Life Cycle Assessment: Vehicle use of Hydrogen – Blended Natural Gas
15. Combustion and emission characteristics of HCNG in a constant volume chamber
16. Hydrogen: towards cleaner and sustainable transport
17. The well-to-wheel analysis of hydrogen enriched compressed natural gas for heavy duty vehicles using life cycle approach to a fuel cell
18. Life cycle analysis of HCNG light duty vehicle demonstration project
19. Sample Questions to ask of pipeline companies proposal new or expanding pipeline projects for your community.
20. Report on transportation through hydrogen fueled vehicles in India
21. Life Cycle Assessment projects by process groups