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Writer: Jan Kristian De La O Mellum Student: 233485	…………………………………………… (Writer's signature)

Faculty supervisor: Frank Asche

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1 Abstract

In the recent decades the focus towards renewable energy sources has increased drastically. The global energy consumption is increasing each year, but we are consuming more than we can sustain. Associated with the increase of energy consumption is the increase of greenhouse gases, which further leads to global warming. Most of the energy comes from fossil fuels, but these energy sources are limited and are harming the environment. In the global energy transition the world needs to gradually transition towards environmentally friendly solution and that is what the low-carbon energy from Qatar will do.

The low-carbon energy supply complex will be in Ras Laffan, Qatar, because of the large access to raw materials such as natural gas and water, a harbour for shipping, and reservoirs that can store large amounts of CO_2. The complex will be self-sustainable meaning that the natural gas will be provided from the North Dome and the electricity will be provided from powerplant on location. The project addresses the use of about 70% of the annual gas production towards the production of ammonia and the remaining 30% goes to other petrochemical products or export.

The project will address technical solutions, supply chain and the investment scenario related to the establishment of a comprehensive low-carbon energy supply from Qatar. The production of ammonia in this complex is estimated, revealing that the cost per ton of ammonia can be estimated as low as 247,90 USD/ton Ammonia without the shipping cost or as high as 418,326 USD/ton ammonia. Compared to the average price of 320 USD/ton ammonia in 2021 it is very much plausible to implement this project and create competitive prices against other renewable recourses.

The ammonia produced is environmentally friendly, but this comes at the cost in the form a reduction of energy that could have potentially come from the natural gas, this is the price to pay for low-carbon energy. For ammonia to reach the same energy output as natural gas, the amount of ammonia needed is 2,44 times larger compared to natural gas. For ammonia to be competitive in price a global CO_2 tax ranging from around 250 – 300 USD/ton CO_2 must be implemented.

2 Acknowledgements

With this master thesis I conclude a 5-year master's degree at the University of Stavanger, consisting of a 3-year bachelor's degree in Petroleum Technology and a 2-year master's degree in Industrial Economics.

I would like to thank my brother Steven Mellum for helping me through this master thesis and guiding me in the right direction. I couldn't have done it without him the past 5 years of my study.

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6 Abbreviations

Sm^3	Standard cubic meters
Km	Kilometre
Km^2	Cubic kilometres.
Tcm	Trillion Cubic Metres
SMR	Steam Methane Reforming
GHG	Green House Gases
CO	Carbon monoxide
C^o	Celsius
CCS	Carbon Capture and Storage
NH_3	Ammonia
N_2	Nitrogen
H_2	Hydrogen
CH_4	Methane
K_2CO_3	Potassium Carbonate
Atm	atmosphere pressure
K	Kelvin
HCO_3	Hydrogen Carbonate
EOR	Enhanced Oil Recovery
MEA	Monoethanolamine
VLGC	Very Large Gas Carrier
MMBtu	Metric Million British Thermal Unit
USD	United State Dollars
t	Tonne
Heca	Hectar
GJ	Giga Joule
K. Cal	Kilo Calorie
G. Cal	Giga Calorie
MW	Mega Watts
GW	Giga Watts
GWh	Giga Watt hour
TWh	Terra Watt hour

W	Work
n	mole
R	Gas constant
T	Temperature
Bara	Bar atmosphere
“	inch

7 Conversions

Haber-Bosch method gives 2.16 tons CO_2/ton NH_3 and energy need is over 30Gj/ton NH_3

1 MMBtu = 28,32 m^3

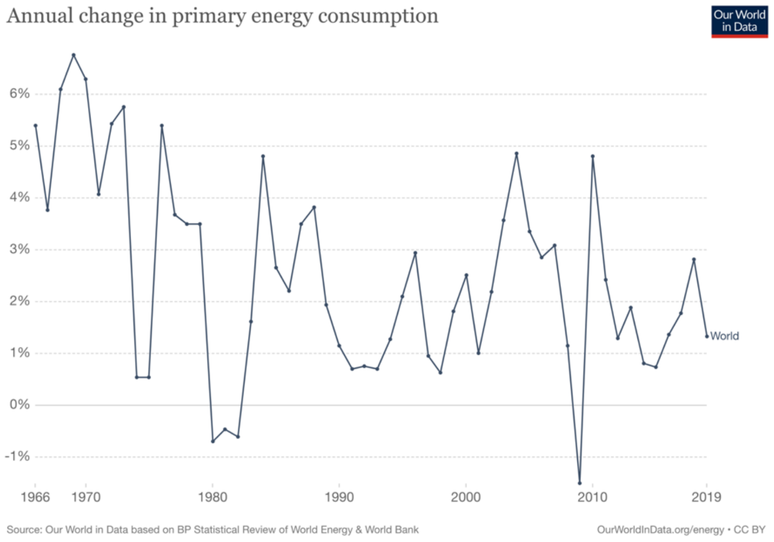
Ammonia density = 0,73 kg/m^3

1 ton ammonia = 1 369 m^3

8 Introduction

In the recent decades, energy availability from resources has changed the trajectory of mankind. Not only have new energy sources been discovered - first fossil fuels, then nuclear, hydropower, and now other green technology – but also the amount of power we can generate and consume, with associated emissions of greenhouse gases such as CO_2 and NO_x into the atmosphere. We live in a highly interconnected world, and for economic development and sustaining our standards of living, having access to sufficient and reliable energy resources is a crucial component in all elements of society.

However, existing fossil-based energy consumption and production are unsustainable, and measures must be taken to reduce, or eliminate, greenhouse gas emissions that arise from the utilization of these energy sources. The global energy consumption will continue to rise year after year if increased energy demand is not balanced by other efficient energy sources. Although global energy demand continues to rise, its growth appears to be declining – observations from Figure 7-1 presents an average of about 2% increase per year (Ritchie, 2019). Even with the slowing energy consummation growth, the world's growing energy consumption makes the transition from fossil fuels to a low-carbon energy source difficult. New solutions of low-carbon energy sources must satisfy the increased demand while still attempting to displace existing fossil fuels in the energy mix.



Source: Our World in Data based on BP Statistical Review of World Energy & World Bank
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Figure 7-1: Annual change in primary energy consumption (Ritchie, 2019)

As of today, it is demanding to replace the enormous amounts of energy that fossil resources provide, which can also be utilized in a flexible and logistically affordable way.

The world's standard of living and ability to lift people out of poverty has largely been based on increasing energy consumption, so a decline in energy consumption to reduce emissions will largely go beyond living standards and will probably increase world poverty. Furthermore, there are still large exploitable deposits of oil and gas, with measures to prevent emissions, can be used to cover the world's energy needs without leading to significant global warming.

9 Objective

The primary focus of this thesis is to address technical solutions, supply chain and economics related to the establishment of a comprehensive low-carbon energy supply from Qatar. Utilizing ammonia as a low-carbon energy supply from Qatar could provide large amounts of energy in the transition towards cleaner energy. As well as providing energy to the world, the cooperation in such a complex could also contribute to better diplomatic relations between countries in the middle east as such a complex can create technical and economic interdependencies between the countries in the region.

Qatar currently controls the world's largest natural gas field, North Dome, which originally had estimated recoverable reserves of 26,000 billion Sm^3 (QP, 2020) and if the world's energy supply were to exclude oil and gas as an energy source for reasons of global warming, it will be difficult to justify further recovery.

To further defend the future of gas extraction from the North Dome, measures of carbon emission reduction will be necessary. Technical solutions such as Carbon Capture and Storage (CCS) will be implemented because of the proximity of large formations where the CO_2 can be deposited, as the world has limited large scale possibilities for storing CO_2.

As presented in this thesis is as follows:

1. Produce gas from North Dome
2. Use the natural gas to produce ammonia and electricity (for the purpose of the project)
3. Implement Carbon Capture technology in facilities that produce CO_2 as a by-product
4. Capture CO_2 from steam reforms in the ammonia plants and from the power plants

5. Compress and transport CO_2 to locations with heavy oil fields or depleted reservoirs
6. Develop a supply chain system for transportation of ammonia.

Technical solutions and technology for creating such a complex exist to a large extent today, but not in the scale and composition presented in this thesis. The same technical concept is transferable to other locations in the world, for example the USA, where it can be implemented together with an increase in shale gas production.

10 Background

The world has seen an increase in man-made CO_2 emissions since the beginning of the industrial revolution, and the worlds energy needs have been largely met by the consumption of fossil energy sources such as petroleum, coal, and natural gas. These fossil fuels have been used in combustion processes that exhausts greenhouse gases into the atmosphere, further contributing to global warming as CO_2 works as a heat preserving agent in the atmosphere.

In the recent decade, there has been greater focus on reducing CO_2 emissions, and research is being carried out working towards improved methods for capturing and storing CO_2. Due to the low CO_2 concentration in the atmosphere, it has proved challenging to find methods that extract CO_2 directly from the atmosphere. The most relevant and efficient carbon capture method has been point-emissions capture from larger CO_2 producers, for example from incineration or industrial processing plants.

As a major oil and gas producer compared to the population, Qatar has become very dependent on the activity created by the petroleum industry, and because of the industry's sharp ups and downs, Qatar needs to establish alternative industries to create a diverse and stable business and labour market. Since Qatar's economy is built upon the production of fossil fuels, a solution for further and increased production of natural gas would be to expand the usability of methane towards the production of ammonia. Constructing a large ammonia production complex will allow Qatar to produce cleaner energy in the form of ammonia. The process of producing ammonia is not low-carbon, but introducing point-emission carbon capture technology could allow for a large-scale low-carbon energy supply. The captured CO_2 can either be used for production of other chemicals such as amino acids, ammonium carbonate, phenol, hydrogen cyanide and much more, or it can be compressed and stored in depleted reservoirs, removing the carbon from the carbon cycle.

Even if the world is focusing on a global energy transition from fossil fuels to cleaner energy, transitioning to renewable energy will take time considering it does not have the capacity or energy density to replace fossil fuels. Working towards reduction of carbon emissions, several countries aim to reduce greenhouse emissions by displacing coal with natural gas for heating and power generation, since natural gas is a low-cost, sufficient, and dependable fuel that emits 40 to 65 percent less pollutants than coal, but this is not a long-term solution (CAPP, 2020).

The climate change has been in focus over several years and initiatives towards global warming goes back to Kyoto, Japan 1997, when around 192 parties agreed on reducing carbon emissions and the presence of GHG in the atmosphere through the Kyoto protocol. The Kyoto protocol operationalizes the United Nations Framework Convention on Climate Change through committing developing countries and industries to a transition in GHG. The convention stated a requirement from certain countries to implement mitigation policies and interventions and to report on a frequent basis (UN, 2021b). There were issues with the agreement when there were major industrialized countries such as USA and China that outweighed the GHG emissions that participant countries reduced. Their pollution would cancel out the effort of the countries that had signed the protocol, which resulted in the Kyoto protocol to come to an end in 2012 and was later replaced with the Paris agreement.

The Paris agreement came in 2015 which aims to limit global warming to below 2 degrees Celsius. Hopefully it will reach 1.5 degrees Celsius which uses the levels before the industrial revolution as a reference. For the global temperature to reach this level, countries plan to meet global peaking in GHG emissions to achieve climate neutrality by mid-century. This is the first time a binding agreement is meant to bring all nations together towards a common goal and fight the climate change and adapt to its consequences (UN, 2021a).

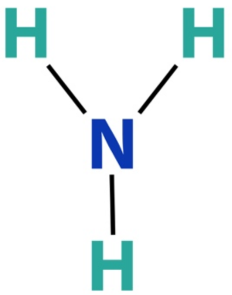

Figure 9-1: Ammonia molecule

10.1 Ammonia

Ammonia is an inorganic compound made up of three hydrogen atoms and a single nitrogen atom, attached to each other by a covalent bond, as seen in Figure 9-1. This composition can be produced naturally through bacterial processes and the degradation of organic matter. The compound is a colorless gas or compressed liquid with a strong smell, usually considered non-flammable but can burn at certain vapor concentrations and with a strong ignition. Ammonias fire danger increases in the presence of other combustible materials (PubChem, 2021).

Today's climate challenges, urges industries to look for better alternatives when it comes to renewable, carbon neutral or low-carbon energy. Ammonia is among the overlooked solutions in this energy transition that could possibly help in the increasing global energy demand, as well keep emissions to a minimum. Today, about 75-90 percent of the global production of ammonia goes towards producing fertilizer which is used to help sustain food production for billions of people around the world (Boerner, 2019). Ammonias potential reaches beyond being only considered just a fertilizer, as it also can be used as an energy carrier.

The production of ammonia with current technology requires either a constant supply of purified water in large quantities for hydrogen production by electrolysis, or large amounts of natural gas as a hydrogen source with related GHG emissions. For large scale industries, ammonia is mass-produced through the common Haber-Bosch method, but due to the high energy consumption coming from high operating pressure and temperature, about 2.16 tons of Carbon Dioxide is produced per ton ammonia. Today, about 90% of global production is produced from fossil fuels and 96% of the hydrogen comes from Steam Methane Reforming (SMR). Steam methane reforming produces approximately 9-10 tons of carbon dioxide for every ton of hydrogen produced (Ghavam et al., 2021).

10.1.1 Ammonia properties

Table 9-10-1: Ammonia properties (ToolBox, 2008)

Property	**Value:**	**Unit**

Boiling point – sublimation point	-33,33	ºC
Critical density	243,99	Kg/m^3
Critical pressure	113,57	Bar
Critical temperature	132,41	ºC
Critical Volume	0.00410	m^3/kg
Density	0,699	Kg/m^3
Density at 0 ºC and 1 atm	696	Kg/m^3
Molecular weight	17,0305	Gram/mole
Energy density	22.5	MJ/kg

10.1.2 The future of ammonia

Using ammonia as an energy source is a lesser-known solution compared to hydrogen, but its potential is highly promising as a feedstock for the global energy transition and is currently being developed as a part of the emerging green energy scheme. Ammonia consists of a single Nitrogen molecule and three Hydrogen molecules, meaning that burning ammonia in a thermal powerplant will not release any carbon dioxide or GHG, given that the exhaust is treated to prevent the emissions of NO_x. There are several ways ammonia can be synthesized, either as conventional ammonia, blue ammonia, or green ammonia. Conventional ammonia is produced using fossil fuels, blue ammonia is produced the same way but nearly all CO_2 is captured in the process using Carbon Capture Technology (CCS), and green ammonia is produced completely from renewable resources. Currently, blue ammonia is mostly synthesized by the petrochemical industry but is seen as a steppingstone towards green ammonia.

Ammonia can be used as an energy source either through direct combustion of ammonia, or as a medium for hydrogen storage. Its properties allow it to be liquified at mild conditions allowing for less complications when transported, very similar to propane, meaning that ammonia has a vapor pressure at 9.2 bar and can be safely contained in low-cost pressure tanks. In addition, ammonia has a high hydrogen fraction of 17.65% of the mass of ammonia. Combining these two properties we get a liquid that is roughly 45% greater than liquid hydrogen. Using a catalyst, ammonia can be decomposed to create hydrogen and nitrogen, non-toxic, non-greenhouse gasses (Thomas and Parks, 2006).

11 Haber-Bosch process for production of ammonia

11.1 Origin of Haber-Bosch

The Haber-Bosch process, also called Haber ammonia process was developed by the German scientist Fritz Boch, which is a method to produce ammonia (NH_3) from nitrogen (N_2) and hydrogen (H_2). Through this process, Haber made the production of ammonia economically feasible and was awarded with the Nobel-prize in chemistry in 1918. Later, Carl Bosch further developed this method into a large-scale process using a metal catalysator, high pressure and high temperature, resulting in creating the foundation for large-scale industrial production of nitrogen fertilizer, earning both Carl Bosch and Friedrich Bergius the Nobel Prize for high-pressure studies.(Britannica, 2020)

11.2 Chemical reaction during the Haber-Bosch process

The molecular formula for the Haber-Bosch process is given by:

Table 10-11-1: Ammonia Chemical reaction formula

N_2+3H2 $\rightarrow$ $2NH_3$					
N_2(g)	+	**$3H_2$(g)**	**$\leftarrow\rightarrow$**	**$2NH_3$(g)**	**ΔH = -92.4 KJ/mol**
Nitrogen		**Hydrogen**	**Heat, Pressure, Catalyst**	**Ammonia**	

The Haber-Bosch process involves the reaction of 1 mol of N_2 gas with 3 moles of H_2 gas to create 2 moles of ammonia. It is in equilibrium and is a very tough reaction to get started so the use of high pressure and high temperature are utilized in the presence of an iron catalyst to break the nitrogen triple bond and activate the reaction to form ammonia. Considering Le Chateliers principle, this is a very unfavourable equilibrium, even under the given conditions. As a starting point for the Haber-Bosch process, pure hydrogen or nitrogen are not used, but is rather a product that comes from the reaction of natural gas (CH_4), air, and water vapor (H_2O). Hydrogen is obtained from the reaction of methane and steam, where CO_2 is a by-product. Using potassium Carbonate (K_2CO_3), Carbon dioxide is removed from the gas stream. The hydrogen also reacts with the oxygen in air, producing water and leaving the nitrogen behind. These gases are compressed and delivered to the reactor where ammonia is produced.

11.3 The chemical process behind ammonia production

Methane and water vapor are passed through a Nickle catalyst at a pressure of 30 atmosphere (atm) and 750^{0}C

$$CH_4 + H_2O \leftrightarrow CO + 3H_2$$

$$CH_4 + 2H_2O \leftrightarrow CO_2 + 4H_2$$

Only 10% of the methane is used in the first reaction and gives the products hydrogen (H_2), carbon dioxide (CO_2) and carbon monoxide (CO). Following, air with 1/4th oxygen and 3/4th nitrogen.

$$2H_2 + [O_2 + 4N_2] \leftrightarrow 4N_2 + 2H_2O$$

The temperature increases to 1100^{0}C when the newly made hydrogen reacts with oxygen, creating the products water vapor and nitrogen. Further, with the increased temperature, the remaining methane reacts with water vapor and is converted to carbon monoxide and hydrogen. The temperature increase is also used to evaporate water at the beginning of the process.

Temperature is relocated, providing cooling of the gasses, leaving behind the mixture consisting of gases such as N_2, H_2, CO, CO_2, and H_2O. Carbon monoxide destroys the iron catalyst in the final step of the Haber-Bosch process, and is therefore removed in a catalytic reaction with water vapor, producing more carbon dioxide and hydrogen.

$$CO + H_2O \leftrightarrow CO_2 + H_2$$

In the next step, gasses are passed through a solution of potassium carbonate for the removal of carbon dioxide, creating potassium hydrogen carbonate ($KHCO_3$). Finally, a correct ratio mixture of nitrogen and hydrogen to be converted into ammonia using the Haber-Bosch catalyst, resulting in the final product ammonia (Aarnes, 2011).

The Haber-Bosch reaction is a reversible reaction, and the forward reaction is an exothermic reaction. The process uses Le Chatelier principle to maximize ammonia production while keeping operating and production cost in mind. The principle explains that an increase in pressure will favour the side with fever moles. High pressure is therefore favourable in the process of creating ammonia but maintaining and building a high-pressure plant is not cost effective. A pressure of 200 atmospheres (atm) is therefore used. This process is also exothermic, meaning there is a release of energy. In favour of the exothermic reaction a low temperature is favourable, but the speed of equilibrium would be slow. Therefore, a temperature of 450^0C is used as a compromise to ensure the reaction proceeds with sufficient yield. To speed up the reaction, an iron catalyst is used, which will not affect the equilibrium but will speed up the process.

The system will always go in the direction of equilibrium and to continue the reaction of creating ammonia in the right direction, the ammonia created is therefore condensed and collected, and completely removed from the system, which will then try to re-establish this equilibrium. The system is constantly trying to reach equilibrium, but it is not achieved because the ammonia is collected and removed from the equation.

All conditions are set as compromised conditions to maximise ammonia production and the economic profit making it feasible for large scale production. A simple illustration of the Haber-Process is seen in figure 10-1:

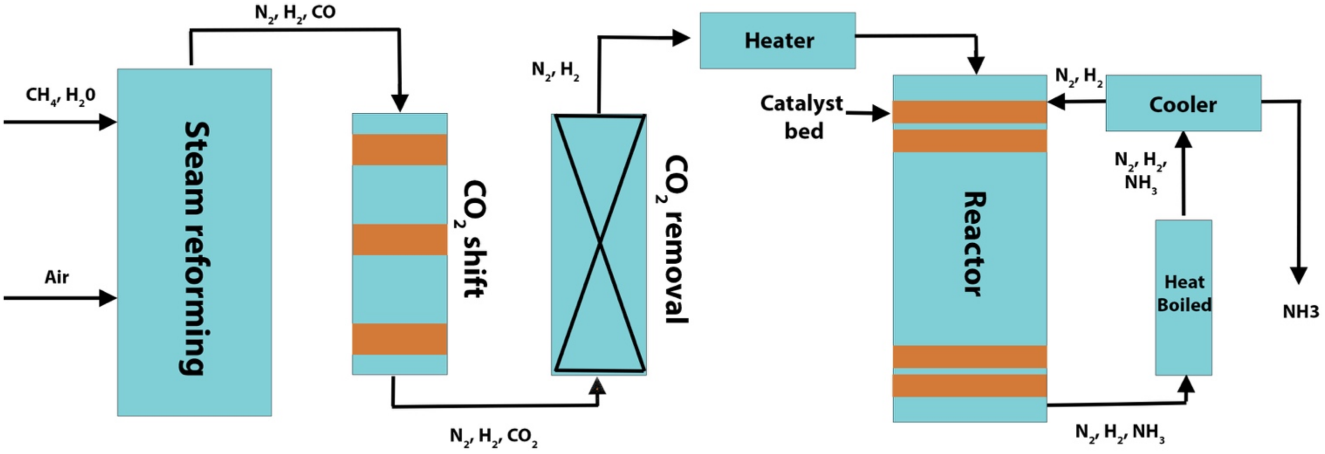

Figure 10-1: Haber-Boch process scheme (Palma et al., 2020)

12 Carbon Capture and Storage

12.1 Challenges

In the Haber-Bosch process, hydrogen is produced from natural gas or other hydrocarbons, and during the production, all hydrocarbons are removed from the ammonia process by converting it to carbon dioxide. The nitrogen is either distilled from liquid air or an oxidative process where the air is burned, and the remaining nitrogen is recovered. Nitrogen also has strong stable bonds that require a larger amount of energy to break apart so that nitrogen can bond with hydrogen to create ammonia (Parmet, 2020). Current methods to make ammonia are very energy-intensive that require a lot of fossil fuel and the main contributor of direct greenhouse gas emissions in the process is CO_2. Since the production is energy intensive, the use of an external energy source will be necessary. Due to the large availability of natural gas, the external energy source will be provided from using gas-fired powerplants that will power all the facilities. To keep the emissions as low as possible, each plant will be equipped with carbon capture technology to further prevent further CO_2 release.

The captured carbon dioxide is transported and stored safely underground in empty reservoirs for sequestration or for enhanced oil recovery (EOR). Carbon capture and storage technology is already well developed and commercially accessible, but few industries utilize it because there are few incentives to undertake further expenses just to reduce CO_2 emissions.

To produce blue ammonia, carbon dioxide is separated in the beginning of the process and is further distributed for carbon storage. The gas-fired powerplants on the other hand needs to either implement a conventional and effective carbon capture method such as the use of the chemical monoethanolamine (MEA) that can separate CO_2 in flue gas or utilize a concentrated gas in the beginning of the process such as Oxyfuel, so that the exhaust emissions are a more concentrated form of CO_2. A gas-fired powerplant needs access to an airstream so that the methane can combust. The airstream contains 78% nitrogen, 21% oxygen and the rest are a mix of other components, thus using air for combustion will create a flue gas that is not pure carbon dioxide but a mixture of different components. These components need to be separated from the CO_2 later in the process with the use of either MEA or the airstream can be filtered of nitrogen in the beginning of the process so that the by-products in the combustion are a cleaner mix of CO_2.

12.1.1 Monoethanolamine for carbon capture

Monoethanolamine (MEA) is an amine that is highly reactive with CO_2 and has been utilized in the industry for carbon dioxide capture for many years. The CO_2 rich gas mixture which is retrieved from the power station and ammonia process is sent through an absorber column and a stripper column. The CO_2 passes upwards an absorber column, and the MEA solution flows down over a large mesh grid to increase the surface area of the MEA liquid that will react efficiently with the CO_2. The CO_2 rich MEA solution is further pumped to the top of the stripper column and flows down over another mesh grid which is heated by a steam reboiler, and the CO_2 is separated from the MEA. Most of the CO_2 is separated from the MEA but is fully separated in the condenser. All the MEA is returned to the beginning of the process and is reused for further CO_2 absorbing. The end product is a nitrogen gas stream that is clean and safe for the environment and can be released into the atmosphere, and a CO_2 solution which is further compressed into liquid form and utilized for EOR or sequestration (Lv et al., 2015).

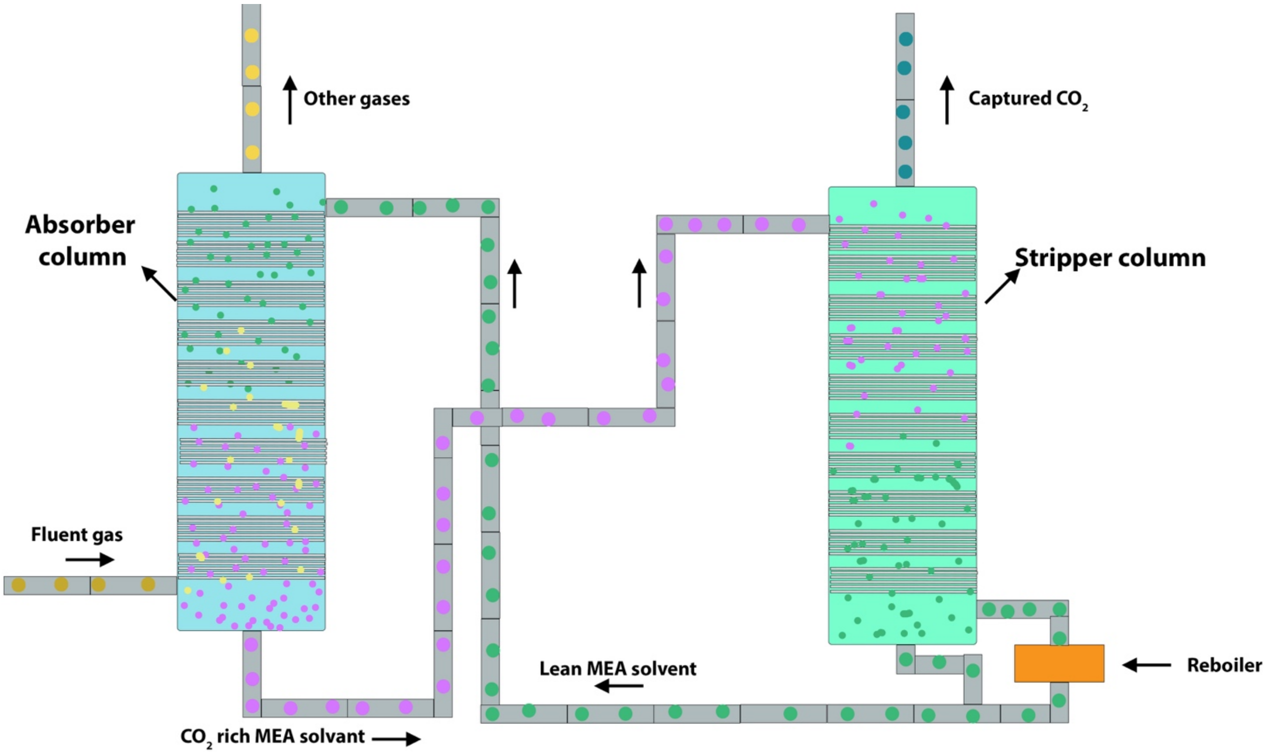

Figure 11-1:Monoethanolamine process scheme

CO_2 separation from gas is an expensive procedure since it requires large amounts of energy. The large energy utilization comes from the heat needed for the separation process and these kinds of processes are more profitable in industrial operations that creates waste heat that can be recycled. The chemical reaction used to produce ammonia, releases a lot of excess heat because it is an exothermic reaction. Optimization and exploitation of the excess heat from the reaction and the dessert climate in Qatar will contribute to saving energy, helping minimize expenses from the CO_2 separation process (LSE, 2018).

12.1.2 Oxyfuel for pre-combustion filtering

The main purpose of this method is to create a flue gas that has a high concentration of CO_2 and water vapor, making it a CO_2 rich flue gas that is ready for EOR or sequestration. In the beginning of the process, nitrogen is filtered out from the airstream, leaving a higher concentration of oxygen, approximately 95%. Using pure oxygen for combustion results in a very high temperature, therefore a diluted recycled flue gas mixture is combined with the oxygen. Using oxygen for combustion produces less flue gas and the remaining emissions consist primarily of H_2O and CO_2, which is mostly the main reason why this method is utilized for sequestration. Using Oxyfuel reduces the flue gas mass, volume, and less heat is therefore required, allowing the facility to utilize smaller machines for the process. High concentrations of flue gas allow for easier separation because these gases are condensable. Condensable gases can be separated with compression, separating the CO_2 from the H_2O and since nitrogen is absent from the solution, the heat from the condensation can be reused. Oxyfuel is costly due to the high amount of energy needed to separate the oxygen from the air, making it less competitive but is among the best solutions for carbon capture in conventional air fired fossil fuel plants.

Oxyfuel process in steps:

Step 1: Separate oxygen from the air, for example by filtering out nitrogen through a nitrogen membrane.

Step 2: Utilize and/or discharge surplus nitrogen to the atmosphere, utilize oxygen for combustion of natural gas.

Step 3: Remove water through condensation

Step 4: Compress CO_2 for storage.

$$\mathbf{CH_4 + O_2 = CO_2 + H_2O}$$

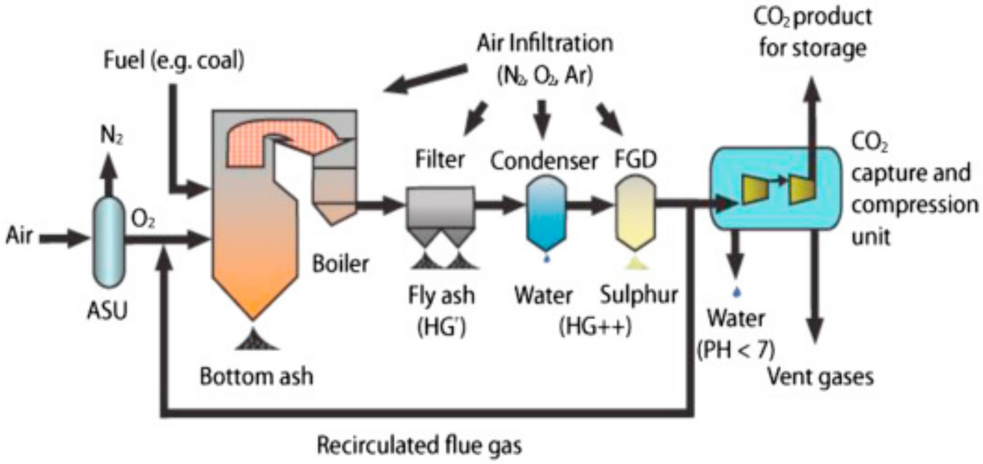

Figure 11-2: Oxy-fuel combustion system (Carpenter and lll, 2017)

12.1.3 CO$_2$ physical properties

Carbon dioxide (CO$_2$) is a colourless gas with sour taste, pungent odour and is among the greenhouse gases that are linked to global warming but is only a small part of the Earth's atmosphere. The compound is generated from the combustion of materials containing carbon and is also used in photosynthesis. CO$_2$ works as a reflector, trapping some of the radiated energy from the sun within the atmosphere, thus contributing to global warming.

The physical properties of CO$_2$ vary depending on the temperature and pressure in its surrounding. These are some of the important properties of CO$_2$:

Table 11-12-1: CO2 Properties (ToolBox, 2018)

Property	**Value:**	**Unit**
Boiling point – sublimation point	-78,464	ºC
Critical density	467,6	Kg/m^3
Critical pressure	73,8	Bar
Critical temperature	30.98	ºC
Critical Volume	0.00214	m^3/kg
Density	1,795	Kg/m^3
Density at 0 ºC and 1 atm	1,97	Kg/m^3
Molecular weight	44,01	Gram/mole

(ToolBox, 2018)

13 Enhanced oil recovery (EOR)

The process of removing carbon dioxide from industrial processes requires a large amount of energy, which in return increases the CO$_2$ output. The more profitable solution is then to use the CO$_2$ for enhanced oil recovery before permanently storing the CO$_2$ in a depleted reservoir.

There are three different phases in crude oil development: primary, secondary, and tertiary, where tertiary is enhanced oil recovery (EOR). The primary recovery phase allows for recovery by only using earth's natural gravity to drive the oil into the wellbore, and further bring the oil up with artificial lift techniques, like pumps etc. Secondary phase allows for further recovery by pumping water or gas into the reservoir for oil displacement, pushing the oil towards the production wellbore, resulting in the recovery of 20% to 40% of the original oil in place.

Oil producers in the U.S have already tried out several tertiary recovery methods techniques which have shown an increase in recovery of around 30 to 60 percent of the reservoirs original oil. The three major EOR categories that were among the most successful were Thermal recovery, Gas injection and chemical injection. (Energy, 2021)

Typically, reservoirs have an impermeable layer of shale or cap rock that the oil and gas are beneath. This layer creates a barrier that naturally prevents fluids or gases from rising to the surface. The process of using CO_2 for enhanced oil recovery and permanent CO_2 sequestration is by injecting the CO_2 strategically into the reservoir to improve the oil production and to permanently store the CO_2, removing it from the carbon cycle.

The produced CO_2 is transported from Ras Laffan to the heavy oilfield Manifa in Saudi Arabia, which will then be used for EOR to extend the life of the field before permanently storing the CO_2. The process involves compression of CO_2 into a liquid like form, which is then injected down a wellbore that is strategically located in the formation for optimal enhanced oil recovery and permanent CO_2 storage benefits. The CO_2 then mixes with the oil and reduces its viscosity allowing for better flow between the interconnected pore spaces towards the production well and will increase the production by 20-40%. Then the CO_2 is displaced with the oil and is permanently stored beneath the cap rock in the pore space the same way oil was stored. Another way of storing the CO_2 is through mineralization of the CO_2 within the pore space. As the oil is produced, the oil will be transported to a facility where oil and gas flows through a series of vessels that separates the oil into storage tanks. Since the CO_2 is used to reduce viscosity, a portion of the injected gas will be produced with the oil. This CO_2 is separated from the oil and combined with the CO_2 coming from the ammonia production plant, creating a closed loop system, ultimately containing the CO_2 within the reservoir preventing it from entering the atmosphere.

13.1 Issues with CO_2 in EOR

CO_2 is an effective viscosity reducing agent for oil but high content of CO_2 in natural gas will deteriorate the quality of the natural gas. Therefore, it is not favorable to use CO_2 for EOR in fields with free natural gas or high levels of associated natural gas as the CO_2 will turn gaseous in the low-pressure separation stage. Heavy oil fields are known for their low content of associated natural gas and rarely have free gas therefore the use of CO_2 for EOR will not affect the natural gas as there is barely any natural gas, as the CO_2 is produced together with the heavy oil. One is dependent on separating/capturing the CO_2, this can be done through low pressure separation of the heavy oil stream, where the CO_2 is compressed and sent either back into the reservoir or for sequestration.

13.2 Manifa; Heavy oil production

For low-cost transportation of CO_2 and utility the Manifa oil field will be utilized which was discovered in 1957 and is among the largest reservoirs in the world. The heavy oil field reservoir consists of six-reservoirs stretching 18 km wide and 45 km long, beneath 15 meters of shallow water (Aramco, 2021). Standard offshore drilling is impossible for these fields due to the shallow waters. As a result, Saudi Aramco made the decision of building 25 different drilling islands that would cover the whole Manifa oil field.(Jandenul, 2021)

Since Manifa is a heavy oil field, the oil has high viscosity which requires high pressure for natural production. The typical recovery factor for conventional oil production is greater than 30%, whereas it is only 5-10% for heavy oil (Ganat, 2019). When the reservoir cannot unload naturally at a cost-effective rate, one must resort to artificial lift that will counteract the depleting reservoir pressure to maintain a continuous production rate. The artificial lift will be provided by the injected CO_2 received from the ammonia factories in Qatar. The CO_2 will help maintain the reservoir pressure and it will improve the oil displacement because it reduces the interfacial tension between water and oil. There exist many different types of gases used for oil displacement in EOR but CO_2 is mostly used as it reduces the viscosity and is cheaper than the other gases (Ahmad et al., 2019).

14 Qatar North Dome – Reserves and possibilities

14.1 Discovery

The North Dome natural gas field was discovered in 1971 by exploration engineers and further extension of the northern reservoir known as South Pars was later discovered by Iran, nearly two decades later. The reservoir has a wide dome or anticline structure that has collected significant quantities of gas and condensate. North Dome is located in in the Persian Gulf, divided by the political border between Qatar and Iran. It took 15 exploration wells over a period of 14 years before it became clear the gas field was the world's largest non-associated natural gas field, with recoverable reserves exceeding 26.000 Billion Sm^3. On the Iranian side (South Pars), the reservoir is originally estimated to contain recoverable reserves of 10.000 billion Sm^3 gas. These estimates shows that North Dome and South Pars hosts approximately 19% of the world's total natural gas reserves. Only the discovery of North Dome increased Qatar's reserves respectively by 99%, making it the third largest natural gas holder in the world, after Russia (Esrafili-Dizaji et al., 2013).

The North Field dome is located off the North-east coast of the Qatar peninsula and occupies an area of more than 6,000 km^2, which makes up for approximately half of Qatar's land area. Discovering and production of this important natural resource played an important role in the economic growth of Qatar. This opened up a multibillion-dollar venture in production of Liquid Nitrogen Gas (LNG), Gas to Liquid (GTL), and a variety of gas-related industries, in comparison to export of pipeline gas. (QP, 2021)

14.2 Energy and exports

Qatar's economy is mainly focused on the extraction of natural gas and petroleum, which is the cause of the massive economic bloom since the 1970's. These large reserves are further used to diversify and secure Qatar's future beyond being merely a fuel supplier. Standing with a wealth fund of US$38 billion in foreign exchange reserves and US$335 billions of sovereign wealth fund, makes Qatar a major player in oil and international markets. . (USQBC, 2016)

Qatar stands as the second largest natural exporter, exporting $44.2 billion worth of gas per year, where the most common export destinations are India, South Korea, China, Singapore, and Japan. As of 2019, Qatar exported an estimated value total of $77 billion, making it the number 42 largest in total exported in the world. Looking at the estimated export values, Qatar's export has seen a decrease by \$53.6 billion over the years, from \$131 billion in 2014 to \$77 billion in 2019 (OEC, 2019).

Qatar also exports \$15.5 billion worth of crude petroleum from conventional oil fields, that estimates to roughly 500 thousand barrels per day and condensate which is produced in the world's largest gas to Liquid (GTL) facility. These values together with non-natural gas energy exports helps diversify the product mix to protect the wealth against the world fluctuating gas prices, even with this mix it does not completely diversify the countries dependency on export of energy. Through exporting to different nations such as Japan, South Korea, China and many other countries in Asia, exposes Qatar's natural gas to several economies, protecting the dependency on gas but not from the fluctuating market prices. (USQBC, 2016)

Through the last decade there has been an increase in export seen from Figure 13-1. The demand for gas is increasing as Qatar takes over larger shares of the global market, due to their low-priced natural gas. As gas takes a major part of Qatar's economic growth, increased production is therefore incentivised and further plans for expansion in field production is therefore set in motion. Another reason for expansion comes from the increased consumption of natural gas in Western countries and Asia. Given the current natural gas production seen in Figure 13-2, the available gas reserves allows for 138 years of production, where increased production and unproven natural gas reserves are not taken into consideration . (WorldOmeter, 2017).

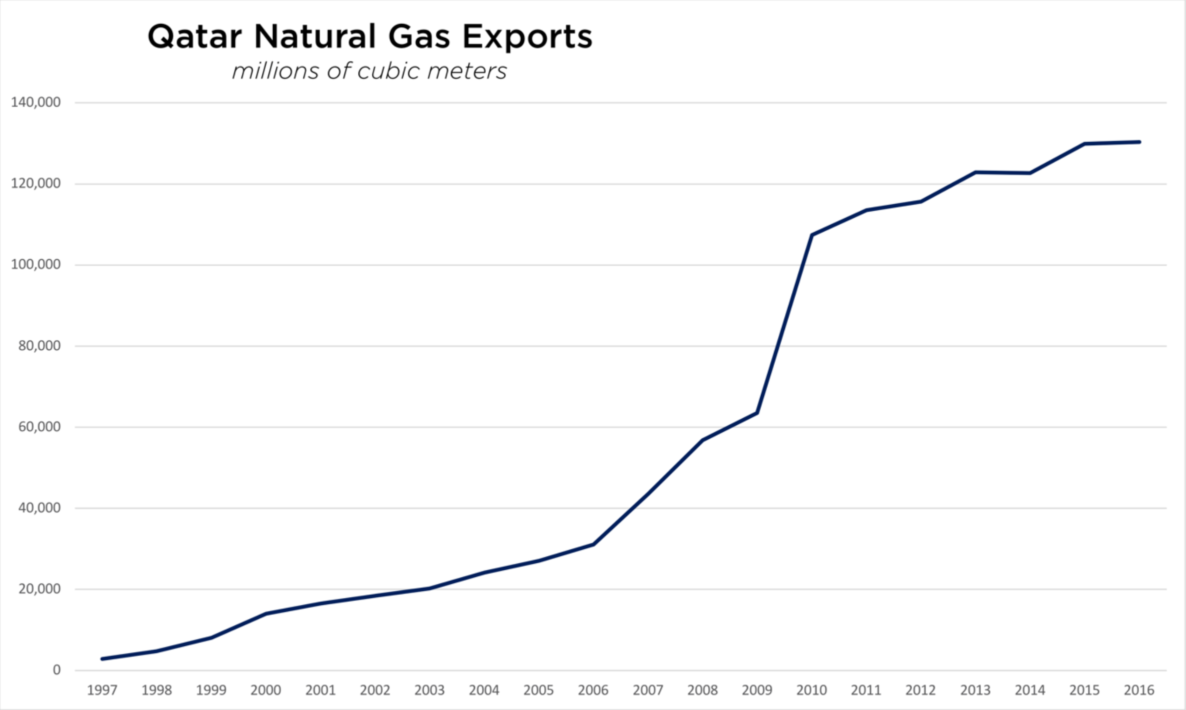

Figure 13-1: Qatar Natural Gas Exports (USQBC, 2016)

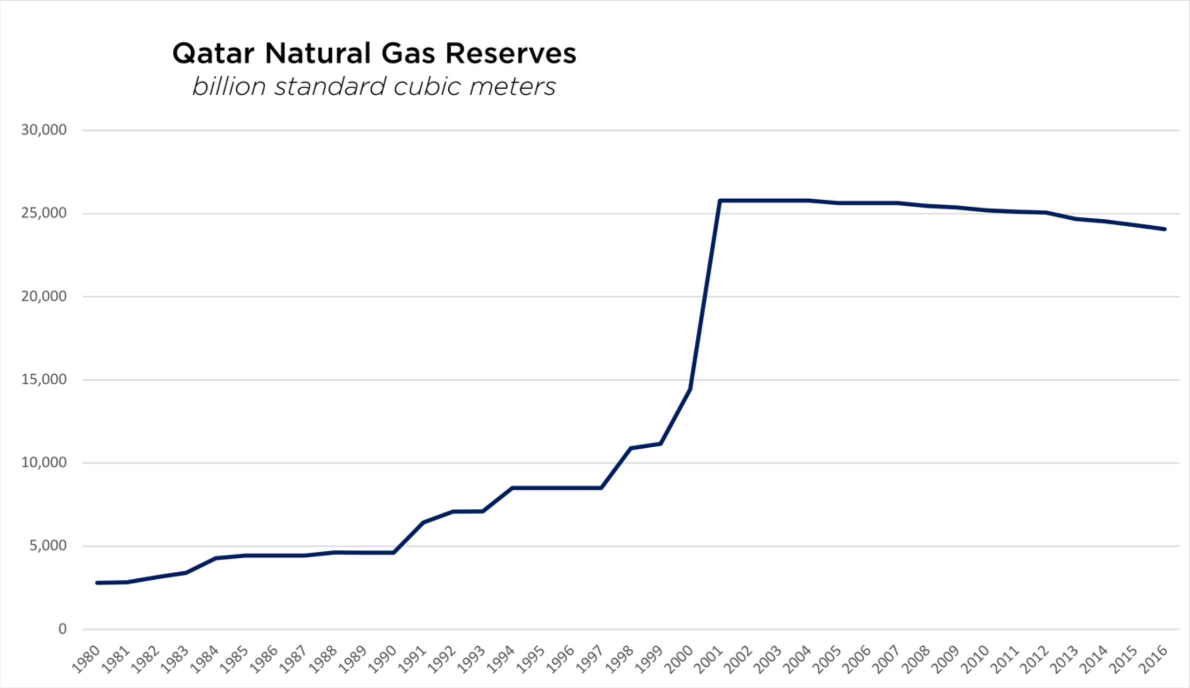

Figure 13-2: Qatar Natural Gas reserves: Incline and decline of reserves over the past decades (USQBC, 2016)

14.3 Diversification and future commitments.

As of today, Qatar is heavily reliant on the production and export of fossil fuels. Through diversification in energy sources, the economy of Qatar will not be fully reliant on the fossil fuels since these depend largely on the global market price. Qatar has had the option to expand their infrastructure towards renewable energy such as solar power. However, there has not been any incentives to work towards this solution, because natural gas has been a much more accessible and cheaper energy source. As we are moving further into the century, the focus on climate change and actions towards GHG reduction has grown and measures needs to be taken. Production of ammonia together with carbon capture and sequestration is a great solution towards carbon neutrality and should be seen as a future solution for Qatar due to their heavy reliance on natural gas.

15 General industrial process

15.1 General process

The industrial process is mainly about the production of ammonia and electricity for this purpose, with a low carbon footprint, calculated up to and including the production stage. This can be realized by using natural gas as an energy source, where CO_2 from the production of ammonia and exhaust gas from the electricity power plant is captured, compressed, and utilized for enhanced oil recovery (EOR) and thereafter stored in depleted reservoirs, alternatively store the CO_2 directly into the geological formations. The ammonia is further distributed with very large gas carriers (VLGC) or through pipelines, ultimately used for electricity generation, and the economic viability is calculated to highlight at what level the carbon tax needs to be to compete with electricity generated from carbonaceous sources.

15.2 Overall chemical processes

The following overall chemical processes will take place in the industrial complex:

1. **Production of energy**

   Combustion of natural gas

$$CH_4 + 2O_2 = CO_2 + 2H_2O$$

2. **Production of hydrogen (H) and nitrogen (N):**

   Steam reform:

$$CH_4 + H_2O \leftrightarrow CO + 3H_2$$

$$CH_4 + 2H_2O \leftrightarrow CO_2 + 4H_2$$

$$2H_2 + [O_2 + 4N_2] \leftrightarrow 4N_2 + 2H_2O$$

$$CO + H_2O \leftrightarrow CO_2 + H_2$$

3. **Production of ammonia:**

Haber-Bosch process:

$$N_2 + 3H_2 \rightarrow 2NH_3$$

15.3 Industries that use ammonia as an input factor

When establishing an ammonia factory, industries in the vicinity of this factory may be able to use the ammonia as an input factor for further processing into a wider range of products, but the focus will be on ammonia as an energy source.

Below are some areas where ammonia can be utilized:

- Production of chemicals such as: amines, nitriles, hydrogen cyanide, hydrazine, hydroxylamine, ammonium carbonate, phenol, urea, amino acids, etc
- Fermentation
- Antimicrobial agent
- Production of acrylic and nylon fibres
- Metallurgy, metalworking, and steel
- Explosives in the form of ammonium nitrate
- Refrigerant in refrigeration systems
- Pharmaceutical products
- Fertilizer products
- Production of proteins for use in animal feed
- Petrochemical industry
- Mining industry
- NO_x and SO_x purification systems
- Food and drink
- Rubber and leather industry

15.4 Conditions for establishing a highly effective low-carbon energy supply

The following conditions must be met to establish a highly efficient low-carbon industrial complex:

1. Proximity to a large and uncomplicated reservoir for storing CO_2, preferably low reservoir pressure.
2. Proximity and good access to water as a raw material and for cooling
3. Labour:
    a. Access to labour with academic competence and operational competence within pipe systems / energy systems for liquid and gas, including temperatures above 100°C, pressure above 100 bar and gas compression
    b. Access to labour with academic competence and operational competence within complex automated systems.
4. For ammonia production: Easy access to methane, through pipeline and/or LNG facilities
5. Proximity to port facilities for loading and unloading
6. Access to sufficient land area for the establishment of processing facilities
7. Acceptance from local people and authorities for the establishment of the industrial complex.

16 Project economy

Information about natural gas production estimations and estimated calculations is retrieved from Qatargas to create a rough overview of how much gas is available for ammonia production and for the power plants. The natural gas will be the key factor for the development of Qatar's ammonia production and the gas will be supplied from the North Dome natural gas field. There is a total of 208 production well that will supply roughly 524 million cubic metres of raw sour gas per day which will be transported to onshore processing facilities in Ras Laffan Industrial City as shown in Figure 15-1(Qatargas, 2021). About 70% of the annual produced natural gas will be relocated to the ammonia plants, and the remaining 30% goes to other petrochemical products. Roughly 367 million cubic metres per day of gas will be supplying the ammonia plants and 157 million cubic metres of gas will go to export or petrochemical industries.

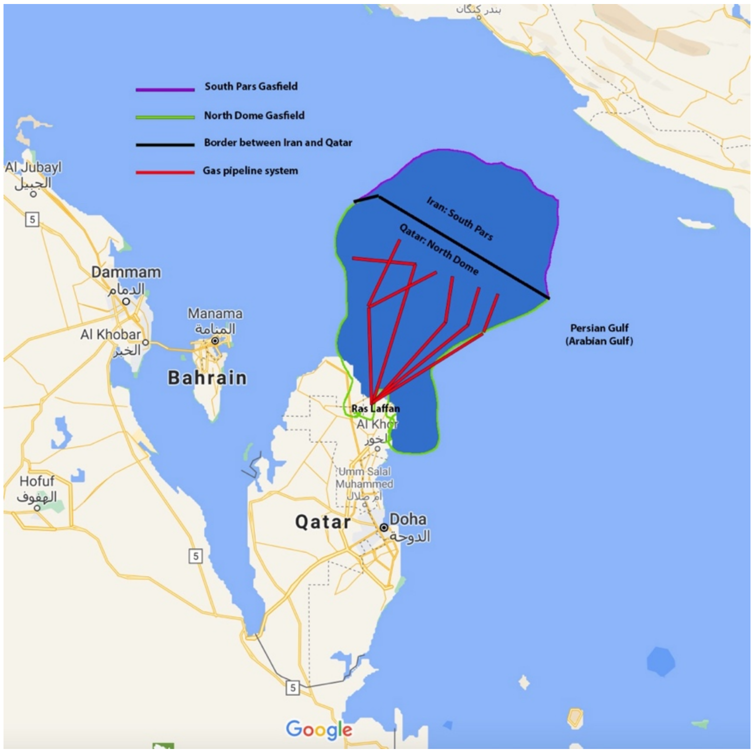

Figure 15-1: North Dome divided between Iran and Qatar

Natural gas will be the main driving force behind the production of ammonia and prices tend to vary depending on the ongoing market. Observations from the graph in Figure 15-2 shows how the price development of natural gas varies. The gas prices are ranging from 5.13 USD/MMbtu to 1.64 USD/MMbtu over the last 10 years, and for estimation purposes, an average cost estimate of 3.3 USD/MMBtu will be used in the production of the low-carbon energy supply from Qatar.

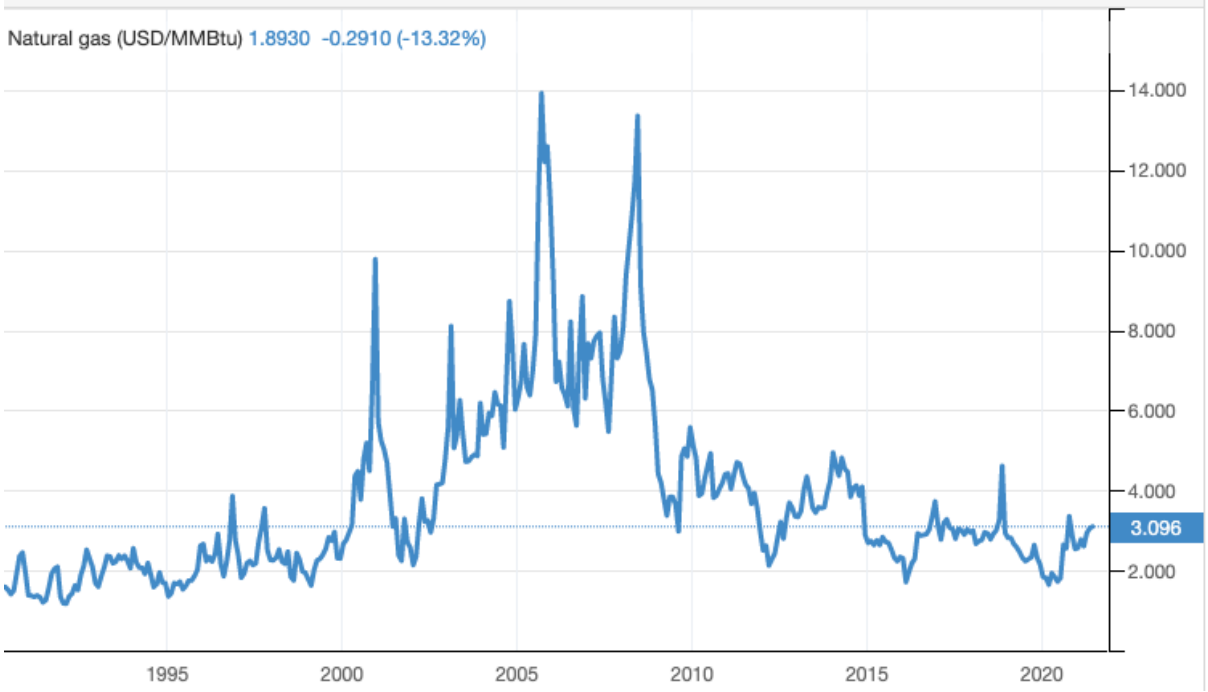

Figure 15-2: Natural gas Price fluctuations 1995-2020 (TradingEconomics, 2021a)

16.1 Ammonia factories

The natural gas produced from the North Dome gas field, will be supplying the ammonia factories located in Ras Laffan and each factory will have a capacity of 2000 tonne NH_3/day, allowing for a total production of 670 000 tonne NH_3/year if each factory has an uptime of 91.6%, meaning that the facility will be operational 11 out of 12 months a year.

Considering the relocation of the 70% of daily natural gas production, a quota of 367 million cubic metres needs to be utilized daily, and 133.95 billion cubic metres per year. To produce ammonia, a relationship of 1020 cubic metres of natural gas per tonne ammonia is utilized, and to produce the yearly capacity of 670 000 tonne NH_3, a total of 680 million cubic metres of gas is used. To meet these requirements an estimate of 197 ammonia production factories will be needed to cover the yearly natural gas production of 133.95 billion cubic metres of natural gas. Considering that each factory produces 670 000 tonne NH_3/year, then 197 factories will produce an annual combined total of 132 million tonne NH_3/year which means that the facilities will approximately cover half of today's world total ammonia production of 235 million tonnes (Garside, 2020).

Table 15-16-1: Ammonia factory gas consumption and ammonia production capacity

Description	**Values:**
Daily natural gas production	367 million m^3
Yearly natural gas production	133.95 billion m^3
One Factory daily natural gas consumption	2,04 million m^3
One factory yearly natural gas consumption	680 million m^3
Qatar project ammonia production	132 million tonnes NH_3
Global ammonia production	235 million tonnes NH_3

16.2 Land Area

Ras Laffan is strategically the best location for the factories, as this city is already dedicated for industrial purposes, close access to natural gas and there are a lot of available land plots that are ready to be used for construction and since most of the land is desert, further expansion of land is possible if necessary. Figure 15-3 demonstrates the marked-up land around and inside the industrial city that will be utilized for construction, which constitute approximately 269 square kilometres (km^2).

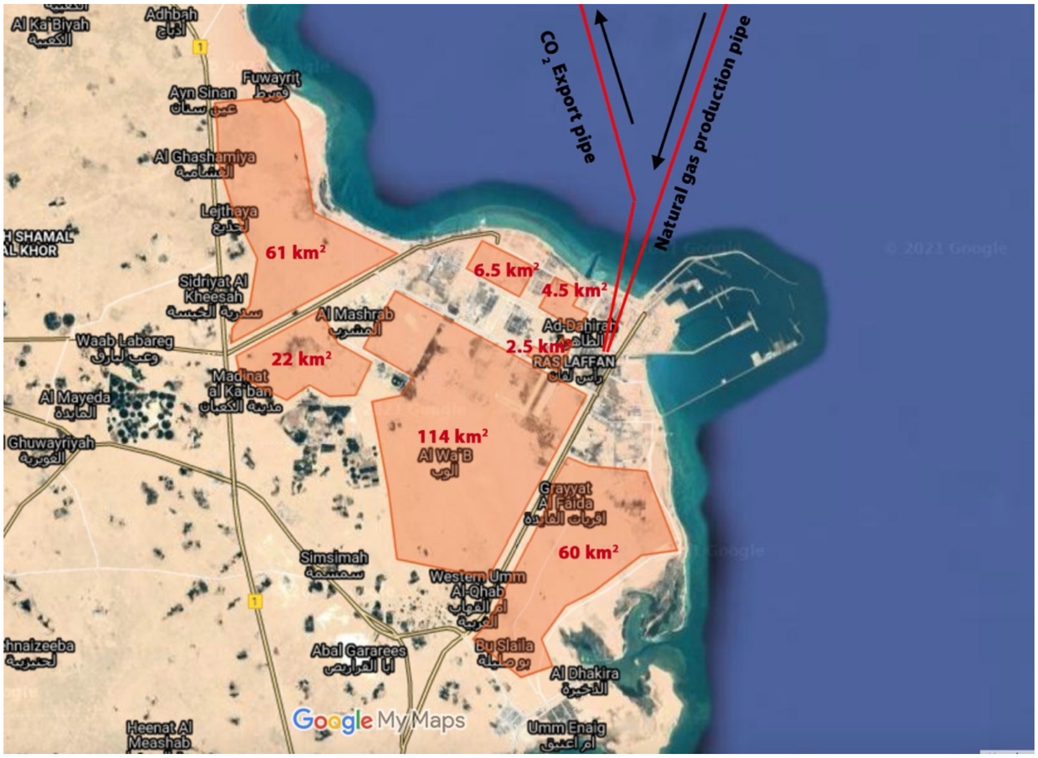

Figure 15-3: Marked up construction sites for factories/plants (Earth, 2021d)

The construction of an ammonia plant with a capacity of 2000 tonnes NH_3 per day will be compared to the Ammonia plant in Herøya, Porsgrunn, Norway industrial facility which is approximately 0.75 km^2 and the 197 factories will in total use approximately 150 km^2 of land. The rest will be used for pipelines, powerplants and other facilities needed for the project.

Table 15-16-2: Ammonia facilities details

Description	**Values:**
Available land	269 km^2
Ammonia plant area	0.75 km^2 per factory
Total land dedicated to ammonia factories	150 km^2

The illustration of land plots has not taken into account for the conversion of LNG facilities into ammonia factories or demolishing current existing factories to create ammonia plants. The land chosen is either empty or there are powerlines in the market up lots, which can be relocated. Each ammonia factory will be cost estimated individually to create an overview of potential construction cost. The creation of a large ammonia complex will have a variety in cost, land area and how the raw material is utilized, but for this estimate all factories will have the same cost, as each factory is the same and will take an uncertain amount of time to construct, as this largely relies on how much resources is dedicated to performing the construction. Mass producing factories might impact the efficiency as construction experience increases, resulting in a reduction of total construction time and construction optimalization. This effect can be compared to the experience curve effect model that shows the efficiency development over time. Increasing the experience in ammonia factory construction will lead to the fact that they become better at constructing the factories. Becoming better at construction will lead to increased efficiency and therefore lead to a reduction in cost per factory. The experience curve in figure 15-4 shows the development of the factories after X number of constructed facilities, seeing a decrease in direct cost after numerous constructed plants.

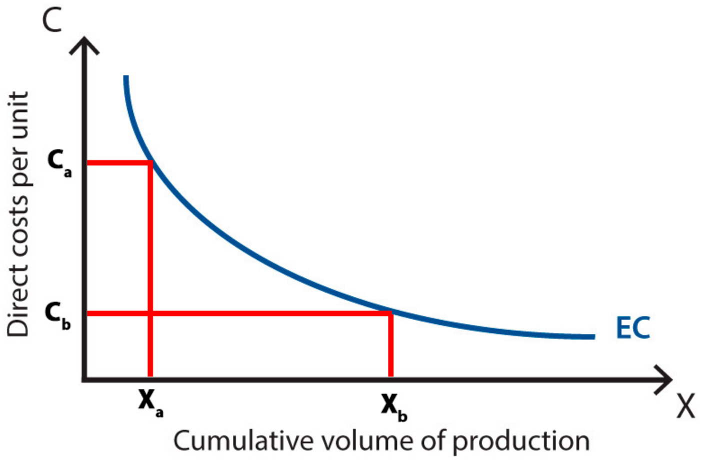

Figure 15-4: Experience curve effect (Dictionary, 2020)

The construction cost of a full-scale ammonia factory with a capacity of 2000 tonnes ammonia per day using the Haber-Bosch method varies depending on location. Yara has provided information showing that a conventional gas conversion to ammonia with Haber-Bosch costs roughly between US$ 700 million and US$ 1 billion. For calculation purposes an estimate of US$ 850 millions will be used as a cost for constructing an ammonia plant.

Table 15-16-3: Ammonia factory cost

Description	**Values:**
Factory Cost	US$ 850 million
Total Factory cost (All 197)	US$ 167,45 billion

16.3 Factory energy consumption

Each ammonia factory will need an external energy source, and this will be supplied from the powerplants. Total amount of constructed powerplants will largely depend on the energy consumption from the ammonia factories. According to (Velázquez et al., 2013) they specify that the average global energy consumption in ammonia production is around 36.6 GJ/t NH_3 and for newer facilities that utilizes newer technology for production, show an average specific energy consumption of around 28 GJ/t NH_3. That is a difference of 8.6 GJ/t between the global specific consumption and consumption by using newer technology.

16.4 Ammonia plant calculations

Calculating the energy demand during ammonia production depends largely on these parameters:

1. Natural gas energy
2. Power energy

Natural gas energy:

Natural gas (NG) energy usage is calculated by the following formula:

$$\text{NG} = \frac{Daily\ natural\ gas\ consumption\ (fuel+feed)*NG\ Lower\ Heating\ Value\ (LHV)}{Daily\ ammonia\ production*10^6} \tag{15.1}$$

(Baboo, 2015)

= G. Cal/tonne NH_3

Where:

Daily natural gas consumption (fuel + feed) = 2.04 million Sm^3

NG LHV = 8134 K Cal/Sm^3

Ammonia production = 2000 metric tons per day (mtpd)

NG energy:

$$= \frac{2040000*8134}{2000*10^6} = 8.296 \text{ G. Cal/tonne } NH_3$$

Power energy consumption:

Energy required to produce ammonia = 106 MW/day

NG/MW = 175 Sm^3/MW

Power consummation per tonne ammonia

$$= \frac{Power\ consummation\ per\ tonne\ ammonia*\frac{NG}{MW}*NH\ LHV}{Daily\ ammonia\ production*10^6} \tag{15.2}$$

(Baboo, 2015)

$$= \frac{106*175*8134}{2000*10^6} = 0.07544 \text{ G Cal/tonne } NH_3$$

16.5 Total energy cost for ammonia production

Total energy cost = NG Energy – Power energy

= 8.296 G. Cal/tonne NH_3 – 0.07544 G Cal/tonne NH_3 = 8.221 G. Cal/tonne NH_3

Converting the result from G. Cal/tonne NH_3 to Giga joule (GJ) gives a total energy cost of 34.41 GJ/tonne NH_3.

Using the calculations shown above shows an energy consumption of 34.41 GJ/tonne NH_3 which is almost the average between 36 and 28 GJ/tonne NH_3 mentioned earlier.
The total energy cost does not represent a lost value of energy, but a representation of how much of the natural gas energy is passed on to the ammonia and how much energy is needed to produce ammonia. Most of the energy comes from natural gas and energy in the form of electricity is not as large, but still a significant factor which will need an external power source in order to operate.

For production purposes the baseline of energy consumption will be concentrated around the use of 106 MW of energy per day for each ammonia factory. An estimate of total energy consumption among all the 197 ammonia factories will roughly be 20 882 MW/day and total of. 6 995 470 MW/year.

Table 15-16-4: Ammonia factory energy consumption

Description	**Values:**
Energy consumption per factory	106 MW/day
Energy consumption per year per factory	32830 MWh per year
Total energy consumption per year	6 995 470MW/year

16.6 CO_2 emissions ammonia production

Ammonia factories release a large amount of CO_2 and the global production stands for approximately 2% of worldwide fossil energy use and emissions is estimated to be roughly 420 million tons of CO_2 (Liu et al., 2020). Synthesising hydrogen and nitrogen from natural gas creates the by-product CO_2 and from conventional production the gas is separated and released into the atmosphere. Instead of releasing the CO_2 into the atmosphere, the CO_2 is then separated, compressed, and stored for further utilization in EOR. It is estimated that one tonne of Ammonia releases approximately 2.16 tons of CO_2 and the production of 2000 tonnes of ammonia per day releases 4320 tonnes of CO_2 per factory. Including all 197 factories which have an uptime of 91.6% will result in 285 million tonnes CO_2 emission per year. As it is common today for CO_2 to be captured at ammonia factories for use in other industrial purposes, there will only be a need for a compressor plant beyond a normal plant.

Table 15-16-5: CO2 emissions

Emissions	**Value:**
CO_2 released per tonne NH_3	2.16 tonnes CO_2
Emission per factory per day	4320 tonnes CO_2
Emissions all factories per day	851 000 tonnes CO_2
Emissions for one factory per day (Sm^3)	2 180 000 Sm^3
Emissions all factories per day (Sm^3)	430 000 000 Sm^3
Emissions per factory per year	1 447 200 tonnes CO_2
Total emissions combined	285 million tonnes CO_2

For comparison, the total emissions (CO_2-equivalent) of Norway was 50 million tonnes of CO (Øvrebø, 2021).

16.7 CO_2 generated and compression energy

The produced CO_2 is compressed, transported, stored in a reservoir and the electricity produced from power plants will be used to power the compressor trains. The discharge pressure from the compressors is set to be 150 bara to create enough drive and pressure to exceed the reservoir pressure. Delivering the CO_2 at this pressure will make it ready for EOR or sequestration as well as maintaining the CO_2 in a supercritical stage that is optimal for transportation. To compress CO_2 from 1 bara to 150 bara, the following calculations are used:

For isothermal compression:

$$W = n * R * T * \ln(V_2 - V_1) \qquad (15.3)$$

- W = Work (Joule (J))
- n = mole
- R = Gas constant (Joule/(Kelvin (K) * mole)

- T = Temperature (K)
- $\ln(V_2 - V_1)$ = ln (volume change)

To compress 2.16 tonnes of CO_2 from 1.0 bara to 150 bara with a temperature of 300K, the following values from calculations is used:

$$n = \frac{gram}{grams/mole} \tag{15.4}$$

$$= \frac{2160000gram}{44.01gram/mole} = 49080 \text{ moles}$$

W = 49080 * 8.314472 * 300 * ln (150-1) = 612 594 544 joules = 170.17 kilo watt hours (Kwh)

Producing one ton of ammonia, generates 2.16 tonnes of CO_2 and for every 2.16 tonnes of CO_2, approximately 170.14 kwh of energy is needed to compress the CO_2 from 1 bara to 150 bara. A factory produces 2000 tonnes NH_3 per day, meaning that a total of 4320 tonnes of CO_2 is produced and energy needed to compress the total CO_2 is 340 340 kWh per day. The energy needed to compress the CO_2 generated from all 197 factories is 67 046 980 kWh per day. Resulting in 22.460 Terra Watt hours (TWh) needed per year.

Table 15-16-6: Compressor energy usage

Description	**Value:**
Discharge pressure from compressor	150 bara
Energy per 2.16 tonnes of generated CO_2	170.17 kWh
Energy to compress emissions from a factory that produces 2000 tonnes NH_3 per day	340 340 kWh
For all 197 factories per day	67 046 980 kWh
All factories for a whole year	22 460 738 300 KWh = 22,460 TWh

16.8 CO_2 compression facilities

To compress, transport and store 285 million tonnes CO_2 per year, multi-stage compressor plants, offshore pipelines and a well down a suitable formation for storage are required. CO_2 has physical properties that can be challenging in terms of compressions. From the illustration in figure 15-5, using our pre-determined values of 150 bara and 300K it can be observed that the compressed CO_2 will either exist in a physical state that is either liquid or supercritical fluid. A compressor that can handle these challenges is the eight-stage CO_2 compressor that can handle up to 200 bara provided by Atlas Copco. Their largest compressor train has the capacity of compressing 12 million Sm^3 per day and the cost for one compressor is around US$ 1.2 million. To sustain the maximum capacity of compressing 430 million Sm^3 of CO_2, it is estimated that the facilities will minimum need 36 compressors, but for safety margin and expected downtime/maintenance a total of 50 compressors will be installed, allowing for a max capacity of 600 million Sm^3. Available safe margin will then be 170 million Sm^3 and the risk of not having enough compressors is minimized. The total cost for all 50 compressors is US$ 60,5 million.

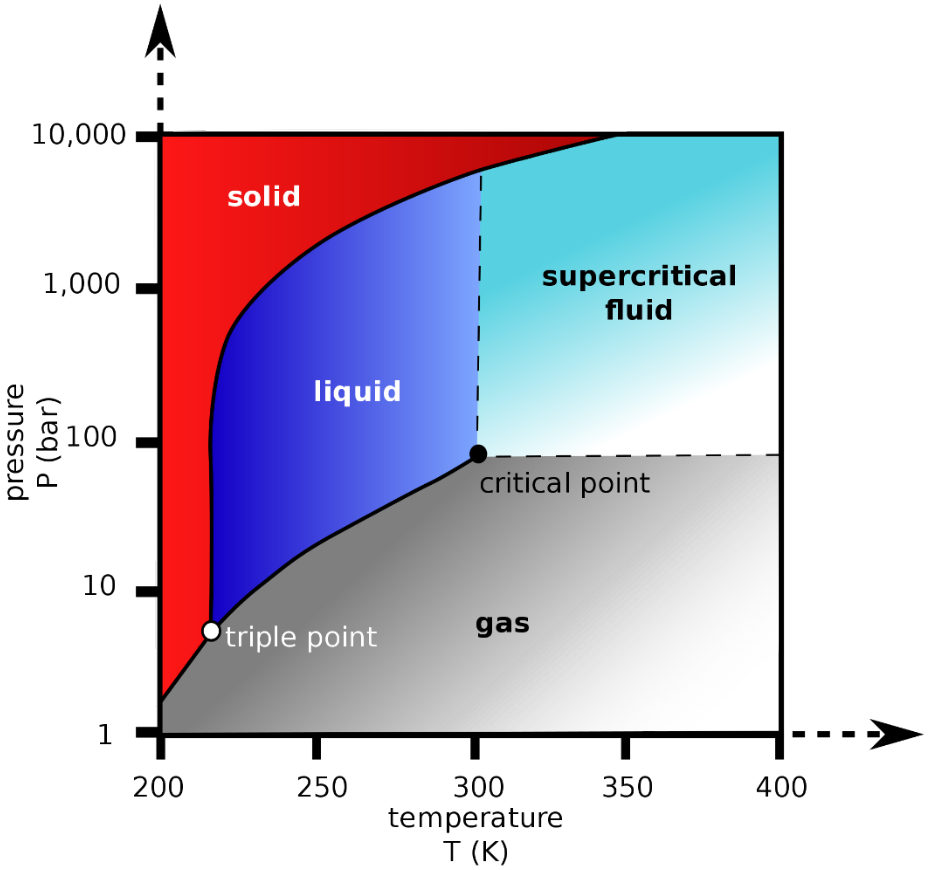

Figure 15-5: CO2 Thermophysical properties (Jacobs, 2021)

The compressors will be installed in compressor facilities and each facility can hold up to 4 compressors that will compress the CO_2 for transport. The compressor facility set to have a total cost of US$ 15 million where the compressors cost US$ 4,8 million and the building cost US$ 10,2 million.

Table 15-16-7: Compressor properties and facility costs

Description	**Value:**
Compressor capacity	12 million Sm^3
Compressor Cost	US$ 1,2 million
Total compressor capacity	600 million Sm^3
Capacity safe margin, downtime etc	170 million Sm^3
Total compressor cost	US$ 60,5 million
Total compressor facilities	13 facilities
One compressor facility with 4 compressors	US$ 15 million
Total compressor and facility cost	US$ 195 million

There are some things to keep in mind when transporting CO_2 in the supercritical form. By exceeding the critical parameters of pressure 74 bar and a temperature 31℃, the supercritical stage shows comparable density to liquid, and the compressibility and viscosity that can be compared to gas phase. Because of these supercritical CO_2 properties, thermodynamic transportation of CO_2 in supercritical state is an advantageous approach. Maintaining this phase requires additional CO_2 heating stations, due to the high critical temperature. In the result of pressure and temperature drop below the critical limit, the formation of a two-phase system might occur. This will cause a decrease in CO_2 viscosity and pressure drop. Even with the challenges that are associated with liquid CO_2, transport by pipeline is the most cost-effective option due to the favorable thermodynamic parameters (Wojnarowski et al., 2019).

16.9 12-inch CO_2 Onshore Pipeline system

The CO_2 will be filtered out from the flue gas, allowing for a higher CO_2 gas concentration which is then transported out from the factories and towards the compressor plant. The CO_2 is transported through an onshore 12-inch pipeline over to a compressor facility. Each compressor facility has the capacity of retrieving CO_2 from maximum 4 factories, as illustrated in Figure 15-7. Each compressor is not connected in series as shown in Figure 15-7 but uses separate transporting pipes to the main pipe. Figure 15-6 is mostly an illustration of how the total complex could look like. There will be an estimated 600 meters of 12-inch pipeline between the factories and compressor facilities and USAID estimated in 2007 that the price for a 12-inch onshore pipeline is approximately US$300.000 per mile(USAID, 2007). These prices were estimated in 2007 and to use the same numbers it requires consideration towards the inflation over the past decade.

Equation for calculating value drop due to inflation:

$$\text{Value in X dollars} = \text{Value in Y dollars } \left(\frac{CPIx}{CPIy}\right) \tag{15.5}$$

Where:
X = dollar value of that specific year
Y = dollar value of that specific year
CPI = Consumer Price index

According to bls.gov the CPI_{2007} = 207,949(bls.gov, 2020) and CPI_{2021} = 268,551(TradingEconomics, 2021b)

Resulting in:

Value in 2021 dollars = US\$300 000$\left(\frac{268{,}551}{207{,}949}\right)$ = US\$ 387 428 ≈ US\$ 390 000

By considering the inflation over the past decade the price is estimated to be US$390 000 per mile or US$ 245 000 per kilometre. Total length of the 12-inch pipelines reaching from each factory to a compressor facility is 118 200 metres, resulting in a total cost of US$ 29 million.

Table 15-16-8:12-inch pipeline cost from ammonia plant to compressor facility

Description	**Value:**
Pipeline dimension	12-inches
Pipeline cost per kilometres	US$ 245 000
Pipeline length between factory and compressors	600 metres
Total pipeline length for all factories	118,2 kilometres
Total estimated cost	US$ 29 million

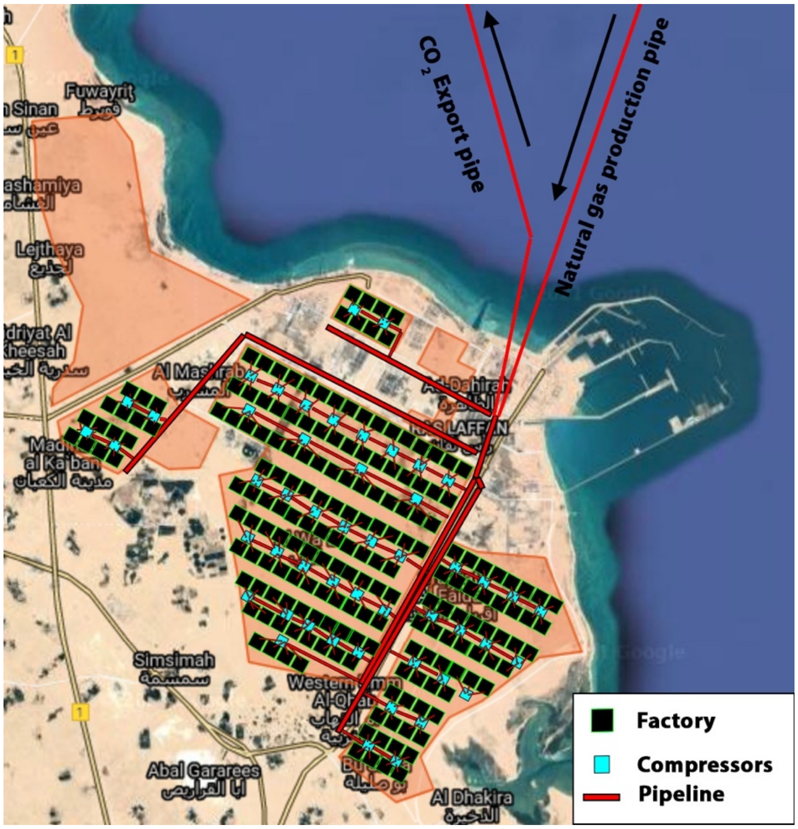

Figure 15-6: Ras Laffan facility complex, example illustration

Figure 15-7: Illustration of a compressor facility(blue square) connected to 4 different ammonia plants (black squares). The tine red lines represent a 12-inch pipeline

16.10 36-inch CO_2 pipeline onshore and offshore

The collected CO_2 will be compressed and transported towards the offshore pipeline that is beneath sea level in the Persian Gulf as this is the most economical method for transporting large quantities of CO_2 from Ras Laffan to Manifa. For better transportation efficiency the CO_2 will be transported with the density as of a liquid. The CO_2 will then need to be transported with a pressure above 105 bara to maintain levels in the super critical stage and frictional losses needs to be accounted for. As the compressor compresses the CO_2 from 1 bara to 150 bara, it is important to make sure that the friction pressure loss does not decrease the pressure below 75 bara so that the gas does not go out of super critical stage and into a two-stage phase. The Polarled pipeline is used as an example since the 36-inch pipeline has a flow capacity of 70 million cubic metres per day and travels 480km. The pipeline had a construction cost of US$ 762 million and given that the pipeline was 480 km long, an estimate of US$ 1.600.000 per kilometre is estimated (Technology, 2021). It is estimated that the onshore pipeline has a length of 450 km and the offshore pipeline has a length of 340 km from Ras Laffan to Manifa as seen in Figure 15-8.

Figure 15-8: 36-inch offshore pipeline from Ras Laffan to Manifa

Considering the daily CO_2 production of 430 000 000 Sm^3, there will be a need for approximately 7 offshore pipelines to maintain the CO_2 flow capacity and the total cost will be US$ 4.6 billion. The maximum flow capacity from these pipelines is calculated to be 490 000 000 Sm^3, providing a safe margin of 60 000 000 Sm^3

Table 15-16-9: Onshore and Offshore 36-inch CO2 pipeline properties and cost

Description	**Value:**
Number of offshore pipelines	7
Pipeline flow capacity	70 million Sm^3
Total flow capacity	490 million Sm^3
Dimension	36-inches
Cost per km pipeline	US$ 1,6 million
Pipeline length onshore	450 km
Pipeline length offshore	2380 km
Total pipeline cost (offshore and onshore)	US$ 4.6 billion

16.11 Natural gas pipeline distribution onshore

The ammonia factories need to be supplied with gas from the North Dome and the gas will be processed and transported from the natural gas processing plants already located in Ras Laffan. To accommodate the large amount of natural gas flow from the reservoir, using a 12-inch pipeline should be sufficient to handle the daily natural gas consumption of 2,04 million m^3 per factory. It is estimated that there will be a need for 450 km of pipeline to cover the distances from the natural gas processing facilities to all 197 factories. The estimated price for the pipeline is set to be US$ 245 000 per kilometre and the total cost will approximately be US$ 110,25 million.

Table 15-16-10: 12-inch natural gas onshore pipeline cost

Description	**Value:**
Pipeline dimension	12-inches
Pipeline cost per kilometres	US$ 245 000
Pipeline total length	450 km
Total estimated cost	US$ 110,25 million

16.12 Power plant Construction and needs

The production of ammonia and compression of CO_2 requires energy to be operational. For this scenario there will be used gas-fired powerplants that will be supplied with gas from the North Dome. The gas supplied will not be part from the 70% of yearly production from North

Dome but will be taken from the other 30% of production. Gas-fired powerplants require methane to produce power, and by-products from this is additional CO_2 emissions. To maintain a low-carbon energy supply there must be implemented some form of carbon capture at these plants, such as the pre-combustion filtration method called Oxyfuel. This method purifies the air, creating a more concentrated Oxygen gas that will be used for combustion. The by-products from the combustion will mainly be water and CO_2 allowing for separation through condensation. The CO_2 is then transported to the compressors for compression and used for sequestration or EOR.

16.13 Ammonia factories energy consumption

The total capacity that the powerplants needs to cover depends on the energy consumption from all different parts of the project.

The power consumption required to produce one tonne ammonia is:

$$1{,}0 \text{ GJ} = 0{,}27778 \text{ MWh}$$

$$34{,}4 \text{ GJ/tonne } NH_3 * 0{,}2777 = 9{,}555 \text{ MWh/tonne } NH_3 \approx 10 \text{ MWh/tonne } NH_3$$

$$0.07544 \text{ G. Cal/Tonne } NH_3 = 0{,}3157 \text{ GJ/tonne } NH_3 * 0{,}2777 = 0{,}087 \text{ MWh/tonne } NH_3$$
$$\approx 0{,}1 \text{ MWh/tonne } NH_3$$

$$\frac{0{,}1\frac{MWh}{tonne\ NH3}}{10\frac{MWh}{tonneNH3}} = 0{,}01 = 1{,}0\%$$

Meaning that the power needed to produce one tonne ammonia stands for 1% of the total energy consumption.

One ammonia plant produces 2000 tonnes NH_3/day and requires daily energy consumption of:

$$0{,}1 \text{ MWh/tonne } NH_3 * 2000 \text{ tonne } NH_3 = 200 \text{ MWh per day}$$

And with an operational time of 91,6% there is 67000 MWh or 67 GWh per year

The total planned ammonia plants are 197, giving a total yearly energy consumption of:

$$67 \text{ GWh} *335 = 13199 \text{ GWh/year} = 13{,}199 \text{ TWh/year}$$

$$\text{Convert the number to MW: } \frac{13199000\frac{MWh}{year}}{365*24} = 1506{,}7\ MW \ \approx 1507\ MW$$

Meaning that the energy consumption from all the 197 ammonia factories will need energy from a plant with minimum capacity of 1507 MW to operate.

Table 15-16-11: Total Ammonia factory energy consumption

Description	**Value:**
Total energy consumption from all ammonia factories	1507 MW

16.14 Compressor Energy

From previous calculations, all the compressors consumed a total of 22,46 TWh.

$$22{,}46 \text{ TWh} = \frac{22460000}{365*24} = 2564\ MW$$

Table 15-16-12: Total compressor energy consumption

Description	**Value:**
Total energy consumption from all compressors	2 564 MW

16.15 Powerplant Energy

The energy consumption needs to take into account the consumption from the compressors and the factories, which are 22,46 TWh and 13,199 TWh.

1 507 MW + 2 564 MW = 4071 MW

To cover the required energy capacity, there needs to be a minimum of 3 different 1 400 MW capacity power plants, but a total of 5 different gas-fired powerplants will be constructed. This is to have a higher capacity than what is needed, so that each powerplant is not at max capacity all the time. Constructing several powerplants with lower capacity to cover the total capacity is to diversify the risk of shutdown/downtime of the factories. As the gas compressors is highly dependent on a constant supply of energy, a downtime in energy would mean that the CO_2 produced from the different facilities do not have anywhere to go.

Construction of these 1400 MW facilities can be provided from schematics used in the Hanging Rock Energy Facility in Ironton, Ohia USA. This facility utilizes a natural gas fired combined cycle that has a construction cost of US$ 550 million, and each power facility only covers 0,2 km^2 of land as seen in Figure (CountyOffice, 2021).

Figure 15-9: Hanging Rock Energy Facility in Ironton, Ohio. Covering a 20 hectares(0,2km) land plot (GoogleMaps, 2021)

The minimum annual power generation needs to be 35,659 TWh. Using a gas-fired power plant requires consideration towards the energy efficiency of gas, and this is set to be 30%. Calculated total natural gas needed to operate the powerplants.

$$\frac{35{,}659\,TWh}{0{,}3} = 118{,}86\,TWh = 118\ 863\ 333\ \text{MWh}$$

Meaning that the required natural gas needs to have total energy of 118,86 TWh where only 30% is usable for energy.

The relation between Sm^3 and MWh is given by:

$$1\ \text{Sm}^3\ \text{Natural gas} = 22{,}9722\ \text{Mwh}$$

$$\frac{118\,863\,333\ MWh}{22{,}9722\,\frac{Mwh}{Sm3}} = 5\,174\,225\ Sm3\ per\ year$$

Total amount of natural gas needed to power the power plants is 5 174 225 Sm^3 per year. Assuming that CO_2 and Methane CH_4 has a one-to-one ratio gives a total of 5 174 225 Sm^3 CO_2 per year. Knowing that 556,2 Sm^3 is equal to one tonne CO_2 gives:

$$\frac{5174220\ Sm3}{556{,}2} = 9\,302\ tonnes\ CO2\ per\ year$$

$$\text{Energy per tonne CO}_2 = \frac{170{,}17\ KWh}{2{,}16\ tonne\frac{CO2}{tonne}NH3} = 78{,}78\ \text{KWh/tonne CO}_2$$

$$78{,}78\ \text{KWh} * 9302{,}8 = 732{,}874\ \text{MWh/year}$$

These results show that the energy needed to compress the additional CO_2 that is released from the gas-fired powerplants is 732,87 MWh/year and compared to the larger picture of compressors and ammonia factories, this extra energy is therefore negligible.

Table 15-16-13: Powerplant cost

Description	**Value:**
Total powerplants	5
Cost for 1 plant	US$ 550 million
Total cost for 5 plants	US$ 2,75 billion

16.16 Labour across all facilities

The factories will be operating all year around and is thus in need of labour to operate. For estimation purposes there is allocated 200 employees per factory and per powerplant. Meaning that there will be a rough total of 40 400 full-time equivalents (FTE) on all facilities. Setting the standard towards the western work culture, one full-time equivalent will represent an annual cost of US$ 70 000 for estimation purposes. Annual labour cost is then US$ 2,828 billion.

Table 15-16-14: Full-time equivalents and annual labour cost

Description	**Value:**
Full-time equivalents per factory	200

Annual salary	US$ 70 000
Total facilities	202
Total full-time equivalents	40 400
Annual labour cost	US$ 2,828 billion

16.17 Shipping of ammonia

The construction of 197 ammonia factories will provide a total production of 132 million tonnes of ammonia. Converting the weight of ammonia to volume relies on the main factor, density. When ammonia is at the boiling point, the density is at 681,9 kg/m^3 and this is used for the conversion.

$$\text{mass} = \text{density} * \text{volume} \tag{15.6}$$

394 thousand tonnes NH_3 per day = 578 thousand m^3
132 million tonnes NH_3 per year = 194 million m^3

The Ras Laffan harbour will be used for marine transportation for the export of ammonia, as the harbour is a deep-water port covering an area of 850 hectares and can handle the world's largest ocean-going vessels, vessels up to 345 meters. The port has three berths that is capable of handling 135 thousand cubic metres of natural gas product, which can be utilized for ammonia as well. (WorldPortSource, 2021)

Assuming that all factories are operational there will be a daily total ammonia production of 394 tonnes, which equals to 578 thousand m^3. A fleet of Very Large Gas Carriers (VLGC) will be used as these have a capacity of 80 000 m^3 of Liquid Petroleum Gas (LPG). LPG ships transport butane and propane, and propane has a boiling point of -42^{0}C which is almost the same boiling point as ammonia which is -33^{0}C. Since propane has a lower boiling point than ammonia, the equipment that is utilized to maintain pressure and temperature can also be used for keeping ammonia in liquid form. Ammonia is a corrosive chemical thus the tankers need extra coating within the tanks before transporting.

According to Hellenic Shipping News (2020) the shipping rates are hitting a 5-year high that tops around the US$ 100 000 dollars. These high numbers come from the unforeseen worldwide COVID-19 pandemic and are therefore numbers that do not represent normal day-rates. For a closer future day-rate approximation, using the average rates between the year 2019 and 2020 from Figure 15-10 provides a rough estimate of US$ 60.000 as the day rate. The day-rate will provide sufficient guideline to cost estimate the shipping routes from Qatar to Miami, Louisiana, New York, Los Angeles, Tokyo, Beijing, Rome and Rotterdam. The chosen destinations are targeted after population density, energy import necessity or for further distribution purposes.

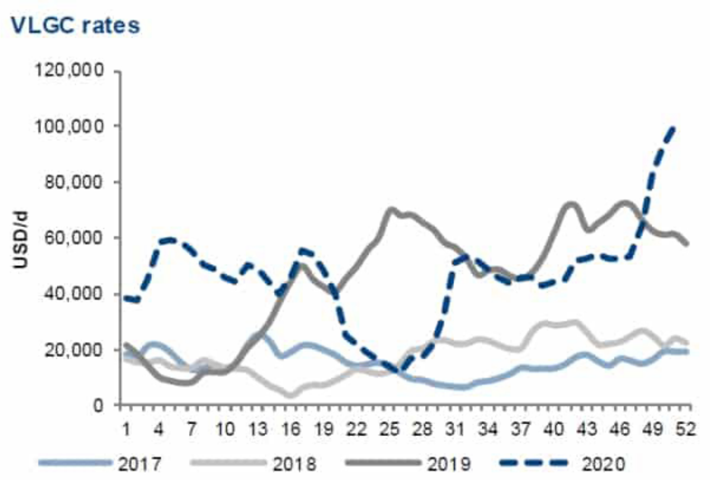

Figure 15-10: VLGC shipping rates (ShippingNews, 2020)

Shipping of ammonia will rely on these key factors:

- Total ammonia production
- Freight capacity and total freights
- Distance travelled

Assuming that the freights travel at a speed of 20 knots which equals 37 kilometres per hour, by using simple physics:

$$\text{Time}=\text{distance}/\text{velocity} \qquad (15.7)$$

Provides the total shipping time to and from each location and adding two days for offloading margin. The routes given and estimates can be seen from Figure 15-11 and Figure 15-12, 15-13, 15-14 and15-15.

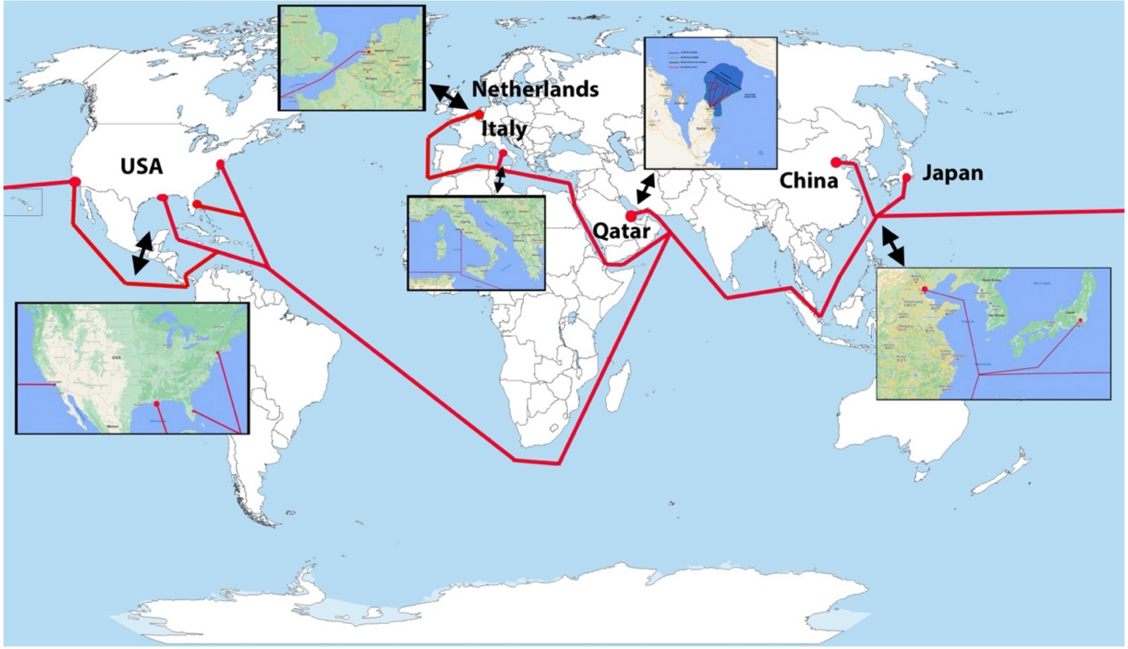

Figure 15-11: Shipping routes around the world (Wikipedia, 2018)

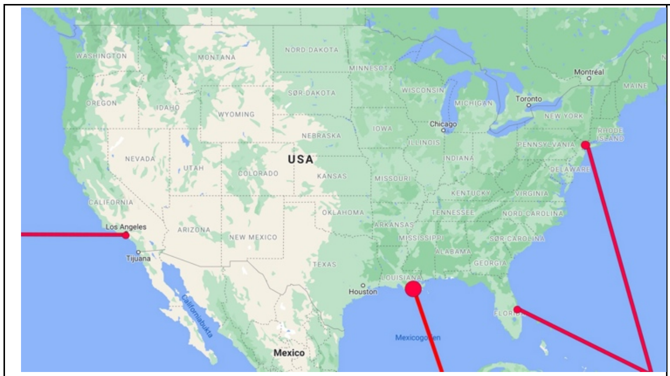

Figure 15-12: USA shipping route (Earth, 2021e)

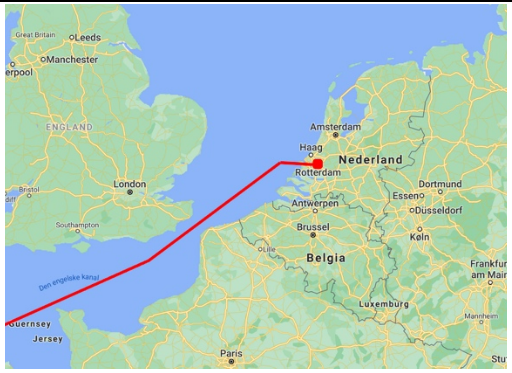

Figure 15-13: Rotterdam Shipping Route (Earth, 2021c)

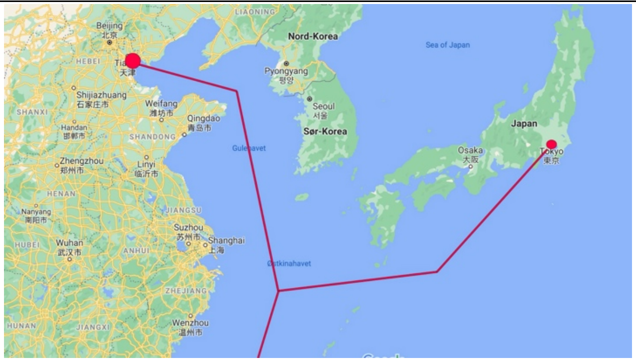

Figure 15-14: Japan and China Shipping Route (Earth, 2021b)

Figure 15-15: Italy shipping route (Earth, 2021a)

Table 15-16-15: Shipping routes, distance, travel time and route cost accounting for all days

Description	**Value:**	**Shipping to destination**	**Shipping from destination**	**Total time**	**Route Cost**
Distance from Qatar to Tokyo	12 990 km	15 days + 2 days	15 days + 2 days	34 days	US$ 2,04 million
Distance from Qatar to Beijing	13 276 km	15 days + 2 days	15 days + 2 days	34 days	US$ 2,04 million
Distance from Qatar to Rotterdam	12 778 km	15 days + 2 days	15 days + 2 days	34 days	US$ 2,04 million
Distance from Qatar to Los Angeles	21 752 km	25 days + 2 days	25 days + 2 days	54 days	US$ 3,24 million
Distance from Qatar to Miami	22 700 km	26 days + 2 days	26 days + 2 days	56 days	US$ 3,36 million
Distance from Qatar to Louisiana	24 600 km	28 days + 2 days	28 days + 2 days	60 days	US$ 3,6 million
Distance from Qatar to New York	22 770 km	26 days + 2 days	26 days + 2 days	56 days	US$ 3,36 million
Distance from Qatar to Rome	8 834 km	10 days + 2 days	10 days + 2 days	24 days	US$ 1,44 million

The shipping cost for each vessel largely depend on location due to the larger or shorter distance travelled. For estimation purposes, there will be assumptions that all vessels have a daily shipping rate of US$ 60.000, independent of how many cubic metres of liquid ammonia they transport.

One important factor to keep in mind while transporting the ammonia from Qatar to all the other destinations is to not have a lack of ships available for transport, so that there are no stops. The daily ammonia production of 578 thousand m^3 will require an estimate of at least 8 VLGC with a max capacity of 80.000 m^3 to be fuelled and ready for shipping each day and that the total production will be divided equally across all destinations and each ship will transport approximately 72 250 m^3 of ammonia. The production of ammonia will continue even if there are no ships available and it is therefore important to have enough ships available to prevent stop in production and export. As a safety margin in case of maintenance, downtime there will be a total of 10 or more freights available per day to prevent the shipping link from being a bottleneck in the whole logistic system.

Considering that there must be a ship at the harbor in Qatar every day the first ship is gone, the ships have max capacity of 80.000 m^3 but carries 72 250 m^3 and the ships are operational 365 days a year with a day rate of US$ 60.000 it will be reasonable to use the following formulas:

$$\text{Cost per day: total ships * US\$ 60.000 = daily cost} \tag{15.8}$$

$$\textit{Cost per year: Daily cost * 365} \tag{15.9}$$

Table 15-16-16: Ships per route and annual shipping cost

Description	**Value:**	**Total ships on this route**	**Annual shipping cost**
Distance from Qatar to Tokyo	12 990 km	34 ships	US$ 744 600 000
Distance from Qatar to Beijing	13 276 km	34 ships	US$ 744 600 000
Distance from Qatar to Rotterdam	12 778 km	34 ships	US$ 744 600 000
Distance from Qatar to Los Angeles	21 752 km	53 ships	US$ 1 182 600 000
Distance from Qatar to Miami	22 700 km	56 ships	US$ 1 226 400 000
Distance from Qatar to Louisiana	24 600 km	60 ships	US$ 1 314 000 000
Distance from Qatar to New York	22 770 km	56 ships	US$ 1 226 400 000
Distance from Qatar to Rome	8 834 km	24 ships	US$ 525 600 000
Total Annual shipping cost		351 ships	US$ 7 708 800 000

16.18 Total shipping cost estimate

Total cost for all shipping routes to the different corners of the world is estimated to be:

Table 15-16-17: Total Shipping Cost estimates

Description	**Value:**
Qatar – Tokyo, Japan	US$ 744 600 000
Qatar – Beijing, China	US$ 744 600 000
Qatar – Rotterdam, Netherlands	US$ 744 600 000
Qatar – LA, USA	US$ 1 182 600 000
Qatar – Miami, USA	US$ 1 226 400 000
Qatar – Louisiana, USA	US$ 1 314 000 000
Qatar – New York, USA	US$ 1 226 400 000
Qatar – Rome, Italy	US$ 525 600 000
Total yearly shipping cost	US$ 7 708 800 000

17 Total investment costs

17.1 Calculating ammonia cost with total average shipping cost

Table 16-17-1: Total investment cost

Investment unit	Total Cost
Ammonia factories	US$ 167 450 000 000
36” CO_2 onshore and offshore pipeline	US$ 4 600 000 000
12” CO_2 onshore pipeline	US$ 29 000 000
12” Natural gas onshore pipeline	US$ 110 250 000
Powerplants	US$ 2 750 000 000
Compressor facilities	US$ 195 000 000
Total investment cost	US$ 175 134 250 000

17.2 Total Capital cost

For the required rate of return (RRR) that is the minimum amount of profit required from this project is set to 10%. This gives an annual RRR of:

Table 16-17-2: Required Rate of Return

Description	Value:
Required rate of return %	10 %
Required rate of return US$	US$ 17 513 425 000

17.3 Depreciation

The constructed facilities and infrastructure will not last forever and this needs to be taken into considerations for further calculations. Assuming that the facilities have a lifespan of 20 years gives a yearly depreciation at 5% to cope with wear and tear. The depreciation estimation includes renewal and maintenance of the facilities and equipment.

Table 16-17-3: Capitol depreciation

Capitol depreciation	Value:
Depreciation %	5 %
Capital depreciation	US$ 8 756 700 000

17.4 Total gas consumed and cost

The gas price is set to be 3,3 USD/MMBtu and the total gas consumed is figured out by summarizing all the utilized gas for the different facilities.

Table 16-17-4: Annual gas cost

Annual gas consumption	**Total Cost**
Ammonia factories gas consumption	133 950 000 000 Sm^3
Power plant gas consumption	5 175 000 Sm^3
Total gas consumption per year	133 955 175 000 Sm^3

Natural gas conversion:

$$1{,}0\ \text{MMBtu} = 28{,}32\ Sm^3$$

Table 17-5: Natural gas cost

Annual gas cost	**Total Cost**
Price of gas	3,3 USD/MMBtu
Total gas consumption	4 730 100 000 MMbtu
Total gas cost	US$ 15 610 000 000

Cost per ton ammonia:

Table 17-6: Ammonia productoin cost

Ammonia cost	**Total Cost**
Total gas cost per year	US$ 15 610 000 000
Total labour cost per year	US$ 2 828 000 000
Total shipping cost per year	US$ 7 708 000 000
Capitol depreciation	US$ 8 756 700 000
Required rate of return	US$ 17 513 425 000
Total annual cost	US$ 52 416 125 000

Given that the total annual ammonia production of 132 000 000 we get a cost per ton of:

Table 17-7: Ammonia cost per ton

Description	**Value:**	**Elementary operation**
Total annual cost	US$ 52 416 125 000	

Annual ammonia production	132 000 000 tonnes NH_3	÷
Ammonia production cost	397.091 US$/t NH_3	=

The calculated results are based on high estimates so that the estimates do not undershoot when introducing the final cost. To further provide an overview over potential cost estimates, there will be further calculations based on a low-case, middle-case and high-case scenario where the changing variables will be gas price, full-time equivalent labor cost, required rate of return and capital depreciation. It is also important to map the costs with and without the shipping due to the fluctuating price depending on distance and time travelled.

17.5 Ammonia Cost without total shipping cost

Table 16-17-8: Ammonia Cost without total shipping cost

Criteria's	**Low-Case**	**Middle-Case**	**High-Case**
Gas Price	3 USD/MMBtu	3.3 USD/MMbtu	3.3 USD/MMBtu
Full-time Equivalent	US$ 25 000	US$ 45 000	US$ 70 000
Required Rate of Return	6%	8 %	10%
Capital depreciation	4 %	4 %	5%
Annual Gas Cost	**Low-Case**	**Middle-Case**	**High-Case**
Total Gas consumption	4 730 100 000 MMbtu	4 730 100 000 MMbtu	4 730 100 000 MMbtu
Total gas cost	US$ 14 200 000 000	US$ 15 610 000 000	US$ 15 610 000 000
Labor cost	**Low-Case**	**Middle-Case**	**High-Case**
Full-time equivalents per factory	200	200	200
Average annual labor cost per Full-time equivalent	US$ 25 000	US$ 45 000	US$ 70 000
Total Facilities (ammonia plants + powerplants)	202	202	202
Total Full-time Equivalents	40 400	40 400	40 400
Annual labor cost	US$ 1 010 000 000	US$ 1 818 000 000	US$ 2 828 000 000
Capitol depreciation	**Low-Case**	**Middle-Case**	**High-Case**
Depreciation %	4 %	4 %	5%
Capitol depreciation	US$ 7 005 370 000	US$ 7 005 370 000	US$ 8 756 712 500
Required Rate of Return	**Low-Case**	**Middle-Case**	**High-Case**
RRR %	6%	8%	10%
RRR US$	US$ 10 508 055 000	US$ 14 010 740 000	US$ 17 513 425 000
Ammonia Cost	**Low-Case**	**Middle-Case**	**High-Case**
Annual Gas cost	US$ 14 200 000 000	US$ 15 610 000 000	US$ 15 610 000 000
Annual labor cost	US$ 1 010 000 000	US$ 1 818 000 000	US$ 2 828 000 000

Capitol depreciation	US$ 7 005 370 000	US$ 7 005 370 000	US$ 8 756 712 500
RRR	US$ 10 508 055 000	US$ 14 010 740 000	US$ 17 513 425 000
Total annual cost	US$ 32 732 425 000	US$ 38 444 110 000	US$ 44 708 137 000
Ammonia Cost per ton	**Low-Case**	**Middle-Case**	**High-Case**
Total annual ammonia production	132 000 000	132 000 000	132 000 000
Ammonia cost per ton	247,904 US$/t NH_3	291,243 US$/t NH_3	338.698 US$/t NH_3

17.6 Ammonia cost with total shipping included

Table 17-9: Ammonia Cost with total shipping cost

Criteria's	**Low-Case**	**Middle-Case**	**High-Case**
Gas Price	3 USD/MMBtu	3.3 USD/MMbtu	3.3 USD/MMBtu
Full-time Equivalent	US$ 25 000	US$ 45 000	US$ 70 000
Required Rate of Return	6%	8 %	10%
Capital depreciation	4 %	4 %	5%
Annual Gas Cost	**Low-Case**	**Middle-Case**	**High-Case**
Total Gas consumption	4 730 100 000 MMbtu	4 730 100 000 MMbtu	4 730 100 000 MMbtu
Total gas cost	US$ 14 200 000 000	US$ 15 610 000 000	US$ 15 610 000 000
Labor cost	**Low-Case**	**Middle-Case**	**High-Case**
Full-time equivalents per factory	200	200	200
Average annual labor cost per Full-time equivalent	US$ 25 000	US$ 45 000	US$ 70 000
Total Facilities (ammonia plants + powerplants)	202	202	202
Total Full-time Equivalents	40 400	40 400	40 400
Annual labor cost	US$ 1 010 000 000	US$ 1 818 000 000	US$ 2 828 000 000
Capitol depreciation	**Low-Case**	**Middle-Case**	**High-Case**
Depreciation %	4 %	4 %	5%
Capitol depreciation	US$ 7 005 370 000	US$ 7 005 370 000	US$ 8 756 712 500
Required Rate of Return	**Low-Case**	**Middle-Case**	**High-Case**
RRR %	6%	8%	10%
RRR US$	US$ 10 508 055 000	US$ 14 010 740 000	US$ 17 513 425 000
Ammonia Cost	**Low-Case**	**Middle-Case**	**High-Case**
Annual Gas cost	US$ 14 200 000 000	US$ 15 610 000 000	US$ 15 610 000 000
Annual labor cost	US$ 1 010 000 000	US$ 1 818 000 000	US$ 2 828 000 000
Annual shipping cost	US$ 7 708 000 000	US$ 7 708 000 000	US$ 7 708 000 000
Capitol depreciation	US$ 7 005 370 000	US$ 7 005 370 000	US$ 8 756 712 500
RRR	US$ 10 508 055 000	US$ 14 010 740 000	US$ 17 513 425 000
Total annual cost	US$ 40 431 425 000	US$ 46 152 110 000	US$ 52 416 137 000
Ammonia Cost per ton	**Low-Case**	**Middle-Case**	**High-Case**

Total annual ammonia production	132 000 000	132 000 000	132 000 000
Ammonia cost per ton	306,2986 US$/t NH_3	349,637 US$/t NH_3	397,0919 US$/t NH_3

17.7 Ammonia cost for different shipping locations

The various chosen shipping locations have different total shipping price and the time used for travel. Meaning that the various locations will have a different ammonia price per ton, thus it is important to highlight price per ton for each location.

Each location price will follow the same routine as previous calculations with a lower, middle, and high case.

The total annual ammonia production will be distributed among all 8 locations equally and each ship will be able to transport 72 250 m^3. Since all locations will import equal amount of ammonia and the shipping cost is constant through low, middle, and high case, the price per tonne for shipping can be calculated:

Table 17-10: Location shipping cost

Description	**Value:**
Annual ammonia imports per location (m^3)	26 371 250 m^3
Annual ammonia imports per location (ton)	16 500 000 tonnes NH_3

Location	**Shipping Cost**	**Ammonia Shipping Price**
Tokyo, Japan	US$ 744 600 000	45,127 USD/t
Beijing, China	US$ 744 600 000	45,127 USD/t
Rotterdam, Netherland	US$ 744 600 000	45,127 USD/t
LA, USA	US$ 1 182 600 000	71,67 USD/t
Miami, USA	US$ 1 226 400 000	74,327 USD/t
Louisiana, USA	US$ 1 314 000 000	79,636 USD/t
NY, USA	US$ 1 226 400 000	74,327 USD/t
Rome, Italy	US$ 525 600 000	31,8547 USD/t

Table 17-11: Total annual cost for different locations

Criteria's	**Low-Case**	**Middle-Case**	**High-Case**
Gas Price	3 USD/MMBtu	3.3 USD/MMbtu	3.3 USD/MMBtu
Full-time Equivalent	US$ 25 000	US$ 45 000	US$ 70 000
Required Rate of Return	6%	8 %	10%
Capital depreciation	4 %	4 %	5%

Annual Gas Cost	**Low-Case**	**Middle-Case**	**High-Case**
Total Gas consumption	4 730 100 000 MMbtu	4 730 100 000 MMbtu	4 730 100 000 MMbtu
Total gas cost	US$ 14 200 000 000	US$ 15 610 000 000	US$ 15 610 000 000
Labor cost	**Low-Case**	**Middle-Case**	**High-Case**
Full-time equivalents per factory	200	200	200
Average annual labor cost per Full-time equivalent	US$ 25 000	US$ 45 000	US$ 70 000
Total Facilities (ammonia plants + powerplants)	202	202	202
Total Full-time Equivalents	40 400	40 400	40 400
Annual labor cost	US$ 1 010 000 000	US$ 1 818 000 000	US$ 2 828 000 000
Capitol depreciation	**Low-Case**	**Middle-Case**	**High-Case**
Depreciation %	4 %	4 %	5%
Capitol depreciation	US$ 7 005 370 000	US$ 7 005 370 000	US$ 8 756 712 500
Required Rate of Return	**Low-Case**	**Middle-Case**	**High-Case**
RRR %	6%	8%	10%
RRR US$	US$ 10 508 055 000	US$ 14 010 740 000	US$ 17 513 425 000
Ammonia Cost	**Low-Case**	**Middle-Case**	**High-Case**
Annual Gas cost	US$ 14 200 000 000	US$ 15 610 000 000	US$ 15 610 000 000
Annual labor cost	US$ 1 010 000 000	US$ 1 818 000 000	US$ 2 828 000 000
Capitol depreciation	US$ 7 005 370 000	US$ 7 005 370 000	US$ 8 756 712 500
RRR	US$ 10 508 055 000	US$ 38 444 110 000	US$ 17 513 425 000
Total annual cost	US$ 32 723 000 000	US$ 38 444 110 000	US$ 44 708 137 500

17.7.1 Low-Case Shipping

Table 17-12: Low-Case shipping based on location

Location	Ammonia Production Cost/t	Ammonia Shipping Price	Ammonia Cost/t
Tokyo, Japan	247,90 USD/t	45,127 USD/t	293,03 USD/t
Beijing, China	247,90 USD/t	45,127 USD/t	293,03 USD/t
Rotterdam, Netherland	247,90 USD/t	45,127 USD/t	293,03 USD/t
LA, USA	247,90 USD/t	71,67 USD/t	319,57 USD/t
Miami, USA	247,90 USD/t	74,327 USD/t	322,227 USD/t
Louisiana, USA	247,90 USD/t	79,636 USD/t	327,53 USD/t
NY, USA	247,90 USD/t	74,327 USD/t	322,227 USD/t
Rome, Italy	247,90 USD/t	31,855 USD/t	279,76 USD/t

17.7.2 Middle-Case Shipping

Table 17-13: Middle-Case shipping based on location

Location	Ammonia Production Cost/t	Ammonia Shipping Price	Ammonia Cost/t
Tokyo, Japan	291,243 USD/t	45,127 USD/t	336,37 USD/t

Beijing, China	291,243 USD/t	45,127 USD/t	336,37 USD/t
Rotterdam, Netherland	291,243 USD/t	45,127 USD/t	336,37 USD/t
LA, USA	291,243 USD/t	71,67 USD/t	362,913 USD/t
Miami, USA	291,243 USD/t	74,327 USD/t	365,57 USD/t
Louisiana, USA	291,243 USD/t	79,636 USD/t	370,879 USD/t
NY, USA	291,243 USD/t	74,327 USD/t	365,57 USD/t
Rome, Italy	291,243 USD/t	31,855 USD/t	323,0985 USD/t

17.7.3 High-Case Shipping

Table 17-14: High-Case shipping based on location

Location	Ammonia Production Cost/t	Ammonia Shipping Price	Ammonia Cost/t
Tokyo, Japan	338,698 USD/t	45,127 USD/t	383,817 USD/t
Beijing, China	338,698 USD/t	45,127 USD/t	383,817 USD/t
Rotterdam, Netherland	338,698 USD/t	45,127 USD/t	383,817 USD/t
LA, USA	338,698 USD/t	71,67 USD/t	410,36 USD/t
Miami, USA	338,698 USD/t	74,327 USD/t	413,017 USD/t
Louisiana, USA	338,698 USD/t	79,636 USD/t	418,326 USD/t
NY, USA	338,698 USD/t	74,327 USD/t	413,017 USD/t
Rome, Italy	338,698 USD/t	31,855 USD/t	370,545 USD/t

17.7.4 The gathered results based on shipping location

Table 17-15: Ammonia price based on shipping route

	Low-Case	**Middle-Case**	**High-Case**
Location	**Ammonia Cost/t**	**Ammonia Cost/t**	**Ammonia Cost/t**
Tokyo, Japan	293,03 USD/t	336,37 USD/t	383,817 USD/t
Beijing, China	293,03 USD/t	336,37 USD/t	383,817 USD/t
Rotterdam, Netherland	293,03 USD/t	336,37 USD/t	383,817 USD/t
LA, USA	319,57 USD/t	362,913 USD/t	410,36 USD/t
Miami, USA	322,227 USD/t	365,57 USD/t	413,017 USD/t
Louisiana, USA	327,53 USD/t	370,879 USD/t	418,326 USD/t
NY, USA	322,227 USD/t	365,57 USD/t	413,017 USD/t
Rome, Italy	279,76 USD/t	323,0985 USD/t	370,545 USD/t

The results given from the calculation of ammonia price per tonne based on the different locations shows a price ranging from 293,03 USD/t to 418,326 USD/t with a difference of 125, 296 USD/t when creating a low, middle and high case scenario. These results display the important factors when calculating the price per tonne of ammonia. Illustrating that there are several factors that have an impact on the price based on accessibility from where the gas is produced for ammonia, travel distance of the ammonia shipping routes and accessibility of reservoirs for EOR or sequestration.

17.8 Ammonia as a fuel for electricity production

The use of ammonia for electricity production is still in a research and development phase, so the following is just for illustrative purposes. Mitsubishi Power are one of the companies that are working on developing ammonia capable turbines for electricity production. They have currently developed an ammonia-fired 40MW class gas turbine system that is still being researched (Power, 2021).

To illustrate the cost per kWh of electricity, which is generated by an ammonia drive power plant, it is assumed that it is possible to utilize approximately 30% of the energy density of the ammonia.

The following tables shows the properties necessary to calculate the price of the energy that is produced.

Table 17-16: Natural gas and ammonia criterias (Association, 2021), (Nord, 2021)

Natural gas	Ammonia
- Energy density = 55GJ/ton methane - 2.8-ton CO_2 emissions per ton methane - Efficiency = 30%	- Energy density = 22.5 GJ/ton NH_3 - Efficiency = 30%

Total energy production per ton methane:

$$55\ \text{GJ/ton}*0.3 = 16.5\ \text{GJ/ton methane}$$

For every 16.5 GJ/ton methane energy a total of 2.8 ton of CO_2 is released

Total energy production per ton ammonia:

$$22.5\ \text{GJ/ton}*0.3 = 6.75\ \text{GJ/ton ammonia}$$

For further calculations, the assumption of 1 GJ = 277,77 kWh will be used:

Finding the kWh of methane:

16.5 GJ/ton *277.77 kWh = 4583,2 kWh/ton methane

Finding the kWh of ammonia:

6.75 GJ/ton * 277.77 kWh = 1 874,94 kWh/ton ammonia

Finding the same energy equivalent in ammonia as in methane:

$$\frac{4583{,}2 \frac{kWh}{ton\ methane}}{1\ 874{,}94 \frac{kWh}{ton\ ammonia}} = 2.444$$

For ammonia to reach the same energy output as natural gas, there has to be used 2.44 tones of ammonia combusted.

17.8.1 Calculating the price

For these calculations it is assumed that the price of natural gas is 3,3 USD/MMbtu:

Finding the volume:

One ton of methane has a density = 0,657 kg/Sm^3

1000kg/0,657 kg/Sm^3 = 1522 Sm^3

To convert from standard cubic meters to MMBtu the relationship formula of 1MMbtu = 28.32 Sm^3 is used:

1522 Sm^3/28,32Sm^3 = 53,74 MMBtu

3,3 USD/MMBtu*53,74 MMBtu = 177.35 USD/t

$$\frac{177{,}35 \frac{USD}{t}}{4583{,}2\ kWh} = 0{,}03869 USD/kWh$$

From the calculations the price for energy using natural gas is 0,03869 USD/kWh.

17.8.2 Ammonia price based on energy

The Miami middle-case scenario price of 365,57 USD/t NH_3 and high-case scenario price 413,017 USD/t NH_3 will be used to calculate the energy price of ammonia:

Middle case:

$$2{,}44*365{,}57 \text{ USD/t } NH_3 = 891{,}99 \text{ USD per ton}$$

17.8.3 CO_2 tax Miami middle case

$$891.99 \text{ USD} – 177{,}35 = 714{,}64 \text{ USD}$$

$$714{,}64 \text{ USD}/2{,}8 = 255{,}22$$

To match the same energy output as methane, ammonia has to utilize 2,44 more mass and to compete in price the CO_2 tax needs to be around 255,22 USD

17.8.4 CO_2 tax Miami high case

$$1007{,}761 \text{ USD- } 177{,}35 \text{ USD} = 830{,}411 \text{ USD}$$

$$830{,}411 \text{ USD}/2{,}8 = 296{,}575 \text{ USD}$$

To match the same energy output as methane, ammonia has to utilize 2,44 more mass and to compete in price the CO_2 tax needs to be around 296,575 USD.

17.9 Results

From the results above, calculations show that for ammonia to produce the same amount of energy, there has to be utilized 2,44 times more mass than with natural gas, assuming for illustrative purposes, that ammonia does not generate climate emissions.

For every ton methane that is combusted a total of 2,8 tonnes of CO_2 is released. According to the middle and high case scenario ammonia price, the CO_2 tax needs to be either 255,22 USD/ton CO_2 or 296,575 USD/ton CO_2 to compensate for the added cost of generating electricity with ammonia as fuel, in order for it to have an equal cost of generating electricity with natural gas. These CO_2 taxes are very much likely to happen since the world is transitioning towards GHG reduction and due to international CO_2 schemes, the price of CO_2 will increase by 2,2% every year towards 2030. As of 2021 the CO_2 price is set to be 50€/ton CO_2.

18 Discussion

The data and results presented in this thesis are made through assumptions that are deliberately over estimated so that the final ammonia production cost is slightly higher than what it potentially could be. This provides a more realistic scenario for the future price of ammonia especially if produced in a natural gas rich location such as Qatar and with access to large, depleted reservoirs that can be used for sequestration. The heavy oil field in Saudi Arabi presents another great opportunity for storing CO_2 with the use of EOR since the gas can be used in a closed-loop cycle. The ammonia production price could potentially be reduced if the CO_2 is sold for a small price but due to limited storage possibilities around the world, the potential price reduction in ammonia price has been neglected since there is too much uncertainty around the deposit price of CO_2.

18.1 Why this project?

The world is constantly growing and so is the global energy consummation. At this current rate the energy consumption and production are unsustainable because of the dependency on fossil-based fuels and the associated greenhouse gas emissions that comes with them. The transition from fossil-based fuels towards renewable energy is a time-consuming process as current renewable sources does not have the energy density to cover the worlds energy needs. The dependency on fossil-based fuels will continue over the years to come and that is why it is important to utilize the fossil-based fuels in new ways, such as the production of ammonia out of natural gas. Converting natural gas into ammonia and creating a low carbon energy supply where the carbon dioxide is captured and stored away will allow for further justification of natural gas extraction. Meaning that it will still be possible to utilize the large amount of energy that comes from natural gas, but in a different form. Ammonia does not have the same energy density as natural gas but that is the price that is paid for cleaner energy.

Ammonia production releases large amounts of carbon dioxide and that is why the most important aspect of the project is the main location of the ammonia factories. To create a viable low-carbon energy supply relies to this day heavily on a location that is close to large, depleted reservoirs to dispose the CO_2 and access to large amounts of natural gas so that the price of production is kept at a minimum. That is why Qatar has been chosen for the implementation of a large-scale ammonia production facility. Qatar is surrounded by giant reservoirs and heavy oil fields that could be utilized for EOR and sequestration, making it the most feasible location to produce ammonia.

As the world works its way towards renewable energy the focus lies upon solar, hydro, wind, and hydrogen but using ammonia as a fuel is not talked about as much as it should be. The use of ammonia as an energy source instead of hydrogen has its advantages. Liquid ammonia has a higher energy density of 12.7 MJ/litre compared to liquid hydrogens energy density of 8.5 MJ/litre. As for transportation the use of ammonia is a lot more economically advantageous as it only requires -33°C to reach its boiling point compared to hydrogen which has a boiling point of -253 °C. Yes, the ammonia gas is hazardous, but the gas is less flammable compared to hydrogen and transportation requires less energy to maintain the substance in liquid form. Allowing it to be more suitable for long distance transport. Not only does ammonia require less energy to transport, but also has higher energy density. Even if hydrogen would be the preferable energy source it is still better to transport the hydrogen in the form of ammonia because hydrogen takes up 17.65% of ammonias mass. The transportation benefits of ammonia outweigh hydrogen in pure form.

Ammonia as an energy source has gotten more attention as the years passes by, even while writing this thesis there are several announcements of collaboration between Yara and JERA which will focus on using clean ammonia to decarbonize the power production in Japan. The collaboration will focus on the development of supply chain for blue and green ammonia and working towards zero-emission in the thermal power generation in Japan. The blue and green ammonia will be supplied from the Yara ammonia plant in Australia and will be further distributed to Japan. This is a large stepping-stone towards the right direction by utilizing ammonia as a clean energy source as it does not release any GHG. The same concept has been implemented in the low-carbon energy supply project in Qatar but in another scale. This only shows that this kind of projects are possible and will be part of the future.

18.2 Costs regarding production of ammonia

The implementation of ammonia largely depends on the cost because it must be affordable and cost competitive with other energy sources that are CO_2 free. The most common way to produce ammonia is through the industrialized Haber-Bosch method that uses natural gas as a feedstock for hydrogen but releases large amounts of CO_2. To create blue ammonia, which is producing ammonia with natural gas and using carbon capture technology, the storage of the CO_2 is the main factor. Qatar is in proximity of large heavy oil fields; depleted reservoirs allowing for better storage of the CO_2 and has access to cheap natural gas.

As of today, the only system regarding climate emissions is the climate quotas that are allocated to different companies that are a part of specific sectors. To release emissions further than the number of quotas allocated, the company must purchase emission quotas from the quota market. There is only a system regarding climate quotas that works so that a company that is part of a sector is subjected to quotas allocated a given number of emissions quotas. For companies that base their business around biofuel can further sell their climate quotas on the market. Assuming that this fact could also be applied to the project in Qatar would mean lower cost per ton of ammonia, making it more competitive in price.

However, as of today, there are no global compensation schemes for actors outside the EU, but it is reasonable to assume that such a scheme will be established in the next few years. As this project does not release CO_2 into the atmosphere, it would be reasonable to assume that there will be some sort of CO_2 compensation alternatively no need to pay for emission quotas, making ammonia more competitive. In the EU's quota system for climate quotas, it works so that one climate quota gives a right to emit on tonne of CO_2 or CO_2 equivalents.
As of May 2021, the price reached a record high of 50 €/ton CO_2 emissions. This price is expected to increase in the years to come, due to the number of quotas being reduced by 2,2 percent per year in the period 2021 to 2030 (Comission, 2021).

Even though this quota system is restricted to the EU there could come a time where it is implemented into the middle east and other parts of the world. These are just assumptions towards the future that could potentially aid the viability of the large-scale ammonia production facilities in Qatar.

18.3 Results

Among the important aspects of this thesis, the results are the key factor. The results display if the project will be viable or not, and if it could be competitive towards other CO_2 free energy sources. To create a broader overview of different cost scenarios, there were calculations based on all the costs including the total average shipping, and other scenarios where shipping based on transport location was included. Several low-case, middle-case, and high-case scenarios were calculated to see how the different factors affected the ammonia price.

The results:

Ammonia cost			
Cost when average shipping was included	397.091 US\$/t NH_3		
Ammonia cost	Low-Case	Middle-Case	High-Case
Without average shipping	247,904 US\$/t NH_3	291,243 US\$/t NH_3	338.698 US\$/t NH_3
With average shipping	306,2986 US\$/t NH_3	349,637 US\$/t NH_3	397,0919 US\$/t NH_3
Results based on location	Low-Case	Middle-Case	High-Case
Tokyo	293,03 USD/t	336,37 USD/t	383,817 USD/t
Beijing	293,03 USD/t	336,37 USD/t	383,817 USD/t
Rotterdam	293,03 USD/t	336,37 USD/t	383,817 USD/t
LA	319,57 USD/t	362,913 USD/t	410,36 USD/t
Miami	322,227 USD/t	365,57 USD/t	413,017 USD/t
Louisiana	327,53 USD/t	370,879 USD/t	418,326 USD/t
NY	322,227 USD/t	365,57 USD/t	413,017 USD/t
Rome	279,76 USD/t	323,0985 USD/t	370,545 USD/t

All the price estimates range between 247,904 US\$/t NH_3 to 418,326 US\$/t NH_3 and are considered good estimates according to the geographical location and access to a large natural gas reservoir.

According to Shiozawa (Shiozawa, 2020) in the article “The Cost of CO_2-free Ammonia” it is said that the price of ammonia pre-shipment and produced in a traditional manner with natural gas at a gas price of 3.0 USD/MMBtu could be estimated to be around 200\$ per tonne-NH_3 which is only USD 47,9 in difference form the lowest calculated price without shipping of 247,904 USD/t NH_3. Meaning that the price for low-carbon emission ammonia only cost USD 47,9 more than regular ammonia that releases large amount of GHG. Just by looking at these results we could get an insight that the potential of ammonia lies in the future when more CO_2 commission schemes arise, profiting those that reduce their carbon footprint.

Furthermore, the International Energy Association (IEA) stated that in their report "The future of Hydrogen" the cost of regular ammonia that releases CO_2 to be around the price of US$220 per tonne-$NH_3$ and that uses a natural gas price of 3,0 USD/MMBtu. This further substantiates our own calculations of 247,904 USD/t NH_3 in the lowest-case and 338,698 USD/t NH_3 in the highest case. With a variance of 118,698 USD/t NH_3 from the highest to IEA's 220 USD/t NH_3 calculations and 27.904 USD/t NH_3 from the lowest case. To create a competitive ammonia cost the price of CO_2 needs to come down so that this will benefit Qatar. These are all costs without shipping.

Shiozama (Shiozawa, 2020) further includes the cost of transporting the ammonia from Saudi Arabia to Japan, estimating a price of 360 USD/t NH_3 and includes transportation inland of Japan. Comparing our own calculations based on ammonia production cost and shipping cost to Tokyo, Japan we get a low-cost case of 293,03 USD/t NH_3 and a high case of 383,817 USD/t NH_3, which does not deviate much form the calculations based in Shiozamas report.

In the IEA report "The future of Hydrogen" further includes the price estimate of CO_2 free ammonia including the shipping cost, presenting a final result of 340 USD/t NH_3 (IEA, 2019). These estimations look very promising compared to today's ammonia price. Due to several shutdowns of key plants around the world, the price of ammonia has spiked up to a price range between 270 USD/tonne to 370 USD/tonne (Ewing, 2021). Implementing the large scale low-carbon energy supply in Qatar could provide very competitive prices and the ammonia from Qatar has the advantage of being low-carbon energy.

19 Conclusion

Developing a low-carbon energy supply in the middle east most certainly provides an economic advantage towards the final product price of ammonia but there is still uncertainty towards how accessible the market is and how the region will handle the transition towards a large-scale ammonia facility. Further challenges are to find reservoirs that either needs EOR or are depleted so that it can be used for sequestration. As of today, there are not many formations that need EOR and for Qatar to utilize the different reservoirs in the region, there has to be better political diplomacy between the countries in the middle east.

Qatar lies in the middle east and there are not many regulations towards CO_2 emission releases so there are currently very low incentives for Qatar to implement a large-scale ammonia facility, but if international agreements start to threaten the use of fossil fuels, then the project could be a very plausible solution.

The feasibility of the project is very much plausible as Qatar has large untouched land areas that could be transformed to industry locations, easy access to low-cost natural gas, opportunity to deposit large amounts of CO_2 in reservoirs or for the use of EOR. The whole project has a total cost of about US$ 175 billion dollars, but this would be implemented as a gradual transition towards a low carbon energy supply. Considering the final price per ton of ammonia after a full complex-installation, the price is set to be very competitive, and this could put Qatar in an advantage towards cleaner energy. Cleaner energy can mean higher demand from the global market and this could help Qatar diversify their economic situation.

Society has become more environmentally conscious, thus looking at solutions like the low-carbon energy supply from Qatar is very important. The numbers support the basic economic investment, and it is reflected in a very competitive price per ton of ammonia. The price ranging from 247,904 US$/t NH_3 to 418,326 US$/t for ammonia that is environmentally friendly is very good compared to today's ammonia price averaging about 320 USD/t.

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