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Ammonia Production from a Non-Grid Connected Floating Offshore Wind-Farm: A System-Level Techno-Economic Review

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Ammonia Production From A Non-Grid Connected Floating Offshore Wind-Farm:

A System-Level Techno-Economic Review

A Thesis Presented

By

VISMAY V. PARMAR

Submitted to the Graduate School of the

University of Massachusetts Amherst in partial fulfillment

of the requirements for the degree

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

February 2019

Mechanical and Industrial Engineering

Ammonia Production From A Non-Grid Connected Floating

Offshore Wind-Farm:

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Approved as to style and content by:

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Bernd F. Schliemann, Member

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Sundar Krishnamurty, Department Head
Mechanical and Industrial Engineering

DEDICATION

To my parents and my sister

for their love and inspiration

ACKNOWLEDGMENTS

I would like to express my sincere gratitude to Prof. Jon McGowan to give me the opportunity to work on this thesis. It would not have been possible to complete this thesis without his exceptional direction and invaluable insights.

I would also like to thank my committee members Prof. James Manwell and Prof. Bernd Schliemann. They challenged me with intriguing questions which allowed me to explore my research abilities.

I would also like to show my appreciation to my family, for their love and support and their belief in me. Working on this thesis was a great learning experience and I sincerely appreciate all the people who made it possible.

ABSTRACT

AMMONIA PRODUCTION FROM A NON-GRID CONNECTED FLOATING
OFFSHORE WIND-FARM:
A SYSTEM-LEVEL TECHNO-ECONOMIC REVIEW

FEBRUARY 2019

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According to U.S. Department of Energy, offshore wind energy has the potential to generate 7,200 TWh of energy annually, which is nearly twice the current annual energy consumption in the United States. With technical advances in the offshore wind industry, particularly in the floating platforms, windfarms are pushing further into the ocean. This creates new engineering challenges for transmission of energy from offshore site to onshore. One possible solution is to convert the energy produced into chemical energy of ammonia, which was investigated by Dr. Eric Morgan. In his doctoral dissertation, he assessed the technical requirements and economics of a 300 tons/day capacity ammonia plant powered by offshore wind. However, in his dissertation, one of the assumptions was connection to the grid which provided auxiliary power to keep the ammonia plant operational and produce at rated capacity. It also allowed selling of excess power to the grid in the scenario of excess power production by wind farm during high winds.

This thesis explores the technical and economical feasibility of a similar system, except that the ammonia plant will be on a plantship and there is no connection to the grid. This creates a challenge as the ammonia synthesis plant must operate between 65-100% loads. Thus, the concept of multiple mini-ammonia plants is used to address the scenario of wind energy production at less than rated power. This will allow operation of one or more mini-ammonia plant (corresponding to the available energy from offshore wind). In the event of wind speed lower than the cutoff wind speed for the turbine, the ammonia plant will use the produced ammonia as fuel, with the help of a gas turbine running on either Brayton

cycle or combined cycle, to keep the plant idling. It will maintain the reaction conditions of the synthesis chamber and will not produce any ammonia. This is an important step as it takes days to reach the reaction conditions to start ammonia production again after shutting down due to unavailability of energy at low winds. Thus, at any windspeed, a mini-ammonia plant would either idle or operate between 65-100% load. This model will be used to simulate the total energy consumption, total energy captured by the wind farm, and the total ammonia produced. This will further help in assessing the final cost of producing, transporting, and consuming ammonia as fuel and thereby provide a better understanding of the feasibility of implementing this technology.

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CHAPTER 1

THESIS DESCRIPTION

The doctoral thesis by Eric Morgan investigated the technical and economic requirements of ammonia production by 300MW wind farm located near shore in Gulf of Maine [1]. It was connected to the grid in case the wind speed is not high enough to generate any power from the turbines. The wind farm consisted of 100 3MW wind turbines, whose size, diameter, rated speed and hub height were similar to Vestas 3MW and WinWinD 3MW turbine model. However, for this thesis, the turbine model selected will be the latest Wind 2 Energy W2E-151-4.5MW turbine. In addition, there is no auxiliary power support as the only source of energy for the operation of ammonia plant will be the offshore wind farm. In case of low wind speed, a part of stored ammonia will be used in Brayton cycle or combined cycle engine and allow idling of the ammonia plant. Therefore, the question of how much ammonia can be shipped back becomes necessary to answer. The levelized cost of energy was three and half times compared to ammonia produced from natural gas in Morgan's thesis. Using the same methods for calculating ammonia production energy requirements, wind farm energy production, cost scaling, and levelized cost of energy, this thesis aims at a more precise quantitative analysis of the costs and physical dimensions of the ammonia plant powered by wind farm and a more complete and updated picture of the work started by Dr. Eric Morgan.

The United States has a huge offshore wind resource. Utilizing all the resource seems improbable but maximizing it in an engineering sense can possibly be achieved by employing ammonia as an energy storage medium. Why ammonia? Ammonia plants are

already operational at industrial level. It is easy to manufacture, store and transport with modern technologies.

The thesis is divided into several sub-parts parts to get a better understanding of the practicality of the proposed solution for energy transportation.

First, the physical picture of the project is defined. The size of the ammonia plant will be such that it produces at least 300 tons per day. The plant will be constructed on a barge which will be termed as "Ammonia Plantships". This is the same concept used by E.J Francis of Johns Hopkins University/Applied Physics Lab in 1977, to convert the ocean thermal energy to ammonia and ship it back to shore [2]. In a way, this thesis reflects a similar approach, except it encounters higher complexity due to higher relative uncertainty of offshore wind.

According to Transition to Renewable Energy Systems by Detlef Stolten and Viktor Scherer (2013), ammonia synthesis plant can be operated between 65 – 100% load [3]. This means there will be no ammonia production when the energy produced from the offshore wind farm is less than the energy required to run ammonia plant at 65% part-load. This will result in wastage of the power generated from offshore wind if it is not sufficient to produce ammonia.

To address this, the 300 tons/day requirement can be achieved by usage of "n" number of ammonia synthesis plants. For example, 6 plants of 50 tons/day capacity could be used. This will result in lower energy threshold to overcome and thus, ammonia can be produced even at lower power generation from wind turbines.

For example, the 300 tons/day ammonia capacity of plant can be achieved through six 50 tons/day plant. This will lower the threshold energy to overcome to about 24 MW. If the assumed rated speed of the turbine is 11 m/s, then the first 50 tons/day ammonia plant should start producing ammonia at around 6 m/s. This calculation doesn't consider

the capacity factor of the wind turbine.

Secondly, based on weibull statistical distribution of wind, the total energy captured by the wind farm is calculated. Using this energy, the ammonia synthesis plant will manufacture ammonia using state of the art technologies. The electrical energy from wind farm will desalinate sea water and the distilled water produced will run through the electrolyzers which will produce hydrogen gas. To produce nitrogen, air separation method is used. Hydrogen is compressed at around 150 to 250 bars in compressors. The next step is to feed the produced hydrogen and nitrogen in an ammonia synthesis loop, which is a continuous cycle of gases that travel at high temperature and pressure through an adiabatic reactor. A pictorial representation of the above-mentioned process is given in figure 1.1
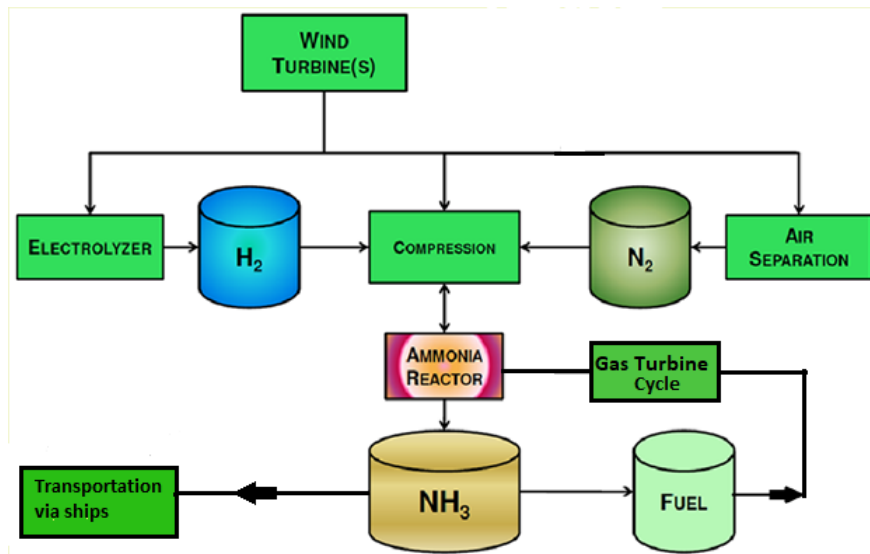
Figure 1.1: Flow-chart showing the flow of offshore wind to ammonia production and its utilization [1]

Once ammonia is produced, it will be stored in pressurized vessels or refrigerated compartments. This will then be transported back to shore via ships or barges. The proposed model incorporates the use of the produced ammonia to keep the plant idling in case of no wind power generation. In this case, idling means there will be no ammonia production, but energy will be supplied from the produced ammonia to maintain of the temperature and pressure of the ammonia synthesis chamber. This step is necessary because it will take days to to restart the plant because of time consumed in regenerating the catalyst used in

the Haber-Bosch process [3], which in turn will make the project less economically viable. Power required for this process will be provided by combusting ammonia through a gas turbine using Brayton/combined cycle. Hence, it is necessary to keep some amount of ammonia on the plant for such scenario.

The next aspect of the thesis is the transportation of the produced ammonia back to shore for its use as either fuel or fertilizer. From the offshore site, ammonia can be brought onshore via ships or barges. Ammonia is regularly transported through ships and the standard transportation cost can be determined [4]. For example, currently, there are 31 barge fleets operational in the United States [4]. Once the ammonia is brought onshore, further delivery can be done through pipelines or, railroads and trucks, in a refrigerated or pressurized tank. There are two pipelines which deliver ammonia as shown in figure 1.2.
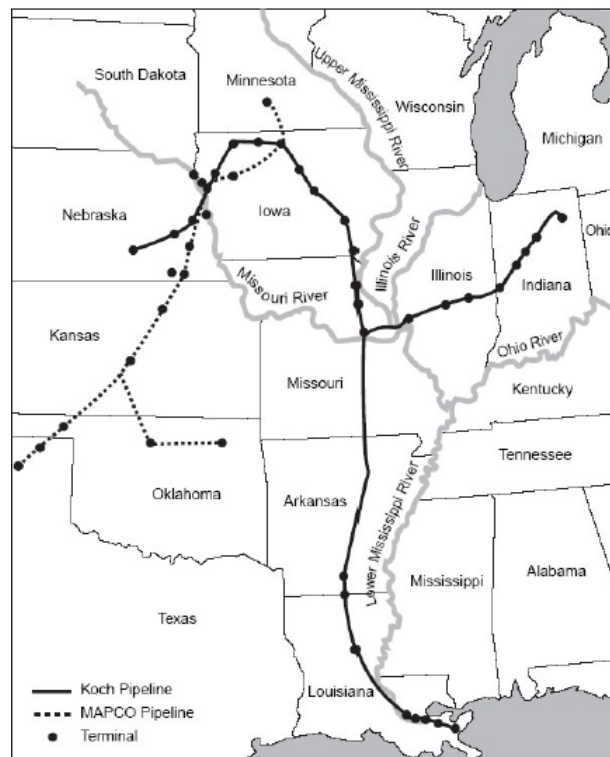
Figure 1.2: Anhydrous ammonia pipelines [4]

One is Magellan Ammonia pipeline, extending from Texas to Minnesota and is 1,100 miles long with 20 terminals and delivers 900,000 tons of ammonia per year. Other is the

Kaneb Pipeline, which extends from Louisiana to Nebraska and Indiana with a length of 2,000 miles and delivering 2 million tons per year [4]. Tariffs on the Kaneb pipeline average around $0.026/ton/mile in 2006 dollars. Converting this value to a price of transporting hydrogen, the cost becomes $0.10/kgH2/1000km in 2006 dollars [5].

After delivered, it can be used either as fertilizer or as fuel. However, direct combustion of ammonia in a gas turbine has not been developed at industrial level and that is why, the cost will be quite sensitive to future technologies.

CHAPTER 2

BACKGROUND

2.1 Overview of current technological and cost trends in offshore wind sector in United States

This section is largely summarized by report published by Department of Energy (Office of Energy Efficiency and Renewable Energy) [6] in 2016. The report is aimed at providing information relevant to domestic offshore wind industry market, its challenges and corresponding opportunities. Using this report, the ongoing projects and how the offshore wind market and technology is shaping up can be determined.

According to this report, the global installed capacity of offshore wind is 12,913 MW of commissioned capacity from 111 projects. The 593 ongoing projects indicate that the development capacity of the offshore wind is around 231,000 MW. In the United States, the 28 proposed projects have potential to develop 24,135 MW. Of the 28 projects, developers have full control over the site for 18 sites totaling to 14,785 MW of potential capacity as shown in figure 2.1.

The offshore wind technology is moving towards larger wind turbines and floating wind turbines. For example, the completion of the Burbo Bank Extension project (United Kingdom) in early 2017 was the first commercial project to use a Vestas 164-meter rotor, 8-MW turbine (V164-8 MW) that was first prototyped in 2014. In addition, an upgraded V164 prototype 9.5-MW turbine was debuted in 2017 (Mitsubishi Heavy Industries [MHI]

Vestas Offshore 2017b; Weston 2017a; de Vries 2017). It can be observed from the figure 2.2 that average global wind turbine size in 2015 was 3.4 MW, which increased to 4.7 MW in 2017, and is expected to cross 7 MW by 2021 [6]. The preference is shifting towards larger turbines because it provides provisions for fewer installations and eventually fewer machines to operate and maintain, which can help significantly in lowering wind energy production costs.
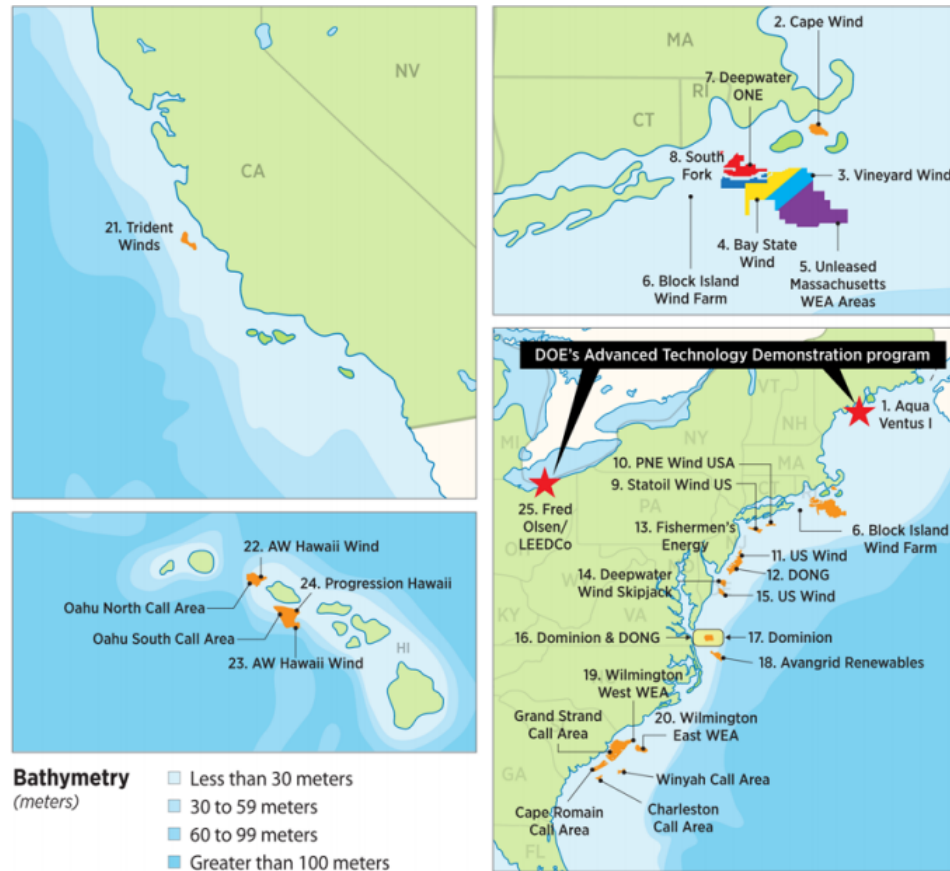
Figure 2.1: U.S. offshore wind projects [6]
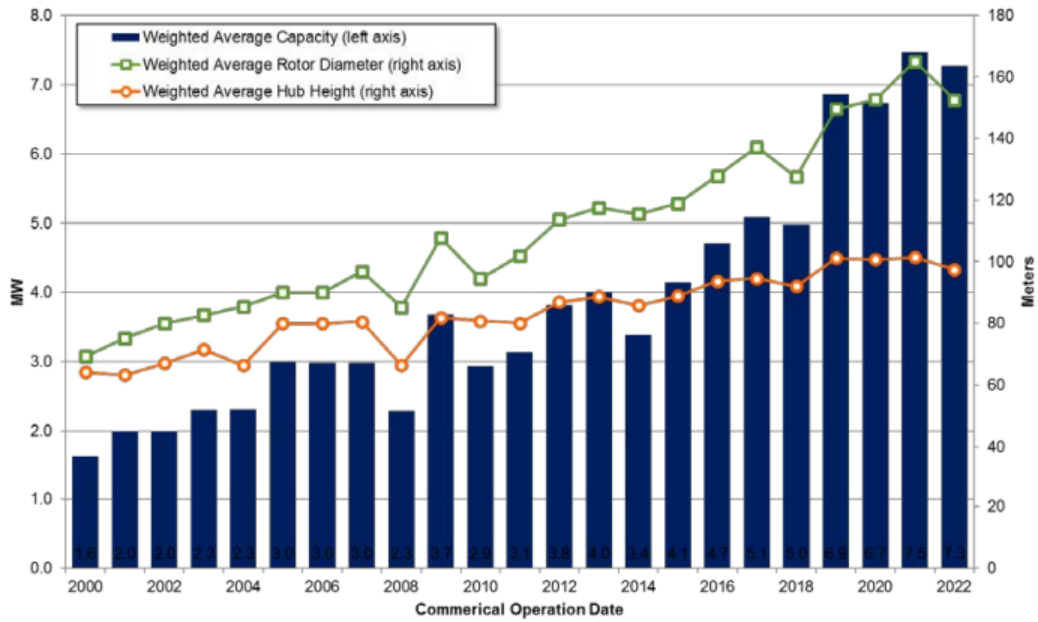
Figure 2.2: Comparison of rotor diameter and hub height with respect to the production capacity. [6]

Another remarkable aspect of this report suggests the shift towards floating wind turbines. The ongoing projects indicate tripling in the installation capacity for floating offshore wind farms to nearly 3000 MW. The global floating offshore wind pipeline has reached 2,905 MW in 2016, with 26 announced projects including 21 demonstration/pilot-scale projects, as well as the five commercial-scale projects in Hawaii, California, and France.

As can be seen from figure 2.4, the offshore wind resource is stronger in areas of deep waters and the use of floating platform wind farms will be pivotal to exploit this resource. There are 11 individual pre-commercial floating projects totaling 229 MW in capacity that have advanced past the planning phase and are either under construction, approved, or have significant resources committed for project development.
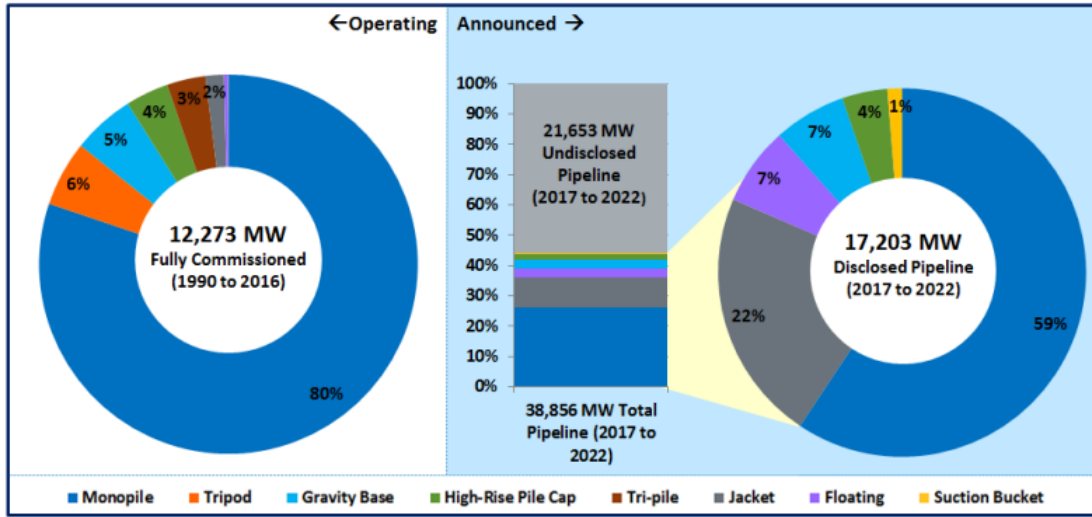
Figure 2.3: Offshore wind projects corresponding to different platforms. [6]
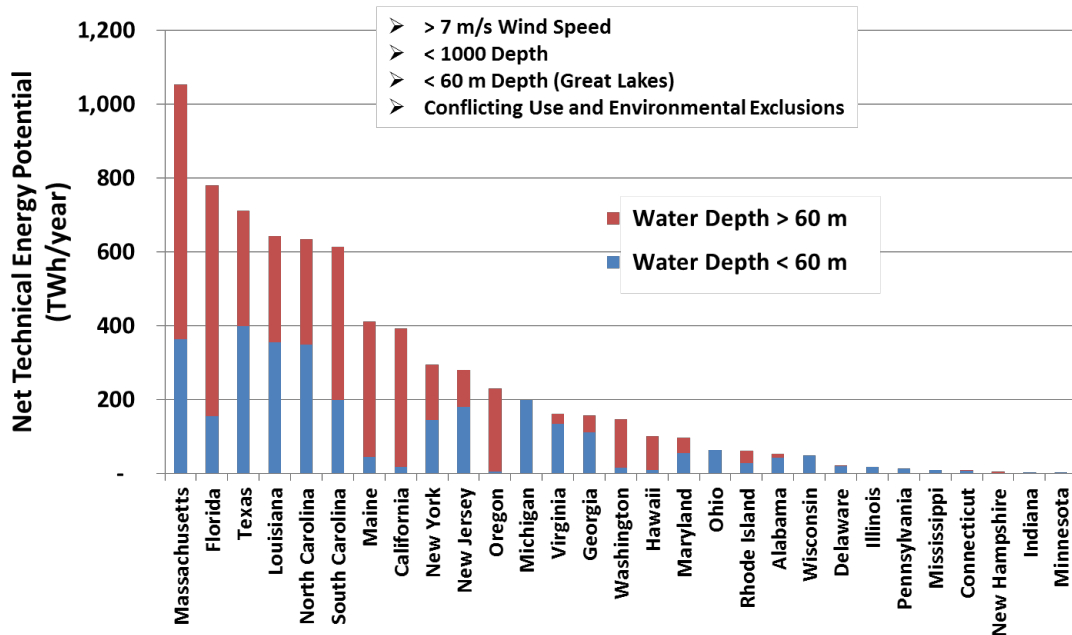
Figure 2.4: Water depth along the coast of corresponding states and offshore wind energy potential. [7]

In summary, it can be derived that there is vast offshore wind resource along the coast of United States. The untapped wind resource is much higher in the deeper waters and further away from the shore. The technology shift in the offshore market indicate that floating platform wind farms will be pivotal in exploiting the offshore wind resource in

regions with deeper water and further away from the shore. It is also a point to note that the design of turbines is shifting to higher power levels.

2.2   Challenges developing in the energy transmission of offshore wind and potential solutions

With distance from the shore increasing, there arise new challenges in transmission. AC electric transmission is no longer economically and efficiency viable owing to large reactive power losses [8]. That paves way to High Voltage Direct Current (HVDC) transmission [9]. But another approach is chemical energy transmission via ammonia, which will be investigated in this thesis. This idea of chemical energy transmission using ammonia is not new and was investigated for OTEC (Ocean Thermal Energy Conversion) in 1977 by E.J Francis and his team in Applied Physics Lab at Johns Hopkins University, where ammonia plant-ships were used to extract thermal energy from oceans and convert to anhydrous ammonia [2].

Other chemicals which can be considered to address energy storage and transmission of offshore wind energy are methanol, hydrogen peroxide, chlorine, sodium hydroxide (caustic soda), and hydrochloric acid. From these, all can be manufactured using electrolysis of sea water except methanol (including other hydrocarbons), because it requires a carbon source [2]. Chlorine, sodium hydroxide, and hydrochloric acid have lower value as energy. They have high production energy demand and would take more number of synthesis plants to saturate existing markets. Hydrogen peroxide production is inefficient and has a low efficiency as combustion booster or energy source [2]. Thus, ammonia and hydrogen can be considered the most promising chemicals to transport the offshore wind to the place of end usage. The physical characteristics of hydrogen, such as low energy density, embrittlement of metals, difficulty in storage and transportation, makes hydrogen a challenging fuel to use. However, with advanced infrastructure already in place to transport ammonia, like pipelines, refrigerated barge, railroads, and trucks, ammonia is chosen

as the suitable chemical for this energy delivery system.

The properties of ammonia which advocate its selection are mentioned below:

- Carbon-free, thus combustion does not produce greenhouse gases [10]

- Ammonia combustion products are pure water and nitrogen [11]

- High energy-density fuel: Properties of ammonia are similar to propane and it can be stored at 17 bars pressure at room temperature. At this pressure it has energy density of 13.77 MJ/L. At the same pressure, that of hydrogen is 0.20 MJ/L. The highest energy-density of hydrogen that can be achieved is 9.98 MJ/L but it is at a temperature of -253 °C [12]

- Currently used as fertilizer to supply nitrogen in plants and is therefore the second most produced chemical in the world [13]

2.3   Using ammonia as energy storage medium

The tecno-economic analysis done in the report "Ocean Thermal Plantships for Production of Ammonia as the Hydrogen Carriers " by C.B. Panchal et. al. conducted by Argonne National Laboratory in 2009 [14], aligns significantly with the design methods to be applied in this thesis. Fundamental difference between that report and this thesis is between the source of energy for the ammonia plant. In Panchal's case, it is ocean thermal energy, whose availability is reliable and almost constant throughout the year. Hence, there will no additional requirement for a backup power source to produce ammonia.

Regardless, this report can be used to determine or extrapolate the physical dimensions of the ammonia plantship proposed for this thesis. The conceptual design of plantship was determined for 265 metric tons per day (MTD) ammonia plant. Considering that the proposed size of ammonia in this thesis is 300 MTD, a reasonable estimate of the dimension of the plant can be scaled. In addition to the dimensions, this literature gives great in-

sight into the day-to-day working of such a plant and recommendations for improving the design with compact aluminum heat exchangers. It also gives directions to implement a commercial scale offshore ammonia plant with capacity of 2600 MTD. And finally, using Department of Energy's H2A model, economic analysis was done to develop itemized cost estimates of for major components and subsystems. This approach, combined with the one given in Morgan's thesis will help in developing cost estimates model for the project. Morgan's cost estimates models were used to develop the economic model for the offshore wind farm and majority of the components of the ammonia plant. However, the underlying approach adopted by CB Panchal in this report will be used to determine costs of the components which were not included in Morgan's model, and achieve an estimate within reasonable accuracy.

In summary, the techno-economical model derived from Morgan(2013) and the plantship design derived from Panchal et. al (2009) form major part of this thesis.

2.4 Combustion of Ammonia

One of the primary reasons behind selecting ammonia as the energy carrier is that the combustion of ammonia yields nitrogen and pure water. This means that in theory, combustion of ammonia is pure and does not produce any greenhouse gases. However, while carrying out the process in actual conditions, some amount of nitrogen oxides production is expected. Combustion of ammonia is also limited in terms of industrial level power production due to the following reasons:

- Low flame speed ($\frac{1}{5^{th}}$ that of methane) [10]

- High ignition temperature 651°C [15]

To address these challenges, Prof. Hideaki Kobayashi of Institute of Fluid Science at Tohoku University in Sendai, Japan, has developed the world's first technology for direct combustion of ammonia in a gas turbine. He applied the use of swirl flow device causing spiral motion of the gases in the combustion chamber. This allowed a better control of the

flow of the ammonia-air mixture. With the help of the device, the swirl flow was created both horizontally and vertically leading to a longer distance of flame stability. Using this concept, his team was able to reach output 41.8 kW using ammonia-methane mixture [10]. Subsequently, they were able to reach the same output using 100% ammonia [10].

However, it is not technologically feasible at this stage in development to scale up from 50 kW to industrial capacity of MW in one step. But with the equipment available to the industries, there is a high probability to use ammonia combustion to generate MWs of power [10].

According to an article published in September 2017 in American Chemical Society by Giddey et. al [16], figure 2.5 can provide a good source of understanding for ammonia utilization at the site of end-use:
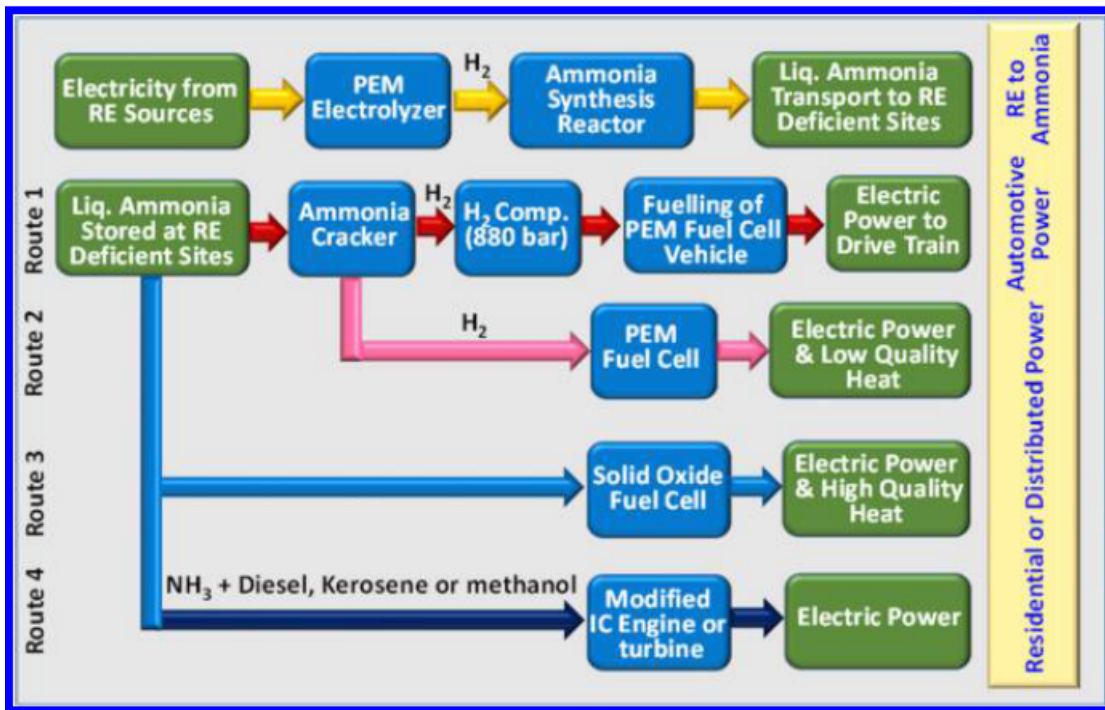
Figure 2.5: Different methods to utilize anhydrous ammonia. [16]

2.5   Storage of Ammonia

The physical properties of ammonia demand high pressure or high refrigeration to store it in a liquid phase. If ammonia is stored in high pressure vessel, it would require nearly 17 bars of pressure to maintain liquid phase and meet minimum safety requirements for storage and transportation. However, full pressure, shop fabricated storage vessels are practical to the size 300 tons [12].

The other method to store ammonia is using refrigerated vessels. They have much higher storage capacity (as high as 66.2 million liters), and do not require high pressure. The temperature requirement for low pressure storage is -33 °C at 1 atm [12]. Depending on the energy requirements to meet these demands and expected storage capacity and costs associated with the system, the decision of whether to use pressurized vessel or refrigerated vessel will be determined.

2.6   Summary

The background can be summarized in the following points:

- Offshore wind farms are moving towards floating platforms allowing the setup distance to be further away from the shore.

- Increased distance from the shore poses challenges for transmission of energy and using anhydrous ammonia as the energy storage and transport medium offers a possible solution.

- Extensive research has been done on how to convert the electrical energy from offshore wind to anhydrous ammonia regarding necessary equipment required and energy associated with the subsystems of the ammonia producing plant.

- There is a wide developed network of ammonia pipelines to transport it long distances at the point of end-use. There are also sophisticated technologies available to store ammonia at high pressure or low temperature.

- Ammonia can be combusted to produce energy (currently not at industrial levels, but much progress has been made to achieve that level) and the combustion process involves significantly lower greenhouse gases emissions compared to the conventional hydrocarbon fuels.

CHAPTER 3

CALCULATION OF NET AMMONIA PRODUCTION

The idea here is to calculate total ammonia produced based on the annual energy production from the offshore wind farm. Using weibull distribution and power curve of the Wind 2 Energy W2E-151-4.5 MW turbine with an upgrade to 164m rotor size, the net annual energy can be determined.

3.1   Wind Conditions at the Site

As mentioned earlier, this thesis utilizes Weibull probability distribution. It gives data on the windspeed and corresponding number of days it affects in a year.

Looking at the offshore wind map at 90m above sea level , the northeast part of United States seem to have strongest winds.
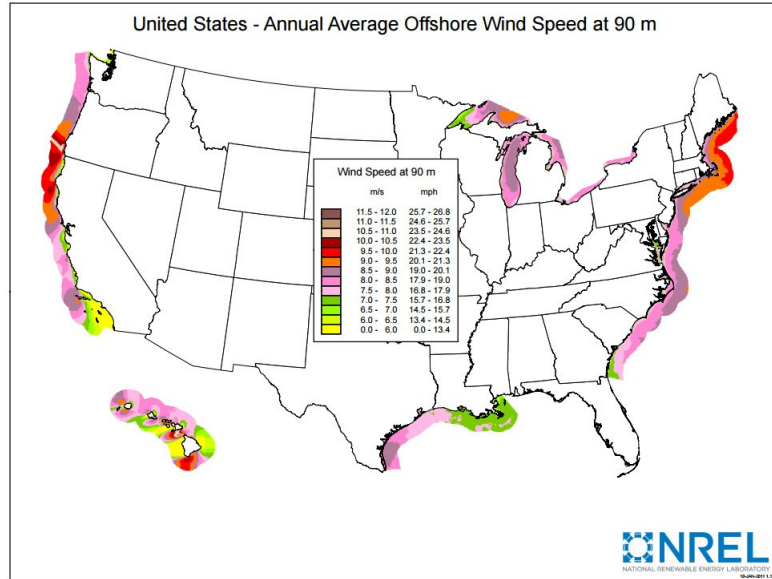
Figure 3.1: Offshore wind map of the United States. Source: NREL

Zooming into the offshore wind map of Massachusetts, the wind at 90m above sea level is 10 m/s at a site which is 50 nautical miles from the shore and has a depth of 60 meters.
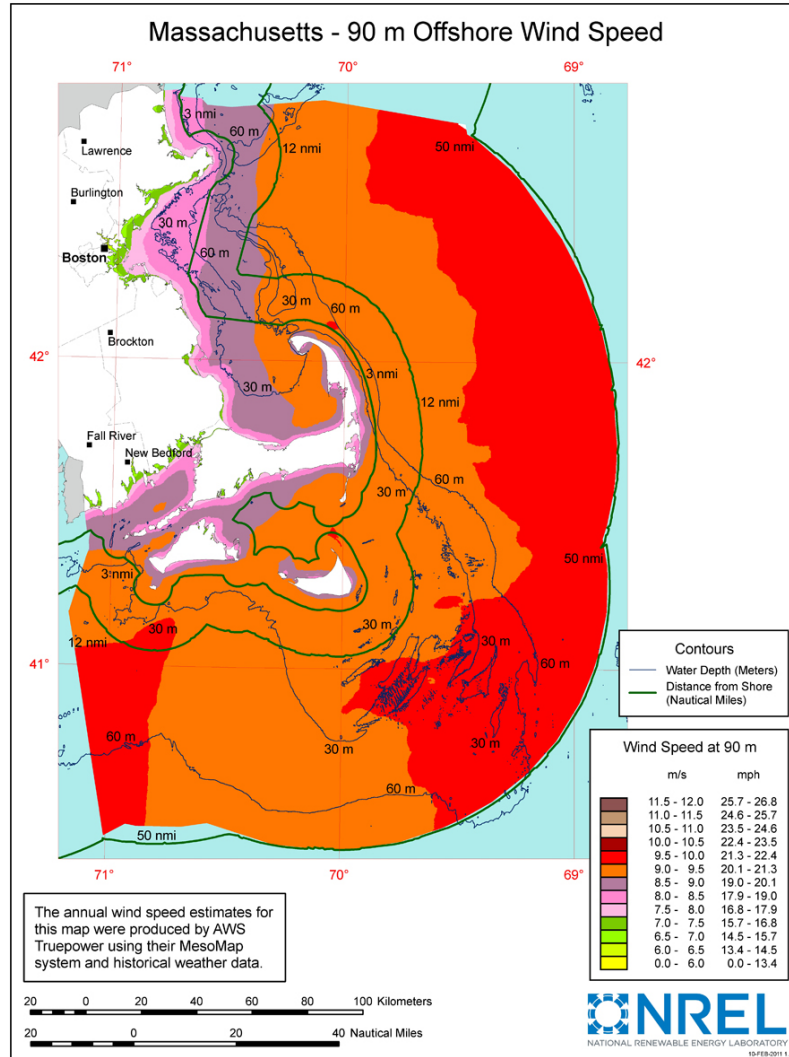
Figure 3.2: Offshore wind map of Massachusetts. Source: NREL

Therefore, the average windspeed $\bar{u}$ at the site is assumed 10 m/s at 90m above sea-level and the Weibull shape parameter (k) is assumed 2.2. Since the hub height of the turbine used for this thesis is 140m, the average windspeed at the hub height can be logarithmically scaled from the formula:

$$u(z_2) = u(z_1)\frac{ln\left(\frac{z_2}{z_0}\right)}{ln\left(\frac{z_1}{z_0}\right)} \tag{3.1}$$

18

where,

$z_1 = 90$m,

$z_2 = 140$m,

$u(z_1) = 10$ m/s, $z_0 = 0.0002$ m, surface roughness for calm open sea [17].

This gives average windspeed at 140m hub height as 10.3 m/s. The Weibull scale parameter can be calculated from the formula:

$$c = \bar{u} \left[0.568 + \left(\frac{0.433}{k} \right) \right]^{\left(-\frac{1}{k} \right)} \tag{3.2}$$

$\therefore c = 11.68$ m/s

The Weibull wind distribution is shown in figure 3.3:
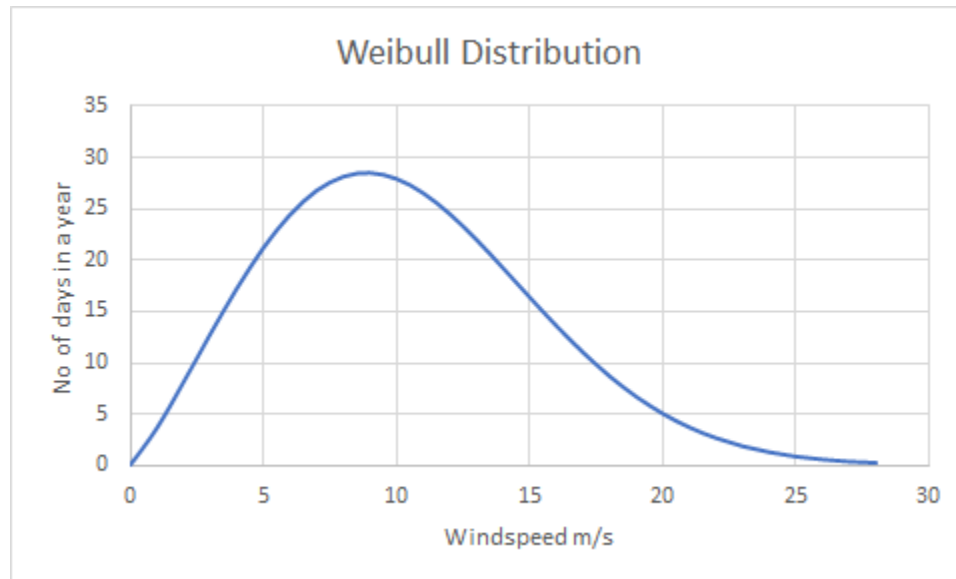
Figure 3.3: Weibull wind distribution for a year

3.2   Wind Turbine Power Curve

The Wind 2 Energy W2E-151-4.5 MW power curve can be obtained from (https://en.wind-turbine-models.com/). However, for the current project, the power curve is adjusted to reflect the power of the same machine but with 164m rotor diameter instead of 151m. The power curve for the turbine is calculated from the formula:

$$P = C_p \frac{1}{2} \rho \pi r^2 \qquad (3.3)$$

where ρ is the density of air ($1.225 \; kg/m^3$).

Therefore assuming the same C_p, it is scaled by a factor of $\left(\frac{164}{151}\right)^2$, to calculate the power curve for the same machine with 164m rotor diameter. Figure 3.4 shows the comparison between power curves of the original W2E-151-4.5 MW turbine and that with 164 m rotor diameter. The rated windspeed is down to 10 m/s from 12 m/s.
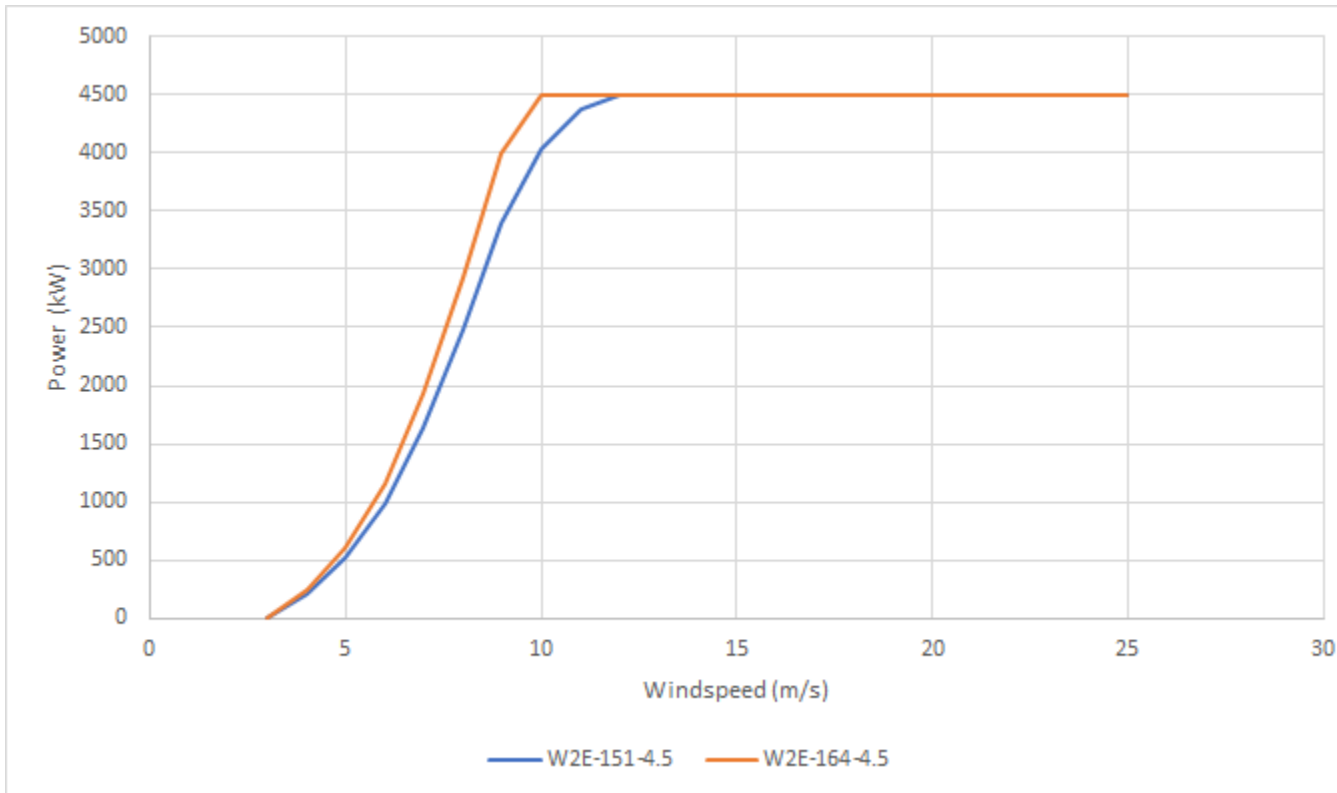
Figure 3.4: Power Curve comparison btw W2E-151-4.5 and W2E-164-4.5 machines

3.3 Capacity Factor at the Site

This factor reflects the ratio between actual energy produced to the energy that could be produced if the wind turbine operated at its rated power in a given period [17]. Since Weibull statistical distribution of wind is used at the site, where the average windspeed at the hub height is 10.3 m/s, the capacity factor at the site can be known [18]. Figure 3.5

shows the value of capacity factor using average windspeed at hub height, rated wind-speed of the turbine, and Weibull shape parameter. For this case, the average windspeed is 10.3 m/s, rated windspeed is 10 m/s and weibull shape parameter is 2.5.
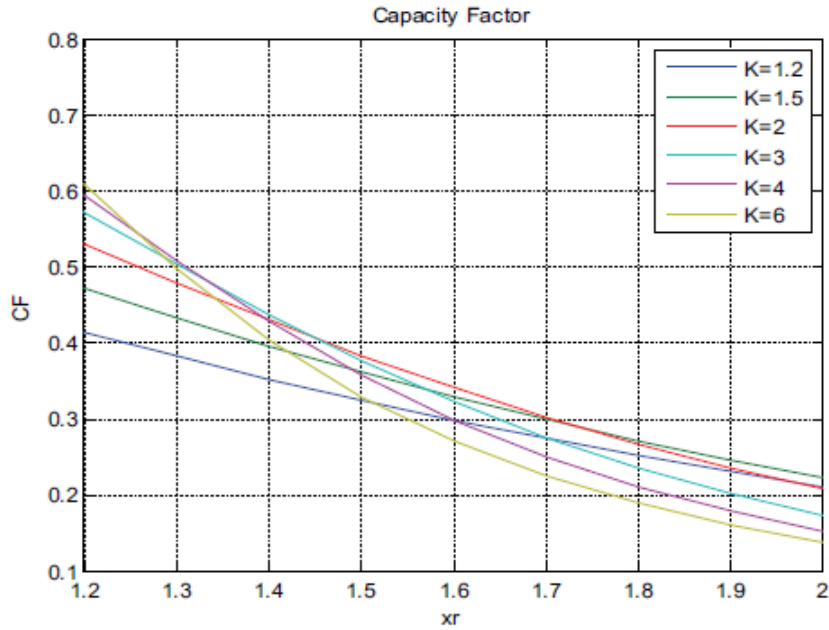
Figure 3.5: Capacity Factor as a function of rated windspeed, average windspeed and weibull shape paramter [18]

Necessary extrapolations were performed using trendline feature in MS Excel to ac-commodate the parameters used for the current design as shown in figure 3.6.
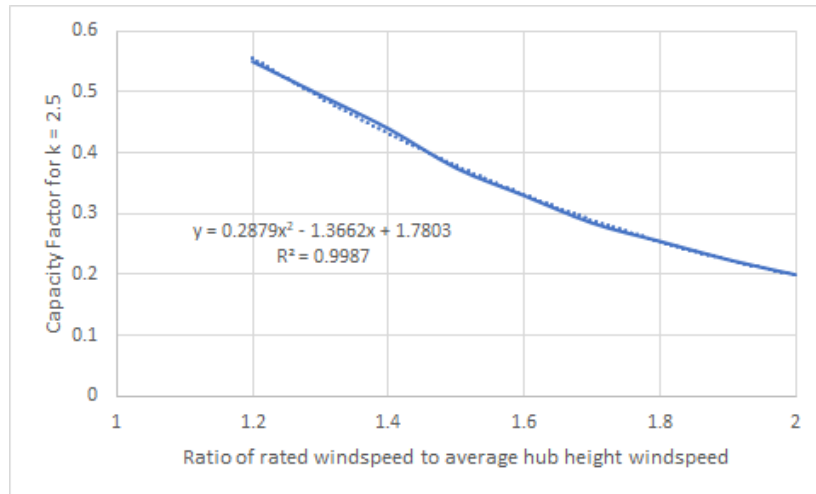
Figure 3.6: Capacity Factor trendline with windspeed

This gave a capacity factor of 0.73. This high capacity factor is due to the fact that average windspeed at the site is 10 m/s which is same as the rated windspeed.

3.4   Size of the Windfarm

According to Morgan(2013), the size of the ammonia plant has a linear relationship with the power required by the ammonia plant [1], given by:

$$P_{NH_3} = 0.482 Size_{NH_3} \qquad (3.4)$$

where,

P_{NH_3} = power required by the ammonia plant in MW

$Size_{NH_3}$ = ammonia plant capacity in tons per day

To meet the requirement of ammonia plant capacity of 300 tons/day, the net power required from the offshore wind-farm should be:

$$Size_{NH_3} = 0.482 \times 300 MW \qquad (3.5)$$

$\therefore Size_{NH_3}$ = 144.6 MW

3.4.1   Number of turbines

When the windfarm is connected to the grid, the number of turbines can be estimated by considering three important factors:

- **Array Efficiency:** Wind turbine reduce the wind speed by extracting its kinetic energy causing the downstream turbines will face relatively lower wind speed. Therefore, the total energy captured by a wind farm will be less than the total energy captured by individual turbines. This energy loss is called "Array loss". It is primarily a function of wind turbine downwind and crosswind spacing, wind turbine operat-

ing characteristics, number of wind turbines and size of the wind farm, turbulence intensity, etc. [17]. It is assumed 90% here.

- **Electrical Transmission Efficiency:** This factor reflects the loss in electrical power transmission from the turbine to the plantship. It is assumed as 98% as electrical losses within inter array cables is negligible.

- **Capacity Factor:** It is calculated as 73% for initial analysis.

However, the windfarm considered for this project is non-grid connected. Therefore, any access energy produced from the windfarm will be lost. This means, that the number of wind turbines should be such that the rated power from windfarm should match the power requirement for the ammonia plant operational at rated capacity.

Considering these factors, the number of wind turbines should be:

$$n_{turbine} = \left(\frac{144.6MW}{4.5MW \times 0.9 \times 0.98} \right) \tag{3.6}$$

$\therefore n_{turbine} = 37$

Therefore, 37 turbines will be required to supply power to the ammonia plantship.

3.4.2   Arrangement of Wind Turbines

Array losses are around 10% when the distance between the turbines in downwind direction is 8 to 10 rotor diameter (D), and 5 rotor diameters apart in crosswind direction [19].
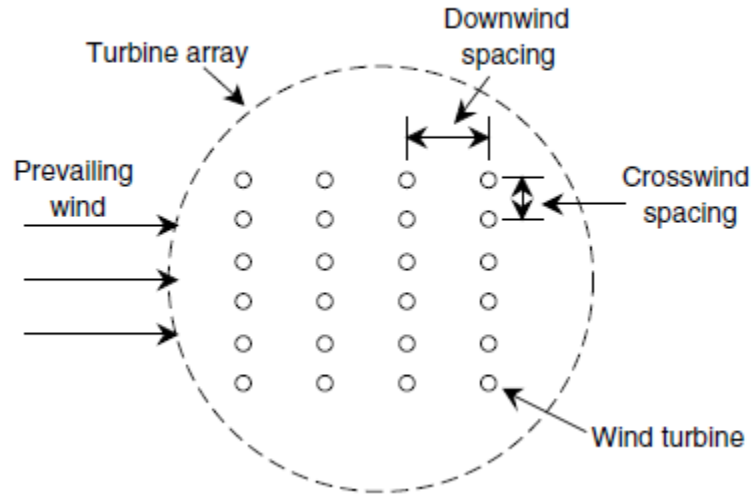
Figure 3.7: Schematic of a windfarm [17].

For this thesis, the downwind spacing will be 10D and crosswind spacing will 5D. And the array efficiency is assumed as 90%. As it is mentioned earlier, the turbines model selected is W2E-151-4.5 MW, which has a rotor diameter of 164m. Therefore, the downwind spacing is 1640 m, while the crosswind spacing is 820 m.

3.5 Energy Flow from Windfarm to the Ammonia Plant

3.5.1 Energy control algorithm

The analytical model of the ammonia production is developed in MATLAB and the code is shown in Appendix A. The 300 tons/day production is divided into "n" number of ammonia plants. Each plant has 2 energy level: the idling level (I) and the production level (P). As mentioned earlier, ammonia plant can be operational at production level of 65-100%. The idling level I) must be met either by the energy from offshore wind or energy obtained from combustion of ammonia. The production level will be met only from the offshore wind.

From Morgan(2013), the ammonia synthesis chamber requires 8 MW power for a 300 tons/day ammonia production capacity. The 8 MW power here also takes into account the power required to pump the reactants through the pump and into the chamber, along with maintenance of reaction conditions. Therefore, the idling power level for ammonia plant with rated capacity of (300/n) tons/day,

$$I = 8 \left(\frac{\frac{300}{n}}{300} \right) \text{ MW} \tag{3.7}$$

$$\therefore I = 8 \left(\frac{1}{n} \right) \text{ MW}$$

Similarly, the production level can be calculated for each ammonia plant as:

$$P = 0.65 \times 0.482 \times \left(\frac{300}{n} \right) \text{ MW} \tag{3.8}$$

The flow of energy from the windfarm will follow the controlling sequence as:

- For any given wind speed, the term $\left(\frac{\text{Net Energy from the windfarm}}{n} \right)$ will be either less than I, greater than P or between I and P.

- If it less than I, then there is additional requirement of energy from the ammonia gas turbine cycle to keep the plant idling.

- If it is higher than P, then all the ammonia plants will be producing ammonia between 65-100% capacity depending on the amount of energy received to the ammonia plant.

- And if it between I and P, then out of n ammonia plants, the quotient of the value $\left(\frac{\text{Total Energy from Windfarm}}{P} \right)$ will be producing ammonia at 65% capacity. The other wind farms will be idling at power level I. If there is still additional energy available, it will be distributed among the plants which are producing ammonia.

3.5.2 Energy extracted from ammonia:

The energy density of anhydrous ammonia is 11.308 MJ/litres [20]. And the mass density of anhydrous ammonia is $681.82 \, kg/m^3$ [5]. Assuming 40% gas turbine cycle efficiency, the mass of ammonia required to reach idling level can be estimated. (Refer to Appendix A)

3.6 Sensitivity Analysis

This section summarizes the effects of factors like the number of divisions of the ammonia plant, and efficiency of the ammonia-powered gas turbine on the net ammonia production. The ratio of the net annual ammonia production to maximum possible ammonia production is analysed here.The maximum possible ammonia production will be 330×300 tons. On an average, ammonia plant shuts down 5.2 times a year and is operational 330 days in a year [1].

3.6.1 Effect of no of divisions of ammonia plant on annual ammonia production

Figure 3.8 shows the ammonia production curve with the windspeed as well as shows how the addition of division s of the ammonia synthesis plant address the part-load situations.
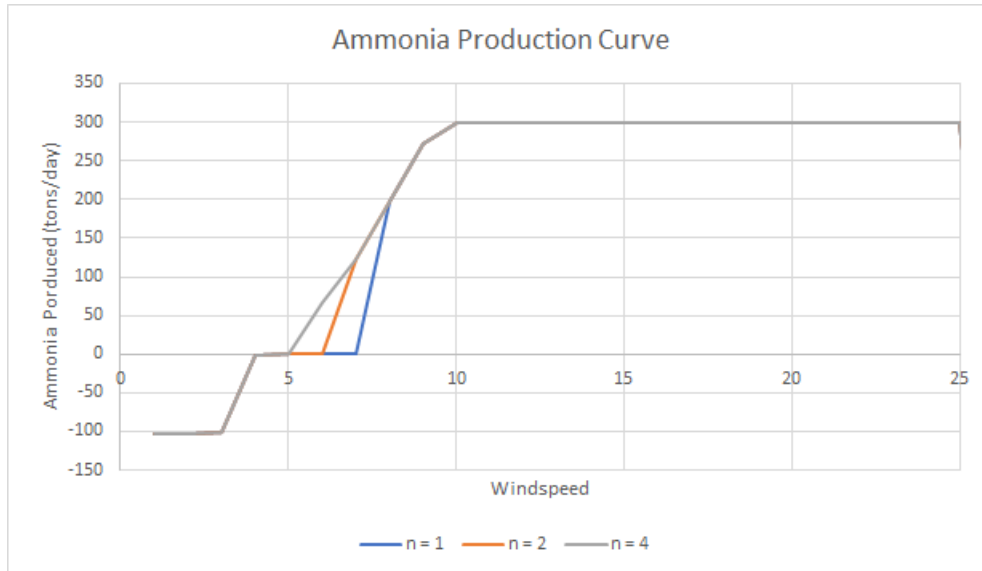
Figure 3.8: Effect of number of divisions of ammonia synthesis loop on the ammonia production curve

Figure 3.9 shows the percent annual ammonia production (capacity factor of ammonia plant) with respect to the number of divisions of ammonia plant.
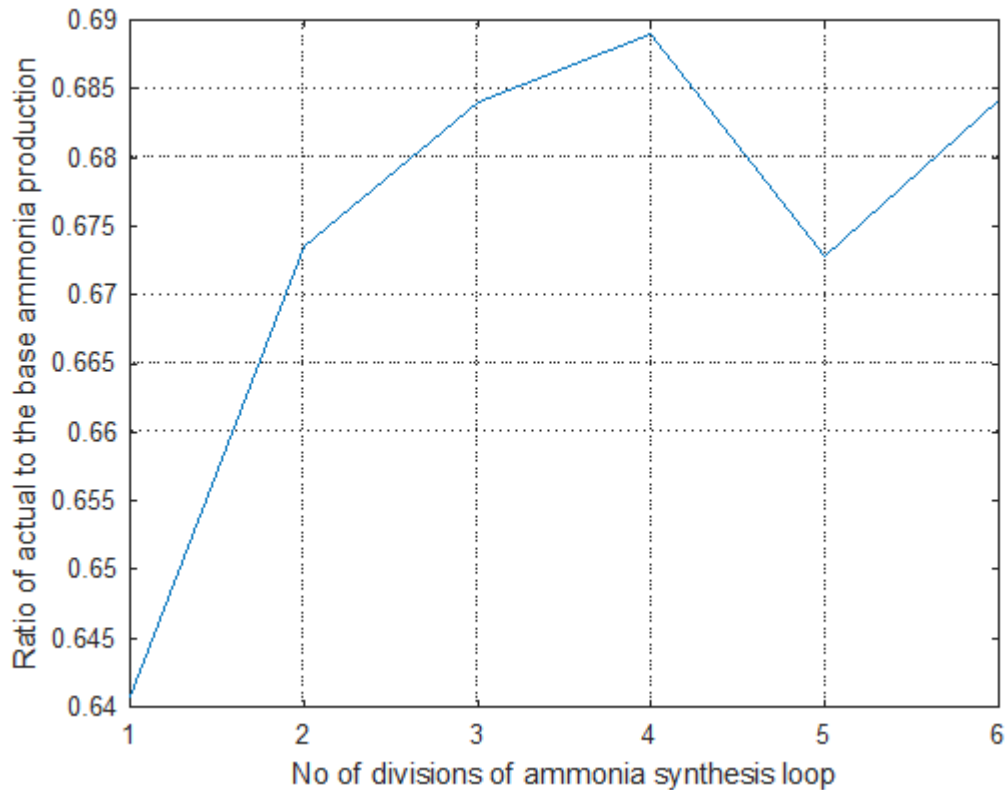
Figure 3.9: Effect of number of divisions of ammonia plant on the annual ammonia production

Having more mini ammonia plants would mean that the threshold energy to produce ammonia at 65% capacity decreases, and so production would start at lower windspeeds. This would increase the annual production. However, it would also utilize more of the produced ammonia to keep it idling during low winds. Therefore, having more number of divisions of ammonia plant does not necessarily mean that it will have higher net annual production, as evident between n = 4 and n = 5 in figure 3.9.

3.6.2 Effect of ammonia gas turbine cycle efficiency

The technology to generate power from ammonia using a gas turbine cycle is not developed at industrial level yet. The review by Valera et. al. covers technologies such as ammonia in cycles either for power, in fuel cells, reciprocating engines, gas turbines and propulsion technologies, and highlightting the challenges with the combustion patterns of

ammonia blends [21]. It is assumed in this thesis, that ammonia can be combusted in a gas turbine at industrial level in megawatts.

Figure 3.10 shows the effects of efficiency of a hypothetical ammonia gas turbine which is used to keep the ammonia synthesis chamber at the reaction temperature and pressure.
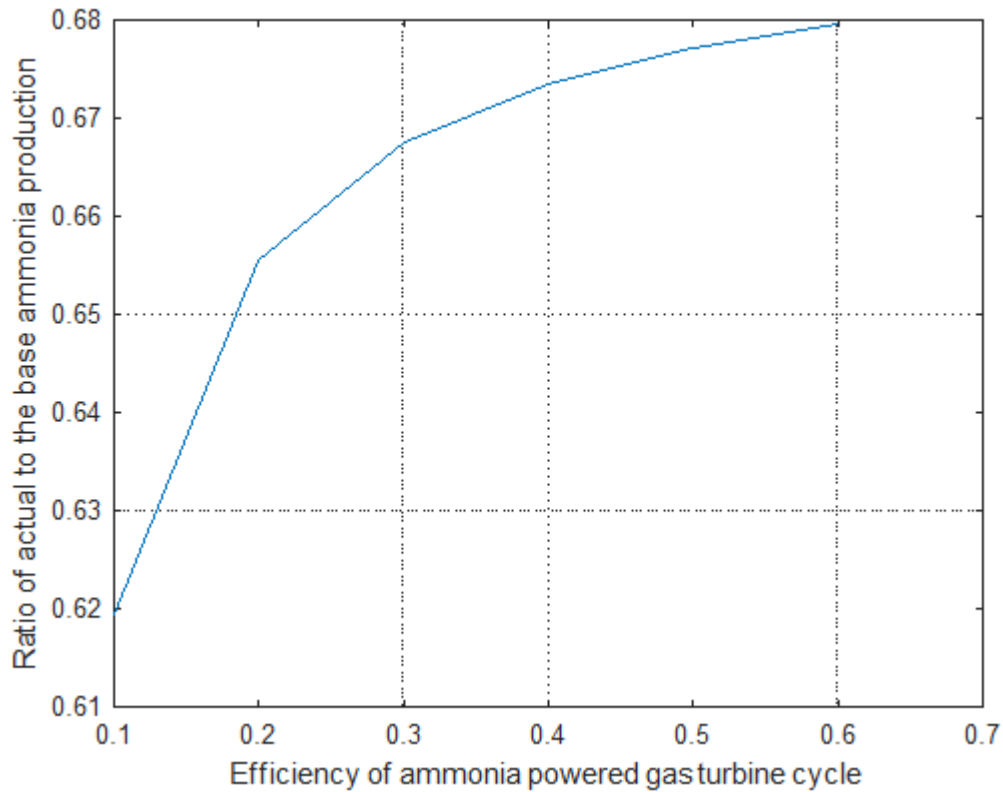
Figure 3.10: Effect of efficiency of ammonia powered gas turbine cycle on the annual ammonia production

It is evident from 3.10 that as the efficiency of the ammonia gas turbine cycle increases, the net ammonia production increases as well because it will take lesser amounts of ammonia from the storage to keep the synthesis chambers idling.

3.7   Summary

In summary, this chapter concludes the system level technological requirements to optimize ammonia production and helps us understand how the parameters govern the net

annual production of ammonia. The emphasis is given only on the net annual production. As the total production increases, it will lower the levelized cost of ammonia (LCOA). But achieving the factors that lead to higher production might increase the overall cost of project. For example, there is more net annual ammonia production when the number of divisions for the synthesis chamber was 4 than that with 2 divisions. However, the LCOA could be higher for 4. This makes way to the next chapter, where the economics of this project are taken into consideration to optimize the design of the project from a techno-economic stand-point.

CHAPTER 4

ECONOMICS OF BASELINE NH$_3$-OFFSHORE WINDFARM

The economics of the NH_3-Offshore windfarm consists of determining capital costs, operations and management costs (O&M Costs) of the entire project, which is used to determine the Levelized Cost of Ammonia (LCOA). The LCOA in $/ton is an important cost indicator and helps in assessing how costly is it to produce one ton of ammonia during the entire lifetime of the project. It can be compared with the LCOA for ammonia production using natural gas to give an indication on the economic viability of the offshore wind produced ammonia. The LCOA is basically the ratio of total average lifetime capital costs and operation and maintenance costs over the lifetime ammonia production.

$$LCOA = \left(\frac{\text{Total Lifetime Project Costs}}{\text{Total Lifetime Ammonia Production}} \right) \tag{4.1}$$

Therefore, the first step in calculating LCOA is to determine capital costs of the subsystems which form the entire project.

4.1 Capital Costs

The major sub-systems whose capital costs need to be determined are:

- Offshore Windfarm

- All-Electric Ammonia Plant

- Ammonia Powered Gas Turbine

- Platform for Ammonia Plant

4.1.1 Offshore Windfarm

The total cost of windfarm is determined from the report *2017 Cost of Wind Energy Review* by Tyler Stehyl et.al. at NREL [22]. A detailed economic overview of a 5.64 MW offshore wind turbine on a floating semi-submersible platform is provided in this report. By using the interdependent ratios between capital costs, balance of system, finances, the capital costs for the turbine used for this project W2E-164-4.5 MW can be scaled as well.

	5.64 MW offshore turbine ($/kW)	Vestas V164-9.5 MW ($/kW)	W2E-4.5-164 ($/kW)
Turbine Capital Costs	**1521**	**1200**	**2533**
Development Costs	190	150	316
Engnieering Management	96	76	160
Substructure and foundation	1653	1304	2753
Site access, staging, and port	67	53	112
Electrical Infrastructure	1175	232	490
Assembly and Installation	137	334	704
Balance of Plant	**3318**	**2148**	**4535**
Insurance during construction	51	40	85
Decommissioning bond	22	17	37
Construction financing	352	278	586
Contingency	290	229	483
Plant commissioning	51	40	85
Financial Costs	**766**	**604**	**1276**
Total CapEx	**5605**	**3953**	**8344**

Table 4.1: Total Capital Expenditures for the offshore wind turbine with semi-submergible floating structure

The costs for the 5.64 MW semi-submergible floating offshore wind turbine were obtained from the NREL's report on 2017 Cost of Wind Energy Review [22]

The cost of W2E-164-4.5 MW turbine in $/kW is derived from Vestas V164-9.5 MW turbine cost, which is hypothesized from the 5.64 MW machine costs given in 2017 Cost of Wind Energy Review [22]. The idea here is that the capital cost of the 4.5 MW turbine

is almost the same as that of 9.5 MW turbine, because it can be imagined as the derated version of 9.5 MW turbine. This will save some costs in the generator. But going with a conservative assumption, the cost of 4.5 MW turbine is considered same as the 9.5 MW turbine. Therefore, the cost of each item on the 4.5 MW turbine can be obtained by scaling the cost of that item in the 5.64 MW column by $\left(\dfrac{1200}{1521} \times \dfrac{9500}{4500} \right) = 1.67$.

One notable increase is the cost for assembly and installation. This is because the the cost for 5.64 MW turbine was estimated for a site which was 30km from the shore. The 4.5 MW turbine site is 50 nautical miles from the shore (almost 93 km). Applying linear relationship between assembly and installation cost with the distance from the shore, the cost came around 704 \$/kW for the 4.5 MW machine.

Another notable aspect of the comparison is the cost for electrical transmission. This project is not connected to the grid. Therefore, it saves the cost for export cables. However, there still needs to be electrical infrastructure required for inter array connection through cables. The cost of inter array cable in 2014 was €190k/km [23]. Using Purchase Price Index (PPI) of 0.737 €/\$ for 2014 (data from Organisation for Economic Co-operation and Development) and then inflating the cost for 2018 with a factor of 1.0682 (from Bureau of Labor Statistics), the cost of inter array cables is \$ 275384/km. For a 300 MW, the expected length of the inter array cables is typically 75 km [24].

The cost of offshore substation in 2014 is €18.6 millions for a 500 MW windfarm and €28.5 for 1000 MW windfarm with floating foundation [23]. This can be used to extrapolate the cost of substation for the current windfarm using the same method mentioned above. This results in the total offshore electrical infrastructure as 490\$/kW.

From this data, the total capital expenditure is 8344\$/kW. For a 4.5 MW turbine, the total CapEx is estimated as 37.6 million dollars.
The CapEx of the windfarm will be 37.6 × no of turbines required.

4.1.2 All-Electric Ammonia Plant

The all-electric ammonia plant uses the same design as defined in Morgan's dissertation except for 2 changes. There are multiple ammonia synthesis chambers and also the

addition of ammonia powered gas turbines to keep the plant idling. The cost estimates can be easily obtained using the CEPCI indexes for 2018 and 2010 and scaling the data available from Morgan's dissertation. However, there is a difference in the synthesis loop calculation. He had used a synthesis loop for 300 tons/day capacity. But for this thesis, multiple synthesis loop are utilized. This will add the necessary complexity to address part-load operations at windpseeds lower than rated for the turbines.
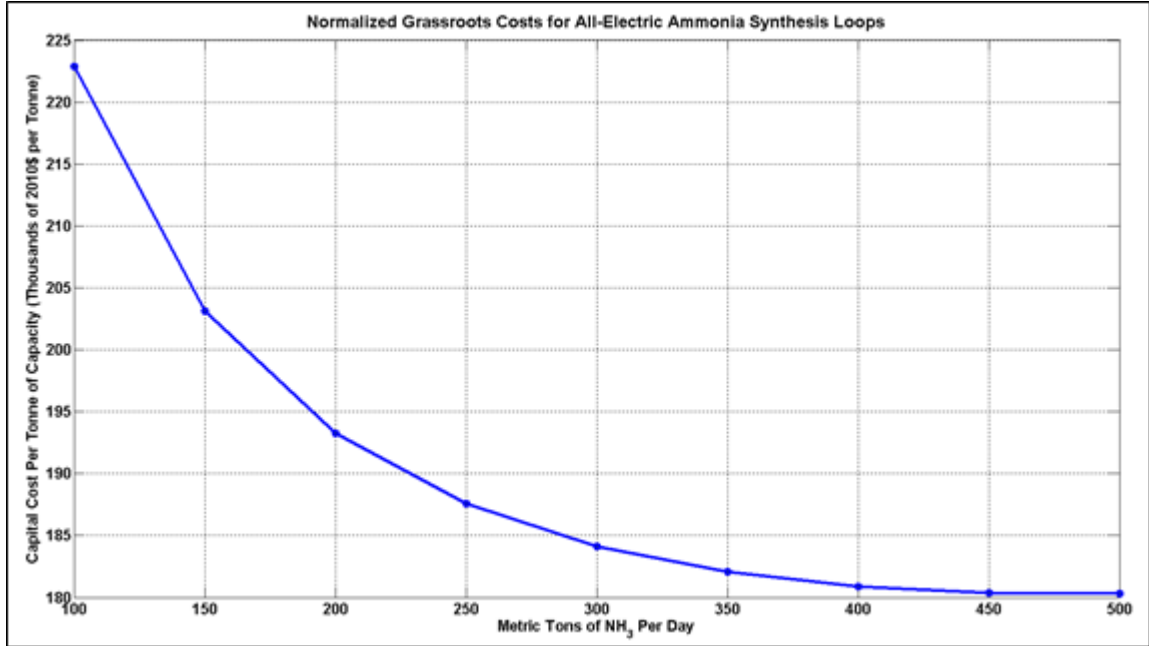
Figure 4.1: Cost of ammonia synthesis loop vs Ammonia plant capacity [1]

Figure 4.1 can be converted into cost of ammonia synthesis loop vs no of divisions of 300 tons/day capacity as shown in figure 4.2 and a trendline can be added to obtain an equation governing the cost of ammonia synthesis loop in 2013 dollars. This can be scaled to 2018 dollars using CEPCI indexes.
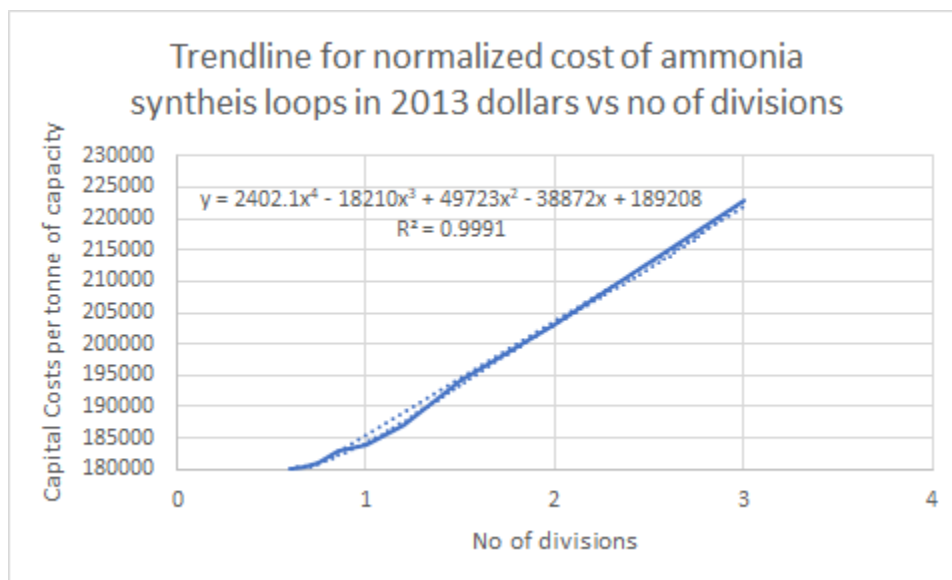
Figure 4.2: Cost of ammonia synthesis loop vs No of divisions

As it can be seen from the figure 4.2, as the number of divisions increase, the capital cost of synthesis loop increase significantly. The only reason to increase the divisions will be to get more ammonia production at part-load conditions. It will be shown in the next chapter how the increase in the number of divisions increase the total ammonia production and how it affects the levelized cost of ammonia. Increasing the number of divisions above a certain number can also be disadvantageous as more ammonia will be combusted to keep all the synthesis loops under idling condition.

4.1.3 Electrolyzer Scaling

The idea here is to scale up the chemical processing equipment common to each electrolzer. This provides opportunity to reduce the overall capital cost of the electrolyzer system [1]. This same concept was used for electrolyzer system in the dissertation by Morgan (2013). However, for this thesis, electrolyzer scaling needs to consider that the minimum load on the electrolyzer system should be 20% under operation [1]. This creates a challenge to the concept of using multiple ammonia synthesis loops. For example, there are 4 ammonia synthesis loops of 75 tons/day rated output and one of the loop is producing ammonia while the other three are idling. Therefore, the electrolyzers system must oper-

ate to match the hydrogen requirements of the synthesis loop under operation. It might be lower than 20% load if the whole electrolyzer system for 300 tons/day rated ammonia output is scaled.

Therefore, the number of electrolyzers scaled are depend on the number of divisions of the ammonia synthesis loop. For example, the 300 tons/day rated ammonia output requires nearly 126 electrolyzers. If the synthesis loop has 3 divisions of 100 tons/day rated output, then a total of $\frac{126}{3} = 42$ electrolyzers will be scaled together. The capital cost in thousands of 2010 dollars of the scaled electrolyzer system can be obtained from equation given in [1].

$$C_{scaledelectrolyzer} = 786X + 712X^{0.7} + 148X^{0.5} + 368X^{0.75} + 442X^{0.8} \tag{4.2}$$

where, X is the number of electrolyzers to be scaled.
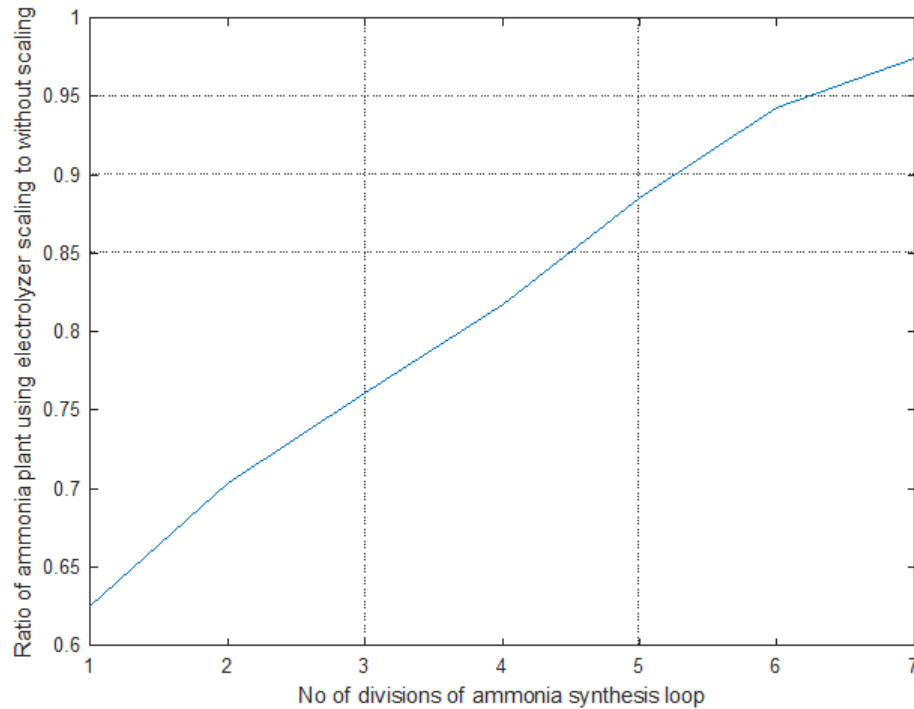
Figure 4.3: Ratio of capital cost of ammonia plant with electrolyzer scaling to the one without scaling vs No of divisions of ammonia synthesis loop

As shown in figure 4.3, using the electrolyzer scaling, the capital cost of the all-electric ammonia is almost 70 to 82% as the number of divisions of ammonia synthesis loop is between 2 and 4 compared to those without electrolyzer scaling. Therefore, to reduce the capital cost of the all-electric ammonia plant, the electrolyzer scaling concept is used based on the number of divisions of ammonia synthesis loop.

4.1.4   Total Capital Expenditure of the All-Electric Ammonia Plant

Figure 4.4 shows the overall capital costs of the all-elctric ammonia plant in 2010$. The costs are considered for the scaled electrolyzer. This makes sense as when there are 3 ammonia synthesis loops of 100 tons/day capacity, then the total capital expenditures of the ammonia plant would be $3 \times$ (the cost associated with the 100 tons/day plant. This method also makes sure the there are 3 systems of electroylzer scaled corresponding to each ammonia synthesis loop. It also makes sure that other equipments, like air separation unit (ASU), mechanical vapor compression (MVC), are scaled according to their require-ments.
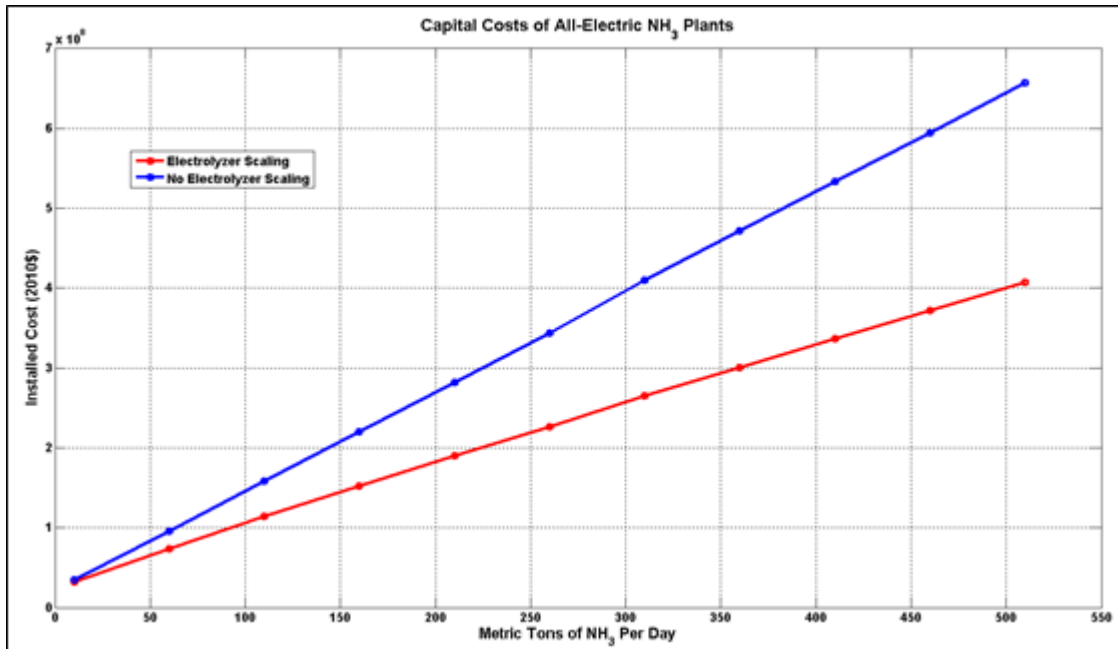
Figure 4.4: Total capital expenditures based on the ammonia plant capacity [1]

It is scaled by a factor of $\left(\dfrac{\text{CEPCI value of 2018}}{\text{CEPCI value of 2010}}\right)$ to get the overall cost of the ammonia plant in 2018 dollars. Using trendline feature in MS Excel, the equation for the cost as a function of ammonia plant capacity is given in figure 4.5
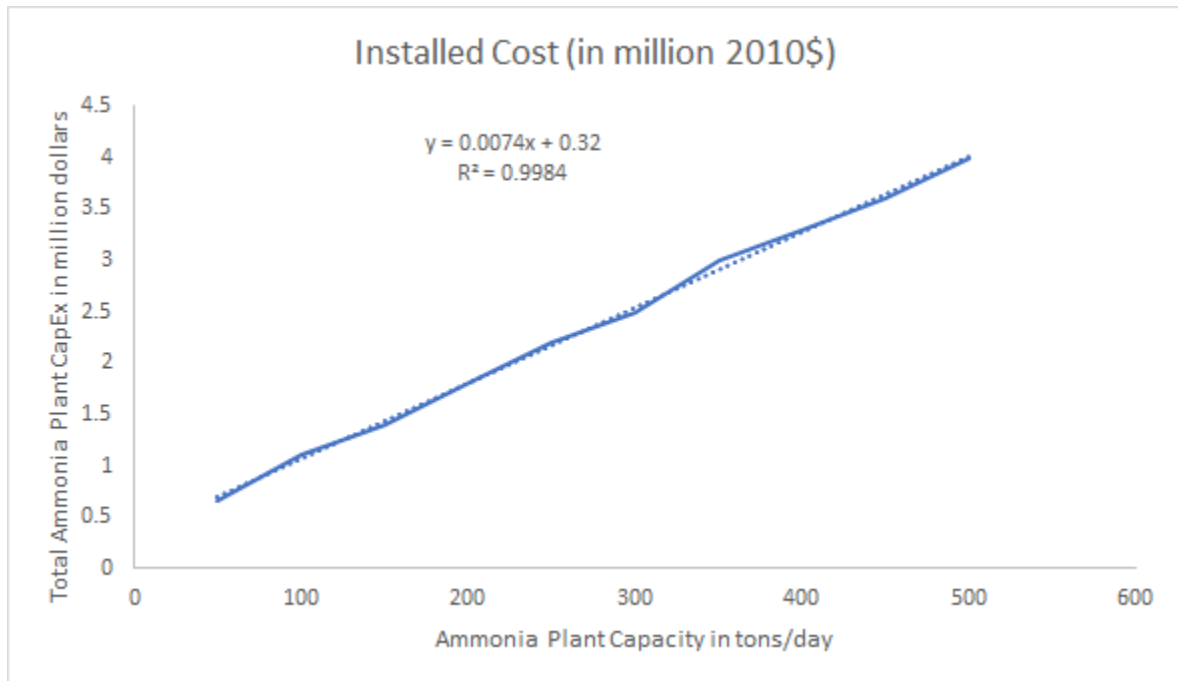
Figure 4.5: Total capital expenditures of the ammonia plant as a function of ammonia plant capacity

4.1.5 Ammonia Powered Gas Turbine Cycle

Ammonia powered gas turbine cycle is essential to keep the ammonia synthesis chamber at reaction conditions. It is evident that ammonia can be combusted in gas turbines to generate electricity. However, the technology is not sophisticated enough yet to produce electricity at industrial level. Valera-Medina et. al. at Cardiff University are using a 2MW gas turbine to conduct research on using ammonia as fuel [25].

Average construction cost

$/kilowatt (kW)
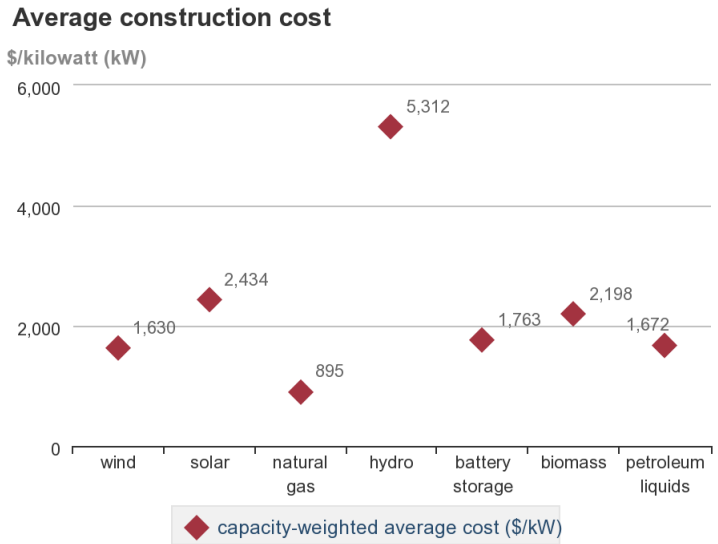
Figure 4.6: Capacity weighted average costs for major energy sources. Source: U.S. Energy Information Administration

Since it unknown at this point how much the cost of ammonia-combustion generator would be, it is assumed at 5000 $/kW. However, there will be sensitivity analysis conducted in the next chapter to determine how much is LCOA dependent on the capital cost of ammonia powered gas turbine cycle.

4.1.6 Platform for the All-Electric Ammonia Plant

The platform or plantship design is derived from the study conducted by Panchal et. al. [14] in 2009. They designed the plantship for a capacity of 265 metric tons of ammonia per day using Ocean Thermal Energy Conversion (OTEC). However, the major subsytems are quite similar to the one in the project. Therefore, the size and cost of the plantship can be scaled for a 300 tons/day plant in 2018 using inflation rate from 2009 to 2018 (17.87%) and multiplying by a factor of $\left(\dfrac{300}{265}\right)$. This comes out to 95.81 million dollars in 2018.

4.2   Operations and Maintenance Costs

4.2.1   O & M Costs of he offshore windfarm and the all-electric ammonia plant

The O& M costs of wind turbine can be obtained by scaling them from the report *2017 Cost of Wind Energy Review* by Tyler Stehyl et.al. at NREL [22]. This was estimated as 21.3 millions dollars per year.

The O& M costs for the ammonia plant can be assumed as 3% of the total capital expenditures of the ammonia plant with the ammonia powered gas turbine and the plantship. In the dissertation by Morgan, it was also assumed 3% of the CapEx of all-electric ammonia plant for estimation of its O& M cost.

4.2.2   Transportation Costs

The other aspect to add in the estimation of O & M cost is considering transportation costs of produced ammonia from offshore manufacturing facility to an onshore facility.

The offshore windfarm is almost 50 nautical miles away from the shore. A reasonable assumption regarding the shipping costs can be derived from the 1977 paper "Alternative form of energy transmission from OTEC plants" by Konopka et. al [26]. The cost was given in dollars per million BTU, which was converted in dollars per ton in 1977 dollars and then using inflation converted to 2018 dollars as 54$/ton for 100 miles. Another source which verifies this cost is the article in 2013 by Dr. Duncan Seddon called "Ammonia Production Cost", where it is stated that the shipping cost of ammonia is in the range of 50$/ton [27].

Therefore, for this project, the cost of ammonia shipping is considered 55$/ton.

4.3   Calculation of Levelized Cost of Ammonia

The LCOA can be derived from the equations 4.3 and 4.4 using the following parameters:

$$LCOA = \dfrac{P_d + P_a \left(\dfrac{\left(\dfrac{1}{1+r}\right) - \left(\dfrac{1}{1+r}\right)^{(n_{loan}+1)}}{1 - \left(\dfrac{1}{1+r}\right)} \right) + (Wind_{O\&M} + NH3_{O\&M}) \left(\dfrac{\left(\dfrac{1+i}{1+r}\right) - \left(\dfrac{1+i}{1+r}\right)^{(n_{life}+1)}}{1 - \left(\dfrac{1+i}{1+r}\right)} \right)}{\text{Total Lifetime } NH_3 \text{ Production}}$$

(4.3)

Where,

P_d = Down Payment on the entire project = 10% of the total CapEx C_c

$Wind_{O\&M}$ = Annual Operations and Mangement Cost of the windfarm

$NH3_{O\&M}$ = Annual Operations and Mangement Cost of the ammonia plant

i = Inflation rate = 3%

r = Nominal Discount Rate = 7%

n_{loan} = duration of the loan = 15 years

n_{life} = project lifetime = 20 years

The down payment and the annual payment on the loan are dependent on the capital cost of the entire project. The operations and maintenance costs are already considered as a percentage of the capital costs. The down payment for the loan is assumed 10% of the entire capital cost, while the annual payment P_a can be calculated from the formula as:

$$P_a = (C_c - P_d) \left[\dfrac{b}{1 - (1+b)^{-n_{loan}}} \right]$$

(4.4)

where,

b = rate of interest on the loan = 4%

4.3.1 LCOA vs no of divisions of ammonia synthesis loop

As the number of divisions increase, the total CapEx of the ammonia plant increases significantly as shown in figure 4.7. The figure 4.7 shows only the total CapEx of the offshore ammonia facility and not that of the project. It is sum of capital expenditure of the ammonia plant, the ammonia powered gas turbine cycle, and the supporting plantship.
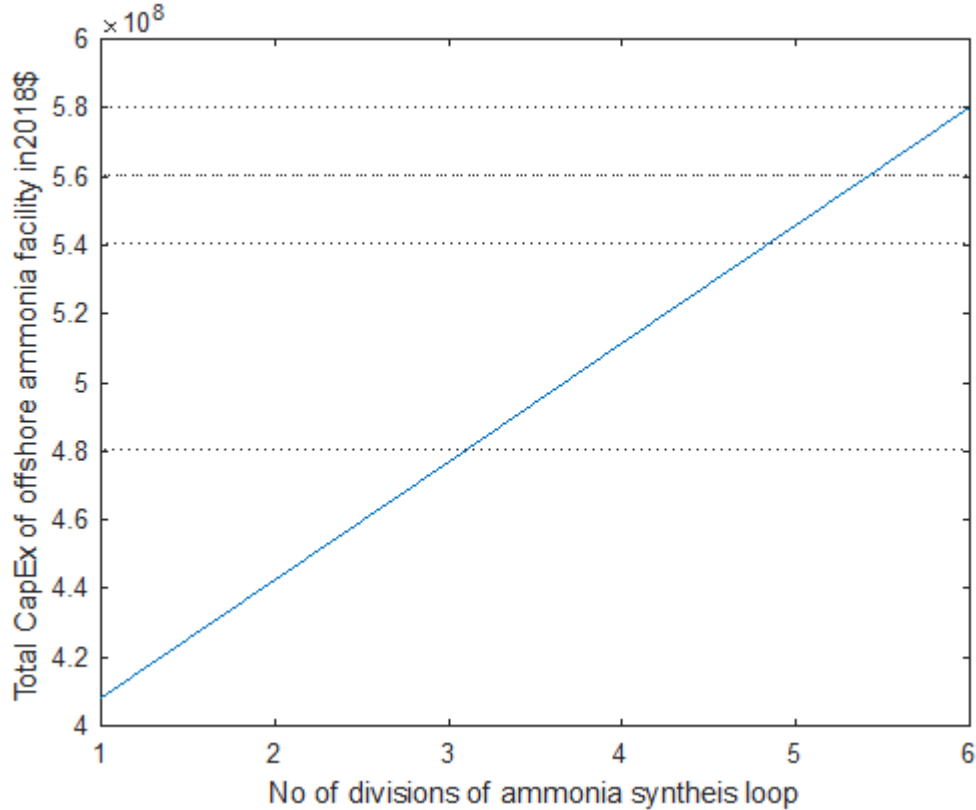
Figure 4.7: Capital cost of the offshore all-electric ammonia production facility vs no of divisions of ammonia synthesis loop

But as shown in figure 3.9, the net ammonia production also increases upto a point. Therefore, it is essential to identify optimum number of divisions to account for both - total production as well as economy of the plant. The LCOA of the plant with respect to the number of divisions is represented in the figure 4.8:
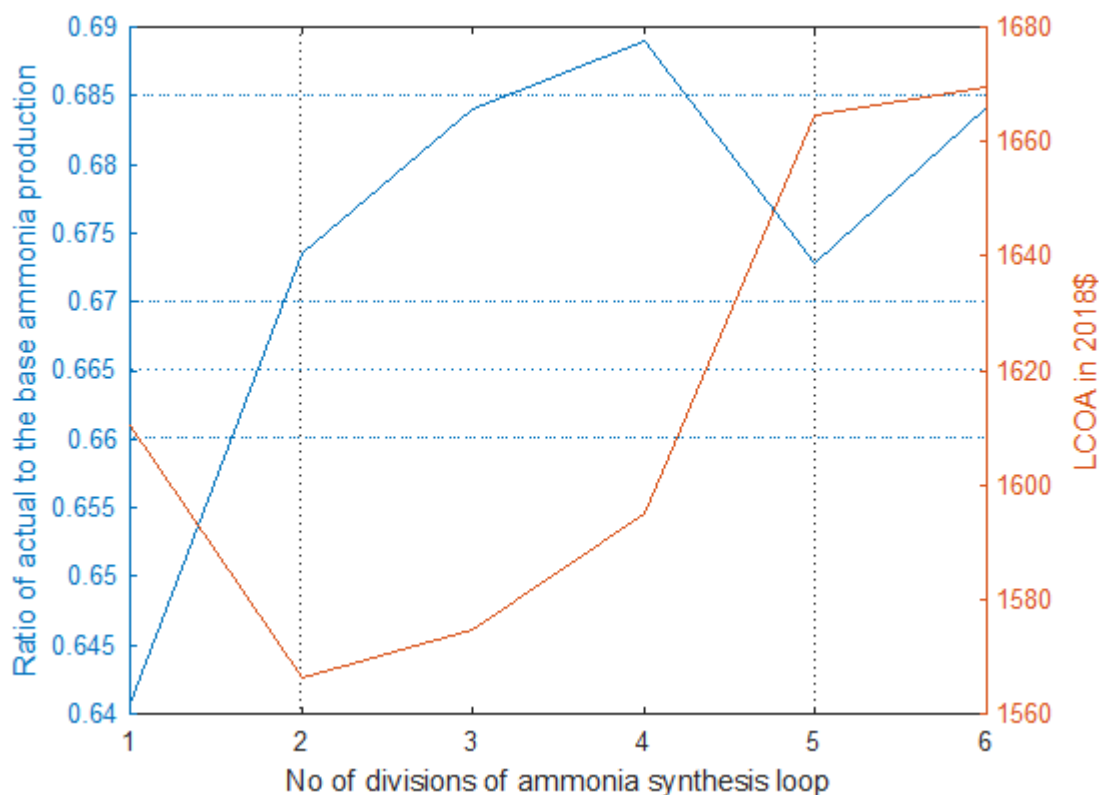
Figure 4.8: LCOA vs no of divisions of ammonia synthesis loop

As expected, the divisions certainly help to increase the net annual production but with considerable increase in the LCOA as well. It can be seen that the LCOA is lowest at almost ($1566/ton of NH_3) when there are only 2 divisions i.e. 2 synthesis loops of 150 tons/day capacity. The difference between net annual production between that obtained with 2 divisions and 4 divisions is also not big. Therefore, dividing the synthesis loop into 2 parts would be optimum and is established as the baseline parameter.

4.3.2 LCOA vs cost of ammonia powered gas turbine cycle

Utility scaled ammonia powered gas turbines are still in the development phase and it is challenging to get a good estimate of how costly the technology would be when it is available. Therefore, using the weighted average costs of the power cycle for different energy sources, the baseline capital expenditure was estimated as $5000/kW. This value

falls on the high end of spectrum of the capital expenditure for gas turbines cycles as shown in figure 4.6.
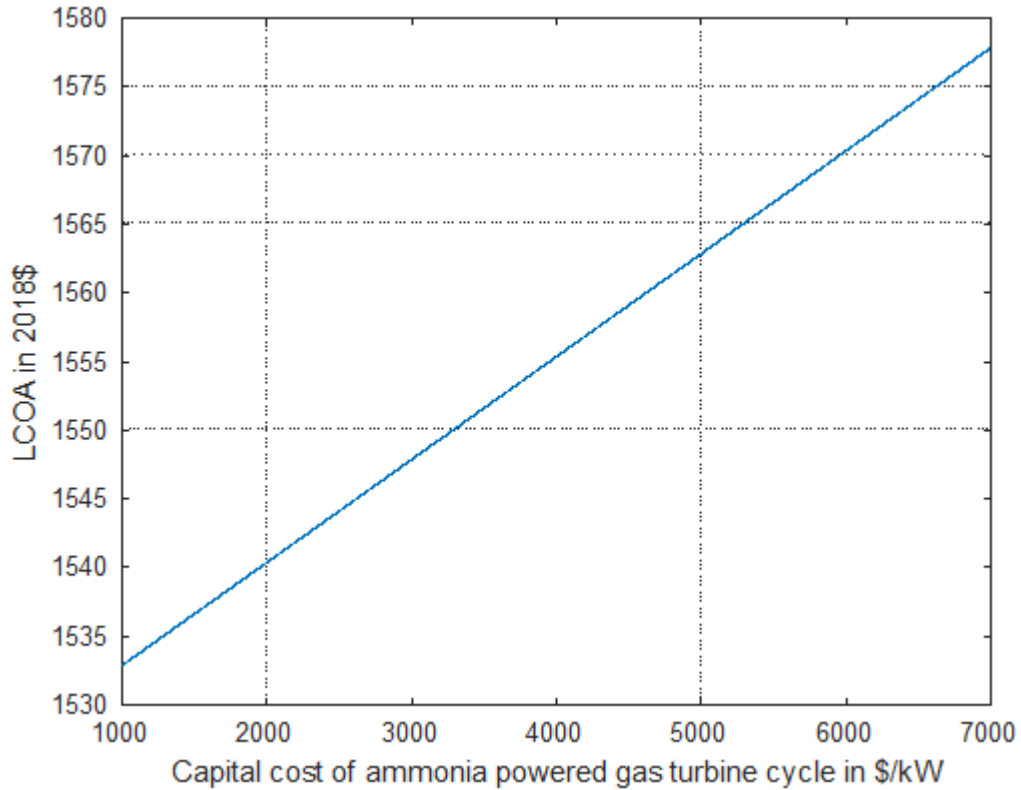
Figure 4.9: LCOA vs Capital Expenditure per kW of the ammonia powered gas turbine cycle

The LCOA certainly increases when the capital cost the ammonia powered gas turbine is higher. However, on a variation of 1000$/kW to 7000$/kW, the LCOA only increases by $40/ton. This is because the total capital expenditure of the gas turbine cycles is relatively small compared to other sub-systems like the windfarm and the ammonia plant. The sensitivity of the efficiency of the gas turbine cycle on the LCOA is shown in figure 4.10:
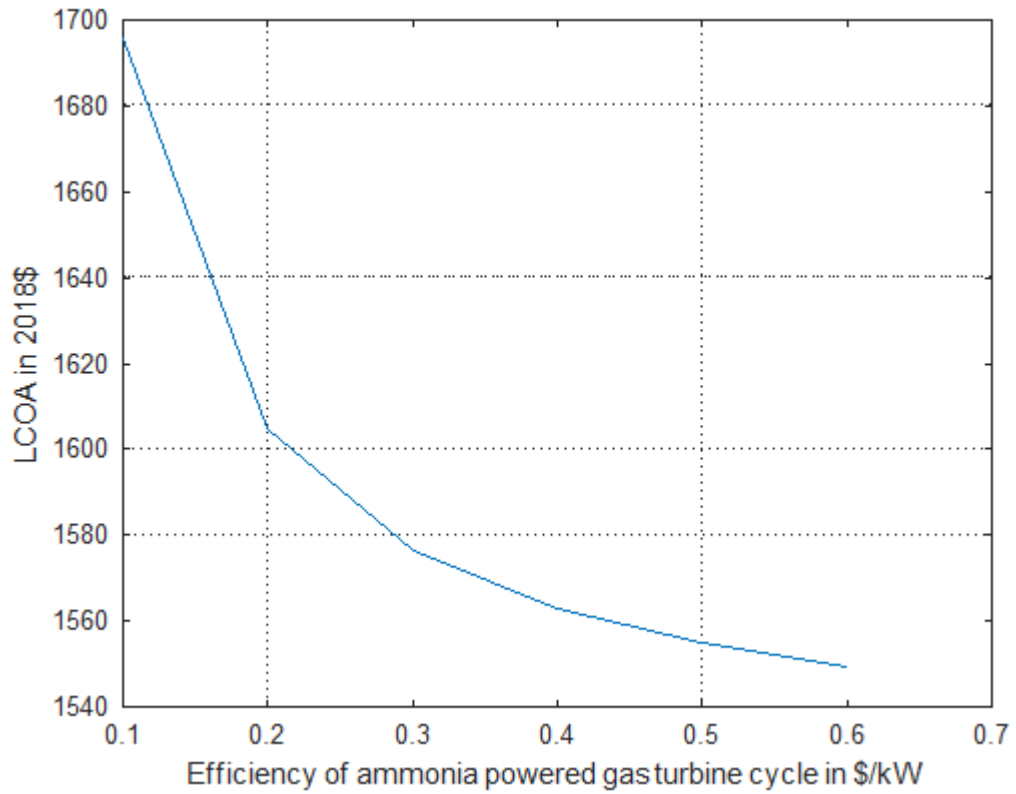
Figure 4.10: LCOA vs Efficiency of the ammonia powered gas turbine cycle

In the context of this project, the future research on developing the ammonia powered gas turbine cycle should be focused more on higher efficiency compared to the cost.

4.3.3   LCOA vs per kW cost of the wind turbine
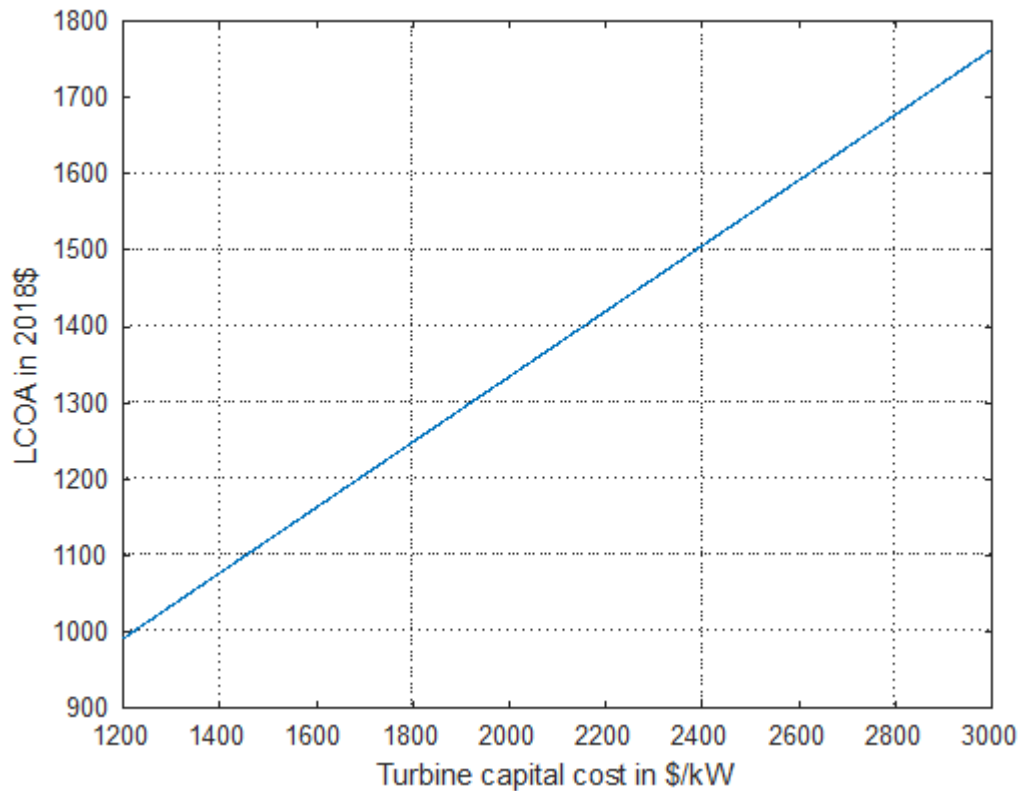
Figure 4.11: LCOA vs pew kW capital cost of the turbine

As shown in figure 4.11, the LCOA linearly increases with increase in per kW cost of the turbine. Since 2008, wind turbine prices per kW have steeply declined, despite increases in size. These price reductions, coupled with improved turbine technology, have exerted downward pressure on project costs and wind power prices [28]. Therefore, it can be expected that with decrease in per kW price of the turbine, the LCOA will also linearly decrease within acceptable range.

CHAPTER 5

RESULTS AND DISCUSSIONS

The Levelized Cost of Ammonia for the current project is almost 350$/ton higher than that calculated by Morgan (2013). There are many reasons to get this higher cost:

- There is no connection to the grid. Therefore, it is not possible to run the plant at a constant rate of 300 tons/day due to variable power output from the offshore wind-farm.

- Other reason is that with connection to the grid, the excess electricity from the wind farm can be sold into the grid. Here, the control system does not allow the turbines to produce more than the required power.

- Multiple ammonia synthesis loops to allow production of ammonia at part-loads. The capital cost increases quite remarkably as the number of divisions of synthesis loop increases.

- Addition of ammonia powered gas turbine means use of ammonia from storage to keep the plant idling. This means that there is a decrease in net ammonia production.

- The ammonia plant is supported by a plantship and it adds around 96 million dollars in the total capital expenditures.

- The LCOA is dependent heavily on the per kW cost of the wind turbine. For this project, a turbine with 164m is used with semi-submersible floating support structure. The estimated capital cost of this turbine was much higher than that calculated

in Morgan's thesis. But with technological advances and steep price reduction since 2008, the LCOA can get lower in the future.

- Although the cost of ammonia powered gas turbine does not affect the LCOA in a significant way, its efficiency plays an important role on how much of the produced ammonia will be consumed and thereby affect the net annual ammonia production.

Another aspect that stands out in this thesis was how the net annual ammonia production is affected by the number of divisions of the ammonia synthesis loop. It seemed that with higher number of divisions, the threshold energy to start ammonia production could be lower and production could be started at lower windspeeds as well. However, the increase in divisions of synthesis loop also demanded certain power to keep them idling which had to be met through the produced ammonia. Therefore, there it was necessary to reach an optimum number of division from production as well as economic standpoint. In this project, that number was 2. But at different site, with different capacity factor, the optimum number of divisions might be affected.

Overall, it was observed that ammonia was produced at much lower capacity (around 65% of the base ammonia production). And it costs around 350$/ton more than that calculated by Morgan (2013). Therefore, there is a significant requirement of further research to lower overall plant capital expenditure. This project warranted the use of turbine with large rotor size and its higher cost was one of the driving factor behind the higher LCOA. Therefore, using ammonia as a possible solution to energy storage medium for far offshore plant to be feasible will require huge reductions in capital costs of wind turbines with larger rotor sizes, along with a matured and efficient ammonia powered gas turbine cycle.

CHAPTER 6

FUTURE WORK

This thesis is a system-level analysis to understand the feasibility of ammonia production from a non-grid connected floating offshore wind farm. It uses Weibull statistical distribution to estimate the wind distribution in a year. Because of this, this model fails to consider the ramp up and down time of sub-system components like Air Separation Unit (ASU), Electrolysers,etc. If a 10 min data point analysis is considered, it will add more complexity to the control algorithm for the flow of energy. However, this will also open opportunities to create a more robust model where the flow of energy at every second can be directed by factoring in the dynamics of the components. Also with higher accuracy of wind forecast for the next few days, reasonable decisions could be made if one or more of the synthesis loops could be shut down, thereby allowing it to preserve the produced ammonia rather than combusting it to keep it idling. Other advantage of performing this analysis with 10 min wind data is the prediction of systematic schedule of the plant using wind forecast. It will be possible to maintain one of the synthesis loops while others are under operation, thereby allowing continuous operation throughout the year. This will certainly increase the net annual ammonia production.

Another aspect which needs to be researched is the estimation of accurate wind turbine prices. As the thesis shows, any reductions or additions in the capital expenditure of wind turbine prices will have an amplified effect on the LCOA. The future update on this work will also require a more accurate estimation of the efficiency and capital expenditure of the ammonia powered gas turbine cycle.

APPENDIX A

MATLAB MODEL FOR ANNUAL AMMONIA PRODUCTION AND LCOA

```
%%Define Initial Paramters
ammonia_plant_cap = 300; %tons/day
wind_farm_size = ammonia_plant_cap*0.482; %MW
Avg_wind = 10; %m/s at 90m above sea-level
Avg_wind = Avg_wind*(log(140/0.0002)/log(90/0.0002)); %Scaling
    windspeed at hub height 140m
n = 2; %no of divisions of the ammonia synthesis loop
capacity_factor = cf(Avg_wind);
array_eff = 0.9;
electrical_eff = 0.98;
no_of_turbines = ceil(wind_farm_size/(capacity_factor*9.5*
    array_eff*electrical_eff));
op_days = 330; %number of days in a year for ammonia plant
    operation
k = 2.2; %Weibul Shape Parameter
c = Avg_wind*((0.568)+((0.433/k)))^(-1/k); %Weibul Scale
    Parameter
Energy_Density_Ammonia = 11.308; %MJ/litre
Mass_Density_Ammonia = 681.82; %kg/m^3;
```

```matlab
Specific_Density_Ammonia = Energy_Density_Ammonia/(
    Mass_Density_Ammonia/1000); %MJ/kg
Ammonia_turbine_eff = 0.4; %Efficiency of ammonia gas turbine
Idling_Usage = 8*(ammonia_plant_cap/300); %MW
I = Idling_Usage/n ; % I = Idling power required per ammonia
    plant
Min_P = 0.65; %Min percentage for part-load ammonia plant
    operation
P = (Min_P*wind_farm_size)/n; %Min power required per ammonia
    plant to operate at min part load
Base_Annual_Ammonia_Produced = op_days*ammonia_plant_cap;


%%Power_curve and wind_distribution
u_wind = ones(30,1);
for i = 1:1:30
    u_wind(i) = i;
end


no_of_days = zeros(30,1);
for i = 1:1:30
    no_of_days(i) = op_days*(k/c)*((u_wind(i)/c)^(k-1))*exp(-(
        u_wind(i)/c)^k); %Weibull probabilitic distribution
end


power_per_turbine=[0.0; 0.0; 0.0; 154.38; 593.75; 1246.88;
    2137.50; 3289.38; 4750.00; 6531.25; 8312.50; 9381.25; 9500.0;
    9500; 9500; 9500; 9500; 9500; 9500; 9500; 9500; 9500; 9500;
    9500; 9500; 0; 0; 0; 0; 0 ]; %kW
power_wind_farm = zeros(30,1);
```

```
for i = 1:1:30
    if power_per_turbine(i)*electrical_eff*array_eff*0.001*
        no_of_turbines > wind_farm_size
        power_wind_farm(i) = wind_farm_size;
    else
        power_wind_farm(i) = power_per_turbine(i)*electrical_eff*
            array_eff*0.001*no_of_turbines;
    end
end
%%End of power curve and weibull distribution
%% Controlling the wind energy flow to the ammonia plants
Power_Idling = zeros(30,n);          %Additional power from
    ammonia to idle
Ammonia_Idle = zeros(30,n);          %Additional ammonia in tons
    to idle
Net_Ammonia_Used = zeros(30,1);
Ammonia_synthesized = zeros(30,n);
Net_Ammonia_Produced = zeros(30,1);
x = zeros(30,1);
for i = 1:1:30
    if power_wind_farm(i)/n < I
        Power_Idling(i,1:n) = I - (power_wind_farm(i)/n);
        Ammonia_Idle(i,1:n) = (0.001*Power_Idling(i,1:n)
            *24*3600)/(Ammonia_turbine_eff*
            Specific_Density_Ammonia);
        Net_Ammonia_Used(i) = sum(Ammonia_Idle(i,:));
        Ammonia_synthesized(i,:) = 0;
        Net_Ammonia_Produced(i) = sum(Ammonia_synthesized(i,:))
            - (Net_Ammonia_Used(i));
```

```
end


if  power_wind_farm(i)/n > P
    Ammonia_synthesized(i,:) = (power_wind_farm(i)/n)/0.482;
    Net_Ammonia_Produced(i) = sum(Ammonia_synthesized(i,:) -
        Net_Ammonia_Used(i));
end


if  ((power_wind_farm(i)/n) > I) && ((power_wind_farm(i)/n) <
    P)
x(i) = floor(power_wind_farm(i)/P);
y = power_wind_farm(i) - (x(i)*P);
if  y > (I*(n-x(i)))
    Ammonia_synthesized(i,1:x(i)) = (P + ((y - (I*(n-x(i))))
        /x(i)))/0.482;
    Net_Ammonia_Produced(i) = sum(Ammonia_synthesized(i,:))
        - Net_Ammonia_Used(i);
end


if  y < (I*(n-x(i)))
 Net_Ammonia_Used(i) = (((I*(n-x(i))) - y)*0.001*24*3600)/(
    Ammonia_turbine_eff*Specific_Density_Ammonia);
 Ammonia_synthesized(i,1:x(i)) = (Min_P*(wind_farm_size/n))
    /0.482;
 Ammonia_synthesized(i,x(i)+1:n) = 0;
 Net_Ammonia_Produced(i) = sum(Ammonia_synthesized(i,1:n)) -
    (Net_Ammonia_Used(i));
end
```

```matlab
    end
    Net_Annual_Ammonia_synthesized = zeros(30,1);
    for i = 1:1:30
        Net_Annual_Ammonia_synthesized(i) = Net_Ammonia_Produced(i
            )*no_of_days(i);
    end
    sum_net_ammonia_produced = sum(Net_Annual_Ammonia_synthesized
        (:));
    ratio = sum_net_ammonia_produced/Base_Annual_Ammonia_Produced;


    %%%Net Capital Costs
%%Estimating the windfarm capital costs
capital_cost_per_turbine = 1200; %$/kW
net_Capital_cost_per_turbine = capital_cost_per_turbine*9500; %
    rated power is 9500kW
balance_of_system_turbine = 9500*(capital_cost_per_turbine/1521)
    *(3318-1175+140+(-137+(137*(92.6/30)))); %ratio estmiated from
     ref [X] and subtracting electrical costs
financial_cost_turbine = 9500*(capital_cost_per_turbine/1521)
    *766;
total_CapEx_turbine = net_Capital_cost_per_turbine +
    balance_of_system_turbine + financial_cost_turbine;
total_CapEx_windfarm = total_CapEx_turbine*no_of_turbines;

%%Estimating the capital cost of all electric ammonia plant
CEPCI_2010 = 550.8;
CEPCI_2018 = 591.3;
plant_capital_cost_2010 = 4*(10^8); %dollars for 300 tons/day
    capacity plant
```

```
synthesis_chamber_2010 = plant_capital_cost_2010 *0.14;
grassroot_cost_300 = 184000; %dollars for a 300 tons per day
    capacity ammonia plant
grassroot_cost_n = grassroot_2018(n); %dollars for a 300 tons per
    day capacity ammonia plant
synthesis_chamber_2018 = synthesis_chamber_2010 *((n*
    grassroot_cost_n)/grassroot_cost_300);
plant_capaital_cost_2018_no_scaling = (CEPCI_2018/CEPCI_2010)*(
    plant_capital_cost_2010 − synthesis_chamber_2010 +
    synthesis_chamber_2018);
plant_CapEx_scaled_2018 = (CEPCI_2018/CEPCI_2010)*(
    cap_elec_scaled(n)− synthesis_chamber_2010 +
    synthesis_chamber_2018);
ratio_plant_scaled_nonscaled = plant_CapEx_scaled_2018/
    plant_capaital_cost_2018_no_scaling;

%%Estimating capital cost of the ammonia plantship
panchal_platform_cost_2009 = 71800000; %dollars for 265 tons per
    day
panchal_capacity = 265; %tons per day
platform_cost_2018 = panchal_platform_cost_2009 *(300/
    panchal_capacity)*1.1787;

%%Estimating capital cost for ammonia powered turbine for idling
    usage
average_construction_cost = 5000; %dollars per kilowatt
net_generator_capital_cost = n*I*average_construction_cost*1000;
    %dollars
```

%%Estimating total capital expenditure of offshore ammonia facility

offshore_ammonia_capex = plant_CapEx_scaled_2018+
    platform_cost_2018+net_generator_capital_cost;

%%Estimating total capital expediture of the whole system

capital_cost_system_2018_non_scaled = total_CapEx_windfarm +
    plant_capaital_cost_2018_no_scaling + platform_cost_2018 +
    net_generator_capital_cost;

capital_cost_system_2018_scaled = total_CapEx_windfarm +
    plant_CapEx_scaled_2018 + platform_cost_2018 +
    net_generator_capital_cost;

%%%Net Operation Costs

%%Operational Costs for windfarms

windfarm_operational_costs = 9500*no_of_turbines*93*(
    capital_cost_per_turbine/1505); *%scaling from capital cost
    used in the ref to the used in this thesis*

%%Operational Costs for all electric ammonia plant

NH3_OM_scaled = 0.03*(offshore_ammonia_capex);

NH3_transportation = 3000000; *%2018 dollars*

Net_OM_scaled = windfarm_operational_costs + NH3_OM_scaled +
    NH3_transportation;

%%Economic Analysis

r = 0.07;   *%Nominal Discount Rate*

i = 0.03;   *%Inflation Rate*

n_loan = 15; *%loan period*

n_life = 20; *%lifetime of project*

```
Pd = 0.1*capital_cost_system_2018_non_scaled; %Total down payment
Pa = (capital_cost_system_2018_non_scaled − Pd)
    *(0.04/(1−((1+0.04)^−n_loan))); %Annual Payment
LCOA_scaled = (Pd + (Pa*(((1/(1+r))−((1/(1+r))^(n_loan+1)))
    /(1−(1/(1+r))))) + (Net_OM_scaled*((((1+i)/(1+r))−(((1+i)/(1+r
    ))^(n_life+1)))/(1−((1+i)/(1+r))))))/(n_life*
    sum_net_ammonia_produced);
end
```

APPENDIX B

MATLAB MODEL FOR CALCULATION OF CAPACITY FACTOR AS A FUNCTION OF AVERAGE WINDSPEED, RATED WINDSPEED AND K = 2.5

```
function y = cf(u_wind, rated_windspeed)
xr_cf = rated_windspeed/u_wind;
y = (0.2879*(xr_cf^2)) - (1.3662*xr_cf) + 1.7803; %equation
    obtained from using trendline feature in MS Excel
end
```

APPENDIX C

MATLAB MODEL FOR CALCULATION OF GRASSROOT COST OF AMMONIA SYNTHESIS LOOP IN 2013 DOLLARS

```
function y = grassroot_2018(n)
y = (2.4021*(n^4)) - (18.21*(n^3)) + (49.723*(n^2)) - (38.872*n)
    + 189.21; %equation obtained from using trendline feature in
    MS Excel
y = y*1000;
end
```

APPENDIX D

MATLAB MODEL FOR CALCULATION OF CAPITAL COSTS OF SCALED ELECTROLYZERS SYSTEM

```
function plant_CapEx_sclaed_2010 = cap_elec_scaled(n)
CapEx_no_elec_sclaed = 4*(10^8)*0.77; %total cost of
    electrolysers without scaling
CapEx_per_elec = 2456000; %capital cost per electrolyzer
X = CapEx_no_elec_sclaed/CapEx_per_elec; %Total no of
    electrolyzer required for 300 tons per day ammonia plant
Xn = X/n; %no of electrolyzers required to operate 1 synthesis
    loop out of n
Scaled_cost_2010_Xn = n*((786*Xn)+(712*(Xn^0.7))+(148*(Xn^0.5))
    +(368*(Xn^0.75))+(442*(Xn^0.8)))*1000; %total cost of scaled
    electrolyzer for n divisions of synthesis loop
plant_CapEx_sclaed_2010 = (2.5*(10^8))−(((786*X)+(712*(X^0.7))
    +(148*(X^0.5))+(368*(X^0.75))+(442*(X^0.8)))*1000) +
    Scaled_cost_2010_Xn; %plant capital cost with scaling in 2010$
end
```

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