Ammonia Production from a Non-Grid Connected Floating Offshore Windfarm

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Abstract: This paper investigates the technical and economic feasibility of a floating offshore wind driven ammonia production system. The ammonia plant is located on a floating plantship with no connection to the grid. An analytical model (MATLAB based) for this system was based on an all-electric Ammonia plant and the use of 4.5 MW wind turbines. The model results showed that ammonia was produced at a much lower capacity and at a cost about $350/ton higher than a land-based grid connected system. Future work recommended includes the use of larger sized wind turbines and cost reductions in the ammonia plant and efficiency increases in the auxiliary ammonia powered gas turbine system.

1.0 INTRODUCTION/BACKGROUND

According to recent estimates [1], 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 floating platforms, wind farms 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 the chemical energy of liquid ammonia. This potential solution includes the following background considerations:

• Offshore wind farms are moving towards floating platforms allowing the setup distance to be further away from the shore [2].
• 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 [3].
• 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 [4].

Previous work at the University of Massachusetts (5,6) has analyzed the technical requirements and economics of a 300 tons/day capacity all electric ammonia plant powered by offshore wind. For this work, one of the assumptions was a connection to the grid, that provided auxiliary power to keep the ammonia plant operational and produce at rated capacity. It also provided for the sale of excess power.
to the grid in the scenario of excess power production by the wind farm during high winds.

This paper explores the technical and economic feasibility of a similar system, except that the ammonia plant is located on a plant ship 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 to power a gas turbine engine in a Brayton or combined cycle configuration in order to keep the plant idling. During this time, 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. Therefore, at any wind speed, a mini-ammonia plant would either idle or operate between 65-100% load.

2.0 DEVELOPMENT OF THE ANALYTICAL MODEL

A MATLAB based model [7] was used to simulate the total energy consumption, total energy captured by the wind farm, and the total ammonia produced. This was used as input to an economic model to calculate the total cost of producing and transporting ammonia. A 300 ton/day (the smallest practical size) all-electric ammonia plant was modeled that included analytical models of the following components: 1) hydrogen production electrolyzers, 2) air separation (nitrogen output), 3) water purification, 4) ammonia synthesis loop, and 5) ammonia storage. Note that a 300 ton/day ammonia plant will require about 246.7 tons of nitrogen and 53.3 tons of hydrogen per day.

The electrical energy from the wind farm will desalinize sea water and the distilled water produced will run through the electrolyzers that will produce hydrogen gas. To produce nitrogen, an air separation method is used. The produced hydrogen is compressed at around 150 to 250 bars via gas compressors. The next step is to feed the produced hydrogen and nitrogen into an ammonia synthesis loop, which contains a continuous cycle of gases that travel at high temperature and pressure through an adiabatic reactor.

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 the temperature and pressure of the ammonia synthesis chamber. This step is necessary because it will take days to restart the plant because of time consumed in regenerating the catalyst used in the Haber-Bosch process [8], 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 a Brayton/combined cycle. Hence, it is necessary to keep some amount of ammonia on the plant for such a scenario. Figure 1 gives a representation of the system components required for the simulation of the proposed system.
2.1 Components of the Analytical Model

2.1.1. Wind Resource
As shown in Figure 2, using an offshore wind map of Massachusetts [9], the annual average wind speed at 90m above sea level was determined to be 10 m/s at a site that is 50 nautical miles from the shore and has a depth of 60 meters. Based on Weibull wind resource statistics the shape parameter was set at 2.2.
2.1.2. Wind Turbine System

The floating offshore wind farm was based on the use of Wind 2 Energy 4.5 MW wind turbines with a 164 m rotor diameter. This turbine has a rated windspeed of 10 m/s and the average windspeed at a hub height of 140m was calculated to be 10.3 m/s. This results in a (corrected) capacity factor of 0.64.

Based on the work of Morgan [5], the size of an all-electric ammonia plant has the following linear relationship with the power required by the ammonia plant:

\[ P_{NH3} = 0.482 \times \text{Size}_{NH3} \]

where,

\( P_{NH3} = \text{power required by the ammonia plant in MW} \)
SizeNH3 = ammonia plant capacity in tons per day

Thus, to meet the requirement of an ammonia plant capacity of 300 tons/day, the net power required from the offshore windfarm should be 144.6 MW.

The windfarm considered for this project is non-grid connected. Therefore, any excess 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 operated at rated capacity. Considering factors such as array efficiency, electrical transmission efficiency, and capacity factor, the windfarm number, n, should be:

\[
n = \frac{144 \text{ MW}}{4.5 \text{ MW} \times 0.9 \times 0.98} = 37
\]

Therefore, 37 turbines were required to supply power to the ammonia plantship [7].

2.1.3. Ammonia Plant

The sizing and technical performance of the ammonia plant was based on the work of Morgan [5]. A 300 ton/day ammonia production was selected, and the system was divided into a number of smaller ammonia plants of equal rated capacity. Each ammonia plant had two operation levels: Production Level “P” (65% of full load) and Idling Level “I”. The Idling Level power input could be supplied by electrical energy from offshore wind or energy produced via an ammonia fired gas turbine cycle.

The energy required for the ammonia synthesis loop was 8 MW for a 300 ton/day capacity plant [5]. This is about 5.5% of the total energy requirement for operation of plant at rated capacity. Therefore, P was set at 65% and I at 5.5% of the total energy required for a mini-ammonia synthesis plants operating at rated capacity.

For any given wind speed, the term \( \frac{\text{Total Energy from Windfarm}}{n} \) will be either less than I, greater than P or between I and P, where “n” is the number of mini ammonia synthesis plants.

Based on this, the flow of energy from the windfarm will follow the controlling sequence as:

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

2.1.4. System Economics

The economics of the proposed system were determined from estimates for the capital and operation and maintenance costs of the entire system [3]. The major subsystems included: 1) offshore wind farm, 2) all-electric ammonia plant, 3) ammonia powered gas turbine cycle, and 4) platform for the ammonia plant.
Next, the economics model produced values for the Levelized Cost of Ammonia (LCOA) was determined in $/ton.

The LCOA is basically the ratio of total average lifetime capital costs and operation and maintenance costs over the lifetime ammonia production given by:

\[
\text{LCOA} = \left( \frac{\text{Total Lifetime Project Costs}}{\text{Total Lifetime Ammonia Produced}} \right)
\]

Following Morgan [5], the LCOA is calculated via the following equation:

\[
\text{LCOA} = \frac{P_d + \left( \frac{1}{1+r} - \frac{1}{1+r}^{(n_{\text{loan}}+1)} \right) + \left( \frac{1}{1+i} - \frac{1}{1+i}^{(n_{\text{life}}+1)} \right) \left( \text{Wind}_{\text{O&M}} + \text{NH}_{3}\text{O&M} \right)}{1 - \left( \frac{1}{1+r} \right)^{n_{\text{loan}}}}
\]

where,

- \(P_d\) = Down payment on the entire project = 10% of the total CapEx \(C_c\)
- \(\text{Wind}_{\text{O&M}}\) = Annual Operations and Management Cost of the windfarm
- \(\text{NH}_{3}\text{O&M}\) = Annual Operations and Management Cost of the ammonia plant
- \(i\) = Inflation rate = 3%
- \(r\) = Nominal Discount Rate = 7%
- \(n_{\text{loan}}\) = duration of the loan = 15 years
- \(n_{\text{life}}\) = 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 to be 10% of the entire capital cost, while the annual payment \(P_a\) is calculated as:

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

where,

- \(b\) = rate of interest on the loan = 4%
3.0 ANALYTICAL MODELING RESULTS

3.1 Sensitivity Analysis

3.1.1 LCOA vs. no of divisions of ammonia synthesis loop

The number of mini-ammonia synthesis plants are defined as the divisions of the 300 tons/day producing ammonia synthesis loop. As the number of divisions increase, the total CapEx of the ammonia plant increases significantly as shown in Figure 3. Note that Figure 3 shows only the total CapEx of the offshore ammonia facility and not that of the project. That is, it is sum of capital expenditure of the ammonia plant, the ammonia powered gas turbine cycle, and the supporting plantship.

As shown in Figure 4, the net ammonia production also increases up to a point. Therefore, it is essential to identify optimum number of divisions to account for both total production as well as the economy of the plant. The LCOA of the plant with respect to the number of divisions is given in Figure 4.

![Figure 3. Capital cost of the offshore all-electric ammonia production facility vs. no of divisions of ammonia synthesis loop](image-url)
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 NH3) 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 as big. Therefore, dividing the synthesis loop into 2 parts was chosen and is established as the baseline parameter.

3.1.2 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 at $5000/kW. This value falls on the high end of spectrum of the capital expenditure for gas turbines cycles as shown in Figure 5.

Figure 4. LCOA vs. number of divisions of ammonia synthesis loop

![Figure 4. LCOA vs. number of divisions of ammonia synthesis loop](image-url)
Figure 5. LCOA vs. Capital Expenditure of the ammonia powered gas turbine cycle

The LCOA increases when the capital cost of the ammonia powered gas turbine increases. 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 cycle is relatively small compared to other sub-systems like the windfarm and the ammonia plant. The effect of the efficiency of the gas turbine cycle on the LCOA is shown in Figure 6.

Figure 6. LCOA vs. Efficiency of the ammonia powered gas turbine cycle
In the context of this project, future research on developing the ammonia powered gas turbine cycle should be focused more on higher efficiency improvements.

3.1.3 LCOA as a function of the wind turbine cost
As shown in Figure 7, 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 [10].

![Figure 7. LCOA vs. capital cost of the wind turbine](image)

Thus, it can be expected that with decrease in the per kW price of the turbine, the LCOA will also linearly decrease within an acceptable range.

4.0 RESULTS/ CONCLUSIONS
The Levelized Cost of Ammonia (LCOA) for the grid-connected onshore ammonia facility was calculated as $1224/ton [5], while the LCOA for a conventional ammonia production facility using natural gas was calculated as $360/tons in 2010 dollars (Current values for this type of production are about $500/ton). The LCOA for the current project is almost $350/ton higher than that calculated by Morgan [5]. There are several reasons for 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 plant ship 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 a semi-submersible floating support structure. The estimated capital cost of this turbine was much higher than that calculated in Morgan’s work [5]. With technological advances and steep price reduction since 2008, however, the LCOA should be lower using current values.
- 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 affects 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 wind speeds 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 divisions 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 [5]. Therefore, there is a significant requirement for further research to lower overall plant capital expenditure. This project warranted the use of turbine with large rotor size and their higher cost was one of the driving factors behind the higher LCOA. Therefore, using ammonia as a possible solution to energy storage medium for far off-shore 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.

5.0 FUTURE WORK

This work considered a system-level analysis to understand the feasibility of ammonia production from a non-grid connected floating offshore wind farm. It used a 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 the 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 time point 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 a wind resource 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 that needs to be researched is the estimation of accurate wind turbine prices. As the work shows, any reductions or additions in the capital expenditure of wind turbine prices will have an amplified effect on the LCOA. Also, future updates on this work will also require a more accurate estimation of the efficiency and capital expenditure for an ammonia powered gas turbine cycle.

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