Gone With the Wind:

An Economic Analysis of Using Onshore Wind Turbines to Power Ammonia Synthesis

Alaisha Sharma and Rowen VonPlagenhoef

Harvard College ESPP 90S

9 May 2020

Table of Contents

Introduction

What do fertilizer, carbon-free fuel, and large scale energy storage have in common? The answer, anhydrous ammonia, is seemingly amongst the less flashy solutions for assisting in the transition to a low-carbon energy system. Ammonia, as we know it, serves a crucial role in the agricultural sector; although ammonia production is both a carbon intensive and energy intensive process, the world hunger crisis we face today would be exponentially worse without the widespread use of ammonia in farms.

An energy dense substance, ammonia may also grow into a crucial role in both the fuel and energy storage industries. In particular, its ability to be burned as a fuel without producing carbon dioxide makes it an attractive alternative to conventional fossil fuels. Yet perhaps the most exciting application of ammonia is in mitigating the intermittency of renewable energy like wind and solar. Today this issue continues to undercut progress towards a more sustainable and reliable energy system. Despite being competitive against market rates of electricity generation, increasing penetration of wind power specifically is slowed by a combination of technological barriers and politics. We seek to overcome these challenges and look to anhydrous ammonia production as the solution. Altering ammonia production to make it compatible with renewable energy generation would not only help to decarbonize a key sector within the global economy, but also serve as a starting point for transforming intermittent renewables into stable power sources that can better compete with fossil fuels.

Background

The amount of ammonia produced globally in 2019 was approximately 150 million metric tons, of which 14 million metric tons were produced in the United States.[1] About 88% of ammonia is used for fertilizer manufacturing in the United States.[2] The importance of ammonia usage in fertilizer production cannot be understated, as conservative estimates suggest at least 48% of the global population in 2015, which is approximately 3.5 billion people, relied upon nitrogen fertilizers for crop yield.[3]

In the early 1900s, German chemists Fritz Haber and Carl Bosch developed a process to synthesize ammonia from nitrogen and hydrogen. Although this revolutionary approach deserves high praise for allowing ammonia production at a scale that exponentially increased agricultural potential, the conventional process is not without consequences. Consider Equation 1 below, which outlines the conventional method of creating anhydrous ammonia (NH_3). Step 3 represents the actual Haber-Bosch process, although it relies on Steps 1 and 2, which together release carbon dioxide (CO_2) as a byproduct.

Equation 1. *Steps of conventional ammonia production via the Haber-Bosch process: 1) splitting of methane, 2) hydrolysis and release of carbon dioxide, and 3) ammonia synthesis.*

1. $CH_4 + H_2O \rightarrow 3H_2 + CO$
2. $CO + H_2O \rightarrow CO_2 + H_2$
3. $3H_2 + N_2 \rightarrow 2NH_3$

This release of CO_2 is primarily the result of using methane (CH_4) as the feedstock for generating both hydrogen and energy simultaneously. Globally, this version of the Haber-Bosch process accounts for 1.4% of global CO_2 emissions; in 2019 alone, this resulted in 560 million metric tons of CO_2 emitted.[4] Ammonia production using natural gas accounts for approximately 2.1 metric tons of CO_2 per ton of ammonia produced through steam reformation and 3.3 metric tons if using partial oxidation; coal accounts for approximately 4.6 metric tons of CO_2 per ton of ammonia produced.[5] As global populations are predicted to rise sharply in the coming decades, so will the amount of synthetic fertilizer needed to support the global food economy.[6] It is thus crucial to consider alternative means of producing ammonia, namely from carbon-free methods.

The Potential of an Ammonia Economy

Beyond fertilizer, many studies also see the future role of ammonia as a carbon-free fuel.[7] If burned at a lower temperature, ammonia combustion produces only water (H_2O) and nitrogen (N_2). In a similar vein as the hydrogen economy, the ammonia economy envisions a world in which instead of powering vehicles on gasoline or generators on fossil fuels, the primary transportable and high energy density fuel is anhydrous ammonia.

Burning anhydrous ammonia as fuel is not a novel concept. As early as 1943, Belgium buses used NH_3 instead of oil in their engines due to fuel shortages across the nation.[8] In the 1960s, NASA scaled up liquid ammonium engines for use on its XLR99 rocket engines.[9] These processes used the same design as a diesel engine and could theoretically be modified for use in a combustion engine or combined cycle power plant that uses ammonia as its energy source. Furthermore, the same volume of ammonia in a fuel cell can achieve three times the energetic output of a hydrogen fuel cell, and is more easily stored and shipped.[10] While the energy density of ammonia (4.32 kWh/L) is about half that of gasoline (9.7 kWh/L), the diverse application of ammonia, from fertilizer, to stored energy, to rocket fuel, make it an appealing candidate for transitioning towards more environmentally friendly fuel resources.[11]

The Role of Wind Power in Ammonia Production

Ammonia cannot truly be a clean fuel unless its production is also made clean. One way to generate carbon-free ammonia is using wind power to replace the carbon intensive preparatory steps of the Haber-Bosch process.

The concept of producing ammonia using electrical processes has almost as long a history as the Haber-Bosch process itself. As early as 1928, several large-scale electrolytic hydrogen facilities were built in Norway in order to produce hydrogen via hydroelectric power.[12] However, the use of hydroelectric power is limited in geographic scope, and today faces growing political opposition from many parties, including environmental groups. Only seven of these ammonia facilities remained active by 1998.[13]

Beginning in the 1960s, the U.S. Army began looking for various ways to power ammonia production through an initiative called the "Energy Depot Concept"; the investigation mainly looked at ways that nuclear energy could be used to create chemical fuels.[14] By the 1970s, this program led to funding and research done by the National Science Foundation and Lockheed California Company to explore the potential of ammonia production using wind power in a standalone system.[15] While the report indicates that such a system could be built, neither a wind-ammonia prototype plant nor the economic feasibility of such a plant were discussed in detail.[16] We hypothesize that since wind power was still in its infancy at the time, the energy intensive process of electrolysis posed both technical and economic barriers to the realization of such a project. In order to justify building such a plant, the energetic cost of generating ammonia via wind power would need to be competitive with present day market rates for electricity.

Over the last decade, the price of wind-generated electricity has fallen dramatically, with rates now between $0.02 and $0.06 per kWh, making it more competitive than coal based and even potentially with natural gas based power generation (this depends on the financing as well as state and local policies).[17] What holds back large-scale deployment of wind power is not the market price of electricity, but a combination of inherent issues of variable power generation, and political opposition to the environmental as well as visual effects.[17] Our proposal to combine wind power with anhydrous ammonia production seeks to address both of these challenges while determining the economic viability of such a facility.

Proposal

The ultimate goal of our project is twofold: 1) to design a carbon-free methodology for producing anhydrous ammonia, and 2) to produce this "green ammonia" at costs low enough that it could feasibly enter the market not only as fertilizer but also as a carbon-free fuel. In order to reach these goals, we propose the construction of a wind-ammonia power plant in an off-grid location, so as to address issues of variable power generation, political opposition, and carbon emissions.

Wind energy, like other forms of renewable energy, is severely limited by intermittency. This results in inconsistent power output that can either exceed or fail to meet the demand. The development of battery technology may eventually solve such issues by partially flattening out power curves for wind and solar, but current battery technology is both prohibitively expensive and requires heavy metals that can be detrimental to human health if not managed properly.[18]

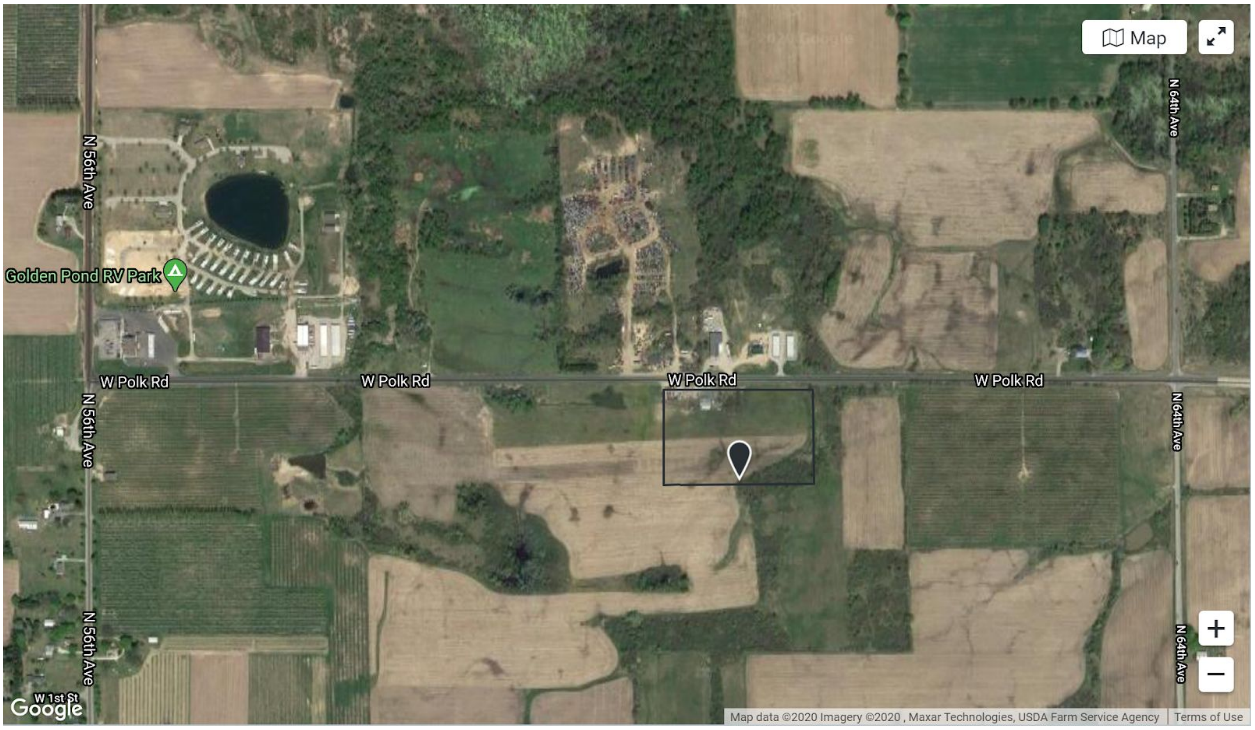
In our combined wind-ammonia power plant, wind is responsible for power generation and ammonia production creates the load. Therefore, rather than have power generation (supply) follow load (demand), we will have demand follow supply. The ammonia plant we propose will be designed in such a way that it only turns on and produces ammonia when the wind is blowing. This overcomes the problem of intermittency with renewable energy, as our power generation profile will not need to match an already fixed load profile. It follows that we do not need a grid connection for a reliable supply of electricity to supplement our wind electricity, allowing us to build both our ammonia plant and wind farm away from densely populated locations. As a result, we are able to overcome much of the political opposition to wind turbines since ours can be located far from residential areas.

Choice of Location

Specifically, we propose building the wind-ammonia power plant on a vacant commercial lot in Hart, Michigan.[19] This 100 acres of vacant land is located between 56th and 64th avenue, surrounded by farmland and one neighboring auto dealership across the street (see Figure 1). The reason why we chose this specific location in Michigan rather than in states with better wind resources is due to the abundance of tappable water. The presence of a steady low cost water supply to drive electrolysis is key to keeping the cost of production low. The average wind speed at 100 meters in Hart is between 7.0 and 8.0 m/s, representing some of the best onshore wind resources in the state.[20]

We plan to use approximately 70 acres of this land to build 30 wind turbines at 2 MW each, and the remaining 30 acres for the ammonia plant itself. Power generated from the wind farm will first produce hydrogen (H_2) and oxygen (O_2) via electrolysis of water and nitrogen (N_2). The nitrogen will be extracted simply from the air outside by an air separator. From here, the ammonia plant will drive the production of anhydrous ammonia (NH_3) via the Haber-Bosch process. The ammonia produced would then be stored in conventional fertilizer storage tanks (these are commonly used across farms in the United States).[21] The main takeaway is that although our power source, onshore wind, is highly variable, producing ammonia with storage facilities on site would allow us to be a consistent supplier of clean fertilizer and eventually a clean fuel as well.

Figure 1. *Vacant lot in Hart, Michigan. The black box marks a portion of the lot itself.*



Technical Components

While there are numerous mechanical components that make up the conversion of wind energy to usable power and the production of ammonia, the wind-ammonia facility essentially breaks down into the following main steps: 1) wind power generation, 2) air separation, 3) electrolysis, 4) syngas compression, and 5) ammonia synthesis.

Wind Power

The amount of power generated by a wind turbine is varies linearly with air density (ρ) and circular area of the blades (A), but exponentially with wind velocity (V).[22] This means that a slight change in wind speed can result in drastic changes in power output.

Equation 2. *Calculation of power generated by a theoretically ideal wind turbine.*

$$P = 0.5\rho AV^3$$

The circular area of the blade is limited by two factors: the height of the turbine and the lengths of cargo trucks that deliver the unassembled equipment. Taller turbines allow for longer blades, but these cannot be longer than physically allowable by cargo trucks on the road. The turbines we have chosen to run our analyses are 2 MW turbines capable of hub heights of approximately 100 meters. The leading wind turbine producers in the U.S. both carry these types of turbines, and they are commonly used throughout the country.[23, 24]

Air density is actually higher at lower elevations and in colder climates, making the long cold winters and low lying region of Hart, Michigan ideal for wind power plants. However, the power generated is not suitable for electronics and must pass through a rectifier followed by a frequency inverter before it can be used.[25] This ensures that the right voltage is being supplied to the equipment and does not cause electronic damage. In total, our 30 wind turbines operating at a 35% capacity factor will generate approximately 184,000 MWh/yr (see Table 1). This estimate is on the conservative side, since our specific location falls within a region of Michigan that has been rated as having a capacity factor of 35% or higher by the National Renewable Energy Laboratory (NREL).[26]

Table 1. *Estimated power output of a 60 MW onshore wind farm.*

	Value	**Units**
Nameplate capacity	2	MW
Number of turbines	30	
Wind capacity factor	0.35	

Hours per year	8760	hr/yr
Total generation	183,960	MWh/yr

Knowing our estimated power output per year, we can calculate our estimated ammonia production. A typical electric ammonia plant producing 300 tons of ammonia per day requires approximately 145 MW of electricity, of which 135 MW, or 93 percent, is used for electrolysis.[27] Scaling this number, as shown in Table 2, gives our facility an estimated production capacity of about 15,858 tons per year equating to about 43.45 tons of ammonia per day.

Table 2. *Estimated ammonia production of a facility powered by a 60 MW wind farm. Power requirements are based upon an offshore wind to ammonia power plant built in Maine.*[28]

	Value	**Units**
Power requirements[28]	145	MW/(300 ton/day)
Conversion to per ton	11.6	MWh/ton
Tons per year	15,858.62	ton/yr
Ton per day	43.45	ton/day

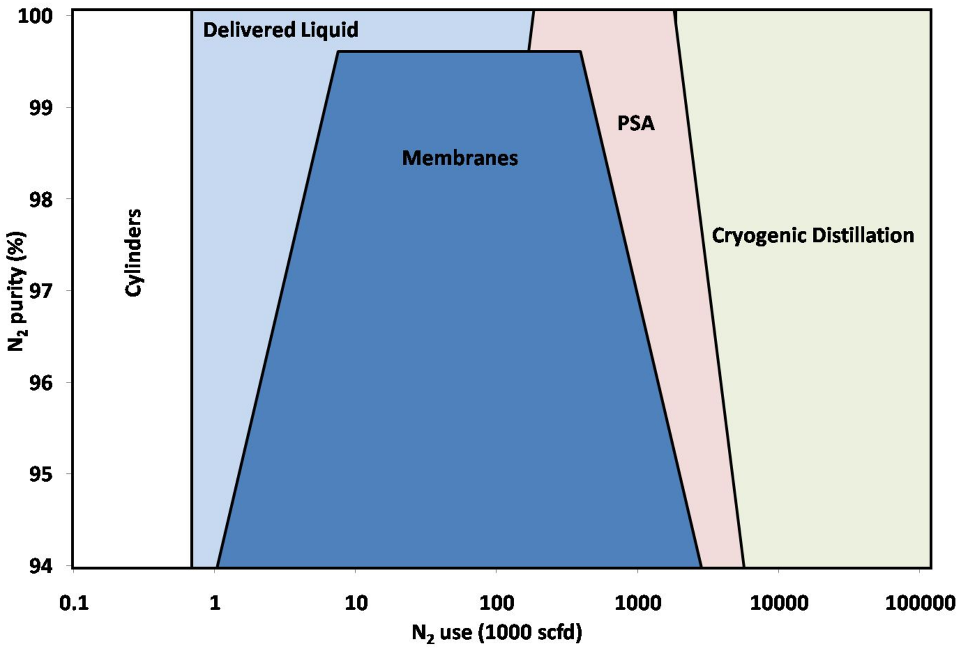
Air Separation

The primary purpose of an air separation unit is to be able extract nitrogen from air. The need for pure nitrogen gas is vitally important to ammonia production. High levels of purity ensure that additional, more costly purification steps to remove unwanted chemical byproducts are not necessary in the final stage of production.

There are three main methods of obtaining pure N_2: 1) membrane separation, 2) pressure swing adsorption (PSA), and 3) cryogenic distillation.[29] Cryogenic distillation comprises about 90% of all commercial production of N_2.[30] This method takes advantage of the difference in boiling points of nitrogen, oxygen, and argon, the three most abundant gasses in the air, in order to separate each out into liquid form. However, cryogenic distillation systems require a constant input of energy to maintain the ultra-low, below 100 K (-173℃) temperatures, which is not ideal for our plant design since our power supply is intermittent.

Membrane separation and PSA both rely upon pressure to drive the separation of nitrogen from other air molecules. The difference between them primarily lies in the types of filter used and the consistency in nitrogen flow.[31] PSA can generate higher quantities of nitrogen at much higher purities than membrane separation. Yet the advantage of membrane separation units is that they can operate with little to no input of electricity, requiring only canisters of compressed air to complete operation and production.[32] However, these units are not necessarily appropriate for industrial ammonia production as their output quantities are quite low. The economically competitive range of each air separation technology is displayed in Figure 2 (with scfd standing for standard cubic feet per day).

Figure 2. *Comparison of nitrogen purity vs. quality amongst economically competitive methods for nitrogen production via air separation.*[33]



The amount of nitrogen our facility would require per day is approximately 1.11 million standard cubic feet as shown in Equation 3. However, this is based upon optimal stoichiometric conversions, which rarely occur in reality for chemical processes. Therefore, a conservative value of 50 percent yield will be used as a basis for comparison, increasing the need for nitrogen production to be 2.22 million cubic feet. High nitrogen demands are the primary reason why cryogenic distillation is such a widespread technology for nitrogen production, as ammonia facilities often operate at ten times the production level as our proposed facility. Yet given the power constraints as explained above, we are limited to the usage of PSA systems for nitrogen production.

Equation 3. *Calculation of the amount of pure nitrogen required per day.*

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

$$\text{Molar Mass } NH_3 = 17.031 \text{ kg/kmol} \qquad \text{Molar Mass } N_2 = 28.013 \text{kg/kmol}$$

$$43.45 \text{ tons } NH_3 = 2551 \text{ kmol of } NH_3 \leftarrow 1276 \text{ kmol } N_2$$

$$PV = nRT$$

$$P = 1\text{atm} \quad n = 1276000 \text{ mol} \quad R = 0.0821(\text{atm} \bullet \text{L})/(\text{mol} \bullet \text{K}) \quad T = 300\text{K}$$

$$V = 3.14 \times 10^7 \text{ L} = 1.11 \times 10^6 \text{ scfd}$$

Electrolysis

The electrolysis of water is the most energy intensive step, accounting for 93% of energy usage for electric ammonia synthesis.[34] This is primarily due to the stability of H_2O molecules, which requires comparatively large amounts of energy to be split.[35] Electrolysis, or the use of electricity to split water into its two components (O_2 and H_2), produces the pure hydrogen feed required for ammonia synthesis.

The main methods of electrolysis are with alkaline electrolyzers and proton exchange membrane (PEM) electrolyzers. While PEM electrolyzers are capable of producing extremely pure hydrogen densities and are able to handle higher variations in power input, the technology is not scalable and has significantly lower output rates per hour.[36] PEM electrolyzers also require deionized water as an input while alkaline electrolyzers are capable of taking even salt water.[37] Therefore, the lower overall capital and operating costs along with the higher H_2 outputs makes alkaline electrolyzers the ideal choice for our project.

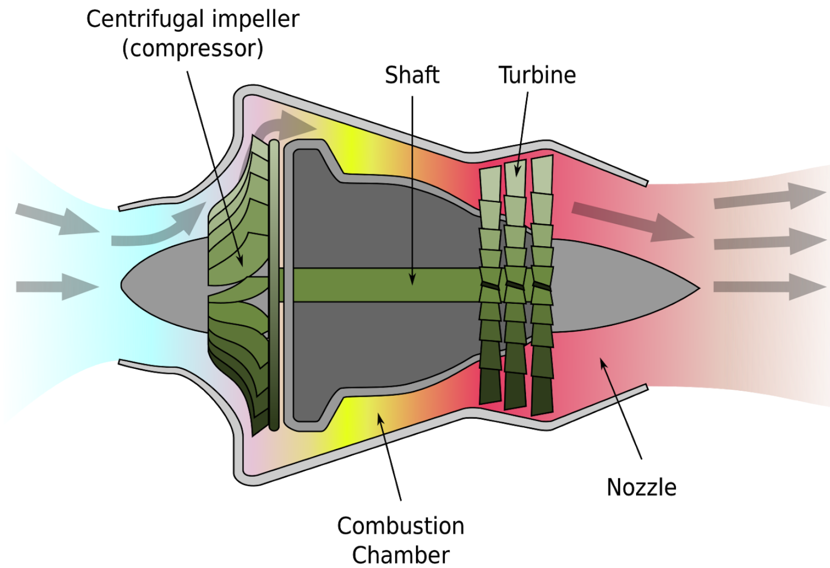
On average, alkaline electrolyzer systems require 52kWh/kg-H_2 . They do not have the advantage of steam reforming systems or partial oxidation systems of generating H_2 and energy at the same through the burning of CH_4.[38] This is the primary reason why electrolytic ammonia facilities are built in regions with inexpensive hydroelectric power; otherwise, electricity costs are too high to compete with a process that can generate electricity itself. Yet burning methane emits carbon dioxide, a major externality that our project seeks to avoid. Furthermore, methane typically cannot be sourced onsite by ammonia plants, and thus add to yearly operating costs. The location we have chosen allows us to tap for water directly onsite, as it is close enough to Lake Michigan to contain aquifers in connection with the lake itself without drawing water directly in a way that would disrupt aquatic life.[39] This will raise fixed costs for the plant itself but eliminate a significant portion of operating costs since the cost of water will be free, leaving the production of H_2 dependent only on the capital costs.

Syngas Compression

Syngas, or synthesis gas, compression is a step that occurs before, during, as well as after ammonia synthesis. It involves mixing hydrogen and nitrogen in the proper stoichiometric ratios and compressing them under high pressure. In a conventional ammonia plant using methane, this step usually involves several filtration substeps to remove hydrogen sulfide, carbon monoxide, and carbon dioxide from the feed stream before ammonia can be synthesized.[40] However, we are feeding pure nitrogen and hydrogen into our system, allowing us to eliminate the filtration steps.

To ensure that ammonia synthesis occurs spontaneously, the syngas must be compressed to pressures of 150 - 300 bars, which is approximately 150 - 300 times the normal atmospheric pressure at sea level.[41] The most common method of compression uses a system of centrifugal compressors (see Figure 3). This is done through rotating a disc via an electric motor to increase the speed of gas through the unit and converting this energy to pressurizing the gas. As pressure must be maintained throughout the system in order to ensure consistent production of ammonia, this process must be kept constant. Unfortunately, centrifugal compressors are designed to run continuously. Cyclic operation cycles can cause damage to the equipment, posing a significant challenge to an offgrid wind farm with far from constant power generation.[42]

Figure 3. *Cross section of an industry standard centrifugal compressor.*[43]



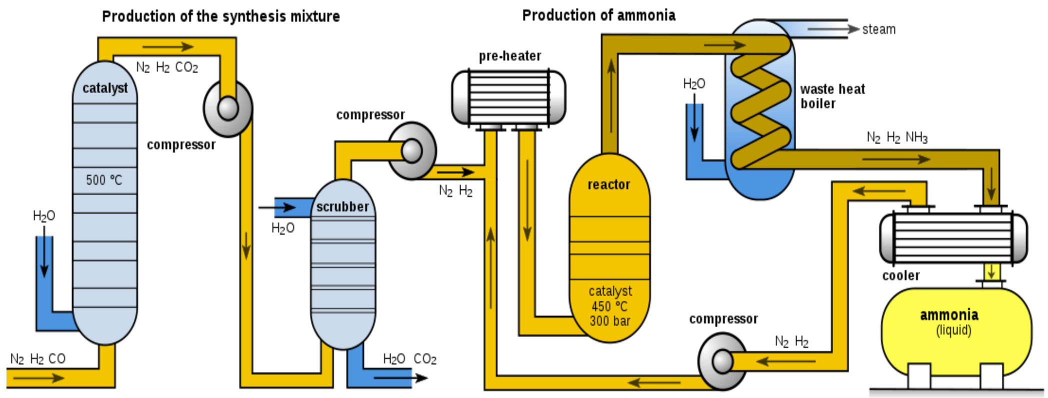
There are two potential solutions to overcome this problem. The first would be to use reciprocating compressors that are commonly used on offshore platforms.[44] These involve a series of pistons that drive air pressure within the synthesis loop, much like the piston system within an internal combustion engine of a car. This allows the system to ramp up and down depending on power and feedstock inputs. A small 1.65 MW wind power test plant using such a design was built in Morris, Minnesota, with relative success in producing ammonia.[45] Yet as with other plant designs, the turbine was connected to the grid, resulting in a higher cost of electricity. Furthermore, the facility was testing ways to create ammonia at low operating pressures, which yields significantly lower amounts of ammonia, thus increasing the cost of production.

The main problem with reciprocating compressor systems is that they are mechanically more complex and require constant maintenance. However, it is also known that centrifugal compressors can be more expensive to replace should they break down.[46] Although it makes more sense for our plant design to use a reciprocating compressor system, these systems were outcompeted by centrifugal compressors in the 1960s for ammonia plants, so there are no current cost estimates for this technology. With this in mind, we will be running our economic analysis using cost estimates for centrifugal compressors. This leads us to the second solution, which would be to use backup generators to ensure the proper startup and shutdown of the compressors. (A more detailed explanation is given following the Ammonia Synthesis section.)

Ammonia Synthesis

The final step of ammonia synthesis occurs simultaneously with syngas compression. This usually involves an iron catalyst that operates around 500℃[47] to allow the reaction to occur in real time. While this is outside the optimal temperature range for the natural formation of ammonia, without the catalyst, only a minimal amount of ammonia would be formed. That being said, only about 15% of ammonia is formed on the first pass through the system, requiring the use of recyclers to feed unreacted N_2 and H_2 back through the loop to obtain yields of 80% or higher.[48] Ammonia is obtained by passing the system through a cooler, which results in the formation of liquid ammonia at room temperature under its own vapor pressure of 8.5 bars.[49] This allows liquid ammonia to be siphoned out of the system with minimal removal of N_2 and H_2 from the system. Figure 4 depicts the basic flow of this process.

Figure 4. *Diagram of Haber-Bosch ammonia synthesis loop.*[50]



Once produced in liquid form, ammonia can be stored in a standard double containment vessel commonly used on farms throughout the United States.[51] It is generally good practice to have at least 30 days worth of storage, especially in Michigan where severe weather conditions could prevent ammonia transport by road. Given an average production of 43.45 tons of NH_3 per day, we estimate that we would need at least 1390 tons of ammonia storage capacity.

Backup Generation

Since our facility is offgrid and draws power directly from our wind turbines, we also plan to build backup generators to ensure the proper shutdown of equipment; this is intended to avoid mechanical and electrical failures should power levels drop suddenly. In order to remain a carbon-free production facility, this will be done through the use of diesel generators running on the ammonia we ourselves produce. As the capability for using ammonia fuel in diesel engines has been proven many times over, with the most recent being an NH_3 fueled car that drove from Detroit to San Francisco in 2007, we assume technological feasibility of ammonia-powered diesel generators.[52] After-market conversion kits exist to modify diesel generators to make them capable of burning ammonia fuel.[53] Their use is currently not widespread, so only limited market data exists on the costs of modifying diesel generators to be capable of running on ammonia fuel. We do not add extra costs for retro-fitting the diesel generators, but in the Sensitivity Analysis section we apply multipliers to various costs to account for this potential discrepancy.

As previously mentioned, electrolysis accounts for about 93% of energy usage in electric ammonia production, meaning that the 7% includes the energy required for the compressors. Since we want the backup generators to be able to keep the compressors running constantly and also handle proper shutdown of all other equipment, we estimate a load of 10% of the total energy usage of the ammonia plant on the backup generators. This requires us to build at least 3.2 MW worth of backup power generation. We expect the backup generators to be in use whenever the wind is not blowing, which we estimate as 65% of the time (since our capacity factor for wind is 35%). This leaves a backup power requirement of 50.4 MWh/day, which will use about 10.61 tons of ammonia as fuel, which is roughly one quarter of our daily production of. This is a significant drop in the amount of ammonia we are able to distribute and thus raises the retail price required in order to break even, but in return, we ensure that our backup generators are completely carbon-free. The LCOE for this fuel cost is $231.72 per MWh since it incorporates the cost of production for each ton of ammonia used.

Table 3. *Backup generation size and fuel requirements when backup generation can satisfy a load equivalent to 10% of daily power usage.*

	Value	**Units**
Power generation	183,960	MWh/yr
Fraction of total power	0.10	
Required backup power	50.40	MWh/day
Ammonia fuel combustion[54]	4.75	MWh/ton

Required fuel (NH_3)	10.61	ton/day
Diesel capacity factor	0.90	
Total backup generator size	3.6	MW
Cost per ton NH_3	1,100.81	$/ton
LCOE	231.72 0.23	$/MWh $/kWh

As an aside, backup generators will still be needed with reciprocating compressors, but with smaller nameplate capacity. Although limited market data exists on reciprocating compressors, we believe its capital and maintenance costs will be less than our current estimates for using a centrifugal compressor with backup generators, as we will be able to consume less of our end product.

Economic Analysis

Standalone Wind Farm

The values in Table 4 give the levelized cost of electricity (LCOE) of our 60 MW wind farm if we were simply to sell the electricity back to the grid. The calculations here are intended to serve as a basis for comparison with those of the proposed wind-ammonia plant. Here and in the Combined Wind-Ammonia Plant section, we use an industry standard interest rate of 4.5%.

The need for customized foundations depending on soil composition makes it difficult to accurately estimate the installation costs of our turbines. However, a 2018 market report by the Department of Energy stated that capacity-weighted average cost of turbines installed in the interior regions of the U.S. was approximately \$1400/kW.[55] We will therefore be using this value to estimate our LCOE as produced by the wind turbines.

Table 4. *Estimated LCOE for a 60 MW wind farm with no ammonia facilities.*

	Value	**Units**
Power output	183,960	MWh/yr
Capital costs of turbines [54]	1400	$/kW
Total capital costs	84,000,000	$
Interest rate	0.045	%
PMT calculation	6,457,596	$/yr
LCOE	35.10 0.035	$/MWh $/kWh

Combined Wind-Ammonia Plant

Capital Costs

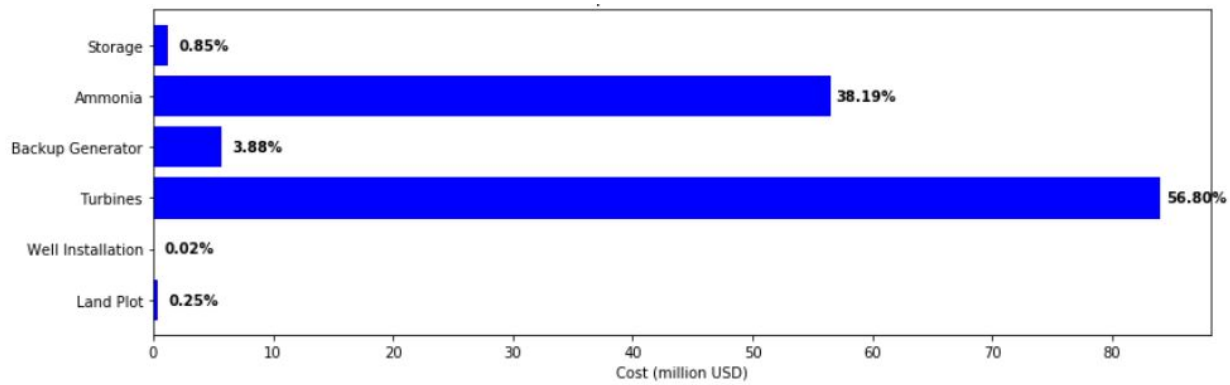
The combination of wind power with ammonia production, which, given the amount of expensive equipment required, leads unsurprisingly to relatively high capital costs. Turbine costs are as calculated in the section Standalone Wind Farm, and ammonia equipment costs are based on a 2010 estimate for a 300 ton per day offshore wind-ammonia plant.[56] We recognize that since our facility is producing only about ten percent of this, that capital costs might be higher given the smaller scale. In the Sensitivity Analysis section, we use cost multipliers to investigate how scale might affect capital costs and thus price.

The storage costs are based on estimates from the International Fertilizer Development Center of the United Nations Industrial Development Organization, approximating $6.47 million per 9000 tons of anhydrous ammonia storage in 2010 dollars.[57] Despite building for about 30 days storage capacity on site, storage capital costs are trivial compared to those of the turbines and ammonia equipment (see Figure 5). The backup generators are also a small burden on capital costs, despite using the high end estimate of $800/kW[58] for diesel generators (this is because our generators are running intermittently with the absence of wind). Lastly, well installation costs are based on well drilling costs for agricultural and commercial property. Drilling can be upwards of $55 per foot, with additional costs for water pumps, pipe casing and labor.[59] We estimate a need for 150 feet of drilling alongside similar pipe casing; this combined with the price of pumps and labor averaged out to around $200 per foot, for a total of $30,000. As irrigation wells can range between $5000 - $75000, we believe this is a reasonable estimate.[59]

Table 5: *Estimated capital costs for a 60 MW, 43 ton/day wind-ammonia plant.*

	Value	Units
Land plot [59]	375,000	$
Well installation [60]	30,000	$
Turbines [61]	1400	$/kW
Backup generators [62]	800	$/kW
Ammonia equipment [63]	1,300,000	$/ton-day
Ammonia storage [64]	900	$/ton
Number of storage units	1390	
Total capital costs	147,901,000	$

__Figure 5:__ Capital cost breakdown for the wind-ammonia plant without any cost multipliers.



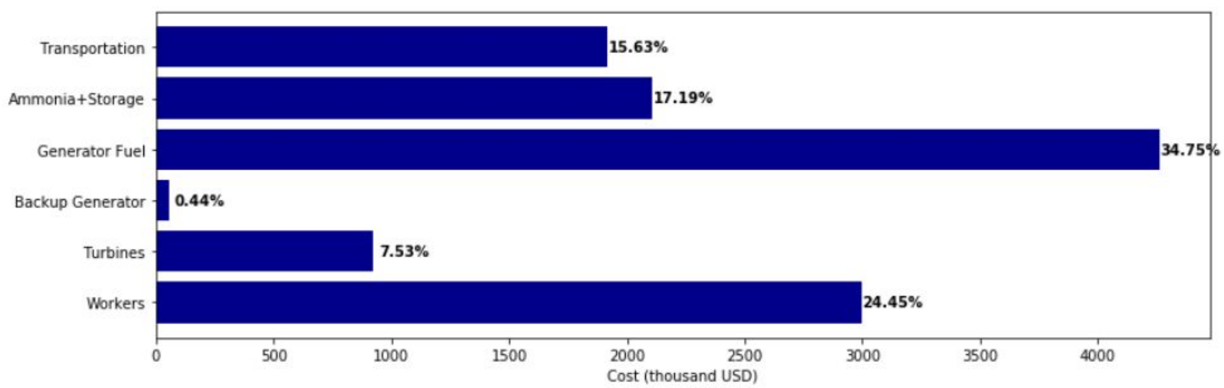
Operation and Maintenance Costs

Operation and maintenance costs begin with the labor required to keep the plant running. We assume about 50 workers would be required to operate a plant of the size we propose, and estimate an annual salary of $60,000 based on the average salary of current job openings at ammonia plants in the U.S.[65] Since we are using our ammonia as fuel for the backup generators, they have no variable O&M costs, so $15/kW-yr is to cover fixed O&M costs.[66] We use an estimate of $133 per ton of NH_3 for combined costs for ammonia equipment and storage units; this value is based on a survey of several small scale (about 91 tons/day) Haber-Bosch ammonia plants across the U.S.[67]

Table 6: *Estimated O&M costs for a 60 MW, 43 ton/day wind-ammonia plant.*

	Value	Units
Labor (annual salary) [68]	60,000	$/yr
Number of workers	50	
Turbines [69]	44	$/kW-yr
Backup generators [64]	15	$/kW-yr
Ammonia Facility[65]	133	$/ton
Total O&M costs	6,087,197	$/yr

Figure 6: *O&M cost breakdown for the wind-ammonia plant without any cost multipliers.*

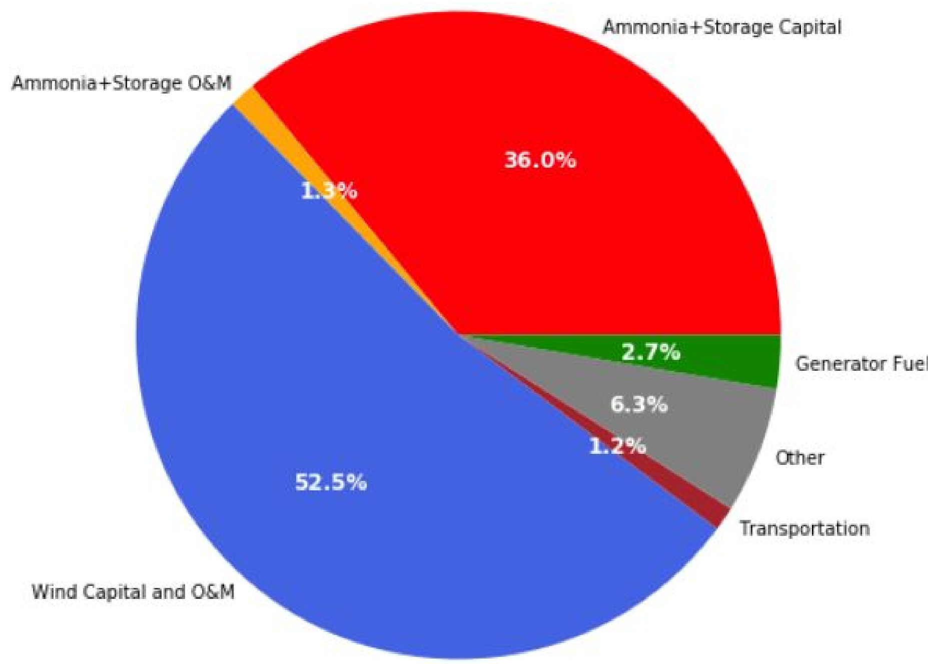


Levelized Cost of Electricity

Figure 7 illustrates the total annual cost breakdown for our proposed plant amongst the main categories: 1) wind, both capital and O&M costs, 2) ammonia and storage capital costs, 3) ammonia and storage O&M costs, 4) transportation or distribution costs, and 5) all other costs, including labor, backup generation, land plot, well installation, etc. Perhaps demotivating is how large a percentage the costs of wind energy are, but the capital costs of wind have been steadily decreasing over the past two decades, and a 2017 NREL report estimated projections of onshore wind capital costs to drop steadily to around $1000/kW before 2050.[70]

If not the costs of wind energy, then the second most desirable place to cut costs would be from the ammonia plant capital costs. See the Sensitivity Analysis section for a more in depth discussion of how ammonia capital costs and synthesis equipment efficiency influence the final breakeven price of production.

Figure 7: *Total annual cost breakdown for a 60 MW, 43 ton/day wind-ammonia plant.*



With the added costs of ammonia equipment, storage, well installation, and backup generators, the LCOE for our wind-ammonia power plant is driven up to almost three times that of the standalone wind farm. We did not factor in land costs or turbine O&M costs to the LCOE calculation for the standalone wind farm, but these are minor enough costs compared to the high capital costs of the turbines that they may be considered negligible for a baseline LCOE estimate.

However, we wanted to make sure we include all costs in the calculations for the wind-ammonia plant to get the most accurate LCOE estimate and ensure that our estimate was conservative.

Table 7: *Estimated LCOE for a 60 MW, 43 ton/day wind-ammonia plant.*

	Value	**Units**
Power generation	183,960	MWh/yr
Ammonia production	43.45	ton/day
Total capital costs	147,901,000	$
Interest rate	0.045	%
Capital PMT calculation	11,370,059	$/yr
Total O&M costs	6,087,197	$/yr
LCOE	94.90 0.095	$/MWh $/kWh

Price of Production

Unfortunately, we cannot use a production rate of 43.35 ton/day to determine the price at which to sell our ammonia in order to break even on annual costs. Because of the fuel requirements of the backup generators (10.61 ton NH_3/day) we are left with about 32.84 ton/day of ammonia available for distribution. Given a production LCOE of $0.095/kWh (and a backup generator LCOE of $0.23/kWh), our price of production comes out to about $1812.08/ton.

Table 8: *Estimated production price for a 60 MW, 43 ton/day wind-ammonia plant.*

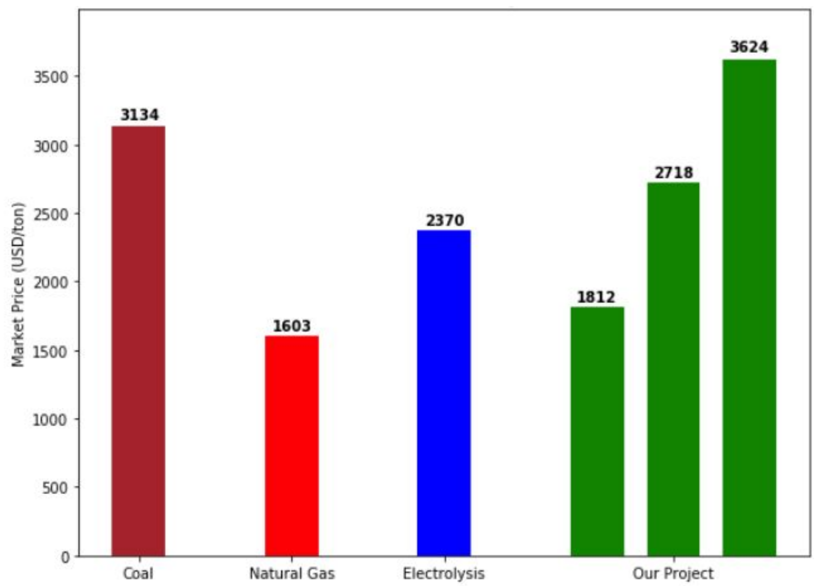
	Value	**Units**
Total ammonia production	43.45	ton/day
Ammonia fuel usage	10.61	ton/day
Net ammonia production	32.84	ton/day
Energy requirement for ammonia production	11.6	MWh/ton
Capital PMT calculation	11,370,059	$/yr
Total O&M costs	6,087,197	$/yr
Generator ammonia fuel cost	4,262,770.37	$/yr
Break even price	1812.08	$/ton NH_3

Market Competitiveness

Based on market data from 2014, the cost of production of anhydrous ammonia in the U.S. ranged from $1000 - $2000 per ton.[71] Figure 7 compares the global averages for natural gas based, coal based, and electrolysis based ammonia production, as well as our proposed wind-ammonia plant production (without any cost multipliers).[72] While coal based ammonia production is mainly seen in developing countries that rely on a majority coal based energy system, the abundance of natural gas in the U.S. has allowed most ammonia plants to drop their costs of production significantly.

Without any cost multipliers, it seems that our price of production is market competitive with all three other methods of ammonia synthesis. However, it is likely that because our project is a small scale plant, some of our cost estimates are on the conservative side. To account for this, we compare our estimated cost of production at 1.5X and 2X in Figure 8. Another thing to note is that our (capital) costs are all assumed directly proportional to the amount of ammonia produced, so it may seem like costs simply increase linearly with production although this is not the case in the real world.

Figure 8: *Wind-ammonia price of production compared to coal, natural gas, and electrolysis.*[70] *Estimates are shown for 1.5X and 2X the price to provide a range of prices calculable using different cost multipliers.*



With a 50 percent increase in price, our plant could still be competitive in niche markets abroad, mainly ones that are vulnerable to the high price of coal based ammonia production. While our plant could be competitive with natural gas based production depending on the region being served and transport costs, the higher 1.5X and 2X estimates put our price of production well above that of natural gas. One thing that would allow us to remain competitive, especially in U.S. ammonia markets, is the presence of a carbon tax. Given the high carbon emissions of conventional ammonia plants, this could add a significant incentive towards buying the "green ammonia" that our plant produces.

Another factor to consider for market competitiveness is capital investment and cost breakdowns; this can help reveal bottleneck costs and pinpoint which cost components are responsible for substantial differences in price of production. Table 9 displays a cost comparison of our plant versus a natural gas reformation plant. We base our values off of a natural gas plant with a production capacity of 91 tons of NH_3 per day.[71] (As our feedstock is based on well water, it is considered free, with capital costs accounting for installing the water tapping equipment.) We do not compare the price of electricity as it fluctuates across regions, and also because the process of natural gas formation itself can produce variable amounts of energy for production.

Table 9. *Cost comparison of a natural gas reformation ammonia plant and our proposed wind-ammonia plant.*

	Natural Gas	**Our Facility**
Capital Costs per ton NH_3 [73]	$113	$697
Capital Cost per year	$1,792,024	$11,051,184
Feedstock per ton NH_3 [71]	$93*	$0
Feedstock cost per year per ton of NH_3	$1,474,852	$0

* natural gas in the form of methane is the primary feedstock

Transportation

For our hypothetical distribution system, we chose to distribute the liquid ammonia by truck. Though we are in an off-grid location, there is sufficient road connectivity (via the highway to the east) that we could feasibly transport ammonia by truck. The main motivating reason for this is that we expect our customers to be local. This seems a reasonable assumption given that most of Hart, Michigan and its surrounding areas are rural farmland, which naturally have a high demand for fertilizer. Since we are not producing bulk quantities of ammonia, we need not look further than a couple hundred kilometer radius in terms of distributing the ammonia produced.

Price of Distribution

Finding estimates for the shipping costs of ammonia by truck was difficult since most ammonia transport occurs in bulk (overseas by barge, and on land mostly by pipeline and some by rail). We therefore used hydrogen fuel transport as a proxy; since ammonia is actually easier and cheaper to transport than hydrogen, we can assume that our cost estimates are liberal.[74] At a distance of 160 km, a 1998 NREL report estimated a cost of $0.10 ($0.16 in 2020 dollars) per three ton capacity truck transporting hydrogen produced at a flow rate of 450 kg/hr.[75] Translating this to our market production of 32.84 ton/day (as we are consuming an average of 10.61 tons per day), we will need 11 trucks per day totaling about $1.918 million in transport costs.

Table 10: *Estimated transport costs for a 32.84 ton/day net market production rate.*

	Value	**Units**
Net ammonia production	32.84	ton/day
Conversion to kg	32840	kg/day
Truck cargo capacity [71]	3000	kg/truck
Number of trucks	11	
Trucking charge (including labor and fuel) [76]	0.16	$/kg

Distance traveled	160	km/day
Total transport costs	1,917,755	$/yr
Conversion to per ton	159.99	$/ton
Breakeven price	1,972.08	$/ton

We imagine that each of the 11 trucks would only need to drive for a few hours each day to deliver its ammonia cargo within the radius of 160 km, so for our purposes it makes far more sense to rent the trucks than to pay the capital costs of buying and replacing them when they would be sitting idle for most of the day. Transportation ends up being one of the lowest annual costs for our facility, adding about $159.99 per ton of ammonia distributed. This brings up our price of production and distribution to $1,972.08 per ton, about a 9% increase.

Further Considerations

There are two main issues that transportation by truck poses. The first is somewhat out of our control, for in the event of extremely windy, rainy, snowy, or icy conditions would prevent any travel or transport by road. In that case, our sales would take the hit and over time this may impact our ability to remain a reliable ammonia supplier. However, as we planned for a storage capacity of 30 days, sales forgone in one week could be fully compensated in another week.

The second perhaps more ethically relevant question is the carbon cost of trucking. A 2011 report from the Logistics Research Centre at Heriot-Watt University estimated the average emissions of road transport at 62 g of CO2 per ton per km.[77] If we assume that all 11 trucks drive the full 160 km distance per day carrying 3000 kg of cargo each, then this amounts to about 263 tons of CO2 emitted per year. This is definitely a negative externality of our project and one that we hope to mitigate as much as possible by selecting the most efficient trucks and prioritizing local over longer-distance customers. As of now, it does not seem economical for our project to consider converting diesel trucks to ammonia, but a recent project by Ontario-based TFX International successfully converted two transport trucks from diesel to ammonia powered using after-market retrofit systems, providing some hope that trucks with dual fuel engines are on their way to becoming market competitive with conventional trucks.[78] As our ultimate hope is for the full transformation to an ammonia based economy, we can foresee a future where all aspects of our process, from the electricity produced to transporting ammonia, is completely carbon free, not just our production method.

If we imagine scaling up production even tenfold, that would put our project on par with most industrial ammonia plants. At that point, it would certainly be more cost effective and less pollutive to transport ammonia by pipeline. Ammonia-specific pipelines Magellan and Kaneb already connect a substantial amount of the midwestern states.[79] Furthermore, ammonia can be transported by the same pipelines as gas, so a mature infrastructure already exists for this use case. This indicates a future direction for further analyses should we decide to scale up our production to match existing producers.

Sensitivity Analysis

Cost Multipliers

The analysis below demonstrates how multiplying various cost components affects end values such as the LCOE and breakeven price of ammonia. Clearly, capital costs of the ammonia facility have the largest effect on both LCOE and pricing, which makes sense since ammonia production requires complex and thus expensive equipment. The next largest effect comes from the ammonia facility O&M costs, which makes sense for similar reasons.

Interestingly, however, the capital costs of storage seem to be low enough that even a twofold increase has negligible effects on the LCOE and distribution price. Another interesting trend is that applying a multiplier to transport costs has a much larger effect on the distribution price than the capital costs of the backup generators, despite needing to build 3.6 MW worth of backup generation. This implies that even with the less than ideal set up of needing to keep the compressors constantly running, backup generation is a flatter cost than transportation. (This refers only to capital and O&M costs, not the fuel cost. See Figures 9-10 for more details.)

Figure 9-10: *Effect of cost multipliers on the LCOE for a 60 MW, 43 ton/day plant before fuel costs are added (top) and for a 3.6 backup diesel generator running on ammonia fuel (bottom). The fuel cost of the backup generator is not considered in terms of cost multipliers because it is calculated from the parameters displayed below, and thus is affected by cost multipliers as opposed to a parameter to be multiplied.*

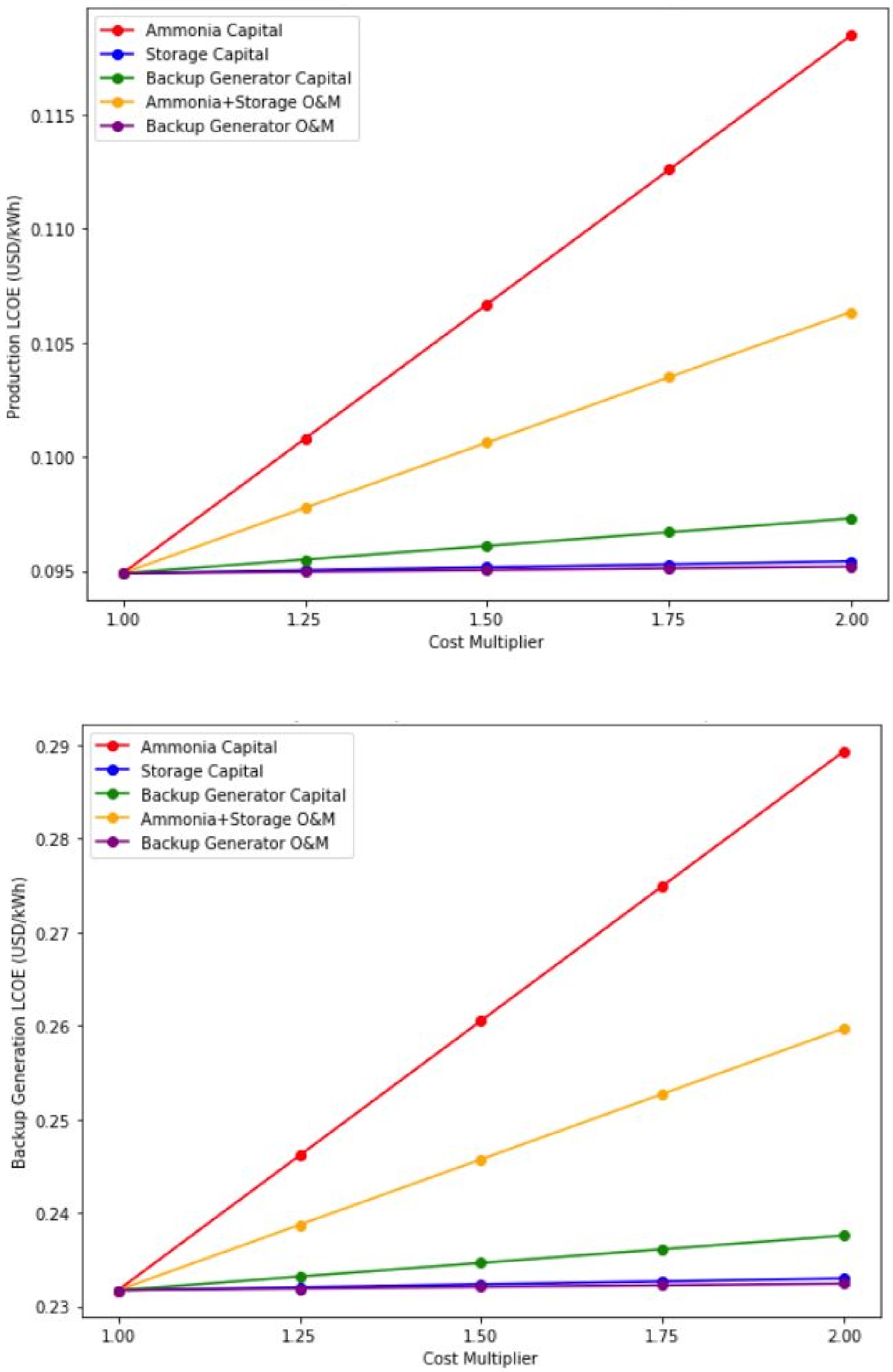
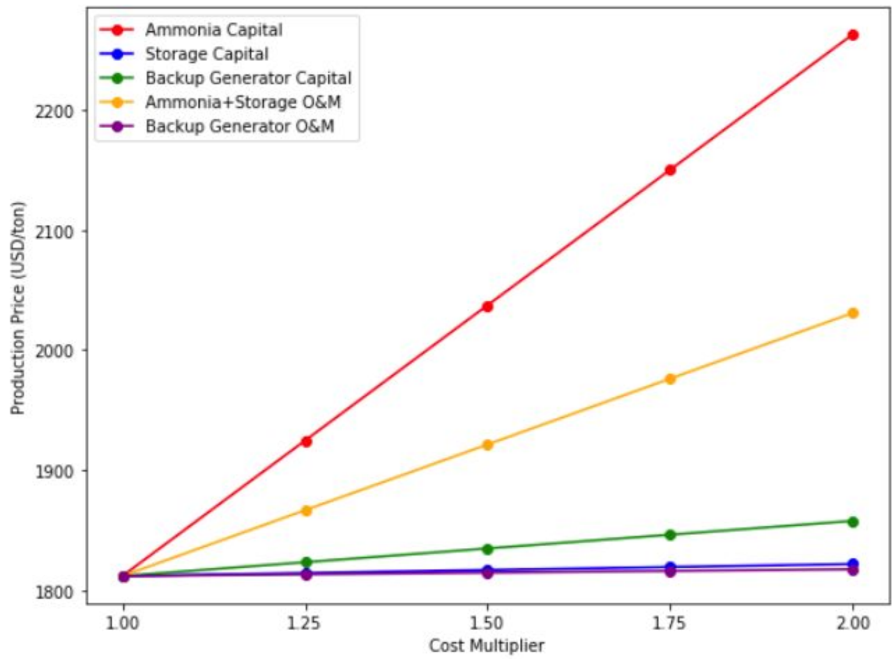
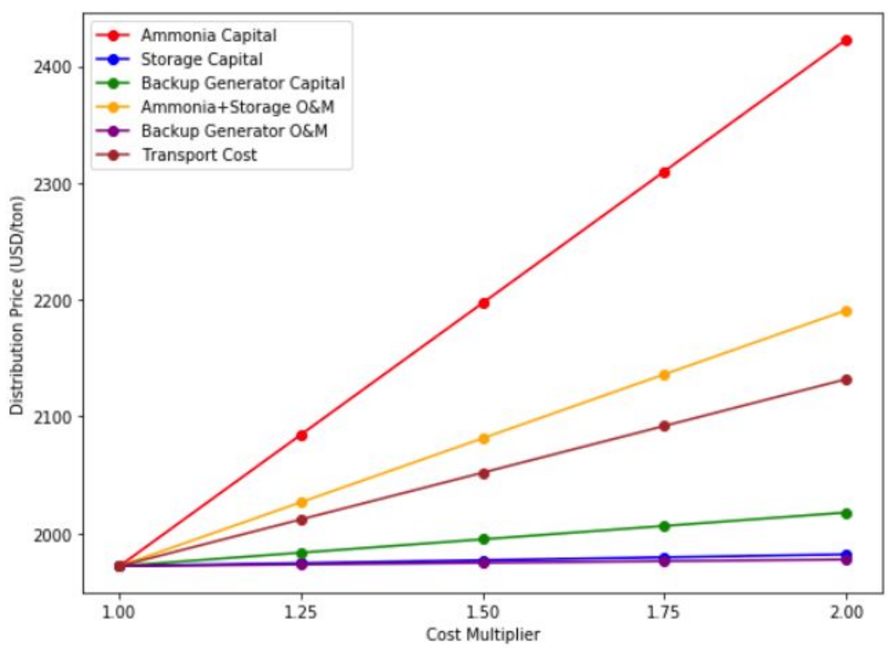


Figure 11-12: *Effect of cost multipliers on the final production price (top) and distribution price (bottom) of ammonia. The fuel cost is not considered as a parameter for reasons explained in Figures 9-10.*


Ammonia Capital
Storage Capital
Backup Generator Capital
Ammonia+Storage O&M
Backup Generator O&M
Production Price (USD/ton)
Cost Multiplier
1800
1900
2000
2100
2200
1.00
1.25
1.50
1.75
2.00


Ammonia Capital
Storage Capital
Backup Generator Capital
Ammonia+Storage O&M
Backup Generator O&M
Transport Cost
Distribution Price (USD/ton)
Cost Multiplier
2000
2100
2200
2300
2400
1.00
1.25
1.50
1.75
2.00

Cost-Efficiency Tradeoffs

The cost multiplier analysis above revealed the bottleneck-like nature of the ammonia equipment capital costs. Naturally, one question prompted by this is whether there is any way of meaningfully decreasing these costs, and if so, what the tradeoffs are.

The main reason why ammonia production equipment is so expensive, especially for electric ammonia synthesis, is that it must be extremely efficient since it consumes so much power in order to produce ammonia. (The assumption here is that power is also expensive, so it is worth the extra cost of optimizing equipment.) This significantly drives up the capital costs of equipment. For our project, however, we have access to relatively cheap power from the wind farm (only $0.035/kWh) and thus it might make sense to sacrifice some amount of efficiency in the synthesis equipment for a decrease in capital costs.

We model efficiency generally using the metric of energy required to produce ammonia (MWh/ton). Figure 13 and 14 below demonstrate the effects of a cost-efficiency tradeoff on our price of production. Intuitively, a linear relationship says that a small sacrifice in efficiency would allow for a roughly equivalent decrease in capital costs, while a logarithmic relationship says that a small sacrifice in efficiency would allow for a substantial decrease in capital costs. (See Equation 4 for more details.)

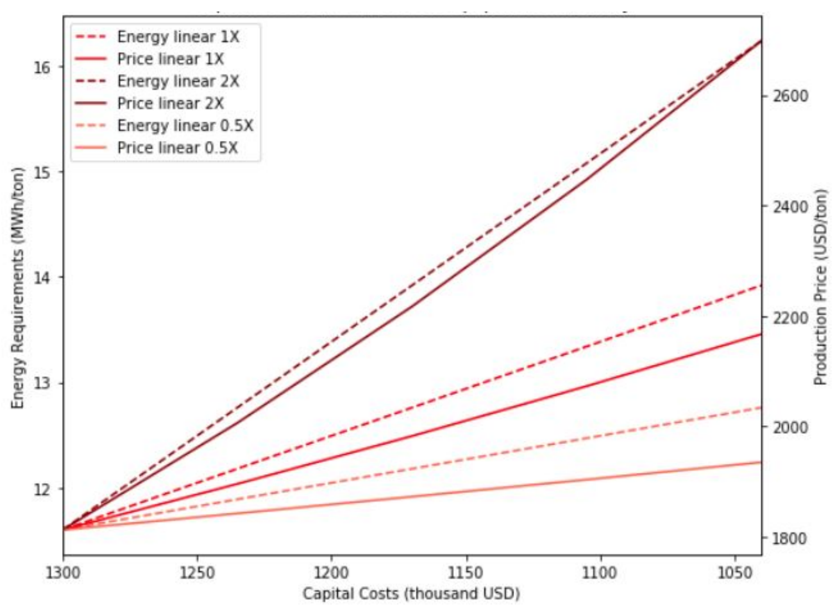
Interestingly, it seems that a linear relationship is actually worse for production because the higher energy requirements undercut production to an extent that decreased capital costs cannot make up for. This could be because the capital costs of the wind turbines, the highest capital cost by far, are held fixed. E is the energy required for ammonia synthesis, a is the multiplicative factor and x is the reduction in capital costs of ammonia equipment.

Equation 4: Possible linear and logarithmic relationships between capital cost and efficiency.

$$E' = (1 + a \bullet x) \bullet E \qquad a = 0.5, 1, 2$$

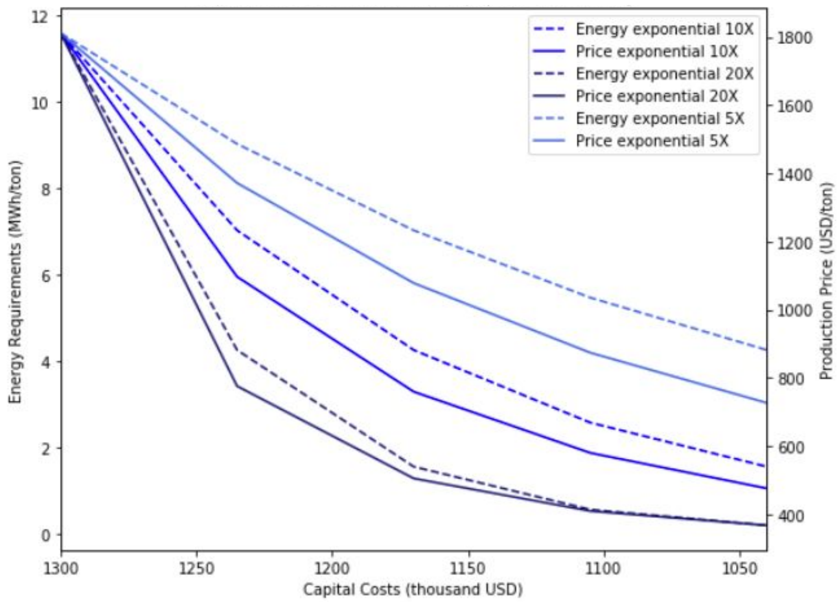
$$E' = E \bullet e^{-(a \bullet x)} \qquad a = 5, 10, 20$$

Figure 13: *Effect on breakeven price of production if efficiency decreases linearly with capital costs. Capital costs of ammonia equipment are reduced in 5% increments and plugged into linear functions with different slopes. Here, energy usage increases to represent the result of using cheaper, yet less energetically efficient equipment. Dotted lines show energy requirements for ammonia synthesis, and solid lines show its resulting production price.*



We find that only a logarithmic relationship (see Equation 4) is sufficient to justify a decrease in efficiency of synthesis equipment for a decrease in capital costs. Yet even here, the slowly decreasing exponential relationship shows a close to linear decrease in cost despite an exponential decrease in capital costs with efficiency.

Figure 14: *Effect on price of production if efficiency decreases logarithmically with capital costs. Capital costs of ammonia equipment are reduced in 5% increments and plugged into exponential functions with different coefficients. Dotted and solid lines represent energy requirements and production price as in Figure 10.*



It was challenging to determine accurate relationships between the capital costs and efficiency of ammonia synthesis, since data on less efficient versions of any equipment, not just ammonia related, is not widely publicized. If the relationship is closer to linear than logarithmic, it may actually not be worth it to purchase less efficient equipment at a lower capital cost. However, less efficient equipment can tend to be more robust so perhaps doing so would also result in lower operation and maintenance costs for the ammonia facility. Since those costs have the second highest impact on the price of production, as demonstrated in the Cost Multipliers section, it may be worth investigating this relationship as well, although as noted it would be difficult to draw conclusions without empirical data.

Discussion

Environmental Impacts

Anhydrous ammonia (NH_3) is a clear, colorless gas at standard temperature and pressure conditions, and has a very characteristic odor noticeable at only 50 parts per million (ppm). Bringing NH_3 from a compressed, cooled liquid to atmospheric pressure can cause it to rapidly expand and drop to below freezing temperatures, while at 16 - 25% volume in air it becomes flammable.[80] As a producer of anhydrous ammonia, we must consider the risks of leakage, both on site and during transport. When NH_3 ammonia comes in contact with water, which it has a strong affinity for, it forms an alkali that chemically burns animal tissue; since we are tapping water on site, contamination of the water supply is another major risk to consider.[81] One of the most high risk points occurs in handling ammonia during transfer into or out of storage containers; to address this, containers with excess flow and back pressure check valves inside will be used to quickly control any leaks.[82] Workers on site will of course be required to wear industry standard protective gear at all times. Similarly, mandating slow driving speeds (40 km/hr at most) will help reduce the risks of damaging the storage tanks and causing leaks while on the road.[83]

Clearly, the production, storage, and transport of anhydrous ammonia is not without significant risks. However, as this process has been perfected over the decades, there already exists a plethora of regulations and equipment necessary to combat any leakage or production of NO_x pollutants.[84] Controlling the release of NO_x pollutants in an ammonia based economy is also relatively straightforward, as the burning of gasoline also releases the same pollutants, which is controlled through the installation of a catalytic converter on all vehicles.[85] As the ultimate use of ammonia currently is fertilizer, some studies even indicate a potential for carbon sequestration through a carbon free ammonia production process.[86] Therefore "green ammonia," has huge potential to avert CO_2 emissions and the cascade of environmental trauma those emissions cause. By conducting regular equipment quality checks and implementing strict safety protocols, we can minimize the risks of producing ammonia and offer the benefits of a cleanly produced dual fertilizer and clean fuel.

With regards to our wind farm, it has been well documented that there is minimal environmental impact of wind turbines on local wildlife.[87] The amount of bird deaths due to collisions with wind turbines is drastically outnumbered by the number of bird deaths caused by tall buildings, automobiles and even house cats.[88, 89] The environmental challenges of wind farms are less environmental than they are aesthetic and political. We will need to overcome them through interacting early and frequently with the local community prior to construction, and establishing strong relations based on good faith.

Local Challenges and Opportunities

For many wind farms, shadow flicker and ambient noise pose significant challenges in winning over community support for such projects. However, we believe both these problems will not be significant barriers due to the location of our facility. While shadow flicker can be detected as far as 1500 meters (4921 ft) away for turbines of 80 meters or taller, distances beyond 1000 meters (3281 ft) are relatively low in flicker intensity.[90] The wind-ammonia power plant is bounded in the east by a highway, meaning that there are no residents living in the area where shadow flicker would cause the greatest annoyance in the late afternoon and early evening. As the sun is rising in the morning, the majority of people will be at work or on their way to work. Therefore, while there is an RV park and a few homes half a mile west, we believe we will be able to convince these residents that the shadow flicker will pose minimal disruption to their lives as they are sufficiently far away and will most likely not even be at home at the time when shadow flicker could possible reach their area.

What may pose a greater issue is the combination of noise from the ammonia facility and shadow flicker for the auto dealership across the street. While we are confident that ambient noise would not be noticeable for residents located half a mile away, the dealership across the street will essentially be experiencing the same amount of noise as the facility grounds itself.[91] As the dealership is to the north of the plant, it will also almost constantly be in line of shadow flicker. We may have to negotiate with the owner of this facility to determine what would need to be done to minimize the impact of shadow flicker and set up sound reduction barriers.[92]

Despite these potential challenges, we believe there is a great opportunity to develop a wind-ammonia power plant at this location. For one, a poll of Hart residents in 2017 showed that 73 percent of respondents saw a future need for manufacturing facilities.[93] While the sample size for this survey was only 66 individuals out of the approximately 2000 individuals that live within Hart itself, the data serves as at least a positive indication of the individuals most involved in city politics and planning.[94]

Furthermore, Hart was established around the fruit farming industry and is mostly still a community surrounded by many farmland.[88] As a result, our facility could become the local supplier of ammonia fertilizer to these farms, as our delivery costs would be significantly lower than any competitor in the region. This alone could prove to be a strong political force in favor of constructing our wind to ammonia facility, as lower fertilizer costs increase profits for farmers, who would most likely be reinvesting those profits within the community itself. Logistically, the property we are looking at is already zoned for commercial and industrial use, so there would most likely be few permitting hurdles to overcome.

Finally, the construction and operation of this wind-ammonia power plant would create many new job openings (we anticipate needing 50 workers to run the facility, not including drivers to transport the ammonia). Our project could provide a much needed boost to this small and economically stagnant community, and would represent a strong investment in an energy system for the future.

The Hydrogen-Ammonia Economy

The term “hydrogen economy” itself was coined by John Bockris during a talk given at General Motors in 1970.[95] The hydrogen economy has been receiving increasingly frenzied attention in recent years because of the potential for hydrogen as a perhaps the cleanest carbon-free fuel (it’s only byproduct is pure water). Although it seems ideal, from a numbers standpoint a hydrogen economy is actually quite cost ineffective. More energy is needed to isolate hydrogen from natural compounds than can ever be recovered from its use, making hydrogen fuel in some senses a wasteful fuel.[96] Compression and storage of liquid hydrogen also results in a much lower hydrogen density (less than 8 kg H_2 per 100 L) than that of anhydrous ammonia (10.7 kg H_2 per 100 L).[97]

Despite these drawbacks to hydrogen, there is markedly less attention around the end uses of ammonia and how an ammonia economy could play a substantially larger role than a hydrogen economy. Most of the discussion around ammonia is as a hydrogen carrier and intermediate storage mechanism within the hydrogen economy. Yet the coupling of ammonia production with intermittent renewables, its ability to be used in diesel engines, and the infrastructure that already exists for bulk ammonia transport (pipelines, tankers, rail, truck, and barge), make an ammonia economy not only closer within reach given existing technology but also much more cost effective.

Conclusion

We see the future of renewable energy in part as riding on technological breakthroughs, but equally importantly on creative combinations of energy systems. This paper demonstrates the potential for an economically viable combined wind and ammonia power plant that not only is run entirely carbon-free, but whose product serves the triple purpose of fertilizer, carbon-free fuel, and dense energy storage.

One of the most appealing things about this hybridization is its ability to be applied to a variety of renewable energy, including onshore wind, offshore wind, solar. Cheap storage is often hailed as the holy grail of the low-carbon energy system, for it would allow us to take far greater advantage of renewable resources and significantly increase their penetration of the electric grid. Anhydrous ammonia may not be quite a holy grail due to its toxicity, but it is certainly a vastly more cost effective method of storing renewable energy than current battery technology, and a vastly more location agnostic (and even environmentally favorable) method than pumped hydro.

Anhydrous ammonia production using onshore wind as an energy source is clearly not without risks and challenges. Looking forward, the biggest hurdle may simply be extremely high capital costs, a running theme in renewable energy projects. Finding investors willing to finance such high cost projects is often prohibitively difficult. However, even with liberal cost estimates, we would be able to sell the ammonia produced by our plant at a price competitive with natural gas plants (lower end estimate) and with coal and other electrolysis plants (higher end estimate). This is a positive indication that if scaled up, our proposed design could be even more cost competitive. Together with existing, mature ammonia infrastructure and the acute need for smoothing out the power curve of renewables like wind, this project demonstrates great potential for the partnership of renewable energy and ammonia in building a more sustainable future.

Endnotes

1. Apodaca, Lori. “USGS Mineral Commodity Summary Nitrogen (Fixed) - Ammonia 2020.” U.S. Department of the Interior, January 2020. https://pubs.usgs.gov/periodicals/mcs2020/mcs2020-nitrogen.pdf.
2. Apodaca, Lori. “USGS Mineral Commodity Summary Nitrogen (Fixed) - Ammonia 2019.” U.S. Department of the Interior, January 2019. https://prd-wret.s3-us-west-2.amazonaws.com/assets/palladium/production/atoms/files/mcs-2019-nitro.pdf.
3. Ritchie, Hannah. “How Many People Does Synthetic Fertilizer Feed?” Our World in Data, November 7, 2017. https://ourworldindata.org/how-many-people-does-synthetic-fertilizer-feed.
4. Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. World Meteorological Organization, Geneva, Switzerland, 32 pp. https://www.ipcc.ch/sr15/chapter/spm/
5. “Ammonia Benchmarks,” Industrial Efficiency Technology Databnase, April 30, 2013, http://www.iipinetwork.org/wp-content/Ietd/content/ammonia.html#benchmarks.
6. Alkusayer, Khalid Tawfik. “Ammonia Synthesis for Fertilizer Production,” 2015.
7. Bartels, Jeffrey Ralph. “A Feasibility Study of Implementing an Ammonia Economy,” 2008.
8. NH3 Fuel Association. “Introduction to NH3 Fuel.” Accessed May 6, 2020. https://nh3fuelassociation.org/introduction/
9. Gibbs, Yvonne. “NASA Armstrong Fact Sheets - X-15 Hypersonic Research Program.” NASA. Brian Dunbar, August 13, 2015. http://www.nasa.gov/centers/armstrong/news/FactSheets/FS-052-DFRC.html.
10. Valera-Medina, A, H Xiao, M Owen-Jones, W. I. F. David, and P. J. Bowen. “Ammonia for Power.” Progress in Energy and Combustion Science 69 (November 1, 2018): 63–102. https://doi.org/10.1016/j.pecs.2018.07.001
11. Soloveichik, Grigorii. “Ammonia as Virtual Hydrogen Carrier.” November 16, 2016. https://www.energy.gov/sites/prod/files/2016/12/f34/fcto_h2atscale_workshop_soloveichik.pdf.
12. Andreassen, Knut. “Hydrogen Production by Electrolysis.” In Hydrogen Power: Theoretical and Engineering Solutions, edited by T. O. Saetre, 91–102. Dordrecht: Springer Netherlands, 1998. https://doi.org/10.1007/978-94-015-9054-9_11
13. Organization, UN Industrial Development, and Int’l Fertilizer Development Center, eds. Fertilizer Manual. Springer Netherlands, 1998. http://www.springer.com/gp/book/9780792350323.
14. Grimes, P. G. “Energy Depot Fuel Production and Utilization.” SAE Transactions 74 (1966): 281–326.
15. Dubey, Michael. "Conversion and storage of wind energy as nitrogenous fertilizer." In 12th Intersociety Energy Conversion Engineering Conference, pp. 525-532. 1977.
16. Dubey, Michael. "Technical and economic feasibility of making fertilizer from wind energy, water, and air." In Sun: Mankind's Future Source of Energy, pp. 1812-1821. Pergamon, 1978.
17. Energy.gov. “Advantages and Challenges of Wind Energy,” May 6, 2020. https://www.energy.gov/eere/wind/advantages-and-challenges-wind-energy.
18. Kuijp, Tsering Jan van der, Lei Huang, and Christopher R. Cherry. “Health Hazards of China’s Lead-Acid Battery Industry: A Review of Its Market Drivers, Production Processes, and Health Impacts.” Environmental Health 12, no. 1 (August 3, 2013): 61. https://doi.org/10.1186/1476-069X-12-61.
19. ColdwellBankerHomes.com. “100 Acres Polk Rd, Hart, MI 49420 - MLS 19018128 - Coldwell Banker,” May 5, 2020. https://www.coldwellbankerhomes.com/mi/hart/100-acres-polk-rd/pid_30121874/.
20. “Wind Speed of Michigan at 100 Meters.” AWS Truewind, 2003. https://www.michigan.gov/documents/dleg/MI_Final_SPD100m_090904_239026_7.pdf.
21. Nowatzki, John. “Anhydrous Ammonia: Managing The Risks.” North Dakota State University, 2016. https://www.ag.ndsu.edu/publications/crops/anhydrous-ammonia-managing-the-risks.
22. Taylor, Derek. “Chapter 7 - Wind Energy.” In *Energy Systems and Sustainability: Power for a Sustainable Future*, 297–356. Oxford Univerity Press, 2012.

23. GE Renewable Energy. "2MW Onshore Wind Trubine Platform," May 6, 2020. https://www.ge.com/renewableenergy/wind-energy/onshore-wind/2mw-platform.
24. Vestas. "V120-2.2 MW™ at a Glance," May 6, 2020. https://www.vestas.com/en/products/2 mw platform/v120 22_mw.
25. Li Fusheng, Li Ruisheng, and Zhou Fengquan, "Chapter 3 - Microgrid and Distributed Generation," in *Microgrid Technology and Engineering Application*, ed. Li Fusheng, Li Ruisheng, and Zhou Fengquan (Oxford: Academic Press, 2016), 29–46, https://doi.org/10.1016/B978-0-12-803598-6.00003-6.
26. Wind Exchange U.S. Department of Energy. "Michigan 110-Meter Potential Wind Capacity Map." Accessed May 6, 2020. https://windexchange.energy.gov/maps-data/191.
27. Morgan, Eric R. "Techno-Economic Feasibility Study of Ammonia Plants Powered by Offshore Wind," 2013, p. 212. https://scholarworks.umass.edu/open_access_dissertations/697/.
28. Morgan, Eric R. "Techno-Economic Feasibility Study of Ammonia Plants Powered by Offshore Wind," 2013, p 212. https://scholarworks.umass.edu/open_access_dissertations/697/.
29. Hardenburger, Thomas L., and Matthew Ennis. "Nitrogen." In *Kirk-Othmer Encyclopedia of Chemical Technology*. American Cancer Society, 2005. https://doi.org/10.1002/0471238961.1409201808011804.a01.pub2.
30. Morgan, Eric R. "Techno-Economic Feasibility Study of Ammonia Plants Powered by Offshore Wind," 2013, p 65. https://scholarworks.umass.edu/open_access_dissertations/697/.
31. Compressed Gas Technologies. "Nitrogen Generators How It Works," May 6, 2020. https://nitrogen-generators.com/nitrogen-generators-how-it-works/.
32. Compressed Gas Technologies. "Membrane Nitrogen Generators (PMNG)," May 6, 2020. https://nitrogen-generators.com/generators/pmng-membrane-nitrogen-generators/.
33. Morgan, Eric R. "Techno-Economic Feasibility Study of Ammonia Plants Powered by Offshore Wind," 2013, p. 66. https://scholarworks.umass.edu/open_access_dissertations/697/.
34. Morgan, Eric R. "Techno-Economic Feasibility Study of Ammonia Plants Powered by Offshore Wind," 2013, p. 212. https://scholarworks.umass.edu/open_access_dissertations/697/.
35. Kroposki, B., J. Levene, K. Harrison, P.K. Sen, and F. Novachek. "Electrolysis: Information and Opportunities for Electric Power Utilities," September 1, 2006. https://doi.org/10.2172/892998.
36. Gazey, R., S. K. Salman, and D. D. Aklil-D'Halluin. "A Field Application Experience of Integrating Hydrogen Technology with Wind Power in a Remote Island Location." *Journal of Power Sources*, Selected papers presented at the Ninth Grove Fuel Cell Symposium, 157, no. 2 (July 3, 2006): 841–47. https://doi.org/10.1016/j.jpowsour.2005.11.084.
37. Morgan, Eric R. "Techno-Economic Feasibility Study of Ammonia Plants Powered by Offshore Wind," 2013, p. 57. https://scholarworks.umass.edu/open_access_dissertations/697/
38. Energy.gov. "Hydrogen Production: Natural Gas Reforming." Accessed May 6, 2020. https://www.energy.gov/eere/fuelcells/hydrogen-production-natural-gas-reforming.
39. "USGS Groundwater for Michigan: Water Levels Oceana County." U.S. Department of the Interior, May 6, 2020. https://nwis.waterdata.usgs.gov/mi/nwis/gwlevels/?site_no=434020086302801.
40. "8.1 Synthetic Ammonia." In *AP 42, Fifth Edition, Volume 1*. U.S. Environmental Protection Agency, 1995. https://www3.epa.gov/ttnchie1/ap42/ch08/final/c08s01.pdf.
41. Hochman, Gal, Alan Goldman, Frank A. Felder, James Mayer, Alexander Miller, Patrick L. Holland, Leo Goldman, Pritricia Manocha, Ze Song, and Saketh Aleti. "The potential economic feasibility of direct electrochemical nitrogen reduction as a route to ammonia." (2019).
42. Morgan, Eric R. "Techno-Economic Feasibility Study of Ammonia Plants Powered by Offshore Wind," 2013, p. 73. https://scholarworks.umass.edu/open_access_dissertations/697/.
43. Emoscopes. *Centrifugal Compressor*. December 14, 2005. https://en.wikipedia.org/w/index.php?title=Centrifugal_compressor&oldid=945948852.
44. Sam Mannan, ed., "Chapter 12 - Pressure System Design," in *Lees' Loss Prevention in the Process Industries (Fourth Edition)* (Oxford: Butterworth-Heinemann, 2012), 509–617, https://doi.org/10.1016/B978-0-12-397189-0.00012-4.
45. Cussler, Edward, Alon McCormick, Michael Reese, and Mahdi Malmali. "Ammonia Synthesis at Low Pressure." *Journal of Visualized Experiments : JoVE*, no. 126 (August 23, 2017). https://doi.org/10.3791/55691.
46. Rempfer, L. E. "100# Air Centrifugal or Reciprocating." Purdue University, no. Paper 131 (1974). https://docs.lib.purdue.edu/cgi/viewcontent.cgi?article=1130&context=icec.

47. Lan, Rong, John T. S. Irvine, and Shanwen Tao. "Synthesis of Ammonia Directly from Air and Water at Ambient Temperature and Pressure." *Scientific Reports* 3, no. 1 (January 29, 2013): 1–7. https://doi.org/10.1038/srep01145.
48. Cussler, Edward, Alon McCormick, Michael Reese, and Mahdi Malmali. "Ammonia Synthesis at Low Pressure." *Journal of Visualized Experiments : JoVE*, no. 126 (August 23, 2017). https://doi.org/10.3791/55691.
49. National Center for Biotechnology Information. PubChem Database. Ammonia, CID=222, Accessed on May 6, 2020. https://pubchem.ncbi.nlm.nih.gov/compound/Ammonia.
50. Williams, Francis E. *Flow Diagram for the Production of Ammonia*. December 2, 2010. https://en.wikipedia.org/w/index.php?title=Haber_process&oldid=954452965.
51. Morgan, Eric R. "Techno-Economic Feasibility Study of Ammonia Plants Powered by Offshore Wind," 2013, p. 201 - 202. https://scholarworks.umass.edu/open_access_dissertations/697/.
52. Gillespie, Donald E, Shawn Grannell, and Casey Stack. "How It Works." NH3 Car, 2008. http://nh3car.com.
53. Hydrofuel Inc. "Green Ammonia: Manufacturing and Utilization Technologies and Research." Presented at the REFUEL launch, August 18, 2017. https://arpa-e.energy.gov/sites/default/files/1%20Hydrofuel%20-%20UOIT%20Presentation%20for%20ARPA-E%20Aug.%2017-18%2C%202017%20FINAL.pdf.
54. Soloveichik, Grigorii. "Ammonia as Virtual Hydrogen Carrier." November 16, 2016. https://www.energy.gov/sites/prod/files/2016/12/f34/fcto_h2atscale_workshop_soloveichik.pdf.
55. Wiser, Ryan, Mark Bolinger, Galen Barbose, Naim Darghouth, Ben Hoen, Andrew Mills, Joe Rand, et al. "2018 Wind Technologies Market Report." *U.S. Department of Energy*, 2018, 103.
56. Morgan, Eric R. "Techno-Economic Feasibility Study of Ammonia Plants Powered by Offshore Wind," 2013, p. 207. https://scholarworks.umass.edu/open_access_dissertations/697/.
57. Morgan, Eric R. "Techno-Economic Feasibility Study of Ammonia Plants Powered by Offshore Wind," 2013, p. 235. https://scholarworks.umass.edu/open_access_dissertations/697/.
58. "Lazard's Levelized Cost of Energy Analysis." *Lazard*, September 2014, 20. https://www.lazard.com/media/1777/levelized_cost_of_energy_-_version_80.pdf.
59. ColdwellBankerHomes.com. "100 Acres Polk Rd, Hart, MI 49420 - MLS 19018128 - Coldwell Banker," May 5, 2020. https://www.coldwellbankerhomes.com/mi/hart/100-acres-polk-rd/pid_30121874/.
60. Home Advisor. "Well Drilling Cost," May 6, 2020. https://www.homeadvisor.com/cost/landscape/drill-a-well/.
61. Wiser, Ryan, Mark Bolinger, Galen Barbose, Naim Darghouth, Ben Hoen, Andrew Mills, Joe Rand, et al. "2018 Wind Technologies Market Report." *U.S. Department of Energy*, 2018, 103.
62. "Lazard's Levelized Cost of Energy Analysis." *Lazard*, September 2014, 20. https://www.lazard.com/media/1777/levelized_cost_of_energy_-_version_80.pdf.
63. Morgan, Eric R. "Techno-Economic Feasibility Study of Ammonia Plants Powered by Offshore Wind," 2013, p. 207. https://scholarworks.umass.edu/open_access_dissertations/697/.
64. Morgan, Eric R. "Techno-Economic Feasibility Study of Ammonia Plants Powered by Offshore Wind," 2013, p. 235. https://scholarworks.umass.edu/open_access_dissertations/697/.
65. Guzman, Gloria G. "American Community Survey Briefs." *U.S. Census Bureau*, September 2019, 13.
66. "Lazard's Levelized Cost of Energy Analysis." *Lazard*, September 2014, 20. https://www.lazard.com/media/1777/levelized_cost_of_energy_-_version_80.pdf.
67. Hochman, Gal, Alan Goldman, Frank A. Felder, James Mayer, Alexander Miller, Patrick L. Holland, Leo Goldman, Pritricia Manocha, Ze Song, and Saketh Aleti. "The Potential Economic Feasibility of Direct Electrochemical Nitrogen Reduction as a Route to Ammonia," 2019.
68. Guzman, Gloria G. "American Community Survey Briefs." *U.S. Census Bureau*, September 2019, 13.
69. Mone, Christopher, Maureen Hand, Mark Bolinger, Joseph Rand, Donna Heimiller, and Jonathan Ho. "2015 Cost of Wind Energy Review," April 5, 2017. https://doi.org/10.2172/1351062.
70. "Annual Technology Baseline: Electricity." *National Renewable Energy Laboratory*, https://atb.nrel.gov/electricity/2019/index.html?t=lw. Accessed 7 May 2020.
71. Brown, Trevor. "The Capital Intensity of Small-Scale Ammonia Plants." *AMMONIA INDUSTRY* , January 19, 2018. https://ammoniaindustry.com/the-capital-intensity-of-small-scale-ammonia-plants/.
72. Brown, Trevor. "Ammonia Plant Cost Comparisons: Natural Gas, Coal, or Electrolysis?" *AMMONIA INDUSTRY* , August 11, 2017. https://ammoniaindustry.com/ammonia-plant-cost-comparisons-natural-gas-coal-or-electrolysis/.

73. Hochman, Gal, Alan Goldman, Frank A. Felder, James Mayer, Alexander Miller, Patrick L. Holland, Leo Goldman, Pritricia Manocha, Ze Song, and Saketh Aleti. "The potential economic feasibility of direct electrochemical nitrogen reduction as a route to ammonia." (2019).
74. Thomas, George, and George Parks. "Potential Roles of Ammonia in a Hydrogen Economy: A Study of Issues Related to the Use of Ammonia for on-Board Vehicular Hydrogen Storage." *US Department of Energy* 23 (2006).
75. Amos, W A. "Costs of Storing and Transporting Hydrogen." National Renewable Energy Lab (NREL), January 27, 1999. https://doi.org/10.2172/6574.
76. Amos, W A. "Costs of Storing and Transporting Hydrogen." National Renewable Energy Lab (NREL), January 27, 1999. https://doi.org/10.2172/6574.
77. McKinnon, Alan Campbell, and Maja Piecyk. "Measuring and Managing CO2 Emissions in European Chemical Transport." European Chemical Industry Council, 2010. https://cefic.org/app/uploads/2018/12/MeasuringAndManagingCO2EmissionOfEuropeanTransport-McKinnon-24.01.2011-REPORT_TRANSPORT_AND_LOGISTICS.pdf.
78. Brown, Trevor. "Heavy-Duty Diesel Trucks to Be Converted to Use Ammonia Fuel in Canada." *Ammonia Energy Association* (blog). Accessed May 6, 2020. https://www.ammoniaenergy.org/articles/heavy-duty-diesel-trucks-to-be-converted-to-use-ammonia-fuel-in-canada/.
79. Hattenbach, Ray. "Transportation & Delivery of Anhydrous Ammonia." 2012.
80. Tanner Industries. "Anhydrous Ammonia Material Safety Data Sheet," January 2011. http://www.tannerind.com/anhydrous-msds.html.
81. Phillips, Jennifer. "Control and Pollution Prevention Options for Ammonia Emissions." U.S. Environmental Protection Agency, 1995.
82. Occupational Safety and Health Administration. Storage and handling of anhydrous ammonia, Pub. L. No. 1910.111. Accessed May 6, 2020. https://www.osha.gov/laws-regs/regulations/standardnumber/1910/1910.111.
83. Nowatzki, John. "Anhydrous Ammonia: Managing The Risks." North Dakota State University, 2016. https://www.ag.ndsu.edu/publications/crops/anhydrous-ammonia-managing-the-risks.
84. Phillips, Jennifer. "Control and Pollution Prevention Options for Ammonia Emissions." U.S. Environmental Protection Agency, 1995.
85. Chemistry LibreTexts. "Catalytic Converters," October 2, 2013. https://chem.libretexts.org/Bookshelves/Physical_and_Theoretical_Chemistry_Textbook_Maps/Supplemental_Modules_(Physical_and_Theoretical_Chemistry)/Kinetics/Case_Studies%3A_Kinetics/Catalytic_Converters.
86. Erisman, Jan Willem, Mark A. Sutton, James Galloway, Zbigniew Klimont, and Wilfried Winiwarter. "How a Century of Ammonia Synthesis Changed the World." *Nature Geoscience* 1, no. 10 (October 2008): 636–39. https://doi.org/10.1038/ngeo325.
87. Wiser, Ryan, Mark Bolinger, Galen Barbose, Naim Darghouth, Ben Hoen, Andrew Mills, Joe Rand, et al. "2018 Wind Technologies Market Report." *U.S. Department of Energy*, 2018, 103.
88. Miao, Ruiqing, Prasenjit N. Ghosh, Madhu Khanna, Weiwei Wang, and Jian Rong. "Effect of Wind Turbines on Bird Abundance: A National Scale Analysis Based on Fixed Effects Models." *Energy Policy* 132 (September 1, 2019): 357–66. https://doi.org/10.1016/j.enpol.2019.04.040.
89. Sovacool, Benjamin K. "Contextualizing Avian Mortality: A Preliminary Appraisal of Bird and Bat Fatalities from Wind, Fossil-Fuel, and Nuclear Electricity." *Energy Policy*, China Energy Efficiency, 37, no. 6 (June 1, 2009): 2241–48. https://doi.org/10.1016/j.enpol.2009.02.011.
90. Tetra Tech. "Shadow Flicker Impact Analysis for the Wilton IV Wind Energy Center," September 2014. https://www.wapa.gov/regions/UGP/Environment/Documents/WiltonIVShadowFlicker090814.pdf.
91. Kellner, Tomas. "How Much Noise Does A Wind Turbine Make?" GE Reports, August 2, 2014. https://www.ge.com/reports/post/92442325225/how-loud-is-a-wind-turbine/.
92. Wind Exchange U.S. Department of Energy. "Wind Turbine Sound," May 6, 2020. https://windexchange.energy.gov/projects/sound.
93. "City of Hart 2017 Master Plan." Hart City Council, December 19, 2017. https://cityofhart.org/documents/Hart_Master_Plan_Adopted_12-19-17-reduced_Y59eA.pdf.
94. United States Census Bureau. "Hart Michigan Demographic and Housing Estimates," May 6, 2020. https://data.census.gov/cedsci/table?q=hart,%20michigan&g=1600000US2636920&hidePreview=false&tid=ACSDP5Y2018.DP05&vintage=2018&layer=VT_2018_160_00_PY_D1&cid=DP05_0001E.
95. "The History of Hydrogren." U.S. Department of Energy, 2010. https://web.archive.org/web/20100714141058/http://www.hydrogenassociation.org/general/factSheet_history.pdf.

96. Bossel, Ulf. “Does a Hydrogen Economy Make Sense?” Proceedings of the IEEE. Vol. 94, No. 10, October 2006.
97. Kojima, Yoshisugu. “Liquid Ammonia for Hydrogen Storage.” NH3 Fuel Association, September 6, 2014. https://nh3fuelassociation.org/2014/09/06/liquid-ammonia-for-hydrogen-storage/.