# Can Land-Based Wind Farms Decarbonize Agriculture and Ocean Cargo Shipping?

Ammonia production and cargo shipping account for roughly 5% of greenhouse gas emissions. See footnote 1. In this Report we conclude that eliminating this 5% of GHG by using green hydrogen produced by electrolysers will require 7,100,000,000,000 kWh per year or 7.1 TWh/yr of renewable power. To generate 7.1 TWh/yr using land-based wind farms will require 115,785,900 acres of land. To replace present-day ammonia with green ammonia will require 1.7 TWh from 27,723,300 acres See footnote 2. To produce enough additional green ammonia to fuel a cargo shipping fleet as large as the present-day fleet will require 5.4 TWh from 88,062,600 acres. See footnote 3. These acreage calculations assume that the electrolysers used will require 50 kilowatt-hours for each kilogram of hydrogen produced. As electrolyser efficiency improves, and the electricity required to produce each kilogram of hydrogen is reduced, eventually approaching 40 kWh/kg, the reduction in the acres required approaches 20%. See footnote 9.

We consider these agriculture and shipping together because of a flurry of activity in the Middle East regarding the production of green ammonia on a very large scale and the adoption of ammonia as a fuel for large ships, including work that is the subject of ten announcements, listed, with links, in footnote 8:

About 80% of ammonia is used in fertilizer and about 65% of all fertilizers are nitrogen, and, therefore, ammonia-based. https://ourworldindata.org/fertilizers#explore-data-on-fertilizers Greening ammonia will substantially decarbonize agriculture, but greening the phosphate- and potassium-based fertilizers means greening the required mining. Decarbonizing the mining industry will be the topic of a separate Research Report.

According to the International Energy Agency's 2022 Global Hydrogen Review at page 29, global ammonia production used about 34 megatons (34,000,000,000 kg) of hydrogen. Our research suggests 92,411 land-based 6MW wind turbines could supply enough renewable electricity to the appropriate number of electrolysers to generate this amount of green hydrogen. See footnote 2.

One 6MW turbine with a blade swing diameter of 400'and blade swing area of 125,664 sq ft might be installed on five acres of land, or even three acres, suggesting a density of 1.2 to 2.0 MW per acre, but utility scale windfarms cannot operate at such high densities. In the US, large western windfarms typically use 50 to 80 acres per installed MW.
http://www.aweo.org/windarea.html
A recently permitted wind farm in Maine is expected to locate 126 MW on 16,580 acres of land, or 131 acres per installed megawatt. largely because of the mountain ridge location, and, like other large wind farms, because of the need for access and service roads, generator lead lines, and support buildings, all required to obtain an operating permit. In this report we are assuming an optimistic 50 acres per installed megawatt in recognition of strides being made in wind farm design. Even with this optimistic assumption, 6 MW turbines, in a large array, require 300 acres each and 92,411 such turbines require 27,723,300 acres of land. See footnote 2.

An  International Maritime Organization February 20, 2022 statement puts maritime fuel use at "over" 300 million tons per year; the USDOE, reporting in gallons, says shipping uses 105 billion (105,000,000,000) gallons.  Ammonia has roughly half the energy per gallon as the heavy fossil fuels used now, suggesting that completely replacing  fossil fuels in shipping would require over 600,000,000 tons or 221,000,000,000  gallons of ammonia per year. This is an order of magnitude more than all of 3021's ammonia production. Approximately 180 kg of H2 is required for each ton of ammonia. Using the same calculations used for replacing today's ammonia with green ammonia, we can determine that producing enough additional green ammonia to power the shipping fleet requires an additional 293,542 turbines on 88,062,600 acres of land. See footnote 3.

Consequently, a total of 115,785,900 acres of 6MW 35%-capacity factor wind turbines, producing a yearly total of 7,100,000,000,000 kWh is required to both replace present-day ammonia with green ammonia and produce enough additional green ammonia to fuel a shipping fleet as large as the present day fleet.

For comparison, it would require 711 nuclear power plants the size of New Hampshire's Seabrook station, located on 639,900 acres to generate enough electricity to power enough electrolysers to make enough hydrogen to use to make a sufficient amount of green ammonia to replace today's ammonia,  and enough additional green ammonia to power the shipping fleet. See footnote 4.

As daunting as the need for this much land may seem, whether 115,785,900 acres for land-based wind, or 639,000 acres for nuclear power plants, we remind ourselves:

a) federal and state governments owns 136,000,000 acres of land in Arizona, Nevada and Wyoming. See Footnote 5

b) Based on only slightly older data, we calculate that only 1,787,873 acres of land would be required to replace current US-only ammonia production with green ammonia production. See Footnote 6.

c) NEOM Hydrogen's site in Saudi Arabia is over 256,000 acres and expects to produce 201,000,000 kg H2 per year from solar and wind working together in the same location.

d) Ten countries, led by Australia in number of facilities, already have green hydrogen production facilities. They include Chile, on track to develop its southern Patagonia wind resource into a green hydrogen exporting power.

https://www.statista.com/statistics/1311948/number-of-green-hydrogen-plants-by-country/

https://www.imf.org/en/Publications/fandd/issues/2022/12/country-case-chile-bet-on-green-hydrogen-Bartlett

e) land rich areas of Africa, India China have detailed green hydrogen "road maps" for significant green hydrogen development https://mnre.gov.in/img/documents/uploads/file_f-1673581748609.pdf

https://asia.nikkei.com/Spotlight/Caixin/China-s-hydrogen-roadmap-4-things-to-know

https://www.csis.org/analysis/south-africas-hydrogen-strategy

In cases where electrolysers cannot be co-located with a wind (or solar) farm, the additional land area required for off-site electrolysers must be considered. The world's largest electrolyser is Mingyang's 225 kg/hr machine. To generate the enough green H2 rfor both replacing existing ammonia and fueling the cargo ship fleet, 84,758 such electrolysers on 67,807 acres would be required. See footnote 7. Such an acreage requirement contemplates  centralized production and further distribution. If, however, a sufficiently robust transmission system is developed for the renewable power, decentralized green hydrogen and green ammonia production at or near agricultural end-users' locations and bulk shipper locations, will result in a larger number of smaller land areas being devoted to the eletrolysers.

This report highlights the scale of the decarbonization challenge. Only 5% of GHG emissions is addressed here. The production of electrolysers is growing rapidly but today there is less than 1GW of installed electrolyser capacity in the world, according to IEA, which also estimates that to be on track for net-zero by 2050, more than 700GW will be required by 2030. At the moment, having sufficient HVDC transmission lines is just an aspirational goal. US land area is theoretically ample for land-based wind to support decarbonizing agriculture, but decarbonizing shipping will require substantial help from other countries. Future Research Reports will look at transmission line and pipeline issues and centralized green hydrogen production around the world, comparing the likely pace of progress among the nations seeking to become green hydrogen and green ammonia users and exporters.

Footnotes

Footnote 1.  GHG 5%. The IEA says ammonia production's contribution to GHGs at 1.8%. Other sources say 2%.  Container ships and tankers  accounted for 2% of global CO2 emissions in 2021, according to a September, 2022  IEA report. The US DOE reports shipping's general CO2 contribution as 3%. Despite some disagreement in the statistics, it is fair to say that shipping and ammonia production,  together, are contributing close to 5% of world GHG emissions.

Footnote 2 see next page

Footnote-2

Modified 1/6/23
1/15/23
1/18/23

HYDROGEN FOR GLOBAL AMMONIA PRODUCTION

Global H2 ammonia production uses = $H_G := 34000000$ tons H2

1000 kilograms per ton

kg H2 required for ammonia production = $H_{kg} := 1000 \cdot H_G$ $H_{kg} = 3.4 \times 10^{10}$ kg H2

Power required per kgH2 = $P := 50$ kWh per kgH2

Total power to electrolyze water to H2

$$P_T := P \cdot H_{kg} \qquad P_T = 1.7 \times 10^{12} \qquad P_T = 1700000000000$$ kWh/year

NUMBER OF TURBINES

Turbine capacity = $T_{LB} := 6 \cdot 10^6 \ \frac{W}{Turbine}$

Capacity factor = $C_F := .35$

Operating days per year = $D_Y := 365$

Hours per day = $h := 24$

Land area per megawatt = $L_T := 50$ Acres per megawatt

The number of land turbines of 6-megawatt each requires = $N_T := \frac{1000 P_T}{C_F \cdot T_{LB} \cdot h \cdot D_Y}$ $N_T = 92411$ Turbines

Total land area required for turbines ------------------ = $L_{TA} := 6 \cdot N_T \cdot L_T$ $L_{TA} = 27723418$ acres or 43318 square miles or a square of 208 miles on a side.

For comparison to other wind farm projects the $I_{NDEX}$ is calculated as follows:

$$I_{NDEX} := \frac{N_T \cdot T_{LB} \cdot D_Y \cdot h}{1000 \cdot L_{TA}} \qquad I_{NDEX} = 175200$$ kilowatt hours per acre per year

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Footnote 3

Footnote- 3
Ammonia Production
Global Shipping

Revised
1/9/23
1/15/23
1/18/23

It is estimated that if global shipping were to replace maritime fuel with green ammonia it would require over 600 million tons of ammonia. Further it is known that 180 kilograms of hydrogen are required for each ton of ammonia. The following calculations determine the number of wind turbines and land area that would be required to produce the green hydrogen.

Weight of a gallon of water = 8.34 lb = 3.79 kg

Weight of a gallon of bunker C = same as water

Weight if gallon of ammonia = 6 lb = 2.72 kg.

Power to electrolyze 1 kg H2 --------- $P := 50 \cdot 10^3$ Wh per kgH2

Wind turbine capacity ---------------- $T_{LB} := 6 \cdot 10^6$ Watts per turbine

Capacity factor ----------------------- $C_F := 0.35$

Operating days per year ----------- $D_Y := 365$

Hours per day ------------------------ $h := 24$

Land area per megawatt of turbine capacity -------------------- $L_T := 50$ Acres per megawatt of turbine capacity

Amount of ammonia to replace maritime fuel ----------- $A_M := 600 \cdot 10^6$ tons

Amount of hydrogen per ton of ammonia -------------- $H_{AM} := 180$ kgH2/ton $A_M$

Total amount of hydrogen required for ammonia production ------------------- $H_{kg} := H_{AM} \cdot A_M$ $H_{kg} = 1 \times 10^{11}$ kgH2 per year

Total power to electrolyze the water for hydrogen------------------- $P_T := P \cdot H_{kg}$ $P_T = 5 \times 10^{15}$ watt-hours per year

Number of turbines to generate the power per year -------------------- $N_T := \dfrac{P_T}{T_{LB} \cdot C_F \cdot D_Y \cdot h}$ $N_T = 293542$ Turbines

Total land area to accommodate all turbines -------------------------- $L_{TA} := N_T \cdot L_T \cdot \dfrac{T_{LB}}{10^6}$ $L_{TA} = 88062622$ Acres or 137,598 square miles, or a square of about 370 miles on a side.

For comparison to different projects it is useful to calculate a unit called an $I_{NDEX}$:

$$I_{NDEX} := \frac{N_T \cdot T_{LB} \cdot D_Y \cdot h}{1000 \cdot L_{TA}} \qquad I_{NDEX} = 175200 \text{ kWh/A/y}$$

Footnote 4. Seabrook nuclear power station in New Hampshire is rated at 1246 MW and, in 2017, generated 9990 GWh (=9,990,000,000 kWh). 7,100,000,000,000 kWh required / 9,990,000,000 kWh/yr/power plant = 711 If they all used a site similar in size to Seabrook's 900 acres, it would require 639,900 acres to site all 711 plants.

Footnote 5. https://www.nrcm.org/documents/publiclandownership.pdf

An upside of using land in the desert southwest is the availability of a reliable 29% solar capacity factor, suggesting that the co-location of wind and solar in this area, as in the NEOM Hydrogen project in Saudi Arabia , could reduce substantially the total land area needed to generate the power required. Reaching the goal will be easier if green hydrogen and ammonia are made on the wind/solar farm site. However, a downside to using the desert southwest is water. With Lake Powell and Lake Mead struggling, introducing a new thirsty global-scale industry may not make sense. Instead of locating electrolysers and ammonia plants in the desert with the wind and solar farms, they could be located closer to water, and closer to a hydrogen or ammonia distribution system (pipeline, rail, ship) or near large agricultural or shipping end-users. This, in turn, requires using high voltage direct current electric transmission lines to bring the power from the renewable power source. The Dakotas, too, should be considered. The two states combined own nearly 100,000,000 acres of land. Future Research Reports will take a closer look at the impact of adding solar and off-shore wind to land-based wind, and increasing the capacity factor in other ways,  comparing electric transmission against pipeline or bulk hydrogen and ammonia transportation and managing the water supply.

Footnote 6 next page

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| | 12-12-22 |
| Footnote-6 | 12-30-22 |
| Calculation | 1/9/23 |
| | 1/15/23 |

The world production of ammonia in 2018 was 175 million tons. The United States portion of this production was 7.1%. Nearly all of the required hydrogen was made from SMR; leaving thousands of tons of CO2 as a byproduct. The hydrogen could be made from water in an electrolyzer with electricity made from wind power; not leaving behind any climate harmful byproducts.

The following calculation show the amount of hydrogen, the number of turbines, and the land area to produce the equivalent amont of green ammonia.

The results are repeated here:
Hydrogen = 2.193 giga kilograms = 2.193 million tonnes H2 per year for ammonia production in US only.
Number of turbines = 5960 6-megawatt turbines.
Land area for turbines = 297979 acres, or a little more than 466 square miles equivalent to a square of a little less than 22 miles on a side.
The number of electrolyzers is dependent on the size of the electrolyzers and is shown at the end of this calculation for different capacity electrolyzers calculated from dated from Kapsom.

Ammonia synthesis : $3\,H_2 + N_2 ---> 2\,NH_3$

Annual world production of ammonia, tonnes [1] ---------- $W_{PA} := 175 \cdot 10^6$ tonnes

United States portion of world production, tonnes [2]-------- $US_{\%} := 7.1$ percent

Molecular weight ammonia---------- $MW_A := 34$ molecular wt.

Atomic weight hydrogen---------- $AW_H := 1$ atomic wt.

Power to electrolyze one kg H2, Wh/kg---------- $P := 50000$ Wh/kgH2

Land based wind turbine capacity, Watts---------- $T_{LB} := 6 \cdot 10^6$ Watts/turbine

Land based wind turbine capacity factor---------- $C_F := 35\%$ capacity factor

Land area, acres per megawatt---------- $L_T := 50$ acres per megawatt

Kilograms of H2 for US ammonia consumption---------- $H_{US} := 1000 \cdot W_{PA} \cdot \frac{US_{\%}}{100} \cdot \frac{6}{34}$ $H_{US} = 2.193 \times 10^9$ kg H2 per year required for ammonia production in US only.

NUMBER OF TURBINES

Number of land based turbines ---------- $N_T := \frac{H_{US} \cdot P}{8760 \cdot C_F \cdot T_{LB}}$ $N_T = 5960$ Number of land based turbines.

Footnote 7 Mingyang electrolyser. 24x225x365x.85=1,675,350 kg/year. To generate the 142,000,000,000 kg of green H2 required for both replacing existing ammonia and fueling the cargo ship fleet, 84,758 such electrolysers would be required. At an assumed 0.18 acres per machine, the land area required is approximately 15,257 acres.

Footnote 8

i) the NEOM Green Hydrogen Company's (NGHC) project in Saudi Arabia that will use wind- and solar- powered electrolysers to make green hydrogen to produce green ammonia to be shipped to Rotterdam and other ports around the world. NGHC's partners are NEOM, ACWA Power and Air Products. The Rotterdam facility will not only have green ammonia available for fertilizer companies, it will also separate green hydrogen from green ammonia and distribute that green hydrogen throughout northern Europe for other zero-carbon purposes;

https://www.airproducts.com/news-center/2021/12/1213-air-products-awards-thyssenkrupp-uhde-chlorine-engineers-contract-for-neom

https://www.airproducts.com/news-center/2022/06/0628-air-products-and-gunvor-to-cooperate-on-green-hydrogen-import-terminal-in-rotterdam

ii) Salala H2's January 2020 announcement that its partners, OQ, Marubeni, Linde and Dutco, will invest $1 billion in a green ammonia export project to be powered by 1 GW of wind and solar powering 400MW of electrolysers to supply green H2 to OQ's existing ammonia production plant https://www.ammoniaenergy.org/articles/oman-consortium-to-invest-1-billion-in-green-export-project/ ; and,

iii) Yara International's July 2022 announcement that it will buy 100,000 metric tonnes/year of green ammonia from Scatec ASA's green ammonia plant in Oman, with the expectation that that amount will increase to 1,000,000 metric tonnes per year https://www.pv-magazine-india.com/2022/07/15/acme-scatec-sign-green-ammonia-sale-agreement-with-yara/ .

Additional support for decarbonized shipping comes from announcements by:

i) the Green Hydrogen Coalition and C40 Cities seek to create green shipping corridors worldwide, the first one of which may well be between Shanghai and Los Angeles.

https://www.ghcoalition.org/articles-news/c40-shanghai-green-hydrogen

https://www.c40.org/news/green-shipping-corridors/

ii) Amon Maritime on October 31, 2022 that it will build a fleet of ammonia -powered supply ships for the Norwegian Continental Shelf https://www.amonmaritime.com/offshore/launch-of-amon-offshore-carbon-free-supply-ships-approved-by-class-and-flag/

iii) Greek fleet operator Avin International in  February 2022 that it had taken delivery of an ammonia-ready tanker https://www.ship-technology.com/news/avin-international-ammonia-ready-ship/ .

iv) Hoegh's January 2022 announcement that it has ordered four ammonia-ready car carrier ships, the world's largest, to be built by China Merchants Heavy Industry https://maritime-executive.com/article/hoeegh-orders-world-s-largest-ammonia-ready-car-carriers   ; and,

v) Grimaldi Lines October 2022 order, also placed with China Merchants, for battery-electric hybrid car and truck carriers built to be converted to ammonia at a later date. Four ships have been ordered with another five likely.
https://www.automotivelogistics.media/sustainability/grimaldi-orders-ammonia-ready-dual-fuel-car-carriers/43594.article

FOOTNOTE-9

Electrolyser efficiency is improving. The theoretical power to electrolyse a kilogram of hydrogen from water is 39.7 kWh/kg. Typically, it takes 48 to 50 kWh/kg. However, developments have brought that number down to 41-42 kWh/kg. The following table and chart illustrate the change in land area required for 6-megawatt wind turbines operating electrolysers with a range of power requirements from 40 to 50 kWh/kg.

| kWh/kg of Green Hydrogen Required by Elecrolyser Series1 | Global Wind Farm Land Acres Required for Agricultural Green Ammonia Multiply by 10^6 Series2 | Global Wind Farm Land Acres Required for Cargo Ship Fuel Green Ammonia Multiply by 10^6 Series3 | Total Global Wind Farm Acres Required for Green Ammonia for Agriculture and Ship Fuel Multiply by 10^6 Series4 |
|---|---|---|---|
| 40 | 20.14 | 70.45 | 90.59 |
| 42 | 21.12 | 73.97 | 95.09 |
| 44 | 22.11 | 77.50 | 99.61 |
| 46 | 23.10 | 81.02 | 104.12 |
| 48 | 24.23 | 84.54 | 108.77 |
| 50 | 25.21 | 88.06 | 113.27 |