

1. A Deep-submergence Option for Hydrogen Storage also 2. How Green Ammonia Can Supplant Oil

by

Richard L. Garwin
IBM Fellow Emeritus
IBM Thomas J. Watson Research Center
Yorktown Heights, NY 10598
RLG2@us.ibm.com

Garwin Archive: <https://rlg.fas.org>

Search in any browser with, e.g., [site:rlg.fas.org](https://rlg.fas.org) “breeder reactor” [19 results]

The Ettore Majorana Foundation and Centre for Scientific Culture (EMFCSC)
Hydrogen Symposium

June 12-14, 2022

Toward enabling a decarbonized energy sector in the relatively near future, I present two concepts here. (I have long benefitted from the Centre Ettore Majorana -- a long and happy story.)

Energy storage is of prime importance in smoothing the delivery from intermittent sources such as wind or solar electricity, and also in providing for peak demand throughout the day or week or month. A recent MIT report is a helpful reference,

<https://energy.mit.edu/wp-content/uploads/2022/05/The-Future-of-Energy-Storage.pdf> I will cite it as [FoES]. Storage of green liquid fuel may also enable it to supplant oil in its myriad energy applications.

I discuss here storage and transport of green hydrogen and later of green ammonia, which are very different.

First: A Deep-submergence Option for Hydrogen Storage

I will begin by describing deep-submergence storage of hydrogen either to support local electricity production where the geography allows it, for general support of renewable energy generation on nearby land, or for a large facility at sea supplying liquid hydrogen to specialized tanker fleets.

I judge that green hydrogen can be stored at lowest cost in bladders deeply submerged in the ocean; fuel or water bladders on the ground are widely used for temporary storage of such fluids. To be specific, I assume a unit bladder inside a cylindrical anchoring weight (“ballast”) in the form of a concrete culvert, whose purpose is to prevent the hydrogen-filled bladder from forcefully floating to the surface. For a nominal 1000 cubic meters contained volume of gas, the same culvert can be used at 3,000 m depth as at 1,000 m depth or at 30 m. But the mass of hydrogen, or the MWh of contained energy, is proportional to the density of the hydrogen and thus increases approximately in proportion to the depth.

I take a nominal 500kg H₂ per day per MW feeding the electrolyzer (i.e., 48MWh/tonne-H₂),

<https://www.ammoniaenergy.org/articles/renewable-ammonia-in-sweden/>

Project “Green Wolverine” will feature 600 MW of electrolyzers and produce 500,000 tonnes per year of carbon-free ammonia. [Per day, 1369 tonnes of green ammonia from 600,000 MWd; or 2.28 tonnes/MWd. At \$0.04/kWh, this is \$420/tonne of ammonia. Note that the price of ammonia >\$600/ton since 2006, and before the Russian invasion of Ukraine exceeded \$1400/ton in 2022.]

<https://greenhydrogensystems.com/wp-content/uploads/2021/02/A-Series-brochure-120421.pdf>

[One Nm³ of hydrogen is 0.083 kg, so the A90 model delivering 90 Nm³ per hour, gives 24*90*0.083 kg/day at a feed of 450 kW, for 0.398 tonnes of H₂ per MWd. When 3 kg of that hydrogen is converted to green ammonia with N₂ from the air, this becomes 17 kg of green ammonia, or 2.26 tonne NH₃ per MW. Note that these electrolyzers deliver H₂ at a pressure of 35 bar.]

Thus I feel confident in my projection in the main text.

The density of H₂ at 300 bar is 22.15 kg/m³, so the volume to store 1MW-month of production – about 15 tonnes of H₂ – is 15,000/22.15 = 677 m³. To store 4 MW-months at 300 bar would require 4 * 677 m³ or 2708 m³. A bladder 6.56m diameter has a volume 33.8m³ per meter of length, so it needs to be 20.0 m long to have the nominal volume of 677 m³. My unit of H₂ storage is thus a concrete culvert 20m long and 8m outer diameter containing a bladder 6.6m diameter, which stores 15 tonnes of H₂ at the hydrostatic pressure of 300 bar; in air, the culvert weighs 677 * 2,500/1,000, or 1692 tonnes. Four such units of storage at 3,000 m depth hold 4 MW-month of hydrogen production.

Slide 16-1a assumes storage of H₂ produced by some 3000 MWh, or about 4MW-months -- roughly the output of a single offshore turbine for an average month. A full month of average production is a useful amount of storage, approximately capable of delivering the annual average wind power without interruption

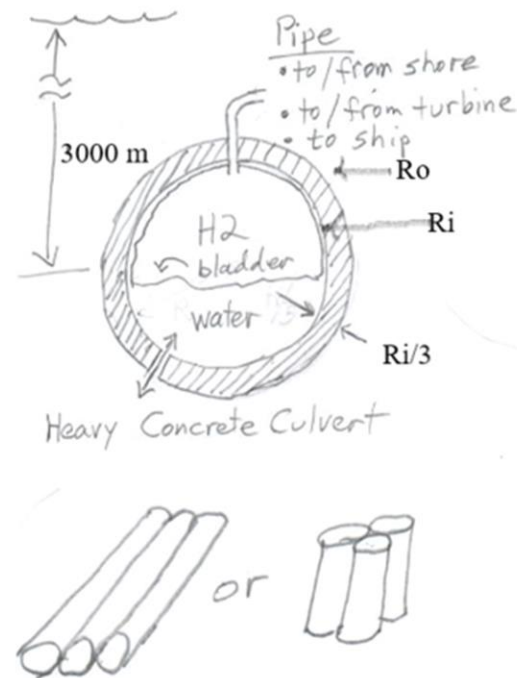
Hydrogen Storage Innovation

Today's only inexpensive H₂ storage is geological: salt caverns bring the cost below \$1/kWh (cf. battery capex: \$200/kWh). But ocean depths exceeding 1 km offer better costs in many more locations. H₂ can be stored at high pressure, in any low-strength 'bubble trapping' structure heavy enough not to float away. Examples are thick-walled or gravel-weighted culverts or silos. Pipe thickness to counter buoyancy, not for strength.

Applications: Dispatchable Electricity: A wind farm turbine (8MW capacity, 50% capacity factor) can electrolyze water with excess wind power and generate fuel-cell electricity when wind is low. One month of stored production (about 3000 MWh, with vol. 2708 m³ at 3 km depth, capex \$0.40/kWh) will provide dispatchable power through a weak season.

Hydrogen Shipping Fuel: Wind farm can produce and store H₂ for ship fueling, no shore connection

Hydrogen Storage for Land Use: Deep water storage can buffer H₂ produced offshore or onshore, and pipe it to land as needed.



16a

The indication "Ri/3" (actually 0.29Ri) for the thickness of the concrete is not for strength, but to provide ballast to counter the buoyancy of the object when gas replaces water in the interior of the culvert.

Again, our unit bladder at 300 bar and 3,000 m depth in the ocean holds about 4 MW-week of green hydrogen, generated by electrolysis from a wind turbine above (in some cases) or from green hydrogen production on nearby land. It is important to understand that one is not building pressure vessels for storing compressed hydrogen, but is relying on essentially a large-scale inverted cup in the ocean, served by a relatively small diameter high-pressure line. For the same chemical energy content in stored hydrogen at 1 km depth, the required in-water weight to counter buoyancy is 3 time larger.

On P.161 of FoES:

Table 5.4 Techno-economic estimates for hydrogen storage technologies (2020 and 2050)

Technology	Case	Capex [\$/MWh]	FOM [\$/MW-yr]	Efficiency [%]
Aboveground	Current	8,000 ⁷	80 ⁸	96% ⁹
	High	8,000	80	96%
	Mid	7,000	70	96%
	Low	6,000	60	96%
Geologic	Current	1,179 ¹⁰	29 ¹¹	93% ¹²
	High	1,179	29	93%
	Mid	1,144	26	93%
	Low	1,120	22	93%

In Tsble 5.4, “FOM” is “fixed operations and maintenance (FOM) costs” and “Efficiency” is round-trip efficiency of putting H2 into and removing it from the storage.

Also from P.161:

⁹ Ramsden, et al. assume 1.2 kWh needed to store 1 kg of hydrogen. This implies compressor efficiency of 96%. We assume that compressor efficiency does not improve for future cases (Ramsden, Kroposki and Levene 2008).

FoES does not consider this deep submergence “ambient pressure” storage, which I hope will be included in future versions of the FoES.

I have priced the contribution to capex for a pre-cast concrete culvert weighing 1692 tons at something like \$160 per ton of culvert (delivered retail price), or \$271,000, which for 15,000 kg of H₂ is about \$18/kg-H₂, compared with some \$1,144/MWh or \$54.9/kg-H₂ for the storage in salt domes (Table 5.4), showing that the cost of countering buoyancy is less than half that of the currently least expensive option. Culverts built from concrete-mixer deliveries to a coastal plant may lead to a capex as low as \$60 per ton of culvert produced.

I now make preliminary cost estimates for the high-pressure pipeline in two cases. The first is the 3-km line from a wind turbine above an ocean-floor hydrogen storage system, capable of transporting the hydrogen from a pressurized 5-MW electrolyzer set, to the bottom at 3km depth, and then back; a 300-bar fuel cell at the surface can recover the electrical energy for delivery, or a high-efficiency decompressor can add to the electrical output of a fuel cell at 35 bar, for example.

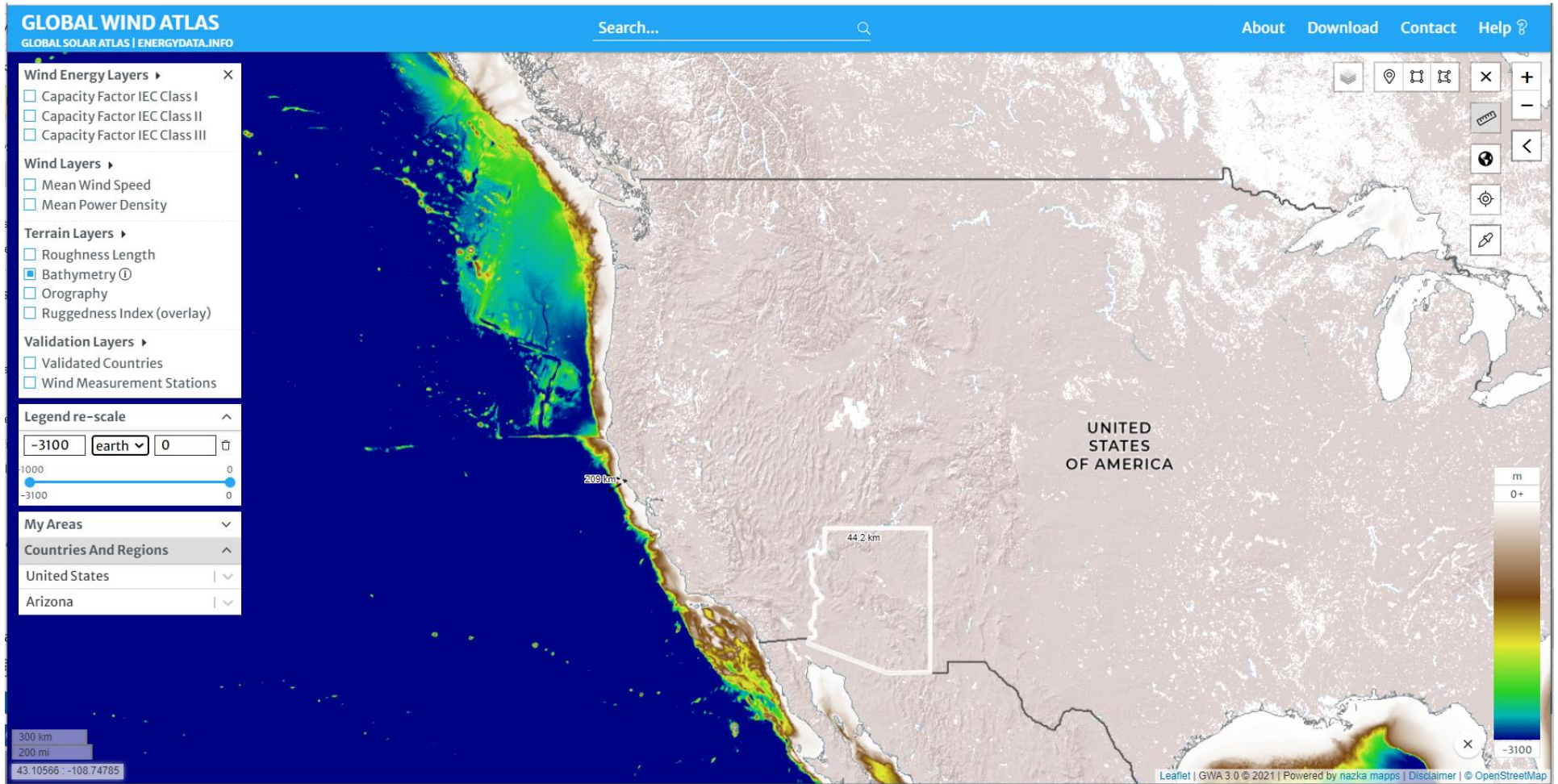
The energy required for compressing H₂ to the 300 bar storage pressure is less than 1% of the chemical energy stored, so the pipe is sized to avoid unnecessary investment in the compressor—say for a trivial 3 bar pressure drop over 3km -- a gradient of 100 Pa/m. A friction factor f of about 0.05 from the attached Moody chart is readily achievable and leads to a 0.15m diameter for the 3km tube from surface to storage units.

The second application is the equivalent of a "battery" for a relatively large solar or wind farm on land, storing some multiple of 500 MW-months of energy –i.e., the output of a farm of 100 5-MW wind turbines at full power for most of a month. Storing hydrogen for such purposes from nuclear electricity is also an option for some coastal nuclear power plants.

The green hydrogen would be transported from its source on land to a shore terminal, assumed 300 km from the deep-submergence hydrogen store, in a pipeline of economically optimum size and pressure. At that point it would be compressed further to 300 bar and sent to the storage system 300 km away, through a pipe that initially has a diameter of about 0.28 m, of sufficient strength to work safely at 300 bar of hydrogen. Fiber-reinforced plastic is reputed to be somewhat cheaper than steel for this purpose, although it will require additional, non-strength-providing armor and buoyancy compensation for the sea-run.

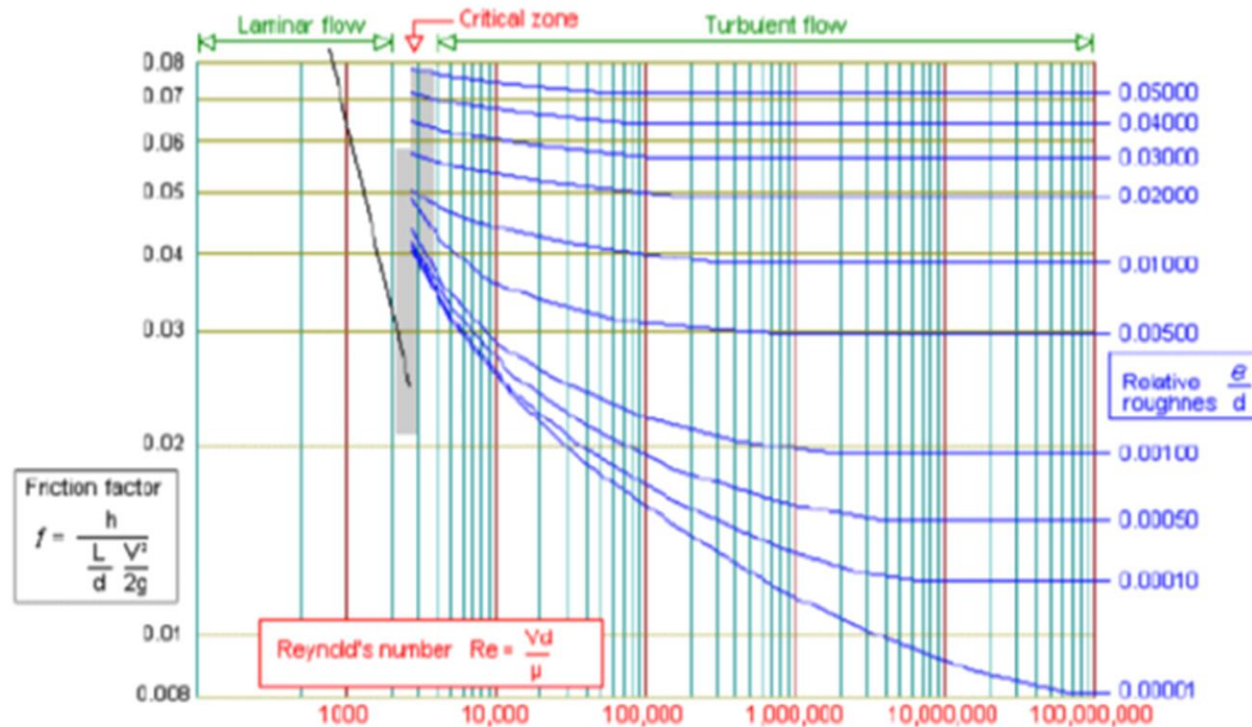
For the assumed 300km run to the offshore sea-bottom at 3km depth (e.g., for Massachusetts and Long Island, NY), and for a pressure drop of 3 bar in the pipe transferring the hydrogen from a 500MW source, the pipe diameter is some 0.28 m. If sea floor at 3,000 m depth is available at < 100 km distance, the capex for the pipe is correspondingly lower – e.g., 200 km for Louisiana, 85 for Lompoc, 65 for Point Reyes, 55 km for southern Oregon, 75km from Sicily, generally <100 km from much of Italy's west coast.

Here is a map of water depth >3,000m off the coast of California, together with a depth scale in the lower right. Featureless white strips along the coasts are shallower than 100m or so.



Reynolds Number Calculation (pipetflow.com)

The relative roughness of the pipe and the Reynolds number can be used to plot the friction factor chart.



When flow occurs between the Laminar and Turbulent flow conditions (Re 2300 to Re 4000) the flow condition is known as critical and is difficult to predict. Here the flow is neither wholly laminar nor wholly turbulent. It is a combination of the two flow conditions.

Deep-submergence storage of hydrogen thus can enhance local electricity production, can enhance renewable energy generation on nearby land; it can also play a role in a large facility at sea, supplying liquid hydrogen to specialized tanker fleets.

Deep-submergence hydrogen storage is a near-term technology, cheaper than salt-dome storage of pressurized hydrogen, which has limited geographic availability. In contrast, there are many regions where ocean depth of 3km are within 100-200 km of shore. Indeed, a subduction zone of 6,000 m depth is only 120 km off the SW coast of Guatemala or adjacent countries in Central America. From the technological point of view, the first deep submergence hydrogen store could be deployed within two years to serve as a first of a kind – FOAK – for a large global program. Depths of 3 km are only a few km off the big island of Hawaii, and such locations can serve local interests of enabling decarbonization.

Second: How Green Ammonia Can Supplant Oil

The use of green ammonia for storage and shipment of chemical energy produced from solar or wind sources is vigorously underway, with especially active programs in Chile, reported, for instance, at the Baker Institute in Houston. I have already referred to Project Green Wolverine in Sweden and details of green hydrogen production in Denmark.

For the last few months Dr. Jim Papadopoulos and I have been imagining green ammonia as a replacement for oil in world energy commerce. This would supply energy not only for electrical generation and transmission, but also to the much larger sectors of industrial and commercial heating, manufacture, processing, and the like. Ammonia can also serve as a convenient vector for hydrogen for chemical applications, replacing oil in that regard as well. Here is Slide 13 from a presentation I made in February and again in early May. This features the T-Omega Wind (TOW) novel floating turbine (in development) in a conventional moored off-shore ocean application; more traditional ocean wind turbines could also serve. We are far from the first to look at green ammonia in this way, and offer novelty in proposing “drift harvesting” of wind energy and also the vast resource of the Southern Ocean. However, the production of green ammonia by farmers well-sited with respect to wind resources and collected by tank truck offers an attractive option for farmers and for the nascent NH₃-as-oil economy.

As is well recognized by those planning to commercialize green ammonia produced on land and shipped worldwide, it can be substituted directly in internal combustion engines as well as for direct combustion for heat or power – in boilers or gas turbines. In this it is inferior to oil in fuel value – 19 MJ/kg instead of 43 MJ/kg, but it contains no carbon.

Fuel	Lower Heating Value (MJ/kg)
Ammonia	18.9
Diesel (U.S.)	42.8
Gasoline	43.4
Hydrogen	120
LNG	48.6

TOW turbine system, optimized for the ocean, following the wind and waves



T-Omega Wind (TOW) novel floating turbine (in development) • Swings at anchor, rotor held both sides
 • Efficient structure (=thinner steel) • Structural weight reduced 80% vs. typical • Cost reduced 70% • Local construction in low-tech boatyards • Shallow-water launch, swap & tow maintenance

13

For world-scale production of green ammonia, we propose to modify the turbine to allow "drift harvesting" that eliminates the mooring system but maintains relative wind speed by a permanently deployed large sea anchor.

Drift Harvesting

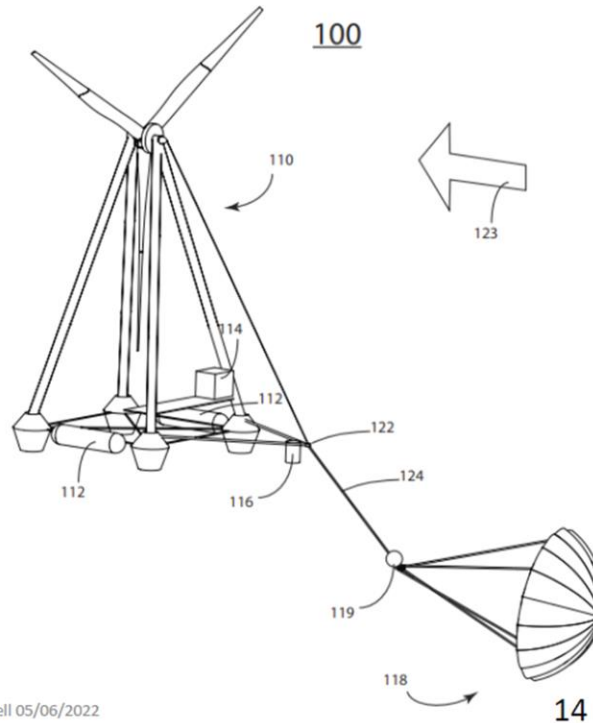
An inexpensive floating wind turbine costs even less with no electric cable or seafloor anchor.

Using a sea anchor, it can harvest energy in deep ocean areas with excellent wind.

Equipment for water electrolysis and ammonia synthesis is contained in box 114.

Liquid ammonia is stored in tanks 112, 5m diameter and 40m long, 1570 cubic meters, holding 1000 tonnes. (Or alternatively, in an attending barge holding 5000 tonnes.)

Garwin Kimmell 05/06/2022



In this Slide 14, this or a conventional wind turbine, instead of being anchored in deep water, is allowed to drift, but the sea anchor is large enough that the drift speed is held perhaps to 0.5% the wind speed, so enabling the turbine to recover 98.5% of its capacity if it were not drifting at all. Of course, ocean currents must be taken into account. The sea anchor must be large, and other approaches are possible, including active propulsion using a fraction of the turbine's electrical output; but also schemes that set cyclic brakes on the motion of a large-scale Venetian blind submerged at optimum depth to milk the circular motion of dominant local ocean waves.

Note that this turbine is fitted with additional boxes labeled as "112" and "114". Two of these are low-pressure tanks for green ammonia, 5 m in diameter and 40 m long, holding 1000 tons, or, alternatively, there could be an attending barge that holds 5000 tons; it might be preferable to have that underwater, below the platform, in order to avoid self-collision from wave

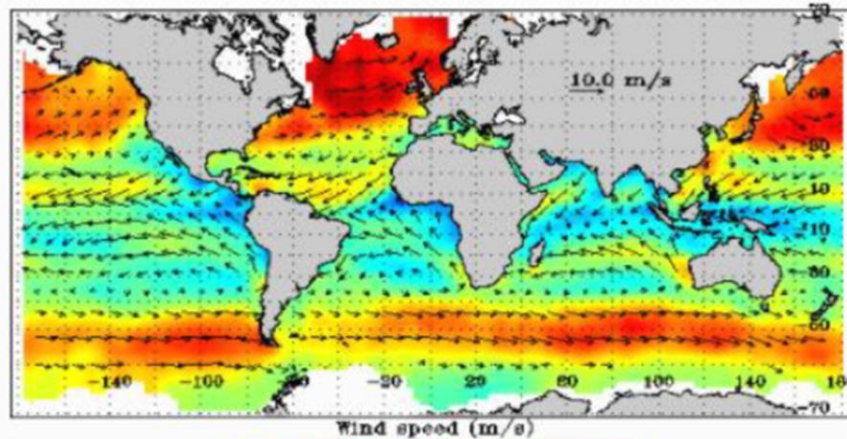
action. These considerations are at an early stage. At an ammonia production rate of 2 tonne/day per MW, 5 MW of turbine power would produce 10 tonne green ammonia per day. We are used to offshore turbine locations with capacity factors 50%-60%, but Tierra Del Fuego is 80% and Greenland ice sheet 90%. One might refer to a turbines for the usual good locations as a 10/5-MW turbine (10MW maximum output power; 50% capacity factor).

In order to avoid the problems of siting and licenses, we propose to deploy a million or more of these 10/5-MW turbines in the Southern Ocean, identified in Slide 15 from earlier presentations, so that they would drift perpetually eastward around the world, producing green ammonia to fill their accompanying local tanks, which would be emptied to collecting ships on a scheduled and weather-permitting basis.

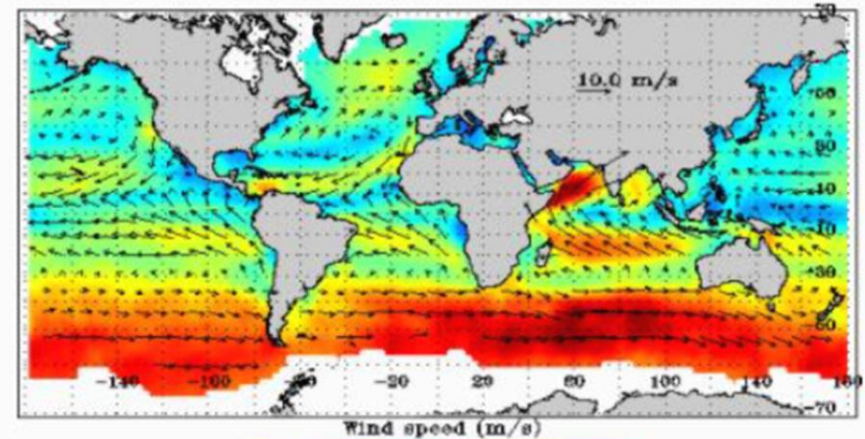
<https://seos-project.eu/oceancurrents/oceancurrents-c02-p02.html>

A global scale-clean energy resource: January & July average wind speeds and directions. Westerly wind in the Southern Ocean would continuously push drifting turbines around the world. Drifting turbines of 6MW capacity could have capacity factors up to 70%, producing 4MW. Three million in the Southern Ocean could produce roughly half the global energy need. With steel content around 500 t, installing 150,000/yr would not stress the steel supply.

2. Prevailing Winds



Wind speed (m/s)
0 2 4 6 8 10 12
Average global wind speed and direction in January



Wind speed (m/s)
0 2 4 6 8 10 12
Average global wind speed and direction in July

Garwin Kimmell 05/06/2022

15

The sea anchor would not be a passive device, but would serve as a smart rudder to steer the turbine's path. The "size" of the sea anchor would be adjusted so that it is larger in regions of scheduled high wind, in order that the turbine spend most of its time in such regions of *high* wind, rather than spending most of its time in regions of *low* wind as would be the case with a

simple sea anchor. The smart sea anchor remains to be simulated and optimized, taking into account the depth distribution of surface currents induced by the continuous wind..

Anhydrous ammonia is already shipped worldwide for use in the chemical industry, as well as for fertilizer, and as a source of hydrogen or nitrogen in the chemical industry. In 2019, the global market was about 170 million tonnes. Industries now involved with transport and storage of oil and natural gas have much to offer and much to gain from a liquid replacement fuel and energy carrier such as green ammonia.

My purpose in this presentation is primarily to advance discussion of green ammonia production by ocean wind turbines, as well as to introduce the concept of drift harvesting for the world-scale supply of green ammonia. An attractive approach to begin this transformation is for farmers with individual wind turbines to add green ammonia production capability and to sell the product to operators of ammonia tank trucks that supply a growing market.

There are already hundreds of companies heavily involved in planning and producing green ammonia and shipping it worldwide; they will carry the burden of general acceptability.

To suggest questions and objections, Slide 18 is an unprioritized list of some problems that must be addressed with the increasingly wide use of green ammonia. Large-scale drift harvesting in the Southern Ocean brings still more questions, including the management of disabled units – of which there will be perhaps 10% at any time.

Potential Risks and Criticisms Any giant system presents large risks, and we outline some below. Must be compared with risks of the petroleum-based system.

On widespread distribution and use of ammonia:

- Just as oil tankers, storage tanks, pipelines and trucks are susceptible of damaging or explosive release, NH₃ toxicity and combustibility demands high standards in transport, storage and use.
- There is extensive experience with farmers handling ammonia, so the risks and mitigations are relatively known.
- Existing standards and practices will have to be extended to consumer interaction (filling a vehicle fuel tank; operating a residential furnace or fuel cell)
- There is also a need to consider larger quantities (tankers may need small sub-tanks so rupture does not release the entire cargo, storage tanks may need to be spaced to limit the spread of a fire doesn't spread).
- Ammonia is not a greenhouse gas. Its combustion can produce NO_x, but see <https://www.ammoniaenergy.org/topics/nox-emissions/>
- Infrastructure security/vulnerability issues may be compared to those for liquefied natural gas -- LNG.

On ocean and extra-national ammonia harvesting:

- Outside national territories, how does one prevent attacks on these facilities on the sea bottom, or slack-moored, or drifting?
- Terrorist or wartime destruction, also 'ammonia rustling' theft must be considered.
- Are slack, thin mooring cables in migration pathways a risk for whale entanglement? The TOW turbine cable is thick and taut. *Noisemakers, sound retroreflectors?*
- The mooring lines in concentrated wind farms will prevent bottom trawling by the fishing fleet
- Drift harvesting – very slowly moving essentially at rest compared to animal or vessel motion?

Garwin Kimmell 05/06/2022

18

Thank you for listening to my views on deep submergence hydrogen storage and on green ammonia for worldwide decarbonization. I am grateful for the collaboration of Jim Papadopoulos (PhD, PE) of T-Omega Wind and for helpful comments from Bob Budnitz.