Likely Feasible Solution to World Energy & Carbon Crises

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Abstract. We examine the following as a sustainable world-energy Plan. Distribute floating wind turbines mainly within the "roaring forties" and "furious fifties" regions of the southern oceans. Anchor them by cables to the sea floor. Running along that floor is a hydrogen pipeline. The turbines generate electricity which is transmitted down to the sea floor by cable. There it electrolyses water to input H_2 into the pipeline. The pipeline outputs are on (or near) land somewhere. Turbine maintenance is mostly by robot. We find it appears entirely technically and economically feasible to satisfy approximately all (or at least a large fraction of) year-2020 human energy demands in this way, but show with a new analysis of wind-energy limitations that much more is impossible. Indeed, we'll show this energy actually will be cheaper than current prices and also cheaper (sometimes greatly) than schemes based on water-currents, other-located wind turbines, or solar power – albeit the prices of the lattermost have been rapidly changing. However, this project, as well as *any* attempt to generate a large fraction of human energy from winds, will cause noticeable alterations in weather and climate. I provide initial guesses about what those alterations will be and discussion of how to modify "global climate model" codes to investigate that. (Basically this would be a 1-line code change, but we demonstrate that many climate modeling codes are incredibly screwed up and lied about.) We conclude with some deprecation of the "hydrogen economy" and instead suggest the "aluminum economy."

1. Is this idea new?

An *E&E News* story by John Fialka (10 June 2020) says there is a "design effort for a 15-MW [ocean floatable wind] turbine [as] a global partnership led by the IEA. It includes major turbine manufacturers such as General Electric Co. and academic institutions like the University of Maine, which is helping to design a floating turbine substructure." (I also saw several other such stories, e.g. Reed 2020; but this one seemed the best.) The "Hywind Scotland array" of floating turbines have successfully operated for 3 years including during Hurricane Ophelia in 2017 and in situations with winds up to 45 meter/sec (100 mph) and waves over 8 meters. So evidently the idea of large floating wind turbines capable of operating in deep ocean did *not* originate from me.

My other main ingredients are (1) location in the "roaring forties / furious fifties," (2) analysis showing the "hydrogen pipeline" seems a feasible-today power-transmission method even over the largest distances needed, (3) demonstration that other alternatives are uncompetitive, (4) recognition & initial discussion of climate effects, and simple & strong upper bounds on extractible power. I have not seen any of those mentioned in this or related sources. The fact that (5) much "hydrogen economy" propaganda was bilge should have been obvious to everybody from day one (certainly it was to me), but keeps getting so much unjustified overfunded hype that it is always worth adding a counter-dose of sanity.

2. World (non-renewable) power consumption facts

Year	Coal mined (10^{12}Kg)	Crude oil extracted (10^{12}Kg)	Natrl Gas extracted ($10^{12}m^3$)	Nuclear Electricity Generated (10^{15}Whr)
2019	8	4.7	4	2.6
2009	7	3.9	3.1	2.6
1999	4.5	3.6	2.4	2.4
1989	4.8	3.0	2.0	1.8

(The density of natural gas is 0.7 to 0.9 kg/meter^3, enabling converting between cubic meters and kg.) Converting those to joules annually using 24 Mjoule per kg of coal, 44.5 Mjoule per kg of crude oil, 38 Mjoules per cubic meter for gas, and 1 watt-hour = 3600 joules, we have (each entry in units of **10^{18} joules per year**):

Year	Coal	Crude oil	Natrl Gas	Nuclear Electricity	total
2019	192	108	152	9	461
2009	168	174	118	9	469
1999	108	160	91	9	368
1989	115	134	76	6	331
1979	73	133	51	2	259
1950	45.4	19.6	7.5	0	72.5
1900	20.6	0.65	0.23	0	21.5
1850	2.05	0	0	0	2.05
1800	0.35	0	0	0	0.35

Of course these "raw energy" figures for coal, oil, and gas pertain to 100% efficient usage, and with actual efficiencies translate into considerably less "usable" energy. The rest of the claimed energy is largely wasted as heat.

The **question** this paper investigates is: can the scheme outlined in the abstract sustainably generate, in a "carbon free" manner, amounts of "raw" energy comparable to or exceeding the present world nonrenewable consumption rate, i.e. **5×10^{20} joules/year, i.e. averaging 16×10^{12} watts**? Our **answer** will roughly be: approximately that amount of power indeed is feasibly extractible, but not much more.

3. Ocean facts

The sphere approximating the Earth has surface area 5.1×10^{14} $meter^2$, of which 71.0% is oceans, 1.2% is inland water (rivers, lakes, streams, & Caspian sea), and 27.8% solid land. The mean ocean depth is 3685(±1%) meters. Pressure at that mean depth: 360 atm. (Useful rules of thumb: 1 atm per 10 meters; also 1 atm≈10^5 Pascals.) Typical ocean floor temperature: 0-4°C (273-277 Kelvin).

It is interesting to compare the oceans versus the atmosphere. Total **mass**: Oceans=1.332×10^{21} kg, which is 259 times the mass of the Atmosphere=5.148×10^{18} kg. The main constituents of the atmosphere by mass (if dried) are N_2=78.08%, O_2=20.95%, and Ar=0.93% (sum=99.96%). The water vapor content varies between 0-5%, averaging about 0.25%. Important smaller components, now as volume fractions in parts per billion, are He=524000, CO_2=416000 (June 2020; 278000 pre-industrial), Ne=18210, CH_4=1866 (year 2019; 722 pre-industrial). The oceans contain dissolved gases whose total masses and/or concentrations can be comparable to their mass or concentrations in the atmosphere. Water usually contains 1-20 mg/L of dissolved O_2, which if it averages 5 would be a total mass equivalent to 1/161 of the amount of oxygen in the atmosphere, and a concentration per volume about 1/50 of its concentration in air. Water usually contains 0.75-1.3 mg/L of dissolved N_2, which if it averages 1 would be a total mass equivalent to 1/3000 of the amount of nitrogen in the atmosphere, and a concentration per volume about 1/940 of its concentration in air. (Global warming will reduce both those concentrations by around 30%.) Water usually contains 1.5-2.5 mg/L of carbon in the form of dissolved CO_2, which if it averages 1 would be a CO_2 concentration per volume about 7.3 times its June-2020 concentration in air, and a total mass equivalent to 23 times the amount in the atmosphere.

The "Roaring Forties" are strong west→east winds found in the southern hemisphere between latitudes 40-50 degrees. These winds occur both day and night, year-round, but exhibit some seasonal variation (strongest in June-August, weakest in Jan.-Feb.). The similar conditions in latitudes 50-60° are the "Furious Fifties" and 60-70° the "Screaming Sixties." The **strongest** winds typically occur between 45°S and 55°S (which I shall denote "the **roaring latitudes**") and are said to usually range between 15 and 25 knots, i.e. **7.7 to 12.9** meter/sec. For more precision about this claim, see actual weather-station measurements from table of islands below. But when reading that table, keep in mind:

i. winds out at sea presumably exceed land-based measurements, especially from comparatively sheltered on-land locations (in the table we star * locations that are inland/sheltered);
ii. what matters for power-generation is not the mean, but rather the mean *cube* of the wind speed (whose cube-root exceeds mean speed);
iii. at about 120 meters up, not near the surface (which also raises speeds, typically doubling them versus at 10 meters up).

In view of the unstarred measurements and assuming factor-2 increase 120 meters up and out at sea, I will assume that 95% of the time, the wind speed 120 meters up in the roaring region will be between 12 and 25 meter/sec. Actually the multiplier perhaps should have exceeded 2 somewhat, but we shall assume 2 to keep the calculations conservative.

In the roaring region *wave* heights regularly exceed 4 meters crest-to-trough. Wave lengths usually are of order 100 times wave heights. Rarely, "rogue waves" occur which can be as high as 25, perhaps even 35, meters. In August *icebergs* occasionally can occur as far north as 40°S in the southern hemisphere (mostly in the Atlantic), even though rare enough so that one normally cannot see any at latitudes≤63°S. About 5 per year reach latitudes≤51°S. Another possible hazard is *hurricanes*. During 1985-2005, exactly one hurricane managed to reach a latitude ≥46.6°S (i.e. got south of the southernmost point of S.Island, New Zealand) while still retaining enough strength to justify its classification as "hurricane," i.e. wind speeds near the eye exceeding 32 meter/sec. (This occurred about 5000 km east of New Zealand and it fizzled at about 48°S.)

The winds are caused by air rising at the equator then flowing towards the south pole, combined with the Coriolis effect, i.e. conservation of angular momentum (that was an oversimplified explanation, see §6 for a better one). The Forties and Fifties latitudes are almost entirely ocean, unobstructed by land, which is one reason high winds build up. Indeed, the northernmost point of Antartica is at 63.2°S (tip of the Trinity Peninsula), while the southernmost point of S.America (Cape Horn) is 55.7°S, and the latitudes between those two consist almost entirely of ocean; and indeed most latitudes between 55 and 60°S are *entirely* ocean. This contrasts with the mirrored situation in the northern hemisphere: every latitude from 46-72°N seems to have at least as much land as ocean, which presumably is why there is no comparable band of globe-encircling west→east winds in those latitudes, although there nevertheless is a tendency for west→east motion especially in the northern Pacific and Atlantic in winter. The only significant land in the region between 47°S and 65°S is southern S.America and especially its Tierra del Fuego islands (52.4-55.7°S), the Antarctic's Trinity Peninsula (formerly "Palmer peninsula"), and the Kerguelen (48.7-49.7°S) and Falkland (51.2-52.4°S) Islands. The seas near the Kerguelens and Falklands remain ice-free year round. The northernmost that sea ice is found (which happens in September) is 55°S. The circumference of the Earth's 40° latitude is 30599 km, at 50° is 25760 km, and at 60° is 20038 km.

Islands and land-spots actually are useful, so here is a list of all important ones in this area:

Name	Latitude °S	Longitude	Population	Wind
Bouvet Island	54.5	+3.3	0	Olav peak: Mean wind speed (whole year) 10 meter/sec?
Gough Island (Tristan de Cunha)	40.3	+9.9	6	Met. Station: Daily mean wind speeds 7.7 (Feb. 5) to 10.1 (July 26) meter/sec
Prince Edward Islands	46.9	+37.7	0-50	Marion Is. Meteorological station: Daily avg wind speeds 8.7 (Feb.13) to 10.9 (July 16) meter/sec.
Crozet Islands	46.4	+52	18-30	Base Alfred-Faure, Ile de la Possession: Monthly avg wind spd 8.9(Feb) to 11.2(July) meter/sec.

Kerguelen	49.2	+69.5	45-100	Port-aux-Francais: Daily avg wind speeds 9.9 (Feb.16) to 11.5 (Sep.2) meter/sec.
Heard & McDonald Islands	53	+73	0	Atlas Cove on Heard Island: Monthly average wind-speeds 7.2(July) to 9.3(Jan.) meter/sec.
Southeast Cape, Tasmania	43.6	+146.8	–	Hobart airport*: Daily avg wind speeds: 4.5 (Apr.21) to 5.4 (Oct.3) meter/sec.
Campbell Island, NZ	52.5	-169.1	0	Beeman Cove: Monthly average wind-speeds 7.5 (Aug.) to 9.8 (Oct.) meter/sec.
Stewart Island, NZ	47.0	-167.8	402+tourists	Oban: Monthly average wind-speeds 8.7 (Feb.) to 12.7 (Oct.) meter/sec.
Macquarie Island	54.6	-158.8	0	Daily avg wind speed: 9.0 (Dec.29) to 10.9 (May 13) meter/sec.
Tierra del Fuego Is.	54.8	-68.3	152K	Ushuaia*: Daily avg wind speed: 5.3 (May 24) to 7.1 (Nov.3) meter/sec.
Trinity Peninsula, Antarctica	62.3	-57	55	Esperanza base*: Monthly average wind speed: 4.9 (Jan.) to 8.0 (June) meter/sec.
Falkland Islands	51.7	-52.5	3398	Stanley: Daily avg wind speed: 8.0 (Dec.22) to 8.9 (Aug.26) meter/sec.
South Georgia Island	54.4	-36.7	16-32	Grytviken: Daily average wind speeds 7.6 (Dec.21) to 9.1 (Aug.28) meter/sec.
South Sandwich Islands	56 to 59.7	-26.4 to -28.1	0	Southern Thule: Monthly avg wind spd 4.9 (June) to 5.8 (March) meter/sec.

We see the widest longitude-**gaps** between these are **99°** (Macquarie to Cape Horn) and **74°** (Heard to Tasmania) corresponding respectively to distances measured along the 50°S latitude of 7084 and 5295 km. For this reason we shall assume that *no point on our giant wind farm is more than* **3540 km** *away from a "terminus."*

The Macquarie-Horn gap contains the "foundation seamounts" which are a 1350-km-long 180-km-wide chain of undersea mountains (which perhaps at one time included islands) extending from about 32°S,127°W to about 38°S,111°W. This suggested that perhaps some **seamounts** exist shallow enough to construct a permanent terminus on. That hope is indeed realized. Yesson et al 2011 compiled a list of 33452 seamounts worldwide. Examining it, I find there are 1086 known seamounts <30 meters below mean sea level (i.e. shallow enough to pose a hazard to shipping) in the world. Of those, 56 lie in latitudes between 45 and 55°S. Here is a table I extracted from the Yesson data:

Depth	Latitd°S	Longit°W	Depth	Latitd°S	Longit°E	Depth	Latitd°S	Longit°E	Depth	Latitd°S	Longit°E	Depth	Latitd°S	Longit°E
2	43.276	98.017	2	54.889	99.045	2	49.477	164.250	2	53.183	-75.246	2	46.249	41.991
2	43.287	97.967	2	54.873	98.935	2	49.599	164.179	22	57.854	-26.546	5	52.704	43.300
32	43.291	97.938	2	54.962	98.935	25	50.699	163.796	2	43.601	-1.307	2	53.459	45.590
105	43.329	97.900	2	54.920	98.883	64	50.699	163.771	2	48.483	7.938	2	52.562	48.054
391	43.637	98.333	4	54.954	98.962	74	52.424	160.638	2	48.470	7.962	2	52.591	48.096
14	45.433	93.788	6	54.959	98.901	83	52.887	160.067	2	47.925	8.809	23	51.362	54.729
105	53.554	140.667	9	54.962	98.850	88	50.012	165.921	2	47.659	10.378	22	49.329	67.000
131	53.608	140.588				92	52.433	160.612	2	47.558	11.188	2	55.141	158.688
135	53.695	140.458	204	43.483	-4.529	99	51.695	161.250	15	46.520	39.563	2	54.451	158.932
187	53.916	139.979	286	46.570	-6.100	99	52.449	160.596	2	46.225	41.864	8	54.449	158.912

Table of Interesting Seamounts: Known shallow seamounts with convenient locations, in particular ones near the midpoints of our two widest inter-island gaps. ["Depth" in meters below mean sea level.] The table has 5 major columns. Seamounts from the top left of the table would shrink our widest longitude-gap from 99° to **60°**, shrinking our maximum distance-to-terminus from 3540 to about **2146 km**. Also using a seamount from the bottom left would further shrink 60° to about **42°**. Using seamounts from the top of the second column would shrink our second-widest longitude-gap from 74° to **48°**, corresponding to max-distance-to-terminus about **1716 km**. The seamounts in the 3rd column of the table can shrink the third-longest (Tasmania-Campbell) longitude-gap from 46° to **25°.** The seamounts in the bottom of the second column could be used to shrink the fourth-largest (Sandwich-Bouvet 30°) island-gap. Finally, the 4th and 5th columns list miscellaneous other shallow seamounts in roaring latitudes.

Given that the Troll A platform in the North Sea, used to produce compressed natural gas, stands on sea floor 303 meters deep (then rises a further 169 meters above surface), it should be feasible to build termini on all the seamounts tabulated.

> Troll A was erected in 1996 and remains in use as of 2020. It weighs about 10^9 kg. Its reinforced-concrete legs are actually hollow and watertight, containing an elevator, and in 2006 a concert was held inside one of them on the seafloor in a makeshift concert hall – the acoustics supposedly are superb. This platform also contains cranes and 10-story housing for workers. Troll A cost about $650M and was towed bodily from shore to its final location about 200 km away; the tow took 1 week. In the late 1990s Troll A was supplanted by Chevron's Petronius oil platform as the deepest. The latter stands in water 535 meters deep about 210 km southeast of New Orleans. Petronius is flexible, unlike the rigid Troll A, and can sway up to 2%.

Nevertheless, to keep our calculations conservative, the rest of this paper shall *ignore* all these seamounts.

Usually the depths are between 2 and 8 km in the seas we shall be concerned with, and tend to be deeper in the "fifties" than "forties."

It is an empirical fact that world-average wind speeds over continents are slightly less than *half* those found over oceans, corresponding to one-*quarter* the kinetic energy density, and one-*eighth* the extractible power density. And the wind speeds found in the roaring latitudes are unrivaled, in a time-averaged sense, on any land anywhere, except near coastlines plus in a few additional isolated locations and times. (Also, the wind averaged over the roaring latitude region is a highly reliable and comparatively unvarying power source – unlike most winds over land, most of which vary greatly with time.) Nor are they rivaled almost anywhere else even in the oceans.

> The **lesson** of that is that, for truly large scale power generation, **land-based wind turbines *cannot compete* with ocean based** ones. In particular, using our upper bound from §6 of 0.21 watt/meter^2 on large-scale wind power *electrical* generation, we see that it would be *impossible* for the USA (contiguous 48 states only) to generate more than 1.6 TWe from wind. And of course since the USA's energy consumers are not located in the USA's windiest places, as well as for other reasons, really far less than 1.6 TW would be possible. But averaged over the year 2012 the USA consumed 3.2 TW worth of energy. So clearly, land-based (and near-land offshore) wind is *inadequate* to meet the USA's energy needs.
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> Furthermore, Pfaffel et al 2017 surveying about 90000 turbine-years of operation data from many different wind farms, found that land-based wind turbines actually generated only 18-25% of their rated output for all data subsets except one (that one got 35% but contained only 1800 turbine-years). For their 3401 offshore (but near-land) turbines, it was 29-40%. This was despite about 5% better availabilities (80-98%) for their land-based turbines than for offshore (80-93%).
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> So: Even if our ocean-based turbines cost *twice* as much per peak-watt and pay a factor 1.5 price for extra transmission inefficiency, they *still* will easily achieve cheaper cost per actual watt due to stronger and more-consistent wind. Plus I suspect that due to their easy towability, floating ocean-based ones actually might be cheaper for installation, decommissioning, and refurbishment.

The total human population in the latitude range we are concerned with is <4100 (islands, ignores Tasmania which we regard as North of our latitudes), plus arguably we also should count the 152K on Tierra el Fuego, plus perhaps 500K more if we were also to count the southern tip of S.America. Also it is estimated there are about 1.5 million professional seafarers in the world, some small fraction of which would be in these latitudes on any given day. So in all, at most perhaps 10^{-4} of the world's humans will, on any given day, be located in this latitude range, and 10^{-6} if we only count the isolated islands and seafarers. My point is: they are too **few** to care. Even if we cover nearly all of that part of the planet with wind turbines, almost nobody will even notice.

This also has the advantage that it **overcomes several objections** to wind turbines:

1. Wind turbines can create perpetual noise, plus "infrasound" air-pressure (and sunlight/shadow) oscillations at a frequency of about 2 Hz; and some regard them as visually ugly – all of which can annoy people near them. Not a problem if there are no people near them.
2. Another objection to wind turbines on land is that they kill flying birds, bats, and insects. Well, as far as I can tell there *are* no flying birds, bats or insects far from land in the ocean regions we are speaking of, *except* albatrosses (we'll discuss them in §11).
   Incidentally, people interested in saving birds from wind turbines in the USA may be a little misdirected. It is estimated (Loss, Will, Marra 2013) that in the USA 1.4 to 3.7 billion birds are killed each year by *domestic pet cats* (and feral former-pet cats), while 10 to 1000 million die annually by colliding with windows. The USA currently has about 60000 wind turbines (which in 2018 generated about 7% of the USA's electricity) whose net direct bird-killing effect has been guesstimated to be (in contrast) probably less than 1 million per year, i.e. <20 per turbine per year. But this contrast is not quite as powerful a defense of turbines as it might sound because the bird types killed by cats are not the same as those killed by turbines. E.g, turbines kill eagles. Indeed there are claims that turbine-rich regions of Germany and India have substantially fewer of certain kinds of birds, e.g. in India a 75% reduction in buzzards and hawks was seen in areas near turbines (causing an increase in lizards, Thaker et al 2018); in Germany a 76% loss of flying insect biomass (Hallmann et al 2017). Smallwood 2013 estimated 888K bats and 573K birds (including 83K raptors) were killed by turbines in the USA during the year 2012; Mark A. Hayes published an independent estimate of "over 600K" turbine-caused bat-deaths that same year. Frick et al 2017 concluded this "may drastically reduce [bat] population size and increase the risk of extinction. For example, the hoary bat population could decline by as much as 90% in the next 50 years." Smallwood in 2020, re-estimating based on more data and better techniques, found, as a 95% confidence interval, that there were between 1.77 and 2.72 million bat deaths in the USA (lower 48 states only) during 2014 caused by 64485 MW of installed wind-energy capacity. But as of January 2020, that had grown to 105583 MW. During 2014 US bats were killed 3-7× more often by wind turbines than by "white nose syndrome" which already had been considered a devastating plague. Bats are ecologically important to the extent they have been claimed to be "keystone species." The rationale for that is: (1) bat guano is the fuel for cave ecosystems, (2) many plants are dependent on bats for pollination, (3) insectivorous bats are by far the largest predator of night-flying insects, e.g. mosquitos. Because of (1) a large fraction of cave life would die without bats. Because of (2) a large fraction of plant species in some parts of the world would die. Re (3), mosquitos in turn tremendously affect all mammalian life by carrying diseases. For example in Africa in the early 1900s it was estimated that 50% of all human deaths were from malaria; and although there currently are only about 400K malaria deaths/year, the former levels might return since drug-resistant strains now are becoming common. Yellow fever was once another very serious threat but a vaccine was developed in the 1930s. So if, for example, turbines killed 80% of all the bats in Africa, that plausibly might increase mosquito populations by 30% (Reiskind & Wund 2009), in turn killing a substantial fraction (10%?) of all human and mammalian life. So: turbines on land genuinely have a devastating effect on certain segments of the ecology.

   > Martin, Arnett et al 2017 found wind facilities could reduce bat deaths by a factor between 1.5 and 4.5 by raising cut-in speed from 4.0 to 6.0 meter/sec whenever nightly wind speeds were <6.0 meter/sec and temperatures were >9.5°C (i.e. preferred weather conditions for bat flight). This reduced energy production only 1% (whole year) and 3% (worst season). Arnett et al 2013 hoped adding a broadband ultrasound noise source to turbines would repel bats; they experimetally evaluated the effect on bat deaths as between +2% and -64%. Unfortunately the mitigation measures suggested by Arnett & friends seem inadequate in view of the huge magnitude of the threat. Limiting lighting on and near wind turbines and associated buildings seems to reduce fatalities among birds attracted by light.

   And even if you do not care about birds, bats, and insects, Corten & Veldkamp 2001 found that insects hit by turbine blades, can *halve* wind turbine aerodynamic efficiency, albeit this is mostly solvable by cleaning the blades (which currently is a horrific exercise done by a team of people rappeling down a stationary blade, then rotate the next blade into position and repeat).

3. Wind turbines can and have failed in dangerous ways:
   - Blades can break off, yielding a 30-ton boomerang flying at 100 meters/sec which can land as far as 1300 meters away. Blades can accumulate ice or dirt. Blade failures occur at a rate about about 1/200 per blade per year.
   - Nacelle fires apparently occur in about 1 turbine per 2000 per year, 90% of them covered up. For example on 20-21 July 2019 in Klickitat County Washington, falling melting/burning turbine pieces ignited a wider fire that burned about 500 acres. Causes include oil lubrication failure or mechanical friction, electrical short circuit, overheating electrical components such as capacitors and convertors, lightning strikes; and the presence of flammable plastics or oils, plus lots of oxygen. (Fire-suppression systems, better lightning protection, and smoke & heat detectors which trigger turbine shutdown, might help.)
   - Hail, dust, rain impacting the leading edge of blades (which can move faster than 100 meter/sec) can damage (reducing efficiency) and, over years, ultimately destroy them. (One might hope that a hard coating on blade leading edges, such as CVD diamond or anodized aluminum Al_2O_3, and/or more intelligent automated control which detects hail, similar hazards, and/or blade damage/weakness, perhaps via sensors built into the blade; and then reacts by shutting down the turbine, could help.)
   - Controller or brake failure can cause blades to spin too fast and self-destruct. (A backup brake system might help.)
   - Mechanical components break including bearings, gearboxes, yaw system, blade pitch control. (Automated self-monitoring could help. Roller bearings, cylindrical and/or conical, should last longer than – which unfortunately have been heavily used in what was a big design mistake – ball bearings, because they feature line not point contact. Case-hardening them also should help. Gearboxes can be eliminated by simply directly connecting rotor↔generator, but heavier and fancier electronics then are needed. Direct drive is probably a good idea from the standpoint of maintenance in the sense that replacing electrical components tends to be easier and faster than mechanical ones, especially gearbox failures.) Moist air can cause rust.
   - Towers have fallen, either bodily like an uprooted tree, or by breaking in two (in some cases resonances may be involved), or most often by tube-buckling followed by foldover of the flattened part of the tube at about half-height. (One might hope the latter could be prevented by adding stiffening flanges, e.g. circular I-beams, to prevent the tube-flattening stage of buckling. Automated detection of tower weakness, e.g. crack-detection or strain gauges, might help.)

Obviously windblown dust/sand/dirt is infrequent out at sea, fires matter less since they cannot spread, "uprooted tree" type collapse due to poor foundations cannot happen if there is no foundation, and flying blades matter less since there is nothing for them to damage and nobody to injure. But salt/moist air, waves, and icebergs are bigger problems at sea.

4. Generating the energy

The largest available wind turbine as of year 2018 is the MHI Vestas V164, able to generate 9.5 MW. It is made by a 50-50 partnership of Mitsubishi Heavy Industries & Vestas Wind Systems A/S. It features a 3-bladed rotor on a single axis (rotor diameter 164 meter) whose hub is 105 meters up, on a nacelle atop a round tower. As of year 2020, blades usually are made of glass-reinforced plastic and take about 1 day to manufacture. Towers are usually steel and/or reinforced concrete (often intentionally stressed with internal cables) and usually contain elevators; erecting a turbine on land from delivered components typically takes 1 month. The V164's rotor mass is about 105 tonnes. The nacelle is 20×8×8 meters and masses 390 tonnes. The bottom part of the tower is made of cylindrical segments, each with diameter=7 and height=24 meters and weighing 200 tonnes. The whole thing weighs 1300 tonnes. It was intended for shallow-water offshore use mounted on a 4000 tonne foundation. It operates in winds between 4 and 25 meter/sec and yields its maximum rated power at every wind speed 12-25 meter/sec (the "**sweet spot**"); at 9 meter/sec it generates half-max power and at 7.7 one-third-power. We have estimated earlier that the winds in our locations will lie inside that sweet spot 95% of the time. It does not operate in, but survives, winds as high as 50 meter/sec (weak "class 3 hurricane"). A 9MW version tested by Denmark Technical University at their Østerild test site succeeded in producing 9MW power throughout a 24 hour day (1 Dec. 2016); an earlier 8 MW version had produced 8MW throughout a 24 hour period on 6-7 October 2014. (Vestas has announced a new-record-power 10.0 MW version will be commercially available for installation in 2021; versus the 9.5MW version it has a "stronger gearbox, minor mechanical upgrades, electrical system upgrade, and a design change to enhance air flow and increase cooling in the converter.") The price of machines of this ilk is treated rather secretively, but according to Smith 2014 in *Windpower monthly* was then about $1 per peak watt. Thanks to our proposed geographic location with nearly-eternal wind, we hope to enjoy average near-equal to peak power. Although this particular turbine's parameters probably are not optimized for our intended usage (e.g. probably it would be better to reduce the rotor diameter to, say, 140 meters while still keeping the same electrical generator, in view of our high wind speeds and planned 1 km turbine separation), we nevertheless shall use it to produce numbers.

> **Note on "energy payback time" (response to critic):** A critic of this paper complained I had made the "classical mistake" of "neglecting the amount of energy that is needed to construct the [wind turbine], its operational energetic costs (replacement parts, maintenance, etc), and for eventual disposal." We should then "compare this amount of energy with the amount [wind turbine produces during] its operational lifetime and see whether net positive or net negative." I agree. Here is a simple calculation. Large wind turbines in 2014 cost $1 per e-watt generation-capacity. This paper shall assume turbine lasts 30 years then replace. The cost of electrical energy delivered to USA residences averaged $0.1044 per kW-hour in 2014, i.e. $1 bought 34483 watt-hours. If the turbine manufacturers paid those same rates for energy, then if their sole expense were energy, that proves the energy payback time is ≤34483 hours<4 years. Because turbine manufacturers have many expenses besides energy, this is a very conservative *upper bound* on energy payback time. (This upper bound of course will remain valid for all dates after 2014, regardless of whether energy prices change.) **Q.E.D.**

Another possibility is vertical-axis wind turbines, which perhaps have only 85% of the efficiency, but enjoy some simplicity, gyro-stabilization, and perhaps balance advantages (no nacelle and yaw-control needed; generators etc. located nearer ground). It also might increase wind-farm efficiency (with either vertical- or horizontal-axis turbines) if spin directions are *alternated*.

But unlike the V164, we have in mind *not* a fixed rigidly mounted turbine, but rather one that *floats* on deep ocean (and stays upright). To accomplish that we need a hollow air-filled float capable of bouyant force of order 5000 tonnes, i.e. volume 5000 cubic meters – a sphere 21 meters in diameter will do – and a long rod extending downward into the sea with a huge *counterweight*, say 2000 tonnes, at the bottom end. Also, we need a long cable to anchor it to, and to transmit electrical power down to, the sea floor. That all might double the cost to $2 million per megawatt. Installation and delivery should actually be much cheaper than for rigidly mounted turbines since they could simply be towed to the desired location then anchored. They need to be designed to permit horizontal towing but then due to some geometrical changes, e.g. weight shifts, hinging, and/or flooding compartments, reoriented vertically; they also need to be designed to allow easy detachment from and (re)attachment to their cables. Similarly, when old or dead turbines need to be replaced, recycled, or refurbished, they can be towed back to a factory, where that will be far simpler. Towing an object this size presumably is no problem since a typical medium size container ship carries 25000 tons of cargo and can be 30 meters wide (which actually suggests trying to tow 10 or 20 at a time).

Also land trains typically weigh 3-18 thousand tonnes with each individual car able to carry 100 tonnes. Higher figures would be possible with special tracks, etc (e.g in W.Australia they use 150-tonne iron ore cars), so it ought to be feasible to transport an entire wind turbine, broken into 200-ton pieces, on land by rail if the route is not difficult. Indeed during world war II, the Germans employed a giant railway gun 47.3 meters long and weighing 1350 tonnes. It was used during several battles in Russia including the siege of Sevastopol. This gun took about a month to assemble and use, once transported. More recently the 99-meter-long 17.5-meter-diameter 6664-tonne "Big Bertha" tunnel boring machine was used to dig a tunnel in Seattle at a cost of $200 million (original planned budget $80M; they broke the machine probably due to irresponsibly mis-operating it). It was shipped there in 41 sections, but while operating, and later during its removal, it traveled along rails.

A pendulum swinging in vacuum with rod length L has period=$2\pi(L/g)^{1/2}$, which for L=100 meters gives period≈21 seconds, so one might worry that ocean waves could stimulate a resonance of our wobbly wind-towers. That could be bad. Wave periods measured by 7 ocean buoys ranged between 4-18 seconds. In one well known theoretical model, ocean waves are sine waves with period≈$(d\cdot g)^{-1/2}$wavelength where d is the depth of the ocean, assumed much greater than the wave lengths and heights. The bouyancy force of water, and the "counterweight on the other end of the rod" both effectively "reduce gravity," increasing pendulum period versus vacuum, so then there fortunately seems to be a substantial mismatch between ocean wave periods and the most naive resonance. And presumably our "pendulum" is highly damped due to water resistance, and we can enhance that damping by designing the undersea portion to increase that resistance. One also could attempt (which I'm dubious is a good idea, but it might be) to gyro-stabilize it by spinning a large mass about a vertical axis; or the turbine-towers could intelligently self-adjust themselves to try to change their resonant frequency (under the right conditions), and/or change their water and/or air resistance versus time in an attempt at active control on a time-scale of seconds.

The cable to the sea floor presumably also will act to prevent such oscillations. I should remark that other cabling schemes besides the simplest "one cable per turbine" scheme, are possible. If each turbine were anchored to the sea floor by *two* cables, with spaced-apart anchorages on the sea floor, or *three* (anchor points forming a triangle), these would successively reduce their horizontal freedom of motion and also provide some redundant protection against breakage. One also could consider linking many turbines via a network of horizontal cables placed, say, 50 meters below surface; this again would serve to keep them all positioned as desired relative to each other and provide redundant strength.

So if we had a "**line**" of 25760 such turbines spaced 1 km apart (east-west) all along the 50°S latitude, they would generate 244 GWatts of electrical energy. So to generate 16 terawatts of electrical energy, we would need 66 such lines, which if they were spaced 1 km apart in a north-south direction, would all fit between the (50±0.3)°S latitudes. And if we expanded the width by a factor 10, e.g. latitudes 49±3°, which presumably is feasible if the original Plan is, then, at least naively, we'd generate *10 times* current world raw energy consumption rate. In this paper, we often shall use the word **naive** to refer to multiplying the mean power output of one turbine by N, to determine the output from N turbines. In reality, when N becomes large enough so that those turbines substantially diminish the amount of wind in the world, then that naive calculation becomes an *overestimate*. We'll see in §6 that this actually will happen and indicates that "10" is impossible. Indeed, even the calculation underlying the original (50±0.3)°S plan was naive. The cost of all those 1700160 turbines, would then be about $\$3.2\times10^{13}$, approximately 1.5 times the year-2019 USA GDP, and also approximating 40% of world year-2017 GDP.

5. Transmitting the energy (two bad ideas and one good one)

1. The most obvious idea (which I do not recommend) is to use an ordinary **copper cable** along the ocean floor. The longest AC undersea power cable presently in use is 120 km long (Malta-Sicily), runs at 220 kVolts AC (RMS), and is rated for 200 MW (corresponding to 909 amps RMS current). It cost $208 million, and became operational in 2015, supplying about 25% of Malta's electrical power. Supposedly it was installed *buried* by a jet process 1.5 meter below sea floor sand. Nevertheless it was damaged, presumably by a ship anchor, in Dec. 2019 at a location where the water was 150 meters deep. (It was unexpected that any ship would have an anchor-chain that long.) That caused a Maltese nationwide blackout, and took 6 months to repair using a special ship.

The longest DC undersea power cable presently in use is the 580 km long "NorNed" cable (Eemshaven Netherlands↔Feda Norway; built 2008) and it is rated for 700 MW at ±450 VDC (778 amps). It cost $684 million. Its maximum sea-depth was 410 meters but over 70% of the cable was at depths shallower than 50 meters. This cable had a fault in 2011, causing 7 weeks downtime. It weighs 73.4 kg/meter, which *if* that weight were almost entirely copper (untrue) would correspond to a copper cylinder 10 cm in diameter, which would cost $244 million at a year-2020 copper price of $5187/tonne.

Note the prices of these cables were $1200-1800 per meter.

Annealed copper has a resistivity of 0.0172 Ωmm^2/meter at 20°C with a temperature coefficient of 0.00393. Hence its resistivity at 5°C is 0.0162 Ωmm^2/meter. Therefore a copper cylinder 10 cm in diameter 3540 km long at 5°C would be a 1.8Ω resistor. Such a resistor would dissipate 1.1 MW if transmitting 788 amps, i.e. 0.31 watts/meter. In fact, though, the cables described above were *not* like that. Typical such cables today are assemblies about 50 cm diameter consisting mostly of insulation and protective covering, and the actual conductors inside have about 1/8 that diameter. Polyethylene is a common insulator, and extruded lead is a common waterproof protective enclosure. They also commonly have fiber-optic communication channels built in.

Anyhow, what I want you to observe is that a "line" of 9.5 MW wind turbines 3540 km long, spaced 1 km apart, is going to generate 33.6 GW, which far exceed both the largest power rating (2.2 GW), and longest length (580 km), of any undersea cable yet built or contemplated. If we tried to use a 10cm diameter copper cylinder 3540 km long to carry 33.6 GW at 300 kV DC (hence current 112 kA), it would dissipate 23 GW, i.e. 6400 watts/meter, which would be a disaster. And actually we'd need 2 such cables (one for the return current) so the total resistive losses would exceed the total power input, so it would not work at all. So for such reasons, at least with present day technology and for long lengths, **copper cables seem infeasible**. If we ignore that infeasibility, then note 66 lines of cable each 25760 km long would cost $\$3\times10^{12}$ if \$1800/meter, which would be a small percentage of the cost (90% of the project cost is the turbines, only 10% would be the cables, if such cables would work, which they would not). One could argue such cables *are* feasible, provided you are willing to pay ≈500× as much money for them. But that seems too high a price.

2. If "**high-temperature superconductors**" ever become available which can transmit high supercurrents at, say, 200 atm pressure and 280 Kelvin, then we could transmit through such a cable along the ocean floor with negligible resistance losses. Unfortunately no such material is presently known.

Superconducting wires presently *are* commercially available but which only work at much colder temperatures. American Superconductor's "amperium 8700" tape has 0.4×4.4mm rectangular cross section and has current-capacity ratings ranging from 70 to 180 amps at 77°K temperature. Sumitomo electric's "type HT-NX" tape is similar: 0.31×4.5mm, available in lengths up to 500 meters, with current-capacity ratings ranging from 180 to 200 amps at 77°K. (Wire tension up to 410 newtons before I_c drops below 95%.) AMSC's "amperium 8502" tape carries 300 amps through a cross section of 12×0.2mm and the tape has mechanical strength ≥40 MPa. These tapes combine YBCO- or BSSCO-family superconductor with normal metal, e.g. copper or nickel. In a many-tape assembly with normal metal between the tapes, occasional superconductor-flaws reducing critical current are readily bypassed (perhaps with some non-super current, but over such a small distance it should not matter because we still have extremely small overall resistivity – each such bypass typically would cause a resistance 10-1000 nanoΩ for that tape). So stacking 60 amperium 8502 tapes would (*if* its magnetic field did not reduce the current capacity) carry 18000 amps through a 12×12 mm square cross section. Actually, *round* cross sections are preferred at high voltages in order to make the electric field more uniform to reduce stress on the insulator. A round assembly with cross-section equivalent to 7 such squares naively would carry 126000 amps, *but* unfortunately would have magnetic field at its surface 14.1 Tesla, which in reality would greatly reduce the critical current. For example the Sumitomo tapes carry over 500 amps at 30°K in low field, but that drops to 25 amps in a 10 Tesla field. And this sensitivity is much worse at 77°K; then even 0.5 Tesla is enough to destroy superconductivity. At 60°K the Amperium 8502 tapes carry over 1000 amps in low field, which drops to 60-130 amps in a 7 Tesla field. The magnetic field would be divided by N if the outer radius were multiplied by N by making its cross-section be an *annulus* instead of a disk. Indeed an annulus arguably is the optimal geometry. It is readily assembled using layers of tape, perhaps with some wound helically at appropriate pitch angles; and the interior could be filled with coolant. *If* that magnetic field did not decrease the current rating below 126000 amps, then this indeed would suffice to carry 33.6 GW at 267 kV DC. I believe this actually would work provided N≥3 and temperature≤40°K from liquid-solid equilibrium in neon.

Any such cable would need to be equipped with *refrigerators* to keep its interior very cold, and thermal as well as electrical insulation. Refrigerators that operate at 600 atm are certainly possible, but would need to be rather stronger than usual; and pumping against 600 atm rather than 1 atm pressure seems energetically very unappealing. Refrigerators based on the thermoelectric (Peltier-Seeback) effect instead of vaporization are possible but at present are much more expensive, less efficient, and less capable of handling large temperature differences, and hence (at least with present technology) seem infeasible. Refrigerators based on the magnetocaloric effect also are possible but at present are uncompetitive even with Peltier. *Waterproofing* is essential since contact with water (indeed even merely exposure to moist air) destroys or degrades BSCCO- and YBCO-type superconductors; also bending the wire too much, pulling on it too hard, or resting heavy objects on it, can damage or destroy its superconductivity. If the refrigeration energy-costs were 50 watts per meter of cable (which might be realistic under normal conditions, but likely is highly optimistic for a high pressure sea floor environment) then our "line" (3540 km long cable) would consume 177 MW, i.e. 5% of the power it carried. American Superconductor's proposed 77°K temperature is convenient for many Earth-surface purposes because nitrogen boils at 77.4°K at atmospheric pressure. However, N_2's boiling point *increases with pressure*, e.g. at 8 atm is 100.6°K, and at 30 atm 123.8°K, ultimately reaching the "critical point" at 126.2°K and 33.5 atm. Argon's critical point is 150.8°K at 48.1 atm (one of the highest). The conclusion is that maintaining a fairly constant low temperature by means of a liquid/gas equilibrium is much less simple on the ocean floor than on Earth surface – likely infeasible. At ocean floor pressures, the only possible liquid coolants would be *supercritical fluids* not ordinary liquids. This is a hard problem to overcome, perhaps fatal. *However*, we might be able to save the day by instead using a *solid*/liquid equilibrium:

Gas	Critical pressure & temp	Melting curve (°K@atm)
He	2.26atm, 5.25°K	4.23@141, 7.91@400, 12.07@779, 13.4@944
Neon	27.2atm, 44.4°K	24.6@1, 24.8@10, 27.5@200, 33.1@629, 41.5@1355, 60@3000
N_2	33.5atm, 126.2°K	63.1@1, 82.5@1000
Argon	48.1atm, 150.8°K	83.8@1, 88.7@200, 104.5@1000, 117.6@1520

E.g. at 1000 atm pressure, solid nitrogen melts at 82.5°K. Unfortunately it would seem rather difficult to fool with (e.g. attach something to) such a cable while cryogenic and refusing to let any superconductor contact water; recovery from cable damage might be very difficult, etc.

In any case, whether for those or other reasons, no superconducting undersea power cable has ever been commercially used as of year 2020. They have been used commercially on land, but only in a few niche applications over short distances of order 1 km. So with present-day technology **the feasibility of the superconducting cable idea, is dubious** but perhaps possible. *If* it really could work, it might be highly attractive.

3. Finally, the power transmission idea I propose (which *does* look **feasible**) instead is this. Each turbine **electrolyses water** to produce high-pressure (at or exceeding sea floor pressures) hydrogen gas (actually, technically, a supercritical fluid, given that H_2 has critical temperature 33.2°K and pressure 12.8 atm). The turbines are connected by a **pipe** to carry that hydrogen.

Seawater electrolysis is a highly developed technology thanks to its use in nuclear subs. (They first purify the water using reverse osmosis, then add KOH, then electrolyse that. This avoids generating chlorine from NaCl, which would kill the sailors.) At typical achieved high-pressure efficiencies of (conservatively) 220 MJ per kg H_2 output, each 9.5MW turbine would produce about 43 grams of high-pressure H_2 per second. Incidentally, note that at high pressures hydrogen becomes somewhat soluble in water, e.g. at 1000 atm and 25°C, 1 gram of water absorbs 1366 micrograms of the H_2 (as opposed to 1.6μg at 1 atm), which is about 1/81 of the amount of hydrogen in 1 gram of pure H_2O. Therefore mild precautions will be necessary to prevent leakage. An entire 3540-km-long line of 3540 such turbines would therefore be producing about 153 kg of high-pressure H_2 per second, which would need to be transmitted to terminuses through the undersea pipeline.

Note that due to the assumed ≈65% efficiency of electrolysis, we actually would need a factor 1.53 *more* turbines with this Plan to generate the same amount of "raw" chemical energy in the form of H_2, as we formerly were planning to generate as electricity. [Much better electrolysis efficiencies, over 95%, have been demonstrated in small scale lab settings, see Oener et al 2020.] So instead of 66 lines of turbines spaced 1 km apart north-south, we now need 102, in latitudes (50±0.5)°S. (Warning: this is a "naive" calculation.)

For concreteness suppose we employ a hydrogen pressure of 800 atm at a temperature of 2°C. Hydrogen under those conditions has density of about 40 kg/meter^3, i.e. about 4% of the density of water, 3.6% of the density of crude oil, and about 43% of the density of 100 atm natural gas. Hence our 153 kg/sec mass flow rate corresponds to a volume flow rate of about 3.8 cubic meters per second through our pipeline (which is at most 3540 km long). If our pipe has inside-diameter 120 cm (typical for a large natural gas distribution pipeline today; submarine pipeline diameters today range from 7.6 to 180 cm), this corresponds to an outlet flow speed of 3.4 meters/sec. If we used only 70 cm diameter, then that flow speed would be 10 meters/sec. Flow speeds 2-10 meters/sec are, in fact, common in natural gas pipelines today; and the pressure gradients we have in mind ought to be more than adequate to propel this flow.

Incidentally, note that at these two flow speeds, the *time* for the H_2 to travel from one end to the other of our 3540 km long pipe, would be 1.04 or 0.35 megaseconds, also known as 12 or 4 days. In other words, our hydrogen pipelines are not just energy *transmission* devices; they are energy **storage** devices. Such storage can reduce energy-generation variations caused by changing wind.

Somewhat embarrassingly, the pipe we just described, when filled with hydrogen, actually would be *lighter* than water and would need to be weighed down. Submarine natural gas pipelines must have the same problem, albeit to a lesser degree. Near-neutral bouyancy might seem best to make installation maximally easy. Also note, our naive Plan with 102 parallel east-west lines is *not* the most economical pipeline geometry, either in terms of construction cost of materials or energy losses via fluid-flow friction. Better is, say, three wide "main arteries" along parallel latitudes, with smaller-diameter north-south "feeder branches" connected to them. To be conservative, though, our cost estimate will be based on the naive Plan.

Also note, "hydrogen embrittlement" is a problem experienced by many kinds of metals exposed to hydrogen especially at high pressures and temperatures. Nevertheless, it is known that some alloys are immune to this problem, e.g. Type 316LSS austenitic stainless steel appears to be immune to 750 atm H_2 at room temperature. Aluminum and many oxygen-free copper alloys also seem immune. One commercial hydrogen pipeline in Germany, 240 km long, has successfully run at over 200 atm for over 80 years. Pressurized hydrogen tanks using organic polymer liners can store 1000 atm H_2 for long durations.

The PetroChina West-East natural gas pipeline (currently under construction, connects 66 cities in China) is to be 8707 km long. Already in operation is the Yamal-Europe Pipeline (Siberia to Austria), 4196 km long and 142 cm diameter. Those both are on land. Underwater is the 1224 km NordStream pipeline carrying Russian natural gas to Europe under the Baltic sea. It is a 48-inch (≈122 cm) diameter twin-pipe system which cost \$10 billion in 2012. We conclude that the pipeline cost for our Plan should be at most \$$2.2\times10^{12}$, a *tiny fraction* of the whole project cost.

The **total project cost** then is dominated by the turbines and amounts to \$$5\times10^{13}$, approximately 2.3 times the year-2019 USA GDP, and also approximating 62% of world year-2017 GDP.

Two benefits of the hydrogen-transmission plan partly compensating for its 65% electrolysis efficiency: The author is well aware that the 0.65 efficiency factor we pay to electrolyze water is distressing. It would be replacable by 1.0 if we had magic superconductors. The "**crossover point**" where the hydrogen pipeline becomes more economically attractive than direct electrical transmission via copper should lie between 100 and 1000 km. The reader here might note than many of the inter-island gaps, especially if we use seamounts, are shorter than 2000 km, suggesting a substantial fraction of the transmission can and should be done via copper not hydrogen. That would allow the electricity to be used directly to produce aluminum for the aluminum economy. Because aluminum smelters allegedly are 90% efficient whereas we've assumed only 65% efficiency for electrolysing water, that could improve matters substantially.

However, I'll now discuss some benefits, which I understand poorly, that partly compensate for hydrogen's efficiency loss. (To keep the analysis simple and conservative, the rest of the paper ignores these benefits and does not use the mixed copper+hydrogen transmission idea.)

A. Simpler electronics. If, say, we were using direct electrical transmission to consumers – then for the USA's grid households are supplied with AC at 60 Hz and 120 volts RMS, and 2 opposed phases on the 120 so consumers can get 240. Now if the power sources were not at 60 Hz, but rather at, say, random frequencies within the range 60±0.0001 Hz, then the whole electrical grid would self-destruct within a few hours! Keeping everything everywhere exactly synchronized, is not trivial. It requires a lot of electrical and mechanical technology.

However, if we only are using the electricity from our turbine to run an electrolyzer, then all that technology is *unnecessary*. That should save money, and gain simplicity, reliability, and efficiency. I no longer need 60 Hz. Any frequency from say 50 to 2000 Hz is fine including if it varies unpredictably. If my voltage changes that does not matter very much. If the plan is to transform the AC voltage then probably 500 Hz is better than 60 Hz (smaller transformers needed, saving money). The AC will be rectified to DC and used to run electrolyzers. If say the electrolyzers wanted 2 VDC, and we had 10000 VDC, then rather than transforming down to 2V, just put 5000 electrolyzers in series, and if the 10000 VDC changes to 15000 then we can automatically switch some electrolyzers into series that used to be in parallel, etc. Such switching schemes can be very simple and efficient.

B. Advantages deriving from built-in storage. Our hydrogen pipe is not only an energy transmittor, it also is an energy storage device on time scales of around 1 week. That is another large benefit.

Why? Because a dirty little secret (well, it is not "secret," but it is a fact that you can read reams of wind industry propaganda without them ever mentioning this, they keep it very quiet) of wind is: if you want wind (or solar) electricity, then you *also* need to keep a conventional fossil fuel power plant running on "low" 100% of the time, so that it can rapidly ramp up the power when the wind dies or a cloud passes over. Fossil fuel plants do not like to run in that mode. It is inefficient and costly. They like to run at steady and fairly high power. My point is, there is an extra inefficiency factor associated with wind that the wind industry propaganda keeps quiet and does not put in their quoted loudly advertised efficiency and cost numbers. With the electrolysis plan, the *storage* levels out wind fluctuations so all that is no longer an issue. Again, I do not know how big an effect this has on efficiency, reliability, and cost, but again it plausibly is substantial.

6. What is the maximum amount of extractible power?

I believe the essential content of this question reduces to the simple "model #1" or "model #2" below – and closer to model #2.

Simple Model #1: Consider a circuit consisting of a voltage-source V, such as a battery, connected to an Ohm-law resistor R. The circuit dissipates power $P_{original}=V^2/R$. If somebody tries to extract useful work by adding an additional load resistor, such as a heater, thus effectively replacing the resistor R by (1+f)R, then the power extracted by this load is

$$P_{extracted} = P_{original} \cdot f/(1+f)^3; \quad \textit{maximized} \text{ by choosing } \quad f=1/2, \quad \text{yielding} \quad P_{extracted}=(4/27)P_{original}.$$

The whole amount of power dissipated then is

$$P_{supplied} = P_{original} / (1+f)^2 = (4/9) P_{original},$$

and the current-flow would be $(1+f)^{-1}$ times original, i.e. 2/3 original. Numerically 4/27≈0.14815 and 4/9≈0.44444. If the heater is built gradually, e.g. by ramping up f from 0 to 1/2 by adding atoms to it one at a time, then the final atom will dissipate 8/27≈0.29630 times as much power as the first atom did at the beginning of the buildup.

Simple Model #2: An airplane flies horizontally, pushed by some constant amount of thrust from its engine, but resisted by air-drag (force proportional to squared velocity). Let $P_{original}$ denote the amount of power supplied (which equals the amount lost to drag) to maintain this situation. If some passenger on the plane tries to extract useful work by sticking a *windmill* out the door, thus effectively replacing the airplane's drag coefficient C_D by $(1+f)C_D$, then the plane will fly at (slowed) speed $(1+f)^{-1/2}$ times its original speed. The power the windmill extracts is

$$P_{extracted} = P_{original} \cdot f/(1+f)^{5/2}; \quad \textit{maximized} \text{ by choosing } \quad f=2/3, \quad \text{yielding} \quad P_{extracted}=(6/25)(3/5)^{1/2}P_{original}.$$

The whole amount of power dissipated then is

$$P_{supplied} = P_{original} / (1+f)^{3/2} = (3/5)^{3/2} P_{original},$$

and the airplane's speed would be $(1+f)^{-1/2}$≈0.77460 times original. Numerically $(6/25)(3/5)^{1/2}$≈0.18590 and $(3/5)^{3/2}$≈0.46476. If the windmill is enlarged gradually from 0 to its final size, then the final windmill will garner $(3/5)^{5/2}$≈0.27885 times the amount of power one would naively have expected based on the performances of the tiny ones.

Model #2 actually would be equivalent to model #1 provided the former's "resistor" R, instead of obeying Ohm's voltage-current law V=IR, obeyed the non-ohmic law V=|I|RI more relevant for "drag" resistance in the flow of a turbulent fluid. (Ohm's law is the electrical analogue of *laminar* fluid flow, in which drag is proportional to *unsquared* velocity.) Non-ohmic resistors certainly exist, for example one 100W incandescent lamp was found to obey V≈(0.2156|I|+8.75)I for V in millivolts and I in milliamps, when I varied slowly between ±800.

We **conclude** that the most power wind-turbines could remove from the roaring latitudes, is somewhere between **14.8 and 18.6%** of the power which originally was being dissipated by friction there. Since I believe model #2 is the one which best captures the situation, I would say 18.6%, but in practice less will be attained, for the following simple *economic* reason. As we keep building more wind turbines, the extra total power we gain per turbine, will diminish, until, when we reach the optimum, each extra turbine will add *zero* to the total power. But in fact (if humanity is rational about this) building a turbine is only economically justified if it adds enough extra power to justify its construction cost – a *non*zero amount. If so, the upper bound will not be reached. Humanity might actually be irrational, e.g. somebody will decide to build a turbine, even though that actually *decreases* total world power, so *they personally* will get more power. That is exactly the sort of thing that is happening with "fossil water" resources throughout the USA's west (with overuse actually *encouraged* by the government), and this sort of personal greed also probably also would keep us below the upper bound. Other examples of suicidal overuse and non-preservation of resources were responsible for the massive die-off and vanishing of the Easter Island and Anasazi civilizations. For this reason some responsible policing agency would be desirable.

So for concreteness (and to be a bit conservative) I shall assume the upper bound is **16.7%≈1/6**, and when error bars are wanted (16.7±1.9)%. And this would happen when the net effect of our wind turbine farm was to exert an amount of extra "drag" or "resistance" somewhere between 2/3 and 1/2 of the drag originally exerted by naturally by, e.g. ocean-air and air-air friction. The whole planet-scale heat engine powering these winds would then be slowed, to the extent where those winds would dissipate somewhere between 44.4 and

46.5% of the power they used to, and have somewhere between 66.6 and 77.5% of their original speed; and each of the final wind-turbines will generate only 27.8 to 29.7% of the power the first turbine generated (when it was the only one).

Furthermore, this whole power upper bound must be multiplied by the efficiency of the turbines (perhaps 0.46; an upper bound of 0.593 is set by "Betz's law") if we instead want to bound the *electrical* power extracted, and then by a further efficiency factor (≈0.65) if we use the water-electrolysis pipeline plan and want to bound the *chemical* power extracted. So for example 16.7%×0.46×0.65≈**5.0%**.

Further, if the entire *world* (not just the roaring latitudes) were being covered with wind turbines, then again the maximum amount of power removable from the worldwide winds presumably again would be between 14.8 and 18.6% of the power which originally was being dissipated by friction.

So the **question** now comes down to estimating the amount of power currently being dissipated by friction in the roaring latitudes (or whole world). For that we shall need the following slightly deeper understanding of why the "roaring" winds exist: Equatorial air becomes lighter due to solar heating and solar-enhanced moisture content, and hence rises. Once high, the moisture precipitates out (causing more heating, and hence more rising). This high altitude air-excess leaves the equator, cools hence becomes denser, then falls back down to Earth at about ±30° latitudes. This falling air then does two things:

a. flows back toward the equator, causing (due to Coriolis effect) the east→west "trade winds" between the latitudes 30°S and 30°N. This circulation is called the "Hadley cell" after George Hadley (1685-1768) who explained this in 1735.
b. flows polewards, causing in the southern hemisphere the "roaring" west→east winds between about 30°S and 60°S. There the air rises and is returned to the 30° latitudes at high altitude. This is called the "Ferrel cell" after William Ferrel (1817-1891) who explained this in 1856.
c. (There also is a "polar vortex"; the rising air at 60°S also travels poleward then returns to the 60°S region at low altitude causing east→west winds circulating round the poles.)

What is the **world-total kinetic energy** of *all* air-motions in the Earth's *entire* atmosphere? Peixoto & Oort in the 1980s were the first to produce a good estimate of this: 6.27×10^{20} Joules. This number was based on 10 years of balloon-borne radiosonde data, plus correcting for nonuniformity of data-location by binning schemes. This is equivalent to 1.23 MJoules per meter^2 of Earth sphere-surface area; and also equivalent to air mass-parcels having RMS speed 15.6 meter/sec (which note involves considerably greater wind speeds at altitude than are found near the ground!). Actually Peixoto & Oort went much further: they *classified* four different kinds of atmospheric energy and devised methods to estimate each, as well as the energy flows between them. Their kinds of atmospheric energy are (all in units of MJ per meter^2 of Earth-sphere surface area)

thermal internal energy=1803,   gravitational potential=693,   kinetic=1.23,   latent heat of water vapor=63.8   (sum=2561).

Peixoto & Oort realized that the best way to measure the rate of frictional *loss* of kinetic energy is to take advantage of the fact that it must (if averaged over long enough times), equal the rate of kinetic energy *input* from pressure variations (while reckoning Coriolis effect). They invented the theory necessary to do that calculation and then did it. In 2017 Pan & 6 others redid Peixoto & Oort with more and better data. Their revised kinetic energy figure was **1.399±0.077 MJ/meter^2**, i.e. **$(7.14\pm0.39)\times10^{20}$ Joules** total, corresponding to **RMS speed 16.66±0.45 meter/sec**. Pan et al divide this kinetic energy into two parts: (1) the energy of the fixed mean-flow field, and (2) of the spatio-temporal variations away from that mean. These respectively are 0.768±0.056 and 0.631±0.053 MJ/meter^2 and are traditionally denoted with the highly unjustifiable names "zonal" and "eddy" kinetic energy. (Peixoto & Oort's earlier estimates had been 0.73 and 0.45.) Pan et al indeed were able to see climate change in their energy data, i.e. found a time-linear trend of 1260±480 Joule/meter^2 *annual increase* in eddy energy.

They found the input (and hence also frictional loss) rate of kinetic energy was **2.69±0.19 Watt/meter^2** (Peixoto & Oort's earlier estimate had been either 2.0 or 2.33, I'm confused which), i.e. a world total loss=input rate of **1370±97 terawatts**. Note that this loss rate would be enough to destroy all atmospheric kinetic energy in $(5.20\pm0.45)\times10^5$ seconds, also known as **6.0±0.5 days** (the traditional but bad name for this is "residence time").

Concerning that time-scale: The average lifespan of hurricanes is 6 days (the longest-lived hurricane ever seen, 1994's Hurricane/Typhoon John, lasted 31 days; short-lived ones such as Ernesto in 2006 last less than 12 hours), and Josh Rosenberg in 2013 collected "accuweather" forecasts for Philadelphia and compared them with the truth, finding "I would not trust a forecast high temperature more than a week out; I'd rather look at the normal (historical average) temperature for that day than the forecast. Similarly, I would not even look at a precipitation forecast more than 6 days in advance, and wouldn't trust it for anything important until about 3 days ahead of time."

> **Warning**: In §12.6 of the *handbook* by Hodgkinson & Stacey 2017 they claim the atmosphere has kinetic energy 5.3×10^{20} joules, i.e. RMS speed 14.3 meter/sec, with residence time 14 days. Meanwhile Russell D. Thompson's text *Atmospheric Processes and Systems* (Routledge Introductions to Environment: Environmental Science 1st Edition 1998) on page 98 claims the atmosphere's kinetic energy is 140 Whr/meter^2=504 kJ/meter^2 which would yield a world total of 2.57×10^{20} joules and RMS air speed 10.0 meter/sec. Thompson then added insult to injury by claiming the average rate of dissipation of this energy by friction is "2 Whr/meter^2" which is not even correct units to *be* a "rate." Apparently by "Whr" Thompson here meant "watt" since he then claims the residence time is "70 hours." Neither gave any evidence or citation whatever to back up their wrong numbers. They were accurate to within a factor of 3. The lesson is *do not trust meteorology textbooks and handbooks* no matter how widely circulated. Demand evidence.

Huang & McElroy 2014 estimated from extensive meteorological data that keeping both *Hadley* cells running consumes 198 terawatts of kinetic power on average (the southern cell consumes a high of about 220 TW in August and a low of about 30 TW in Jan-Dec, and on average about 125 TW; the northern Hadley consumes about 220 TW in January but near-zero in July), derived from 7600 TW of thermal power. Meanwhile the corresponding figure for both *Ferrel* cells together is 275 TW of kinetic power derived from about 3600 TW of thermal power. The southern Ferrel cell consumes a high of 240 TW in August and a low of 105 in January, averaging about 173 TW. Both the N&S Ferrel's together consume between a low of 260 TW in May to a high of 300 TW in Jan-Dec.

We **conclude** by combining this data with our previous simple extractibility models that it is impossible to extract more than **229±30 TW** of kinetic power from world winds, or equivalently **0.45±0.06 watts per meter^2** of Earth sphere-surface area. These are tighter upper bounds than any previous work, and via a much simpler argument. (Indeed, some previous works published absurdly large "attainable" wind powers.) With our efficiency factors of 0.46 and 0.65 this upper bound would correspond to 105±14 TW of electrical, used to produce 68.5±9 TW of chemical, power.

To the extent that our Plan extracts power only from the Southern Ferrel cell, it cannot extract more than **28.9 TW** of kinetic power (yearlong average), nor indeed can *any* wind-powered scheme in the roaring latitudes extract more than that. With efficiency factors of 0.46 and 0.65 this would correspond to 13.3 TW of electrical and 8.7 TW of chemical power.

These contrast with the year-2019 rate 15 TW of world raw unrenewable energy consumption. So it would appear possible to supply approximately all, anyhow certainly at least half, of that provided we mostly, but not entirely, stay in the roaring latitudes.

7. Maintenance

I think most turbine and pipeline maintenance would have to be done by robots not humans. Robots should repair sooner and maintain better, costing less money and less downtime. Humans might be unhappy trying to work inside a rocking, not rigidly anchored, floating wind turbine 100 meter up.

One survey of wind farms found they paid $45 per kW-year in maintenance costs. I want that to halve.

Each turbine should have its own resident maintenance robot (or several), a stock of spare parts, a large collection of sensors, an AI, and the 2-way communication with the outside world. Ships will continually deliver spare parts and supplies as requested, in the manner of a postman delivering mail. Obviously the largest repairs, such as replacing the main bearing or probably a rotor blade, would not be possible in this way and the turbine would have to be towed to a repair shop. But many tasks should be doable by robot such as oil changes and replacing many kinds of components. Suitable robots are not presently commercially available, but the advance of AI technology is such that I believe they could be developed. And even if robots were not possible and we had to hire 1 million "wind turbine repairmen" to maintain our 2.8 million turbines, the annual cost of that still would be a tiny fraction of our budget.

One wind turbine company executive objected that the **development costs** for these robots might be enormous. I disagree. Press reports claim cumulative development costs for "self driving cars" up to year 2020 have been $16 billion spread over more than 80 competing companies (none individually spent more than $4 billion) plus one woman killed. The result of that, allegedly, is that self-driving cars have achieved comparable skill and safety per mile to human-driven cars, and there are over 1400 of them operating – although none are for sale and the extra sensors, computers, and actuators that need to be added to a car would substantially increase its cost (and maintenance worries). As of 2020 self-driving cars are used by several semi-commercial services, and partially self-driving cars are sold (Piper 2020). Those development costs should *upper bound* ours because (1) we have a comparatively simple and unchanging environment compared to all-world driving; (2) if our robots get into trouble, they can call for help. We do not need to be able to handle every situation in every meter of driving with 10^{-11} failure rate; merely handling 99% of maintenance would be very useful, and software-updates could be transmitted to improve over that as we go. Given this upper bound, total robot development cost for our project will be below 1/3000 of the total project cost – microscopic.

An important part of ship maintenance involves repainting and drydocking. SOLAS (International convention for the Safety of Life at Sea) demands inspecting the hulls of merchant vessels in a dry dock twice each 5 years, and for passenger vessels annually. I want such inspecting to be done at sea by AI robots. The US Navy in 2011 *deployed* a robot that cleans barnacles off ship hulls autonomously (hull "BUG", Bio-Mimetic Underwater Grooming system) while they still are microscopic, preventing that "bio-fouling" from ever becoming macroscopic. This was inspired (Ralston & Swain 2009) by observed "grooming" behaviors of various animals. That should happen continually.

It also would be very desirable if automated devices could be created to allow repainting/resurfacing to be done continually *without* a drydock while at sea (e.g. effectively creating mini-drydocks handling movable small subsets of the surface at any given time), say redoing up to 1% of the ocean-exposed surface per week. I believe that will be feasible if the turbine geometry is designed to help.

8. Why wind turbines? Why not water turbines?

The roaring-latitude winds power the **circumpolar ocean current** which circles Antarctica in a west→east direction. This current is estimated to transport (1-1.7)×10^8 meter^3/second, about 135 times the transport of all the world's rivers combined and also exceeding any other ocean current. This current by itself constitutes about 1/3 of the transport of all ocean currents combined. Although the current flows at a rate of about 1.1 meter/sec over the Macquarie Ridge south of New Zealand, a more common speed is 0.2 meter/sec, i.e. about 1/5 average human swimming speed.

This water speed is 10 to 125 times slower than the wind speeds. But seawater is 832 times denser than air. The net effect is that the extractible **power density** in the water is less than in air, by a factor somewhere between 1.3 and 2500. Submarine water turbines would have the advantage versus wind turbines that they could stay well beneath any passing icebergs and "rogue waves," and would not require nearly as tricky a "balancing act" to keep them oriented correctly. However the low power density makes this option **unattractive** except perhaps in selected fast-current locations.

9. Why not solar?

Solar park	$/W_{avg}$	$/W_{pk}$	MW_{pk}	$US	km^2	%capac	Technology	Year
Portion of 2245 MW_{pk} (57 km^2) Bhadla solar park, Rajasthan, India (27.5°N)*	2.72	0.68	136	200	–	≈25%	poly-Si. Nightly robotic dry cleaning.	2016-2020
Enel Villanueva PV Plant, Viesca, Coahila, Mexico (25.35°N)	3.37	0.86	828	710	27.5	25.5%	sun-tracking PV panels	2017-2019
Pavagada Solar Park, Pavagada taluk, Tumkur district, Karnataka, India (14.25°N)*	4.08?	1.02	2050	2100	53	25%?	?	-2019
Kamuthi solar project, Kamuthi, Tamil Nadu, India (9.35°N)	4.4	1.05	648	679	10.1	24%?	Robotic cleaning.	2016-2016
Tengger Desert Solar Park, Zhongwei, Ningxia, China (37.5°N)*	4.4?	0.7?	1547	1000?	43	15%?	?	-2016
Longyangxia Dam Solar Park, Qinghai China (36.1°N)*	–	1.07	850	911	27	?	Hydropower from dam varied automatically to even out solar fluctuations.	2013-2015
Nova Olinda Solar Farm, Ribera do Piaui, Brazil (7.7°S)	4.48	1.03	292	300	6.9	23%?	Sun tracking.	2017-
Bungala solar plant, Port Augusta, S.Australia (32.4°S)	4.77	1.15	275	315	8	24%	poly- and mono-crystal Si, tilt sun-track	2017-2020
El Romero Solar Plant, Vallenar, Atacama Desert, Chile (28.6°S)	6.04	1.39	246	343	2.8	23%	Stationary poly-Si	2016-2018
Ituverava solar plant, Tabocas do Brejo Velho, Bahia, Brazil (12.7°S)	6.36	1.57	254	400	5.8	25%?	?	-2017
Benban Solar Park, 40km NW of Aswan, Egypt (24.5°N)	9.3	2.42	1650	4000	37.2	26%	poly-Si.	-2019
Floating solar+fish farm project, Changhe and Zhouxiang reservoirs, Cixi, Zhejiang, China (30.2°N)	10.4?	1.30	200	260	3	12.5%?	?	2016-2017
48 MW_{pk} portion of 802 MW_{pk} (16.2 km^2) Copper Mountain Solar Facility, Boulder City, Nevada, USA (35.8°N)	10.5	2.94	48	141	–	27.9%	Unit 4 has sun tracking tilts.	2008-2021
De Aar Solar Farm, Northern Cape, S.Africa (30.6°S)	11.45	2.29	175	400	5	20%?	thin film amorphous Si	2012-2014
Huanghe Hydropower's Golmud Solar park, Golmud, Qinghai Province, China (36.4°N)*	14.0	2.52	200	504	5.64	18%?	?	2009-2011
Topaz Solar Farm, San Luis Obispo County, California USA (35.0°N)*	17.5	4.54	550	2500	19	26%	Stationary-tilt CdTe thin-film.	2011-2014
Setouchi Kirei Mega Solar Power Plant, retired salt field in Setouchi City, Okayama, Japan (34.6°N)	–	4.11	235	966	2.6	?	poly-Si.	2014-2018
Agua Caliente Solar Project, Arizona USA (33.0°N)*	21.7	4.39	410	1800	9.7	20%	stationary CdS/CdTe thin-film	2011-2014
Waldpolenz Solar Park, E. of Leipzig Germany (51.3°N)	25.8	2.94	52	153	2.2	11.4%	CdTe thin film PV	2008-2011
Sarnia photovoltaic power plant near Sarnia, Ontario, Canada (42.9°N)*	27.2	5.00	80	400	4.5	18.4%	thin-film CdTe	2010
Ivanpah solar facility, San Bernardino County, California USA (36.0°N)	28.6	5.61	392	2200	14.2	19.6	tracking mirrors, towers, steam turbines, natural gas+solar hybrid.	2010-2014
Kathu Solar park, Northern Cape, South Africa (27.6°S)	39.7	8.11	100	811	8	20.4%	Moving tilt parabolic trough mirrors, steam turbines, 450 MWh molten salt thermal storage system	2016-2019
Crescent Dunes solar project, Tonopah Nevada USA (38.2°N)	44.7	–	110	1000?	6.8	20.3%	tracking mirrors, tower, steam turbines, 1.1GWh molten salt heat storage	2011-2017
Olmedilla photovoltaic park, Olmedilla de Alarcon, Spain, 39.6°N*	53	8.83	60	530	2?	16.6%	monocrystal-Si	2007-2008

Table of over 25 solar parks (latitudes 7-52°): Asterisk (*) indicates solar projects claimed to be world's largest at their time of construction. The land area of the solar park including both PV collector area *and* "wasted" area is stated in units of km^2. Only projects with area>2km^2 built 2008-2021 are listed. We state the invested money in units of 10^6 $US. MW_{pk} denotes the maximum possible electrical power that could be generated during 1 minute under perfect conditions. For the facilities tabulated, MW_{pk} ranges between 29 (Topaz) and 91 (Setouchi Kirei) times the project area in km^2, aka 29-91 $W_{pk}/meter^2$. "%capac" denotes the actual generated power (year-long time average) as a percentage of that peak power; with sun-tracking moving panels at most 50% would be possible; with stationary panels at most 1/π≈31.8%; in practice ranges between 11% and 28% for the facilities tabulated. This causes the long-time-averaged power productions to range between 2.7 (Waldpolenz) and 20.2 (El Romero) $W_{avg}/meter^2$, typically about 10. Conceivably Setouchi Kirei has even greater (23?) $W_{avg}/meter^2$. The maximum theoretically possible power production (100% efficient solar cells, 100% transparent atmosphere, cylindrical planet) would be the solar constant 1361 $W/meter^2$ divided by π, namely 433 $W_{avg}/meter^2$. Known technologies offer no hope of exceeding 100 $W_{avg}/meter^2$. The $\$/W_{pk}$ ratio gives the "unit price" of that solar park in units of $US per peak watt; these range between 0.68 and 8.83 for the PV facilities tabulated. The $\$/W_{avg}$ ratio ranged between 2.7 and 53 for the facilities tabulated, an astonishingly large (factor 20) price range. However, since $\$/W_{avg}$ prices within the factor-2-wide subrange (2.7, 5.4) have now been achieved in 5 different sunny countries during 2016-2021, I believe that price subrange is genuinely here to stay. "Technology" says the type of technology employed (if known to me). Presently the main commercial photovoltaic types are monocrystal-Si (20%), polycrystal-Si (16%), thin film Cu-In-Ga-Se (14%), CdTe (10%), or amorphous-Si (7%). in decreasing order of efficiency (typical efficiencies stated in %); I think poly-Si is the most popular for large projects at present. Some of those can involve front and/or rear layers added to improve optical properties, multiplying efficiencies by ≈1.05. Many panels sold commercially in the USA for residential use in 2021 achieve afficiencies 17-23%. Uniaxial time-varying-tilt panels and robotic cleaning have been used in some projects. PV-solar farms that *float* on lakes also have been made; these can enjoy better cooling, vertical-axis rotatability to track sun, lower land costs, and can beneficially reduce water evaporation in arid areas. Rarer are mirror-concentrator parks using steam turbines (best used at high altitude arid places); for them the MW_{pk} figure is less meaningful. Years states the years during which the park was constructed. Estimated lifespans of PV parks are 20-30 years, although those guesses remain unverified.

> **Cautionary tales.** Crescent Dunes produced only 40% of its design-goal power, hence was shut in 2019. Ivanpah also was a design failure (although it remains operational) in the sense that during 2014 it produced only 69% of its goal power, albeit the amounts increased every year except 2018→2019, so that by 2020 it was producing 91% of goal. (My tabulated numbers for Ivanpah are based on the energy allegedly produced by its solar component.) Topaz continues to operate as of 2021 but probably is a financial failure with its bonds now degraded to "junk."

Comparison of solar versus our wind-based plan. Consider the "empty quarter" (Rub' al Khali) of SE Saudi Arabia as one of the best "bang per buck" places in the world to put a solar panel. This is a hyper-arid sand covered region, elevation≈600 meters, temperatures 12-51°C, getting <35mm annual rain, containing very little animal, plant, or human life (and apparently no towns or roads), with latitude about 20°N, and in a country singlemindedly focused on making money by supplying energy to the world. I estimate – based on the better numbers in the solar-farm table above and assuming optimistically that sand-dune motion does not pose an insuperable problem – that it ought to be possible (per km^2 of land area) to generate 10 MW_{avg} of electricity, using summed solar panel mass ≤10^6 kg (but this figure does not include the additional mass of supporting structures, electronics, wiring, etc), for an investment of $30M.

In contrast, one of our turbines (which we have hypothesized are distributed 1 per square-km) generates 9.5 megawatts average, masses about 4.4×10^6 kg, and costs $19M.

Both last 25-30 years.

If 40% of the entire Rub' al Khali 650000 km^2 region were filled with solar panels (terrain, roads, etc presumably prevent full coverage) that would generate 2.6×10^{12} average watts, i.e. about 1/6 of current world raw energy consumption, at a cost of $\$8\times10^{13}$, i.e. about the present world GDP. (Incidentally, total area of all world roads, and total area of all rooftops, as of year 2020 each are about $10^5 km^2$, i.e. not enough even if they both were somehow completely covered with solar panels.) The need for ultra-pure (≥99.9999%) high-quality-crystal silicon, cut into wafers, would be vast. Assuming 650μm Si-wafer thickness, each square-km solar array would use 1500 tonnes of ultrapure crystal silicon. So this project would require a **vast (≈100×) expansion versus current world production rates**. A square-km solar array instead based on CdTe thin-film technology would consume about 7 tonnes of cadmium and 8 tonnes tellurium. Cadmium is a very nasty toxic heavy metal, which accumulates in human bodies (halflife for expulsion is about 30 years) causing cancer and organ problems including bones, urinary, reproductive, cardiovascular, nervous, and respiratory systems. Covering 40% of the Rub' al Khali with CdTe panels would consume 1.8×10^6 tonnes Cd – enough to kill 500 million people if they were fed that cadmium in CdO form. Also, this much Te would exceed total known geographic ore "reserves" as estimated by US Geological Survey (USGS) in 2015.

In contrast, our wind turbine Plan does not require any substantial expansion of world production rates of any basic material.

What about rapid changes in prices? My original analysis of solar power was written in 2019-2020 before Bhadla and Benban appeared; and also I was not aware at that time of many of the cheaper solar projects tabulated above, and foolishly concentrated mainly on solar projects located in the USA. That prior analysis concluded the wind-based plan would be 6 times cheaper than solar power – no contest. I then had to completely rewrite this section and it now finds the wind-based plan will cost perhaps 60% of solar's cost! The problem was rather astonishingly rapid price changes, differing in different countries. Both wind and solar are getting cheaper and I am unable to predict what will happen to them. One econo-historical advantage solar enjoys over wind, is that solar is usable at *small scales*, e.g. powering single houses.

Conclusion. The present paper's wind-based plan seems to yield fairly similar power, mass, and cost numbers (per area) as modern solar. But at least as of year 2021, the wind-based plan seems cheaper and more feasible. Plausibly both should be involved, because, e.g, generating human energy needs from solar *also* likely will cause climatic changes, and solar and wind perhaps could offset each other's damaging effects (assuming there were any intelligent planning) and/or usefully complement each other's advantages.

Some underlying reasons why our wind-based plan should be superior to solar (and these reasons should remain valid despite any future changes in the techno-economic picture) are worth discussing. Nobody tries to mine iron by just using average rocks (which are about 5.6% iron). They always mine "iron ore" i.e. rocks with iron content enhanced to high concentrations by natural processes. Analogously, the roaring-latitude winds are a natural *energy* concentrator. The 9.5MW MHI/Vestas turbine extracts 450 watts per $meter^2$

of cross-sectional area from such winds (and for the 10MW model, 473 watt/meter^2) i.e. concentrated energy. Current solar photovoltaic panel farms can, at best, extract 23 watt/meter^2 (time-averaged). Hence these winds are **20×** more concentrated "ore." Winds in other locations than ours are much less attractive. And for solar panels, to harvest the power hitting an L×L square area you need to *build* L^2 collector area, and using fairly expensive (ultrapure silicon) or toxic/rare (CdTe) materials. With wind turbines, what you need to build does *not* grow quadratically with large L, but more like **linearly**. E.g. for a 3-bladed turbine the summed blade-length is 0.95L and the tower height is about 0.8L. For the V164 turbine we have been using as our numerical example, L=145 meters, which is much larger than the blade widths (≈3 meters) and tower diameter (7 meters). The materials needed are fairly cheap: fiberglass, steel, concrete. And our plan enjoys easy towability and install/remove, which ought to pay over the long term picture when we consider maintenance, continual rebuild/refurbishment, and decommissioning.

10. Hazard to navigation?

Ships have little interest in crossing 50°S because the conditions are unpleasant and there isn't any destination down there anybody wants to go to. The most important exception is ships that want to round Cape Horn. That is considered one of the most hazardous shipping routes in the world due to the high winds, waves, cold, ice, and a dangerous shallow region. Mostly only ships too large for the Panama canal make this passage. (A "neopanamax" ship, meaning the largest that can pass through the Panama canal after year-2016, would be 120000 deadweight tonnes, with length=366 meters, width=51.2, height=57.9, and draft=15.2 meters.)

The ships that do want to cross 50°S would need to pass through a field of floating wind turbines each about 220 meters high (highly visible) spaced 1 km apart. Since no ship entering or leaving San Francisco's harbor through the "golden gate bridge" has hit a support during 1936-2020 (main span 1280 meters long & 67 meters above the water; tower height 227 meters), one might presume they can manage it.

But unfortunately for that presumption, that city also is joined to Oakland via the "Bay bridge." This is a multi-span bridge; the 3 longest spans are a 430-meter cantilevered span and two suspension spans each 704 meters long. It *has* suffered three ship-**collisions**, one crane hit, and one airplane crash during the years 1933-2020:

- On 11 Feb. 1968 a US navy training plane hit the cantilever span about 5 meters above the upper roadway in heavy fog (pilots killed, plane sunk & destroyed; one bridge truss section damaged & needed replacement).
- In Sept.1977 a towed barge-mounted crane hit the bridge span because the crane was too high.
- On 22 Feb. 1980 cargo ship *Brilliant Star* hit "Delta tower" causing $300K in damage to its wooden bumper protection, but no other damage.
- Both serious ship collisions were blamed on human error and led to loss of pilot licenses and in one case prison time: The first was a 228-meter-long tanker, the *Overseas Reymar*, which hit the "Echo tower" on 7 Jan. 2013 (pilot was on his phone at the time, among other sins). The ship suffered $220K in damage while the bridge's fenders had to be repaired for $1.4M. The second was a container ship *Cosco Busan* which hit "Delta tower" on 7 Nov. 2008, suffering a 27-meter long gash in its hull and spilling 2×10^5 liters of fuel oil. (Ship later renamed *Hanjin Venezia* and repaired for $1.5 million, plus its owners paid $10 million in fines.) It was proceeding at an unsafely high speed in heavy fog with a pilot who failed to, or did not know how to, read the electronic charts. Both these towers were associated with the longest (704m) spans.

The wind and wave conditions in San Francisco are much milder than the roaring region, although SF is worse in the respects that it often has a lot of fog, shallows, powerful changing currents, and other ships to worry about.

As far as I have been able to tell, collisions between ships and bridge supports **do not occur** if the bridge span is sufficiently *wide*. Specifically, I believe the supports of the 704-meter Bay Bridge spans are the widest span ever hit. So it is reassuring that our turbines are planned to be 1000 meters apart.

The supports of important bridges are usually built massive, equipped with fenders to try to protect them in the event of a ship collision, and the bridge is illuminated at night. Nevertheless, worldwide, about 1.5 serious ship-bridge collisions have occurred per year since 1970 ("serious" meaning partly or wholy destroying the bridge) including the 9 May 1980 collision of *Summit Venture* with an anchor pier on the Sunshine Skyway Bridge (Tampa Bay, Florida) during a morning thunderstorm (collapsed 396-meter span, 35 killed). Ship-bridge collisions are by far the largest cause of bridge failures.

There are currently about 50000 ships worldwide. The largest are about 460 meters long, reaching up to 75 meters above water and down to 25 meters beneath. In the USA there are about 150 major bridges that large ships pass through. I deduce that there are $\leq 50\times50000\times2000=5\times10^9$ "potential bridge-ship-collision" events (aka "ship passing under bridge") events per year worldwide, resulting in 1.5 actual major such collisions.

The wind farm also will be vulnerable to collisions with occasional **icebergs**, which can move at speeds of up to 5 km/hour and weigh millions of tons – or more. I have estimated above that up to 5 icebergs might cross the 51°S latitude per year. Some sort of active defense presumably will be necessary against bergs.

1. Oil companies developed a successful iceberg towing technology to keep them away from their oil rigs in the Labrador Sea between Canada and Greenland. They used a floating bridle around the berg made of 8-inch diameter bouyant polyethylene rope, attached to several tugs. This rope often would be heavily eroded during use.
2. Unfortunately it has been speculated that "global warming" might generate a lot more icebergs in future. For icebergs that cannot be towed (e.g. too large), we could detach the threatened turbines from their cables and tow them elsewhere to dodge the threat; then re-attach them later.
3. But the slickest defensive idea would be to design the turbines to be *submersible* as deep as 300 meters. Whan a threat approaches, flood the hollow sphere and sink the turbine. Re-float it later by pumping in air to remove that water. This all could be done by remote control.

Also, any **submarines** would need to exercise caution in this area to avoid the cables linking each turbine to the seafloor. Again, presumably that amount of caution ought easily to be achievable. If desired, gaps in the wind farm wider than 1 km could be designed in to provide wider passageways for ships in infrequent selected locations.

11. Environmental impact and Naive Cost

There are about 20-30 species of **albatrosses** comprised of an estimated 3 million individuals. These are large birds (one kind has wingspan>3 meter and mass>10 Kg) that spend most of their lives aloft (including sleeping, if they can be said to sleep). Some can spend 5 years without ever touching land. Some live 50-100 years, and during those 50 years fly over 6 million km, including some circle Antarctica many times. Under the right circumstances some can sustain flying speeds over 120 km/hr. Some are capable of predicting the weather 24 hours ahead. They can navigate. They catch seafood (mainly octopus, cuttlefish, and squid) in dives but never go more than about a meter below sea surface. Salt-excretion glands enable them to drink seawater. They only visit land in order to breed. They live mainly in the southern oceans, expertly taking advantage of the high winds and nonuniformities in them to glide with little energy expenditure. They can fly over 200 km before ever flapping their wings. They can glide about 20 units horizontally for each unit of altitude lost. Their known breeding locations all lie at latitudes 37-57°S. It is quite possible that the proposed wind farm, featuring blade tips moving at 100 meter/sec, might be very deadly for albatrosses. These birds already are suffering from egg predation by invasive rats on breeding islands, and from interactions with abandoned fishing gear and baited longline fishing. On the other hand, it also is conceivable that albatrosses could learn to use the wind turbines (perhaps with some aid from their designers; I would recommend platforms which can be added or removed to try to optimize the ecological situation) as additional nesting locations, in which case they'd actually benefit. And most of the time, at least during the day, albatrosses fly at low altitudes (<20 meters, indeed, often below high wave crests) which actually should be *below* turbine blades. They exploit a nonobvious energy-harvesting technique dubbed "dynamic soaring" involving speed, direction, and altitude oscillations between about 0.5 and 15 meters above the sea (also works above land), which can enable them to fly up to about 3× wind speed with almost zero effort. At least 90% of the power supply for this activity is extracted from the gradient in wind speed as a function of height; actual muscle-supplied effort is <10% and probably <1%. Unless near land, albatrosses are not interested in wasting energy (plus impeding their ability to see food) by foolishly abandoning this ultra-efficient technique by flying above 20 meters. *If they stick to that policy, then our turbines will not hit them.* Albatrosses also exploit "ground effects" to reduce "drag," a technique again only possible at the lowest altitudes. Another impressive trick is that albatrosses very near land (where there is a slight updraft caused by the wind having to rise to get over the land) can simply hover in the air, remaining almost stationary virtually effortlessly, for seemingly unlimited time. In any case, to be rather brutal about it, as far as I can see albatrosses do not play any important ecological role and if they all were sacrificed that would not really matter. Specifically, about 1 albatross exists per 25 square-km over their part of the oceans. It seems impossible to believe that small a number of birds over that vast an area can exert much ecological effect.

Essentially, my point is the "roaring south" latitudes are a tremendous energy resource. The only ways that living creatures previously have directly exploited that resource are (i) albatrosses and (ii) "clipper ship" sailors during the late 1800s. Our Plan here would now exploit it in a large way, which, to an extent presently unclear to me, would rob it from the albatrosses.

Some of the 20-30 albatross species live in selected regions outside our roaring latitudes (e.g. Galapagos) which presumably still would survive even if the roaring-south latitudes' albatrosses were devastated. Also, even within the "roaring south" latitudes there will still be plenty of ocean left outside the wind turbine belt – for example one grey-headed albatross was found to be ranging between 30°S and 60°S. This suggests even in the worst scenario albatrosses will still be able to survive albeit with reduced territory.

On the other hand some **other bird**, otherwise aerodynamically incapable of adopting an albatross-like lifestyle, perhaps *would* become able to do it if able to rest on a wind turbine with a resting spot always available within a few km away – which if so could introduce some new competing bird-type into the ecology perhaps with potentially large effects, where by "large" I here mean, "larger than the albatrosses formerly exerted." Many of the remote islands in our table are key albatross nest sites and could be devastated if this project introduced invasive nest-predators or if humans trashed those places. I would recommend the pipeline terminuses actually be located *offshore* from those islands both for this ecological reason, and also just to make it easier for, e.g. supertankers to dock there for loading.

Our earlier remarks about the surface-to-seafloor cables being a hazard for "submarines" perhaps also would apply for "**whales**."

Another possible issue is that such **filter-feeding** creatures as barnacles and mussels will attach themselves to the turbines and/or cables, then alter the ecology by eating plankton. It seems safe to assume the amount of such shellfish per turbine will be upper bounded by quantities found in commercial *mariculture*, e.g. 250 clams per meter^2 raised in Drakes Estero. So assume ≤3000 meter^2 of shellfish-habitable surface per turbine, and ≤250 clam-equivalents per meter^2 on it, then there will be ≤750000 clam-equivalents per turbine, which with our 2.8 million turbines is $\le 2.1\times10^{12}$ clam-equivalents total. Florida littleneck clams filter 17 liters seawater per day, while large adult quahogs can filter 90 liters. So these would filter $\le(1.3\text{-}69)\times10^{16}$ liters/year. The top 100 meters of water in the roaring latitudes, assuming 100 km wide turbine-belt centered on the 50°S latitude, is 2.6×10^{17} liters of water. So a lower bound on the time for them to eat the plankton there is 2 weeks to 2 years.

Mussel mariculture can be considerably denser than clams, with up to 9000 mussels/meter^2, and adult mussels can filter 60 liters/day. If each of our turbines had 3000 meter^2 area covered with mussels at this density, then the mussels on our 2.8 million turbines would filter our 2.6×10^{17} liters in only 57 days.

For comparison, ocean phytoplankton is estimated to have a "turnover time" for reproduction of 1-3 weeks.

We conclude from this comparison that *if* all our turbines were fitted out with mariculture accessories to try to be the most productive mussel-farms possible, *then* their net ecological effect on the region's plankton could be substantial. However, a moment's inspection of ship hulls is enough to tell us that mussel, barnacle, etc growth on them is ≈1000× sparser than in commercial mariculture. So if our wind turbines were designed to discourage/remove mussel and barnacle growth, and did so comparably effectively to today's ships, then their ecological impact should be negligible.

The "electrolysis of water" Plan generates not only H_2 but also about 320 grams O_2 per 9.5 MW turbine, per second. (Hence for all 2.8M turbines: 896000 kg/sec. Entire earth-atmosphere oxygen mass generated each 36000 years. This indicates our Plan's chemical power output is approximately 1/8 of the entire biosphere, since according to Walker 1980, the biosphere recycles the atmosphere's oxygen in 4500 years.) I was imagining simply dumping the vast majority of this **waste-oxygen**. If dumped into the water, it would oxygenate that water. Might this cause some sort of ecological problem? (Actually the main such human-related problem the oceans have been experiencing in recent years is *de*oxygenation.) The southern oceans are the most oxygen-rich in the world (presumably thanks to all the wind, and the cold temperatures) with typically 175 micromoles/liter. I.e. a 5×80×25000km chunk of southern ocean already contains 10^{19} moles of dissolved oxygen. To generate that amount via our 2.8 million turbines would take over 5000 years. So I suspect this is not a problem, but if it is then we could avoid that problem by intentionally piping the O_2 up for *surface*-release.

If the turbines last 30 years and then must be replaced, that is a potentially pretty big source of pollution (i.e. the old, now-garbage, turbines); and also this means the whole thing needs to be continually under construction, or at least refurbishment, to be re-built every 30 years. (The same phenomenon actually is happening with today's energy infrastructure too.) Actually, experience suggests the lifetimes of the first generation of large wind turbines has been only 20-25 years. Ships typically last 30 years if the owner wants them to and maintains them.

Vestas claims the "V164 has a 25-year operational life span" after which "80% of it can be recycled." My estimate of 30 presumes some lifetime improvement versus the first turbine generation ought to be possible. And indeed Pfaffel et al's 2017 survey found "an increasing performance and reliability of offshore wind turbines since the first offshore wind farms," while Tavner et al 2007 found "wind turbines are now achieving better reliability than diesel generation." Given the large physical size and easy towability of each turbine I do not think abandoned broken turbines are going to be a big pollution problem since they are too valuable even merely as scrap.

With 2.8 million turbines the **production rate** required for **30-year rebuild cycle** is 255 turbines per day, i.e. one turbine every 5.6 minutes. Is such a rate of production possible? Obviously many giant new factories and an entire industry will be needed. During year 2019, over 4 million "heavy trucks" (each 11700 to over 15000 kg) were manufactured worldwide, i.e. about 8 per minute. While I believe heavy trucks are more difficult to manufacture than our wind turbines, their total **mass** that year was only around 5×10^{10} kg, as compared to all our wind turbines, with total **mass 1.2×10^{13} kg**, i.e. about 240 times greater. This latter mass is approximately equivalent to:

- a cube of rock about 1.7 km on a side;
- about 1500 kg per human (using the year-2020 world population);
- about 30 times the amount of earth excavated during the construction (about 25% by the failed French effort 1881-1889 then the remaining 75% during 1907-1913 by the Americans) of the Panana Canal; also about 30 times the mass of the "Tarbela dam" on the Indus River in Pakistan
- about 1.5 times the total tonnage of coal mined worldwide in year 2019.

In the same year, 92 million automobiles were made worldwide (11 million in USA), with total mass about 1.4×10^{11} kg (or 1.65×10^{10} in USA), i.e. about 18 kg per human, or for the USA's cars 51 kg per US citizen; and about 1200000 houses were built in the USA, with total mass about 6×10^{10} kg, i.e. 185 kg per US citizen, and the USA mined about 1.4×10^{12} kg of crushed **stone**, i.e. 4140 kg per citizen. Total world container-shipping (tons transferred) during year 2017 amounted to about 1.8×10^{12} kg. Year-2019 total world crude steel production was about 1.9×10^{12} kg. The world produced about 4.8×10^{9} kg of glass fiber and 4×10^{12} kg of Portland cement in 2018. In **summary**: the total *manufacturing difficulty* seems well within reach (also financial cost, see below). Although the total *mass* we are speaking of is somewhat daunting, current world production rates of raw materials, and world shipping mass-transfer rates, both seem adequate to do the build, with the exception that glass fiber production would need to triple (if that is what wind turbine blades are made from).

Given this need for perpetual rebuilding (plus also assuming maintenance costs of \$50/kW-year), the **project cost** I mentioned of 0.66 times year-2017 world GDP then actually would *not* be a one-time expense, but rather a **perpetual ongoing expenditure of 2.3% of world GDP** (this assumes GDP and costs both remain unaltered from their year-2020 values) annually. If we compare that to present-day world energy costs, the 2014-2019 average prices of coal, oil, and natural gas have respectively been about \$0.055, \$0.138, and \$0.31 per kg, which in view of our tabulation of fossil-fuel extraction quantities, means the world during that era spent about $\$2.3\times10^{12}$ per year buying those fossil fuels, i.e. 2.7% of world GDP. In other words, the scheme we suggest would actually provide *cheaper* energy than now.

And I suspect production at this rate will reduce prices, in which case this expenditure will lessen; I also expect GDPs will rise, lessening the burden; and finally I also suspect turbine refurbishment will often be more financially attractive than replacement, which also would reduce costs. But even our very conservative cost estimate seems wholy feasible.

If the switchover to our Plan becomes economically more favorable than unsustainably consuming fossil fuels, then it has a good chance to actually *happen*. Governments can and should enact stiff "carbon taxes," both to create additional economic driving forces, and to pay for this – and note the whole Plan will be worse than useless (actually making eventual crisis worse) if it just causes humanity to increase its power consumption. We must *stop* further exponential growth. China's highly successful "one child policy" would be a good start.

12. Climatic impact I: initial examination

The extraction of all that power from the winds in the roaring latitudes likely will cause a noticeable alteration in the Earth's *climate*.

First of all, as we saw earlier the **total kinetic energy** of *all* air-motions in the Earth's *entire* atmosphere is $(7.14\pm0.39)\times10^{20}$ Joules, corresponding to RMS speed 16.66±0.45 meter/sec. This is equivalent to year-2019 human raw energy consumption (which for this purpose I'll take as 16 TW) for 516±28 days. And if human energy consumption were to increase by a factor **10** (which as we said, *naively* is possible with the Plan advanced here) then only about 52 days. Since it is a matter of common experience that weather develops on time scales of that order (e.g. the longest lived hurricane ever seen lasted 31 days), and indeed this kinetic energy's "residence time" is 6 days, this suggests that extracting these amounts of power from wind probably will have **noticeable climatic impacts**.

Lest the reader complain that the ratio 516/6=86 is so large that we do not need to worry, then I point out (a) because of inefficiency factors, 2-4 times more energy than humans use, would need to be extracted, reducing "86" to 21-43, and (b) as Hansen 2009 points out, even **small relative "forcings" over time can have very large climatic effects**.

Long list of Examples of small forcings causing large effects: the 10^5-year-periodic glaciations that covered Canada and the northern USA (down to Kansas & New York City) in ice sheets several km high and lowered sea levels by 120 meters (both occurred in 20000 BC; the mean temperature then was 8-10°C colder) were caused by Milankovitch cycle "forcings" of only about **-1 watt/meter^2** versus the modern but pre-industrial era, plus some feedback-amplification mechanisms. (Note: extracting 64 terawatts, i.e. 4 times human raw energy consumption, from air kinetic energy, would be 1/8 watt/meter^2 extracted.) This is despite the fact that "-1" naively seems *tiny* compared to the "solar constant" 1366 watts/meter^2, i.e. about 241 watts per meter^2 of time-averaged Earth sphere-surface area. The year-2020 CO_2 level is about 413 ppm (as opposed to year-1750 level of 278ppm), and that and other human-caused greenhouse gases are presently yielding +2.7±0.3 watts/meter^2 "forcing" versus the pre-industrial era. The last time world CO_2 levels were comparable to today's was 52 million years BC. Neither the arctic nor antarctic ice sheets existed then (the latter began about 35 Myr BC). *If* this 413 ppm level persists, then evidently all ice caps will melt. Snyder 2016 based on studying the paleoclimate record (which should be considered more reliable than models) expects each **doubling of atmospheric CO_2**, to yield 7-13°C of eventual warming (95% confidence interval). But Sherwood, Webb et al 2020 claim 2.3 to 4.7°C as 5% and 95% confidence limits based on a large review of multiple lines of evidence.

The Earth had a greenhouse climate during the "cretaceous" 145-66 million years BC. This is believed to have been caused by high CO_2 released by geothermal heating of C-containing geological formations, in the latter part of that era mainly due to the Indian subcontinent moving across the carbonate-rich tropical ocean floor at about 6 cm/year starting 100 Myr BC until it hit Eurasia mainly during the era from 50-25 Myr BC, although this collision is not yet complete. Peak CO_2 occurred about 90 Myr BC and was about 4 times modern but pre-industrial (year 1750) levels of 278 ppm. There then were crocodiles and palm trees in the arctic, including *azolla* floating ferns at the north pole, and the Earth was essentially entirely ice-free. (E.g. a "champosaur" crocodile-like fossil was found in Canada at 79°N, only 1100 km from the north pole; it ate fish and turtles. At present this is about 1600 km north of the nearest tree.) That would raise today's sea-levels about 70 meters, flooding numerous cities such as

> Tokyo, Shanghai, Cairo, Dhaka, Mumbai (formerly Bombay), Buenos Aires, Kolkata (formerly Calcutta), Lagos, Rio de Janeiro, Karachi, Seoul, New York, Miami, Singapore, Amsterdam, Algiers, Bangkok, Washington, Jakarta, Havana, Chennai (formerly Madras), Taipei, Pyongyang, Tripoli, Manila, Oslo, Brussels, Rome, London, Lisbon, Stockholm, Phnom Penh, Wellington, Ho Chi Minh City (formerly Saigon), Hanoi, Helsinki, Mogadishu, Paris, Berlin, Baghdad, New Orleans, Houston, Philadelphia, Boston, and much of Istanbul and parts of Shenzhen and Hong Kong, with current total population >300 million. Indeed I believe over 1.5 billion of the world's current 7.7 billion inhabitants would have their homes underwater.

In the other direction, "Snowball Earth" eras have happened where virtually the entire Earth was covered by permanent ice with temperatures ranging between about 0°C and -130°C with mean≈-50°C. This is believed to be a stable planetary state which will automatically take over (due to brightened planet-wide albedo) once the latitudes>30° are iced over, Except that obviously this was not completely "permanent": The clearest snowball era ("Sturtian") started about 716 Myr BC and lasted 36 Myr. It recently was revealed (Terada et al 2020) that, shortly before this snowball era began (which perhaps triggered it), a giant meteor shower dumped at least 4×10^{16} kg on the Earth and Moon. There is evidence for two other snowball eras about 2.2 Gyr BC (and perhaps also at several times between 2.3 and 2.9 Gyr BC) with the last one ending 635 Myr BC after lasting at least 16 Myr. Unicellular life as well as very primitive multicellular plants and animals (algae, sponges, "grypania" 1-cm wormlike creatures; these can survive much greater temperature and oxygen variations than almost all modern life) survived the Sturtian. The "bilaterians," the root lineage of most animals today, first arose about 555 Myr BC, and soon after came the "Cambrian explosion" of biological evolution. It is believed that gradual CO_2 release from volcanos, with*out* counteracting absorption into carbonates from rock-weathering (since all the rocks were ice-covered) and very-slowed photosynthesis, eventually caused the largest greenhouse effect ever, and broke us out of the snowball era whereupon an enormous carbonate-rock-forming period immediately commenced. The Earth mostly avoided the snowball state despite the sun in past eras being dimmer (billions of years ago the sun emitted only 70% of its current power; during the Sturtian 93%) due to much greater greenhouse gases in early atmospheres. In the absence of catastrophes there probably will not be any more snowballs because the sun is now brighter. *Without* an atmosphere (and hence no greenhouse effect), the planets idealized as infinite-thermal-conductivity perfect blackbodies would have average temperatures $(0.5\ R_{sun}/D)^{1/2}T_{sun}$ where D is the sun-planet distance, T_{sun}≈5785°K, and $D \gg R_{sun}$≈6957000 km:

Body	Ideal blackbody temp. °K	Actual (radiatively measured) temp. °K
Mercury	418	440
Venus	327	737
Earth	277	288
Moon	277	203?
Mars	237	210
Phobos	237	218?
Deimos	237	233?
Vesta	175	133?
Ceres	162	133?

Hansen worries that human-caused CO_2 could trigger "**tip-over**" positive-feedback effects yielding catastrophically-*rapid* warming:

1. Icesheet breakup into icebergs, which then melt much faster than a solid icecap would melt since they draw heat from the ocean. Note this is *time-asymmetric*: icesheet formation is slow but breakup can be rapid. Reconstructions of past Earth history indeed indicate a "sawtooth" temperature curve over the last million years, with period≈10^5 years, peak-to-peak amplitude about 10°C, and the rising sawtooth edges having positive slope about 1°C per 1400 years, i.e. about *seven times* (7×) the negative slopes. But during the last 100 years temperatures rose 0.7°C, which is 10× faster still.
2. Decreased ice and snow amounts (year-long averages) darken planetary albedo, *especially* warming the arctic, which especially decreases ice.
3. "Soda bottle effects" where ocean warming and permafrost melting releases CO_2 and methane from seawater, methane-hydrates, peat bogs, and aqueous ecosystems, plus increases nitrogen oxides; all of these are greenhouse gases.
4. "Colored snow" (e.g. pink; not white anymore) caused by algae in the snow which used to be unable to live, but now can due to greater CO_2; darkens albedo and helps melt more. Another related effect: more beavers building dams in the arctic.
5. The "Atlantic meridional overturning circulation" (AMOC) is slowed or potentially stopped by meltwater from arctic ice, which in turn will accelerate that melting.
6. Deforestation due to climate-change-caused ecological alterations (in addition to human-caused deforestation).

All those seem to be happening. Certainly CO_2 currently is rising faster than in all prior Earth history, perhaps overwhelming any compensatory mechanisms. The worst possibility is triggering an irreversible "**runaway greenhouse**" scenario, which should happen to the Earth sometime between (3-20)×10^8 years from now anyway as the sun continues to brighten. In that scenario the heated oceans release their CO_2 then later boil, releasing H_2O vapor, also a greenhouse gas, in a self-amplifying cycle. That happened to Venus billions of years ago, boiling away its oceans. Venus presumably originally had comparable water content to Earth but 99.99% of that now-atmospheric water was lost to space via photodissociation and ejection of hydrogen atoms which exceeded Venusian escape velocity since in the high tail of the Maxwell-Boltzmann speed distribution. (Venus's hydrogen also was more vulnerable due to its lack of magnetic field. The *Earth* currently loses about 4×10^7 kg/year of hydrogen to space by this mechanism [Walker], not a problem as matters currently stand since that would take 10^{13} years to dry the oceans. Venus's peak H-loss rate presumably was about 50000× faster.) This was proven by spectral observations showing Venus's remaining hydrogen has deuterium fraction over 100× that of everyplace else in the solar system. Venus's mean surface temperature today is by far the hottest in the solar system, about 737°K, and its atmospheric pressure is 92 times Earth's. If the same thing happens to Earth its temperature should surpass 500°K=227°C while its atmospheric pressure multiplies by >250. That will kill all life. Given that no life is known to exist anywhere besides Earth, and it is entirely possible none exists anywhere else, this would be unfortunate.

> **A particularly striking quote by James E. Hansen (2009, end of ch.10):**
> *If we burn all the fossil fuels the ice sheets almost surely will melt entirely, with final sea level rise about 75 meters (250 feet)... possibly within a time scale of centuries. It is difficult to imagine how the methane hydrates could survive once the ocean has had time to warm [in which case] a PETM-like warming [presumably would] be added on top of the fossil-fuel warming... I've come to conclude that if we burn all reserves of oil, gas, and coal there is a substantial chance we will initiate runaway greenhouse. If we also burn all the tar sands and tar shale, I believe the Venus Syndrome is a dead certainty.*

Here "PETM" denotes the Paleocene-Eocene thermal maximum, a 170000-year-long global temperature spike 55.5 Myr BC, which was about 13°C warmer than pre-industrial era (year 1750), based on oxygen-18 ocean-core foram and other evidence, and was another crocodiles-in-Alaska era. Although that already was a quite warm no-ice-caps era, the PETM spiked 5-8°C warmer. It was caused by the sudden injection of a large dose of isotopically-neutral carbon into the atmosphere ("onset," believed to have taken <5000 years and which raised temperatures 5-9°C), followed by about 50 kyr of ^{13}C-depleted carbon injection, overall amounting to about that same dose. (A review is Dunkley Jones, Ridgewell et al 2010.) The total carbon dose is thought to have been (2-20)×10^{15} kg. The second, longer-duration release was mainly from methane trapped in hydrates on ocean floors near continental shelves (based on oxygen- and carbon-isotope evidence, Gehler et al 2016). The recovery from the PETM is suspected to be due to enhanced biological productivity absorbing the carbon into deep ocean sediments. Although the PETM's failure to convert the Earth into Venus may provide some feeling of safety, the sun was about 1% dimmer then, the postulated human-caused carbon injection is of the same order *but* 50 times faster, not giving enhanced biological productivity enough time to act; and Hansen may think the PETM came close to triggering a runaway.

Goldblatt et al 2012/2013 disputed Hansen's worry by arguing that burning all that carbon will *not* be enough to trigger runaway; to make it happen we need about +41 Watt/meter^2 forcing. Leconte et al 2013 went further by claiming +134 Watt/meter^2 would be needed, in which case Venus originally must have had liquid oceans. Meanwhile modelling by Hansen, Sato, et al 2013 concluded that although "a terminal Venus-like baked-crust CO_2 hothouse" would require a "billion year timescale," nevertheless "**burning all fossil fuels would make most of the planet uninhabitable by humans**" due to 1500ppm CO_2 amplified by fedback effects from CH_4 and N_2O causing, in all, +12 W/meter^2 of "forcing" yielding 16°C mean global warming via 30°C polar warming, 20°C land warming, and 14°C ocean warming, which would place "much of today's world population in regions with wet-bulb temperature above 35°C=95°F" and end grain production in almost all today's agricultural regions. **This would probably happen by the year 2300**. As Sherwood & Huber 2010 pointed out, humans are *not* capable of adapting to a warming climate beyond a certain point: Six hour exposure to 35°C=95°F wet-bulb temperature is usually lethal, even for fit naked people in the shade in a breeze. For less-fit people, less stress suffices to kill them:

Heat wave	Max. wet bulb	Fatalities
May 2015, Andhra Pradesh, India	30°C=86°F	≥2500
July 1995, Chicago, USA	29°C≈84°F	739 over 5 days
July-Aug. 2003 Europe	28°C≈82°F	≥70000

During 2012, the maximum wet-bulb temperatures recorded in the world were 31°C≈88°F in certain parts of the Amazon and India. The natives in the parts of the world (a) often featuring wet bulb temperatures 80°F, and (b) without large seasonal changes, stayed naked almost all the time (Amazonia, Papua New Guinea, Caribbean before Columbus, some parts of Africa).

Relative humidity, vapor pressure, and air's water mass-fraction all are known functions of temperature and wet-bulb temperature.

Apparently, noplace between years 1900 and 2000 ever experienced wet bulb temperature≥95°F, and even reaching 86°F usually was considered a legendary heat wave and killed thousands. *It would be useful to inspect Venus closely enough to determine whether it ever had a pre-runaway-greenhouse state with liquid oceans, because this would help set a lower bound on the forcing required to trigger runaway, a question of Earth-survival importance.* (Also, if we believe various pseudo-science propaganda that any earth-like watery planet will quickly develop life, then both Venus and Mars must have had life. That question also might be settleable via close enough inspections.)

To return to the topic of wind power: The total amount of **kinetic energy of the air in the roaring region** (for the present purpose regard this as the latitudes 35-55°S and assume 3× the kinetic energy density of the rest of the world) is about 30% of the whole world's, i.e. 2×10^{20} joules, with max value each year about 1.6 times its min. We plan to extract about 2×10^{13} watts, i.e. enough to remove all that kinetic energy in about **115 days**. On the other hand, if we do nothing, that kinetic energy *also* is getting removed, e.g. by friction against the sea and land, but less effectively. Of course, at the same time it also is being continually replenished (the ultimate power source for all this is the sun). The seasonal variation makes it clear that the time scale for this natural removal is less than 1 year. Recall the observed fact that the "roaring" is strongest during the southern hemisphere winter (June-August) than during the summer (Jan/Feb). That fact exactly conforms to the naive expectation that the temperature gradient powering the heat engine, is greatest during the southern winter, so the heat engine ought to run most strongly then. This fact indicates that the replenishment time scale is *less than 1 month*. On the other hand, given the claim that the replenishment mechanism is based on a planet-sized solar-powered heat-engine with heating at the equator and cooling in the antarctic, then given the distances to be traversed and the wind speeds involved, the replenishment time scale necessarily seems *lower*-bounded by about 1 week. So our planned energy-extraction rate actually looks only 1 order of magnitude below the natural energy-input rate.

Other indicators suggesting the same thing are (1) The *fact* that the *land* in the northern latitudes *prevents* comparable "roaring" there, i.e. its air-resistance is enough to greatly diminish, in summer virtually entirely shutting off, the comparable heat engine. The effect of our belt of turbines 220 meters high might be comparable (from the standpoint of wind-resistance) to if the oceans in that region were actually everywhere dotted with islands for, say, 80:20 water:land ratio. This plainly is not a negligible effect. (2) If the water surface is undulating with crest-to-trough amplitude 4 meters, the turbine farm plausibly would effectively amplify the air-resistance effect of that, locally, by about a factor of 30.

On the **other hand**, perhaps the climatic effects of our Plan might be surprisingly small. The *reason* that surprise might happen is that the world's winds are like a human riding on top of an elephant (solar energy input, 130× greater); an extraction of wind power that seems large based on that wind alone, still is small versus its underlying power source, insolation. And alterations to wind do not alter either insolation or radiative losses (at least at first order) at all, leaving the Earth's planet-wide energy budget unaffected.

While it is nice from an engineering perspective that we really seem capable of grabbing a goodly fraction of this whole sustainable energy resource... i.e. tapping fairly efficiently into the whole "planet-scale heat engine"... it also is rather scary that we would be altering the *entire planet* in ways that presumably will be noticeable. And also I hope this makes it clear that a lot of idiots perpetually making noise about how allegedly "easy" it would be to switch the energy economy to sustainability via wind and solar, while hardly altering anything since human energy consumption (<20 TW) is only a fraction $\approx10^{-7}$ of the solar energy input... have been *lying* to you. Fact: we are *not* going to supply present human energy consumption from wind without noticeably altering all world weather!

I doubt, however, that this all will completely shut down this heat engine, because the entire roaring region will remain just as unobstructed at every altitude>220 meters, which is where 97.3% of its air molecules are located. My guess is the engine will still run, but perhaps only at 40-95% of present speed. (Simple model #2 predicted 77%.)

So just what climatic effects will this cause? I am incompetent to provide a confident answer to that question, but can say a few things. The **naive guess** is that the effect of tapping into the planet-size heat engine, will be to slow down that engine! Hence we will slow that engine's natural recirculation of heat from the equator to the antarctic. This would cause the tropics to become hotter, and the antarctic colder, versus now. This might also be expected to cause greater (or, at least, prevent losing) antarctic ice, brightening planetary albedo and hence cooling the planet. Also, diminution of global heat-circulation should, as a *second*-order effect, increase planet-wide radiative heat loss (because, e.g, two equal-size black bodies at 300°K and at 100°K, will radiate more than two 200°K bodies). These arctic and planet-wide cooling effects are respects in which our Plan would *counteract* CO_2-driven global warming effects.

Then in turn, e.g: "El Nino" presumably would occur more often; tropical storms such as hurricanes might be expected to grow stronger and/or more frequent; and the polar ice caps might be expected to grow, versus now. The circumpolar ocean current, and perhaps ocean waves generally, both should diminish (since powered by winds), and I would expect the Hadley cell would widen north-to-south due to the neighboring Ferrel cell narrowing. Perhaps winds in the northern hemisphere will increase. All that will cause unclear-to-me further climatic and/or ecological effects. Perhaps all this might eventually trigger an "ice age" (glacial period) which in fact was scheduled to happen naturally anyway sometime within the next 80000 years in the absence of humans. However Hansen 2009 claims that no further glacial periods will occur because he believes humans have the power to easily prevent them – CFCs have 10000 times as much greenhouse effect as CO_2 per kg – and will exercise that power. It also is conceivable that our turbines by diminishing the "roaring" winds will enhance winds somewhere else.

My claim is that since climate change potentially poses the risk of killing all life in the universe, we need to have **tools** in our arsenal to prevent that. Our proposal, assuming it really counteracts arctic warning, is one such tool. A second would be advanced breeder reactors, which most governments (including the USA), idiotically terminated research on.

A third is the idea (Beerling et al 2020, hyped in at least 10 newspapers) of spreading rock dust on agricultural land to absorb the CO_2 we are artificially injecting into the atmosphere. Unfortunately (which none of those news pieces mentioned), neutralizing the CO_2 from fossil fuels burned each year would take, at current rates, over 10^{15} kg of pulverized basalt annually, arising from over 350 km^3 of solid rock, equivalent to about 6 Mount Everests. At present about 37% of world land area is classified as "agricultural" by the FAO, and if 350 km^3 of stuff were spread uniformly on it, it would be 6.4mm thick. Since nowhere near this amount of rock crushing and distribution is feasible (it exceeds world transport capabilities by 2-3 orders of magnitude) this third solution seems a nonstarter.

13. "Hydrogen economy" versus "Aluminum economy," and post-fossil fuel future

- 25 June 2003: US president George W. Bush announces "$1.2 billion in research funding so that America can lead the world in developing clean, hydrogen-powered automobiles." (Bush also posed cruising in experimental hydogen-powered wheeled vehicles.)
- 2003: "The FreedomCAR Partnership was created by former Secretary of Energy Spencer Abraham and senior executives of DaimlerChrysler Corporation, Ford Motor Company, and General Motors Corporation. The partners consist of the United States Department of Energy (DOE), BP America, Chevron Corporation, ConocoPhillips, Exxon Mobil Corporation, Shell Hydrogen LLC, and the United States Council for Automotive Research (USCAR)-a legal partnership among DaimlerChrysler Corporation, Ford Motor Company, and General Motors Corporation.
- 14 Jan. 2020: "French president Emmanuel Macron visited Pau to discover the city's ecological initiatives, including the eco-friendly hydrogen fuel cell bus..."

The "hydrogen economy" is the vision of replacing fossil fuels, especially oil, petrol, and natural gas, with hydrogen generated (in future) from renewable sources via electrolysis. In the *present-day* economy, hydrogen is made from (nonrenewable) natural gas CH_4 and using it as a fuel is of course far more wasteful than simply burning that CH_4 directly. Some infrastructure for handling and distributing gasoline, oil and natural gas hopefully could be converted to handle H_2 instead. Plus, "hydrogen fuel cells" (used on the space shuttle) are a new, possibly useful, way to get electricity from hydrogen more directly than the old approach of burning fuel to power a heat engine to power a dynamo.

This vision has been one of the favorite propaganda activities of oil & gas companies and their lackeys, perhaps second only to denying the existence of global warming. They perpetually advertise claims like "hydrogen is the most abundant element in the universe!" as though that somehow had some relevance. The US government in https://www.energy.gov/eere/articles/5-fast-facts-about-hydrogen-and-fuel-cells upped the ante by proclaiming as its first "fact" that "HYDROGEN IS THE MOST ABUNDANT ELEMENT ON EARTH." Here is some actual data:

Top 10 most abundant elements (Earth continental crust) with mass percentages:
oxygen 46.1, silicon 28.2, aluminium 8.23, iron 5.63, calcium 4.15,
sodium 2.36, magnesium 2.33, potassium 2.09, titanium 0.565, hydrogen 0.140.
(Oceanic crust has less Si, but about 2.5 times as much Fe, Mg, and Mn.)

Top 10 most abundant elements (ocean water) with mass percentages:
oxygen 83.4, hydrogen 10.5, chlorine 1.89, sodium 1.05, magnesium 0.126,
sulfur 0.088, calcium 0.040, potassium 0.039, bromine 0.0066, carbon 0.0027.

My purpose in this paper is to explore feasible and worthwhile ways to save civilization from the energy and carbon crises. This contrasts with the politicians and government agencies above, who apparently were more interested in demonstrating their slavish unshakable fealty to fossil fuel companies, regardless of logic, facts (no matter how well known), and cost (no matter how enormous). And while hydrogen is an excellent rocket fuel and probably useful for many industrial, home-heating, and large-scale electricity-generation purposes... it should have been immediately obvious to anybody not a professional idiot, that hydrogen is an *incredibly* bad way to try to power vehicles such as automobiles and buses.

Fuel	MJ/kg (oxide) [50-50]	MJ/liter (oxide)	$cost/kg (year 2014)
Gasoline	46.4	34.2	1
Animal Fat	37	31	1.05
Thermal-Coal	30	20 (if one solid lump)	0.066
TNT	4.6	7.6	17
Boron	58.9 (18.3) [27.9]	137.8 (45.0)	5000
Silicon	32.2 (15.0) [20.5]	75.1 (39.8)	3.1
Aluminum	31.0 (16.4) [21.5]	83.8 (64.8)	1.9
Lithium	43.1 (20.0) [27.3]	23.0 (40.2)	95
Hydrogen(25°C)	120	0.010 @ 1 atm, 4.5 @ 690 atm	
H_2(liq, 20.3°K)	119	8.5	0.7 to 6

The table above shows the **energy content of various fuels** both on a per-kilogram and per-liter basis, as well as their approximate year-2014 dollar costs. Obviously the explosive TNT (2,4,6-trinitrotoluene) is intended purely for comparison purposes and not as a serious fuel proposal; it is regarded as a mono-reactant unlike all the others which are regarded as reacting with external O_2. For fuels whose combustion-products are *solid* oxides, we also give in parentheses the energy content per kg and liter *of oxide* because a car powered by this fuel would have to carry that oxide; and per kg of a 50-50 molar *mixture* of oxidized and unoxidized fuel, because that is the time-averaged weight of what that car would carry (if run until fuel exhausted). The claimed energy contents for gasoline and fat assume that H_2O produced as a combustion product is *liquid*. In many applications, e.g. gasoline internal-combustion engines, it actually would be gaseous, in which case our claimed energy content *over*estimates the truth. For hydrogen the figure 120 rises to about 142 if the water is assumed liquid.

Hydrogen is the best fuel tabulated on a per kg basis, which is why it is excellent for giant rockets. But on a per-*liter* basis, boron or aluminum are best, while hydrogen is the *worst*!

If an automobile's 15-gallon gasoline tank were replaced by a hydrogen tank, to supply the same energy that tank would need to be 5130 gallons! By compressing the hydrogen to 690 atmospheres, you could shrink that to the (still absurd) figure of 114 gallons – provided you are willing to convert your fuel tank into an enormous instant bomb with energy equivalent to 51 kg of TNT. Having a country's automobiles work in this manner obviously would be a commercial and safety disaster. It has also been suggested to store the H_2 as metal hydrides (slow interconversion, H_2 reversibly released/acquired by heating/cooling). But that completely sacrifices hydrogen's high energy-per-kg (and often elemental-abundance and/or toxicity) advantages, leaving it with no advantage at all. (E.g. MgH_2 has energy content only about 9 MJ/kg, one of the highest figures for reversible hydrides. Heat it to 300°C to release H_2.) This all is ridiculous.

And boron also would be ridiculous for anybody who thinks the contents of just one fill-up of their car's fuel tank should cost less than $200k, i.e. over 6 times US per capita annual income. (Beryllium due to its toxicity and rarity would be even more ridiculous.)

Recently "Tesla motors" has been able to sell cars powered by lithium batteries to the coveted "rich and stupid" segment of the USA market. Of course, given that about 83% of USA electricity, as of year 2020, is generated from non-renewable sources (mostly fossil fuels), Teslas are effectively powered by fossil fuels just like gasoline cars, a fact remarkably rarely noted in the company's advertising. As of year 2020, the Tesla "model S" liftback costs $75k, while comparable gasoline powered cars cost $20k. Any lithium battery capable of storing 15 gallons of gasoline worth of energy, is going to cost at least $4000 just for the lithium alone. Lithium is a rare element (20 parts per million of the Earth's crust, comparable to scandium and niobium) and has some (comparatively mild) toxicity.

Meanwhile, back in the world of reason, *aluminum* and perhaps *silicon* (the two most abundant elements in the Earth's crust, besides their co-reactant, oxygen!) strike me as excellent fuels reckoned from *all* the standpoints of energy/kg, energy/liter, cost/kg, renewability, fire & explosion safety, and environmental (non)toxicity. Aluminum-air batteries are a long established commercial technology. Silicon-air batteries have also been demonstrated, although as far as I know were never commercialized. These kinds of batteries have essentially infinite shelf life. They are activated by pouring in an alkaline electrolyte (e.g. aqueous KOH). This electrolyte dissolves the Al_2O_3 or SiO_2 barrier-oxide, allowing the reaction to proceed to generate electricity. Removing this liquid deactivates the battery. To power cars with such batteries, you'd simply remove the old battery (or just its Al anodes) and plug in the new one from the fuel station (very fast operation done by machinery). The used-up batteries, filled with oxide, would then be transported back to an electric-powered aluminum smelter to be recycled. (Contaminating KOH presumably would need to be chemically separated from the Al_2O_3 before electrolysing the latter.) Aluminum smelters are about 90% efficient. The resulting aluminum would then be transported to fueling stations.

Post fossil-fuel economy. Much of the natural gas infrastructure for home-heating, cooking, industrial use, and gas-fueled powerplants presumably could be repurposed to be based on H_2 rather than CH_4. But some things would have to change, for example liquefaction temperatures are much lower.

Hydrogen is actually a better feedstock/fuel for some purposes, e.g. nitrogen-fixing and large rockets, than fossil fuels.

Oil and coal for non-fuel uses, such as lubricants, and as a chemical feedstock to produce plastics, dyes, paints, explosives, etc I expect would be replaced by biological sources – which probably will be very painful and would drive prices up and production down. The use of fossil fuels as a chemical feedstock, rather than fuel, is (as of year 2020) on the order of 3×10^{11} kg/year. Meanwhile human food consumption is about 25 times that tonnage.

I do not see any way to produce the enormous amounts of asphalt tar currently used for roads and roofs. Fortunately, it is possible to build roads (and roofs) from, e.g, prestressed concrete without asphalt. (Concrete can be improved via, e.g, adding glass fibers.)

Cheap air travel might end, or it might be possible to power airplanes with aluminum-air batteries or hydrogen, probably with performance diminution.

14. Climatic impact II: saga of deeper examination

1. There is a straighforward way to try to determine the climatic impacts of our Plan: Modify **global climate models** to incorporate the planned wind-turbine belt in the roaring latitudes!

"Model II" described by Hansen et al 1983 is available as *public-domain code*. It relies on numerical ideas put forward by Akio Arakawa. It is somewhere between 5000 and 31000 lines of FORTRAN, depending what should be counted – I suspect close to the larger figure, in which case the program has about half the character-count of the King James Bible. The FORTRAN is 1970s-style, all capitalized. Almost all variable-names are incomprehensible and nowhere-explained, for example "BEAVIS," "BGFEMD," "LATHEM," "NGRNDZ," and "TRGALB." This *engine* code is difficult to understand, to say the least; and the other, *human-usability*, part of the program (the combination is called **edgcm**) is *not* public-source, but rather secret-source commercial, code. Supposedly edgcm is a great contribution to humanity since it enables students to experiment with a global climate model. How it could be particularly useful for a "student" to "experiment" with a program whose code is undocumented and unalterable by them, I do not know. (Edgcm requires 1 GB of free disk space for installation; simulation results may require an additional 4-5 GB and at least 512 MB RAM. 64-bit CPU recommended.) The default version uses an 8°×10° latitude×longitude grid system with nine vertical atmosphere layers and two ground layers.

The three most obvious shortcomings of the Hansen 1983 model are (i) ocean *currents* such as the Gulf stream (and their possible alteration in future climates) are not simulated, and indeed are completely ignored as though they did not exist; (ii) different kinds of *plants* will grow (or not), depending on season, temperature and precipitation, thereby modifying the hydrologic and thermal properties of the ground – and the model is unaware of that; (iii) inadequate understanding of the optical effects of, and amounts of, *aerosols*.

> Re (iii), Hansen has argued that we could learn a great deal with the aid of a few fairly simple monitoring satellites to (A) observe sunlight from arbitrary points on earth from different angles to relative accuracy $\pm10^{-3}$ as a function of both wavelength and *polarization*, and (B) better precision infrared spectra. These satellites would enable deduction of aerosol amount, size,

shape, and index of refraction. Unfortunately, these proposed "ClimSat" satellites were not built, as part of a tremendously stupid and short sighted approach to USA space policy. But perhaps today's SAGE III (2017) space-station instrument and PACE (2019) satellite will begin to redress that. Nevertheless we have for a long time had satellites and tools which measure, as a function of wavelength: (a) the intensity of light from the sun, both above and (a') below the atmosphere, and (b) the same for the radiation emitted from the dark and (b') light sides of the Earth into space. We find that (a) is essentially a 5785°K blackbody except for some modifications in the 400-650 nm range by absorption and emission in the sun's outer atmosphere, while (b) agrees with a 295°K blackbody for wavelengths>800nm except for large diminutions centered at about 950 and 1500nm due to atmospheric ozone (O_3) and CO_2 respectively. Consequently we can measure, essentially perfectly, the overall "energy budget" of the Earth, understanding perfectly, as a function of wavelength, in real time, the effects of greenhouse gases, planetary albedo, etc. Some "climate deniers" have tried to argue the system is too complicated to understand, we could never be sure, etc. That is incorrect: we have not complex theory, but simple *measurements* of Earth's energy budget, in action, in detail.

Despite deficiencies i-iii, Hansen et al found by extensive testing that Model II recapitulated a fairly realistic planet. The worst discrepancies versus observation they noticed were:

- The highest-altitude air layer above the summer pole is 10°C too cold.
- Midwest USA is up to 5°C too cool during summer.
- Rainfall is excessive in the Bay of Bengal and some mid-latitude regions such as USA.
- In summer the subtropical jet stream and tropical easterlies are too weak.

On a 3 GHz machine, edgcm simulates the planet at a rate of about 300 simyears per day per processor.

In *principle* it should be very easy to modify this program to incorporate the effect of building our wind turbine belt: simply multiply the coefficient of "surface drag," only within the latitude interval (48,56)°S at *ocean* locations, by (say) 3.5.

The code modification that does that: After extensive decryption, I *think* (80% chance I am right about this?) that would be accomplished by inserting the new line "`IF(J.EQ.LWNDTB) CDN=3.5*CDN`" immediately after the line (which corresponds to EQ48 p.630 in Hansen et al's paper). "`CDN=.00075+.000067*WSOLD`" in source file `Pjal0C9.f`. Here LWNDTB needs to be a preset integer constant, namely whichever value 1≤J≤24 corresponds to the latitude interval (48,56)°S. Presumably LWNDTB should be a member of the set {4,5,6, 18,19,20} although it is not obvious to me, without experimentation, which.

Alternatively, if we wanted to understand the climatic effect of having wind turbines everywhere on *land*, we could, immediately after the *second* occurrence of the line `CDN=.0231/(ROUGH*ROUGH)` in source file `Pjal0C9.f`, insert the new line `CDN=2*CDN` or `CDN=CDN+WTBCNS` (where WTBCNS is a pre-defined constant representing the increase in surface drag associated with `CDN` from covering the surface with wind turbines), or some such.

On p.618 Hansen et al report that they actually did an experiment "I-22" where they *eliminated* surface drag entirely; this increased atmospheric kinetic energy by about a factor of 3, plus approximately doubled "northward transport of energy and momentum" which I presume was their way of saying this partly or wholy recreated the southern "roaring latitudes" but now in the northern hemisphere(?). They also compared three runs I-9, I-10, and I-11 to explore the effect of multiplying "stratospheric drag" by a factor of 100 for I-11 versus I-9. But this may mean little because "stratospheric drag" is an artificial fictional concept they introduced to diminish certain numerical pathologies. They also tried a much more expensive run I-12 which tried to treat this correctly without the fiction, and found it behaved similarly to I-10, thus supposedly justifying the latter (they then used I-10's stratospheric drag in their other runs). They claimed on p.615 that "the results [of I-9, I-10, and I-11] were not very sensitive to the value of the [stratospheric] drag [once] it was large enough to prevent stratospheric energy from growing."

One then could run the original and modified programs and compute the *difference* **Δ** between their outputs for say, temperature-world-map, wind-map, precipitation-map, and ice cover, 10, 30, 100, 300, and 1000 years into the future. We also could ask it:

a. What are the wind speeds in the roaring region, in both the original and modified climate? Plot "how much power we extract" versus "effect" and see what the limits are on extractible power.
b. Is the climate especially sensitive to any particular small *parts* of the roaring region? (If so, then we could keep wind-turbines out of those "sore spots" to diminish the climatic effect.)
c. What interactions will the wind-turbine Plan have with climate-alteration caused by anthropogenic CO_2? How will these two kinds of impacts compare to each other? How acceptable are they?

The computation to do most of that [albeit part (b) might be substantially more expensive], with edgcm ought to be about 1 CPU-week.

In *reality*, despite probably identifying which lines of code need to change and how to change them, I was (1) unable to get any help whatsoever from any of the people allegedly maintaining and distributing edgcm, (2) unable to find various "ASCII-art" world-maps given in their paper, inside their code, proving crucially important parts of their source code are *missing*; (3) unable to find the numerous optional modifications in the code the authors *already made* to perform experiments such as their "I-22," (4) don't know what the right program-inputs ought to be, (5) unable even to compile and run it (probably it does not help that I am a FORTRAN-novice), (6) doubt it even *can* be run without the missing human-interface part of edgcm, e.g. it contains no `PROGRAM` and `END PROGRAM`. Probably (assuming the continued absence of any assistance from the edgcm authors) one would need to create one's own human-interface from scratch, which given the state of (non)documentation of the engine, might be difficult.

Furthermore, searching databases of the scientific literature for "edgcm" found zero hits. That suggests that despite their propaganda about how "useful" edgcm is for "students," in reality zero people during the last 20 years have ever managed to use it to help create a scientific paper. The online "EdGCM forum" http://www.forumjar.com/forums/EdGCM plaintively asks me to be the first-ever to post a message. Finally I tried the following 1-line email:

To: edgcm-support@edgcm.columbia.edu
Subject: hello?
Do you ever answer any email sent by anybody?

No response, although about 3 days later a message came back from my email service suggesting the recipient no longer existed.

I still suspect this really is an easy job – but only for a very small set of people, and unfortunately I am not a member of that set.

But then I found out that, contrary to implications at the edgcm web site, the underlying climate model edgcm had been based on, still was around, albeit in a vastly updated form called "**model E**", from GISS – Goddard Institute for Space Science – at NASA. The source code for it is freely downloadable, and based on date & time information supplied with it, appeared to be updated daily, which provided optimism that it genuinely was in active use! Model E's code is about 10× the length of the "model II" code I previously had downloaded from edgcm – now over 336K lines of fortran occupying over 12 megabytes – i.e. about 4 times the length of the Bible, or roughly comparable to *The Columbia Encyclopedia*, the physically largest single-volume book that I own with about 2500 large (25×40 cm) pages. While the amount of knowledge that has been incorporated into programs like model E is very impressive, the price to be paid is that (I believe) no single human being is anymore capable of comprehending them. According to its online documentation, Model E runs under any unix-like operating system (including MacOS), albeit the "NetCDF" (Network Common Data Form, 3.6 or later) and "MPI" (High Performance Message Passing Library) libraries, and "perl," must be installed. Unfortunately, those code enhancements came at a price: The user should have "at least 16 cores with at least 1 GB of memory per core." For those wishing to do "dynamic ocean simulations with full atmospheric chemistry" then "one typically would need 88 cores with at least 1 GB of memory per core." Those computational resources unfortunately are far beyond mine. Model E has evolved so tremendously that it is now very difficult for the reader to see any connection between its code and (what I presume was its distant ancestor) "model II." E.g. the particular lines of fortran I quoted earlier (and the files they were in) no longer exist, and indeed Model II's entire surface-drag treatment appears to have been completely abandoned and replaced by something instead based on Hartke & Rind 1997.

I suspect (although given the much greater complexity of model E, the chance I am right about this unfortunately is considerably smaller than the corresponding probability for model II) that the **1-line code change** needed to add our wind farm to Model E is: immediately after the call to subroutine "getcm" in file "PBL.f" – actually "getcm" is called by "dflux" which is called by "stars" which is called by "advanc", and this line should be placed after the call to "stars" within "advanc" – add a line

```
if (itype.eq.2 .and. jlat.eq.LWNDTB) then cm=3.5*cm end if
```

which multiplies cm by 3.5 (or whatever the appropriate multiplier ought to be) if over ocean (itype.eq.2) and if "jlat" represents the latitude-interval containing 50°S.

Model E's web site encouraged me to join their online mailing list `https://lists.nasa.gov/mailman/listinfo/giss-gcm-users-l`. Full of hope and optimism, I did so. No response... but then one came, 11 days later! Unfortunately their "archive" (which I was then permitted to access) claimed to contain zero messages. It still made that claim even after a nonzero number of messages were posted. Further, apparently only a few messages are posted per year.

I am going into detail about this saga because I think it is important actually to tell people the true state of affairs about these climate models – which differs vastly from what any casual internet-searching person would *think* was true, based on the loud and massively-false/misleading advertising. My guess would be that the giant false-front was erected with the goal of deluding finding agencies into supporting those modelers. But that hypothesis only works if the funding agencies never *check* the same things that I checked, which in turn would *also* imply a large degree of fakeness for the "reviews" done by those funding agencies (if any). This whole experience has led me to distrust any claim made by/about any climate modeling code.

There are other climate models besides Model II/E, including allegedly much fancier and more modern ones – I chose edgcm only because it was advertised as "public source," "computationally efficient," and "easy for students." (And I highly recommend the original paper Hansen et al 1983.) If the authors of such codes could be persuaded, it ought to be *very* easy for them to do the study I here am requesting. Some other models, some of which look plausibly promising and plausibly provide source code include:

- HadGEM1 (Hadley Centre Global Environmental Model) from UK meteorological office.
- IPSL models (Institute Pierre Simon Laplace in & around Paris, France), such as CM6 which has about 60 authors and apparently (?) is written in its own language.
- ECHAM model from Max Planck Institute, Germany. This is based on the European Weather Prediction model written in Fortran-95, regarded as the most successful weather predictor and used daily. That is good because climate models, as large programs, are likely to contain bugs. Many of those bugs are undetectable by comparison versus experiment, because "climate," by definition, develops on time scales of ≥100 years. (One could resort to comparing different, and hopefully independently-developed, climate models – but that rarely seems to happen.) This weather model, in contrast, is compared versus experiment daily.
- NCAR CCSM: Community Climate System Model (or WACCM, whole atmosphere community climate model, and/or other NCAR models; NCAR=National Center for Atmospheric Research, Colorado, USA). Requires UNIX-type operating system, Python≥2.7, Perl 5, Fortran 2003, C, subversion & git, MPI, NetCDF≥4.3, LAPACK, BLAS, Cmake.
- MIT gcm, from 17 authors at the MIT Department of Earth, Atmospheric and Planetary Sciences, Cambridge MA. The Fortran package is 154 Mbytes *after* gzip-compression, suggesting this model is larger than the full *Encyclopaedia Britannica*. It seems comparatively well documented.
- Princeton GFDL models.
- University of Reading IGCM1 model: just 4134 lines of fortran in a single file – which seems absurdly short. While the paper Hoskins & Simmons 1975 describing it has some pleasant mathematical attributes that could form a nice foundation for further development, this simply does not incorporate enough information about the planet or its physical mechanisms to be taken seriously as a climate model. (E.g: neither the program nor paper anywhere mention "CO_2," "precipitation," "rain," "ice," "snow," "land," "ocean," "continent," "aerosols," "mountain," "elevation," "heat," or "radiation.")

- E3SM: Energy Exascale Earth System Model Project, designed for USA dept. of energy. "Generally requires a cluster with several hundred nodes to run." Mostly fortran, but also C++, Perl, NCL (NCAR command language), and others.

Unfortunately most of these codes dwarf even "Model E," and require even greater computational resources. RealClimate.org helpfully provides a list http://www.realclimate.org/index.php/data-sources/ of alleged hyperlinks to obtain these and many other models. Unfortunately in reality many of their hyperlinks do not function.

2. Fortunately, I then found that several climate-modeling-based **papers have already been written on the "climatic impact of large scale wind power."** However, these papers assume that all the wind turbines will be located in windy regions on or near *land*. That's quite different from our roaring-latitudes ocean-based Plan, but we'll take a look at them anyway.

The windiest regions on land are mostly associated with land↔sea winds. Therefore, one might naively guess that wind turbines on land would reduce land↔sea heat and moisture exchange, thus (1) reducing rainfall over land and (2) increasing land-temperature extremes, i.e. summers would get hotter and winters colder. Also, turbines by decreasing surface winds might be expected to decrease *vertical mixing* of the atmosphere, thus trapping air temperature variations near the ground; the result would be (near the land surface) warmer nights because the land would lose less heat to the upper air; and conversely, colder days. In contrast (one might continue to naively guess) our ocean-based plan would suffer neither effect (1) or (2); and also effect (3) would matter less because the ocean already was a huge temperature-buffer.

Miller, Brunsell, & 6 others (2015) found a wind-power-extraction **upper bound** of about 1 watt/meter^2 for windy regions of the USA, and on continents more generally. It would, according to them, be *impossible* to extract power at a greater rate, due to "reduction of wind speeds and limited downward fluxes." Refining their method now using sophisticated atmosphere-model codes, Miller & Kleidon 2016 found an upper bound of 0.37 electrical watts/meter^2 on land and 0.59 over ocean, which note agrees rather well with my own bounds, although mine are both tighter and much simpler.

Keith & 6 others (2004) did "climate-model simulations that address the possible climatic impacts of wind power at regional to global scales by using two general circulation models [from NCAR and Princeton GFDL] and several parameterizations of the interaction of wind turbines with the boundary layer." However, their simulations *prescribed*, rather than interactively simulated, sea-surface temperatures – a problem if their prescriptions were incorrect. They found:

- Very large extraction of wind power indeed can produce nonnegligible climatic change at continental scales.
- It would have "a negligible effect on *global*-mean surface temperature," but would cause "*regional* peak-seasonal responses exceeding ±2°C." Specifically, they find winter cooling over most of Europe, but winter warming over either temperate or central North America. With 2 TW of electricity generated on land from wind, their results suggest the resulting peak changes in regional seasonal mean temperatures might be ≈0.5°C. While these "climatic changes are detectable above background climatic variability in model runs of a few decades duration, they might remain too small to detect in the presence of other anthropogenic change and natural climate variability."
- They speculate these effects are *non*local and arise from perturbing poleward heat transport. (But the USA-only wind-farm simulations we discuss below found its effects clearly were localized within 1500 km away.)
- They argue that replacing carbon-based power with wind power will reduce climatic impact sizes by about a factor of 5.
- They did not attempt to assess regional rainfall changes.

Miller & Keith 2018 is a review article on "Climatic Impacts of Wind Power" containing many cites to other studies. They find:

- Generating the year-2018 "US electricity demand (0.5 TWe) with wind power would warm Continental US surface temperatures by 0.24°C." The warming effect is small compared with projections of 21st century warming, and they express confidence wind power's climatic effects are smaller than fossil fuel energy.
- Nemet 2009 points out that widespread use of photovoltaic solar panels will darken the Earth's albedo, causing global warming. But he estimates this warming is a factor 30 smaller than that caused by the carbon-based fuels their energy would replace.
- Fossil fuels cause toxic pollution by sulfur- and nitrogen-oxides, mercury, and particulates – which would not happen with wind power.
- Fiedler & Bukovsky 2011 use NCAR's climate model to analyse the effect of a giant USA wind farm, with installed capacity of 0.46 TW which they expect on average to actually only generate 20% of that maximum capacity, i.e. 0.09 TW (i.e. about 20% of USA's electricity consumption). They find it will cause 1% extra rainfall on average within an area surrounding and to the south-east of the wind farm.
- Miller & Keith use the "WRF v3.3.1 high-resolution regional model" to examine the climatic effect of generating *all* of the USA's present *electricity* demand (specifically 0.46 TWe) via a giant wind farm covering the windiest 1/3 of the 48 states of the continental USA. (Actually that could not directly work because the wind varies, but they ignore that; also the USA's non-electrical power demand would not be supplied.) They find that Kansas to N.Dakota would warm by 1°C, while the temperature of the side and southern regions (Nevada to Idaho & west; Mississippi to Ohio & east; New Mexico to Georgia & south) would mostly be unaltered. Most of that warming would occur at night. Rainfall would decrease about 5% throughout the 48 states except on the east coast; and the already-arid SW region (Arizona, Utah, northeastern Mexico) would become even drier – between 5 and 50% less rainfall depending on location, probably averaging about a 10% reduction. Ecologically, that might be very serious.

15. International laws & agreements

This would need to be a global project, since the cost is probably beyond what any one country can undertake. However, some country or corporation could just build fraction X of it, paying fraction ≈X cost. There would need to be some **international agreements** related to, e.g. laws of the sea, planning, standardization, and probably who pays and gets paid. If this project indeed is what the world should do, then the sooner it gets started, the better, since it will take 30 years to build it, and for human civilization to survive it needs to win the race to build it before we run out of fossil fuels and/or drive the world's climate into some irretrievably bad state.

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