Nuclear Powered "Enhanced Weathering" Geoengineering

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Abstract

Civilization's fossil fuel addiction is generating a host of climate-related changes impacting both humanity and the environment it shares with the rest of the Earth's lifeforms. This work employs simple calculations and readily accessed facts to show why a properly implemented "nuclear renaissance" – not millions of imaginary wind turbines, solar panels, and super batteries linked together with an even more super "grid" - represents a more realistic path forward. Such a renaissance would, could, and must be implemented with reactors utilizing a genuinely sustainable nuclear fuel cycle – not today's – and large enough (~30,000 GW_e) to provide ≥80% of mankind's total "energy services". Anthropogenic CO_2 already in the atmosphere would be removed by devoting a few percent of that "clean" (no greenhouse gas generation) power to making a "rock dust fertilizer" (powdered basalt) which would simultaneously sequester it as "soil inorganic carbon" and enhance food production. This work also identifies some of the reasons/excuses why proposals like this have not received much attention.

Introduction

From 1870 to 2014, mankind's use of fossil fuels generated anthropogenic carbon emissions totalling about 545 GtC. The resulting "greenhouse gas", ~1998 Gt of CO_2, partitioned between the atmosphere (approx. 230 GtC or 42%), ocean (approx. 155 GtC or 28%) and land (approx. 160 GtC or 29%)[a]. The consequences include increasingly devastating and frequent weather "events" (this year's "super El Niño"?), ocean acidification, drought & biofuel production-driven food cost escalation, air pollution, deforestation, potable water shortages, shoreline erosion/flooding, relentless cost of living increases, widespread poverty, and almost constant international squabbles/wars over "energy resources"[1]. Concerted international effort to address these problems began with the UN's 1992 Kyoto Protocol which some, mostly small, nations signed up to. Since then billions of dollars[b] have been spent to support

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[a] http://carboncycle.aos.wisc.edu/ (Excellent!)

[b] The U.S.spent > $32.5 billion on climate science studies between 1989 and 2009 which figure doesn't include the $79 billion spent for climate change technology research, foreign aid and tax breaks for "green" energy, see http://scienceandpublicpolicy.org/images/stories/papers/originals/climate_money.pdf
Climate Change Science Program, Annual Report to Congress: *Our Changing Planet*, see table page 4. http://downloads.climatescience.gov/ocp/ocp2009/ocpfy2009-8.pdf.
Analytical Perspectives Budget of the US Government, Fiscal Year 2010. see page 31, Table 5-2. http://www.whitehouse.gov/omb/budget/fy2010/assets/spec.pdf.

research which has generated thousands of papers/reports/reviews and pay for many subsequent conferences and "topical sessions" both large and small. However, neither that science nor the subsidies paid to purveyors of "alternative" energy (mostly wind turbines, solar panels, low-head hydro plants and bio-fuels) have appreciably affected the rate at which both CO_2 and smoke are dumped into the atmosphere (Fig 1). The most recent such international conference, the International Panel on Climate Change's (IPCC's) "COP 21 Paris Agreement" did not really change anything – hundreds of talks were presented, more goals were set and promises made none of which were binding. In other words, there is no legal mechanism to ensure that countries adhere to their commitments in terms of either promised emission reductions or contributions to the agreed-to $100 billion/a climate mitigation fund. Secondly, some climate models indicate that the sum of the "Intended Nationally Determined Contributions" (INDCs) commitments made by the 195 attending countries would *g*enerate total global warming of between 2.7 and 3 degrees Celsius, well above the 2 degree threshold that most climate scientists consider to be the point beyond which catastrophic climate impact will become irreversible.

The "new" thing revealed at COP 21 is that many climate scientists now feel that heading off the probable consequences of climate change will take more than just slashing CO_2 emissions - it's too late for that alone - some of the excess CO_2 already in the atmosphere must be removed[2]. If not, we'll be stuck with excessive atmospheric CO_2 for at least another century which would continue to poison[3] the oceans and might push global temperatures to a point beyond which positive feedback mechanisms[c] would cause environmental collapse.

There are two basic approaches to "geoengineering" (active transformation of climate via human intervention); i.e., s**olar-radiation management (aka "albedo enhancement")**, which is to reduce global temperature by reflecting more sunlight back into space and **carbon dioxide reduction (aka "negative emissions")**. Researchers now generally agree that the latter is both more promising and safer[d].

Three ways of removing CO_2 currently receive the most attention. The first, **direct air separation**, would remove ("scrub") CO_2 from the air and then sequester it in any of a number of maybe-possible ways. The second, **biological carbon dioxide reduction**, invokes either, 1) planting crops that collect it which then would be sequestered as soil organic carbon (SOC) by either plowing them back into the soil or converting them to "biochar" ("chunky soot") which would also be buried, or 2), adding some sort of "fertilizer" (usually iron) to the oceans which might increase the rate at which anthropogenic carbon ends up in abysmal sediments via organic "fallout".

The third way invokes the addition of a man made (or modified) material to either the oceans or land to enhance their ability to absorb/immobilize CO_2. This paper discusses one such scenario invoking the addition of powdered basalt to farm soils where its "biologically enhanced weathering" would convert atmospheric CO_2 to soil inorganic carbon (SIC). It also

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[c] (e.g., methane-water clathrate decomposition in shallow seas and/or rapid conversion of the tundra's ~400 Gt of permafrost-sequestered soil organic carbon (SOC) to both carbon dioxide and methane)

[d] The movie, "Snowpiercer" relates what might happen to the remnants of humanity surviving a last-minute attempt to turn back global warming via albedo enhancement with "CW7".

demonstrates with quantitative examples why it or any other geoengineering scheme big enough to make a difference would require a "nuclear renaissance".

In my opinion the most useful outcome of the climate science-related work performed to date is that reasonably consistent/accurate estimates of global carbon fluxes, sources, sinks, etc. have now joined the tremendous amount of other technical information freely available to anyone with access to the internet – GOOGLE, WIKIPEDIA, and ENGINEERING TOOLBOX are especially useful. The advent of open access scientific publishing has also been very helpful[e]. [Table 1 pulls-together some of the numbers used in my subsequent caculations.] Such information along with equally readily available computerized spreadsheets has rendered it simple for even an old home/winter-bound retiree to subject any technical proposal described in a properly written/edited scientific paper to a (at least) semiquantitative evaluation and thereby decide if it really has a reasonable chance of working. I've found that most geoengineering proposals don't pass such muster[f].

For example, GOOGLEing "oceanic acidification mitigation" brings up several proposals that would add man-made "bicarbonate" to seawater which would then purportedly enhance its ability to absorb CO_2 (an acidic gas) from the atmosphere due to its so-enhanced "alkalinity"[g]. This is not true because the addition of bicarbonate to water (e.g., seawater) in which pH is primarily determined by (buffered by) the ratio of carbonate to bicarbonate ($K_{2a}=(CO_3^{=})(H^+)/HCO_3^-$) tends to lower, not raise, its pH. Lowering the pH of water renders it able to absorb less, not more CO_2 which is why the oceans are now slightly less "absorbant" than they were before the absorption of ~155 Gt of anthropogenic C lowered their surface-water pH.

If such bicarbonate is generated by contacting air with a caustic solution made by electrolyzing an aqueous salt solution (with some electrolytes, hydroxide ion is generated at the cathode), it would transfer CO_2 from air to that electrolyte, which would then, if dumped into the ocean, indeed "sequester" such CO_2 therein. The following is one such example[4]. It invokes giant chlor-alkai cells which will electrolyze aqueous solutions of pure NaCl (seawater would plug up the cells) to generate sodium hydroxide which would then either be dumped into the ocean to counteract CO_2-engendered acidification or utilized in contactors to scrub CO_2 from the air (see reactions below). The co-produced hydrogen and chlorine would

Electrolysis: $2NaCl + 2H_2O \rightarrow 2NaOH + Cl_2 + H_2$
Air scrubbing: $NaOH$ +water+ CO_2 in air $\rightarrow$ $NaHCO_{3\ aq}$
H_2+Cl_2 (fuel cell) $\rightarrow 2HCl$ (in a water-based electrolyte)
$HCl_{aq}+$ a Mg/Ca-containing rock $\rightarrow CaCl_2 + MgCl_2+$ rock sludge.

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[e] Anything describing anything done with any sort of government support should be "open access", not "proprietary information" (secret) or a "product" to be sold to anyone wishing to learn what his taxes bought.

[f] I have no animus for the authors of any paper cited or discussed herein. To the contrary, I applaud them for demonstrating both the will & ability to try to do something about a serious problem.

[g] In water analysis, "alkalinity" is determined by titrating the sample with a standardized strong acid (e.g., sulfuric or hydrochloric) acid to a pH of ~4.3. Therefore, water can possess a pH well under 7 ("neutrality") and a good deal of alkalinity (bicarbonate).

be recombined with fuel cells to recover some of the electrical power required by the chlor-alkali cells. The fuel cells' product, HCl (a very strong acid) would then be neutralized via reaction with some sort of intrinsically basic rock in high temperature/pressure vessels which process would generate waste comprised of a slurry of decomposed rock sludge in a magnesium/calcium chloride-containing brine.

Since that proposal has too many "issues" to completely cover, I will just focus upon its energetics. While it is characterized as "energetically feasible", real chlor-alkali cells require about 3.9 volts to operate at a reasonably productive rate[5] & real H_2/Cl_2 fuel cells generate about one volt at similarly practical current densities[6] (~ 0.5 A/cm^2). This means that the net energy required to produce one mole (or equivalent) of hydroxide is 2.8E+5 J [1equivalent*(3.9-1) volts * 96,500 coulombs/equivalent)*1J/(volt*coulomb)]. Producing sufficient sodium hydroxide to deal with a year's worth of anthropogenic CO_2 (~33 Gt) would require 2.1E+20J [2.8E+5 J/mole*(33E+9 t*1E+6 g/t)/44 g/mole]. If it is to be done within one year, it would require the total output of ~6660 [2.1E+20 J/1e+9 J/s/3600 s/hr/24 hr/day/365 day/year] full-sized (~1 GW_e- not "small modular") nuclear reactors, ~14.9 million 30% "capacity factor"[h] 1.5 MW wind turbines, or ~70 billion, 1kW, CF = 0.1, rooftop-type solar panels. Burning biofuel equivalent to 100% of the World's total annual grain plus wood production (~4.4 Gt/a) in 40% Carnot efficient electrical power plants would generate 7.13E+19 J (4.4E+12 kg*4.5 kWhr/kg*3.6E+6 J/kWhr) – about one third of the power required to implement this example's geoengineering scenario.

Another superficially attractive and even less realistic proposal[7] invokes scrubbing CO_2 from the atmosphere with a strongly basic 750ºC Li_2CO_3/Li_2O electrolyte from which that carbon is then electroplated-out/sequestered as graphite. Since both the electricity required for the electroconversion and the heat needed to keep the electrolyte hot is to be provided with "solar towers", it is eminently politically correct and has therefore received a great deal of attention. Unfortunately, because 1) its electrochemical step requires four times as many electrons to sequester each carbon atom as does that of the above-described proposal; and 2), scrubbing air with molten salt would heat it to the latter's temperature[i], its total energy requirement would be ~four times higher *if* 90% of its process heat requirement could be recovered/recycled via heat exchangers and 19 times greater if it could not. If implemented with wind power instead of solar towers, the latter figure corresponds to needing ~291 million 1.5 MW_e CF=0.3, wind turbines/33Gt CO_2/a.

Renewable energy enthusiasts have suggested that CO_2 sequestration technologies be powered by their pet technology's "stranded" power. In 2010, 25 TWh's worth of wind power was stranded in the USA. That figure, 9E+16 J, represents 7.1% of its fleet's nominal

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[h] Typical "capacity factors" (CF - ratio of energy generated over one year/nominal nameplate capacity) for US-sited wind and solar power installations are ~0.3 & ~0.1 respectively. The CF of Germany's wind turbines averages about 0.15 see http://www.vernunftkraft.de/85-prozent-fehlzeit-windkraftanlagen-sind-faulpelze/. The CF of modern nuclear power plants is >0.9.

[i] The heat capacity of air is ~1.05 J/g/degree. This means that scrubbing 33Gt of CO_2 from 400 ppmv air would require the heating of ~4.9E+12 tonnes of it from "room temperature" to ~750ºC.

capacity (then 40.27 GW) and is far too low to implement any meaningful geoengineering project[j].

Implementing *any* geoengineering project with wind and/or solar power instead of nuclear power would require much bigger/more expensive process equipment (grinders, contactors, electrochemical cells, etc.) in order to "catch up" after periods when the wind hadn't blown and/or the sun didn't shine.

My Proposal

I could probably generate even more "controversy" (& even more backlash) with more such examples but it's time to describe my own suggestion; i.e., generate ~80% of mankind's total future "energy services" with a properly implemented "nuclear renaissance" – not with today's reactors or millions of wind turbines, solar panels, and imaginary super batteries linked together with an even more super "grid" – and use some of that clean power to make a "rock dust fertilizer" (powdered basalt) to simultaneously convert anthropogenic CO_2 to "soil inorganic carbon" (SIC) and enhance food production.

I will start by estimating the amount of power/energy required to supply all of mankind's future energy needs. This begins with an assumption that future world leaders will decide to size their "clean energy initiative" so that it could comfortably satisfy *everyone's* power needs and thereby eliminate a root cause of human conflict. Humanity's total raw energy use is currently about 570 exajoules/a, ~18% of which is consumed by the USA's relatively wealthy (energy-rich) 0.319 billion people. If human population eventually asymptotes at 9 billion and everyone is to become as energy-rich as US citizens are now (why not?), the total raw energy required/a would be about 2895 EJ (570E+18*0.18*9/0.319). Since the efficiency with which technological civilizations convert raw energy (usually heat energy) to "energy services" is about 40% (Fig 2), this corresponds to a *useful* (e.g., electricity) power requirement of ~3.67E+13 W (2895E+18 J*0.4/(3600 s/hr*24 hr/day*365 day/year). Since "integration costs" render electrical power from intrinsically unreliable sources (e.g., wind & solar) prohibitively expensive above ~20% market penetration[k] and fission-based nuclear power is simultaneously "green", reliable, and *potentially* capable of satisfying Mankind's requirements indefinitely[l], I will assume that an appropriately implemented "nuclear renaissance" provides 80% of it. Such a renaissance would require ~30,000 (3.67E+13*0.8/1E+9/3600/24/365) full-sized[m] nuclear reactors. Because 30,000 "advanced" ("Gen III") versions of today's light water reactors

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[j] Stranding is due to a combination of renewable energy's unreliability, grid limitations, & customer penny-pinching ("conservation") induced by subsidy-driven high electricity costs. The numbers are from: http://cleantechnica.com/2011/03/27/25-twh-of-wind-power-idled-in-2010-in-us-grid-storage-needed/ http://apps2.eere.energy.gov/wind/windexchange/wind_installed_capacity.asp

[k] Ueckerdt et al, *"System LCOE: What are the Costs of Variable Renewables?"*, http://dx.doi.org/10.2139/ssrn.2200572

[l] Assuming 200 Mev/fission and an average crustal rock density of 2.7 g/cc, the ~15 ppm U plus Th within the topmost kilometer of the Earth's crustal landmass (about 1.72E+12 t of U &Th), could generate 2895E+18 J/a for ~0.49 billion years. In other words, breeders could render nuclear power as "renewable" as sunlight as well as far more dependable.

[m] Most of today's power reactors are "full sized "(capable of generating ~1 GW_e) because economy-of-scale strongly favors large reactors. 6 million of US DOE's front-running "small modular reactor" (SMR) candidate (NuScale's 50 MWe SMR - a LWR) would be required to generate 30,000 GW_e.

(LWRs) would consume 100% of the world's "affordable" uranium resources in under 5 years[n], it must be implemented with a fuel cycle capable of "burning" either natural uranium or thorium; not just ^{235}U. This would require "breeder" reactors which fact has been repeatedly pointed-out to decision makers during the last six decades[8].[9]

Next I will explain why plowing freshly powdered (unweathered) basalt into farmland has a reasonable chance of mitigating the root cause of climate change. In 2014, Gislasen and Oelkers[10] reminded us that, "All the carbon in the atmosphere, living creatures and dissolved in the oceans is derived from rocks and will (eventually) end up in (basic) rocks, the largest carbon reservoir on Earth". That observation first appeared in the scientific literature in 1845[o] and has subsequently served as the rationale for the "enhanced weathering" carbon sequestrationl proposals described in Hartmann et al.'s comprehensive review[11][p].

My rationale for this proposal is as follows...
1) Plants transfer CO_2 from the air into dirt which then "respires" about 7 times as much of it (currently about 275 Gt/a) as humanity currently discards because the minerals in unmodified soils are already saturated with it (don't react).
2) Biologically active soils accelerate rock dissolution (farmed land is biologically active)
3) Earth's soil does not possess as much acid-side buffering capacity as do its oceans (there is much less dirt than water and it contains less carbonate/bicarbonate).
4) Dirt is porous & much nearer to the atmosphere's CO_2 than is most of the earth's water (0-1 meter. vs >1 km).
5) Adding powdered rock to dirt is more politically correct than is dumping it or anything else into the oceans.
6) People are more apt to cooperate because it would likely increase crop yields (probably the most important feature over the long haul) & farmers would likely receive a subsidy for performing such service.
7) It would be much cheaper than anything invoking point source collection or processing.

Manning & Renforth's[12] measurements of the rate that soil-respired CO_2 converted calcium in a grass-covered English "urban soil" containing Portland cement-based demolition waste to "calcite" suggests a possible mechanism. That rate in terms of elemental carbon so-fixed was ~25 tC/ha/year. Dividing one- half of the world's current total soil respiration rate (60-77 Gt/a depending on source) by its "13.8 million km^2 of arable land" (half of all especially biologically active land?), suggests an area-normalized respiration rate of 21-27 t/C/ha - a good match. This suggests (but of course, does not prove) that soil containing enough of a sufficiently reactive adsorbent will fix CO_2 as fast as the mechanisms collectively responsible for soil respiration generate it.

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[n] Today's nuclear fuel cycle consumes about 160 tonnes of natural U/GW_e/year. The uranium industry's estimate of "proven" plus "undiscovered" (likely to be found at concentrations high enough to be worth extracting) uranium resources is ~18 million tonnes http://www.oecd-nea.org/ndd/pubs/2014/7209-uranium-2014.pdf.

18 million/(30,000*160) = 3.75 years

[o] Ebelmen, J. J. (1845), Sur les produits de la décomposition des espèces minérales de la famille des silicates, Anna. Mines, 7, 3–66.

[p] This paper is a must-read for anyone wishing to learn about this subject.

This is particularly important because if we do not ***act*** fairly soon, the rate of soil respiration across the globe will rise as methane and CO_2 are respired from melted permafrost which will generate even higher global temperatures - a positive feedback loop. Most climate models suggest that a rise in mean global temperature of ~2 degrees Celsius is apt to lead to an additional release of 10 Pg C/a to the atmosphere from such soil respiration – more than the current anthropogenic carbon emission rate.

While I expect objections to this proposal "because we/they don't know enough" about what happens when powdered basalt is added to soils, it is pretty safe to assert that doing so is almost surely apt to do more good than harm. For example, unlike most of today's scientists and nuclear engineers, Mother Nature is both willing and empowered to perform large-scale, messy, and sometimes even risky experiments. The volcanos that occasionally spew huge clouds of volcanic ash – tiny frozen droplets of molten basalt – constitute one such example. Farmland so impacted invariably soon becomes at least as productive as it was before which is why people have insisted upon living on/near Mt Vesuvius for thousands of years. Much of the world's best arable soil consists of the miscellaneous oxides, clays, zeolites, etc. generated by the weathering of volcanic ash-falls plus remains of the organisms which helped to weather them (SOC). Additional evidence for this proposal's "safety" is provided by books[q] and websites devoted to sustainable agriculture.[r]

The number of full-sized reactors needed to power this scheme would depend upon: 1) how quickly future decision makers choose to remove CO_2; 2) the amount of power required to render the basalt capable of reacting (weathering) sufficiently rapidly; and, 3) C fixation reaction stoichiometry. Rough estimates can be arrived-at as follows.

1) To be consistent with my first examples, I will assume that future decision makers choose to sequester anthropogenic CO_2 at the rate it is currently generated; i.e., 33 Pg/a (probably optimistic).

2) The rock dust is fine/reactive enough for biologically enhanced weathering to release all of its calcium and magnesium within one year in farmed soils. For this example, I will assume that the required degree of subdivision is achieved with 100 kW/hr of electrical energy per tonne (see Hartmann's review article[7]) – about five times that required to reduce cement clinker to cement powder[s].

3) The rock assumed is "average crustal basalt"; i.e., 12.4 wt% CaO and 7.9 wt% MgO[t].

First, how much of it must be mined, crushed, ground, shipped, and plowed-in? Each gram of my basis basalt contains 0.00196 (0.079/(24.32+16) mole of magnesium and 0.002214 mole of calcium, a total of 0.00417 mole. If the soil/basalt's C fixation reactions convert soil-

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[q] e.g., Peter Van Statten, Rock for Crops, (book) p 33, section 4.7, Department of Land Resource Science,University of Guelph, Guelph Ontario, Canada, 2002 http://www.worldagroforestry.org/downloads/Publications/PDFS/B11891.pdf

[r] e.g., http://www.paramountgrowth.com/images/rockdust_sdiver01.pdf

s Hewlett, Peter C., "*Lea's Chemistry of Cement and Concrete*" (Fourth Edition) ISBN: 978-0-7506-6256-7.

[t] Sanloup et al, Structural change in molten basalt at deep mantle conditions, Nature, 503. 104-107 2013

respired CO_2 to water insoluble “dolomite” ($Ca_xMg_{2-x}(CO_3)_2$), each gram of powdered rock would immobilize 0.184 g (0.00417 mole*44 g/mole) of it. If the reaction generates a mobile (water-soluble) Ca/Mg bicarbonate (not carbonate) salt instead (which salt would likely eventually end up in the ocean), each gram of rock would immobilize 0.368 gram of CO_2. Enhanced weathering scenarios usually assume the second reaction. Sequestering 33 Gt CO_2 via the first would require 179 billion (33Gt/0.184) tonnes of basalt - the second, 89.5 Gt.

Any enhanced weathering scheme’s primary energy consumer is apt to be rock-grinding. At 100 kWhr/tonne (100*1000J/s*3600 s/hr = 3.6E+8 J/t) this scenario’s basalt-grinding would require either 6.44E+19 J/a (179E+9 t *3.6e+8J/t) or 3.22 +19 J/a depending on C fixation reaction stoichiometry. These figures represent roughly 30 or 15% of the energy/power required by the first electrochemistry-based proposal that I have described (i.e., require ~ 2000 or ~1000 full-sized nuclear reactors to implement) and much smaller fractions of the second’s.

If this scheme were to be implemented with high-magnesium olivine (Forsterite - Mg_2SiO_4) instead of “average crustal basalt”, only about one fourth as much rock would have to be mined, crushed, etc.; i.e., 24 Gt rock/33 Gt CO_2[u] (~250 full-scale reactors).

Where should we start? Since warm, well watered, & already productive soils/fields are especially biologically active, the world’s ~400 million acres (1.61 million km^2) of rice fields might be the “best” place. Land devoted to corn and soybean production (combined about 2.8 million km^2) is apt to work pretty well too. Assuming 90 Gt/a and a basalt density of 3 g/cc, if land currently devoted to all three of those crops were to be so-employed, field soil build up (basalt application rate) would be about 6.8 mm/year. If it were applied to all of the Earth’s 1.4 billion ha of arable land[v], soil-buildup rate would be ~2.1 mm/a

Since that “fertilizer” is comprised of the same elements in roughly the same proportions as is the inorganic moiety of most “good” soils, regulatory approval and public acceptance should be straightforward. It should not take decades of study to prove its “safety”.

Figure 3 is a real time record of the output of Germany’s entire wind turbine “fleet” throughout 2014. The ratio (CF) of power actually produced to its “capacity” (the latter figure is what wind power enthusiasts usually quote) was 0.148 and there were many times when essentially no power was generated. “Unfiltered” data like this demonstrate why it is both irresponsible and callous for the “first world’s” technical experts to continue to insist/pretend that any combination of intrinsically unreliable “renewable” energy sources - windmills, solar panels , biofuels, etc. – could provide the energy required by nine billion people possessing a fair/equal share of a totally connected, cleaned-up, and “rich” technological civilization. Both realization of this admittedly utopian (but possible) vision and subsequent implementation of any significant-scale geoengineering project would be possible only if future decision makers decide to implement an appropriately scaled (big) nuclear renaissance. One of its key characteristics must be sustainability, which, in turn, would require a closed nuclear fuel cycle

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[u] To put these figures into perspective, mankind currently mines, “treats” (wash/screen/crush, etc.), transports, and uses ~130 Gt of sand & gravel/a. http://www.indexmundi.com/en/commodities/minerals/silica/silica_t11.html

[v] https://en.wikipedia.org/wiki/Arable_land

and breeder-type reactors. One of the Generation IV International Forum's (GIFs) Advanced Reactor ("Gen IV") concepts seems especially promising[13]. That paper explains the hows and whys of a possible implementation of the European EVOL program's "thorium burning" Molten Salt Fast[w] Reactor (MSFR) concept (Fig. 4). At steady state it would "isobreed" - generate only as much new fissile (^{233}U) from "fertile" ^{232}Th as is "burned" to generate heat energy, no extra - because doing so would greatly simplify operation (only one "reprocessing" separation step required) and mitigate proliferation concerns. A second molten salt reactor concept not considered by GIF, the Molten Chloride (salt) Fast Reactor (MCFR, Fig. 5)[14] *might* be able to generate even cheaper power because it would be simpler to build – its ^{238}U -to- ^{239}Pu breeding cycle's superior neutronics should permit isobreeding without a "blanket" surrounding its core[x]. Both would quantitatively convert all "heavy metal" (HM - all actinides both introduced and generated in-situ), to relatively simple-to-manage fission products (FP). Both would obviate the cost, waste, and safety-related issues intrinsic to any potentially sustainable, solid-fueled, reactor concept such as the sodium-cooled "Integral Fast Reactor" (IFR) or General Atomic's helium-cooled "Energy Multiplier Module (EM$^{2)}$[y]. Both of them should be cheaper to build/GW$_e$ than "advanced" versions of today's LWRs because they would operate at much lower pressures and generate higher temperature (more useful/efficient) heat energy Finally, and most important, either could continuously generate 30,000 GW$_e$ from abundant & readily accessible, "natural" uranium and/or thorium for hundreds of millions of years.

Issues & Questions

Surprisingly few "technical experts" choose to believe that these problems either exist and/or are solvable[z]. Consequently, anticipated questions/issues include:

Why not use lime (CaO) instead?

Answer: One reason is that lime manufacture involves the calcination of limestone which process generates as much "new" CO_2 as its product could sequester. Another is that lime is a

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[w] "Fast" means that the reactor's core does not contain a moderating material (e.g., liquid water or elemental carbon) to slow the rapidly moving (fast) neutrons initially generated by nuclear fission. This enables superior fuel regeneration capability, less transuranic element (TRU) build-up, and the ability to operate with a high fission product "ash" build-up which, in turn, means that less "reprocessing" is needed to keep it at steady state.

[x] The MCFR would also be better suited to utilizing fuel comprised of the uranium, plutonium and minor actinides (TRU) extracted from "spent" LWR fuel assemblies. That would serve two purposes because doing so would also simplify long-term management of today's huge accumulation of such "waste". This may be one of the reasons why the Bill Gates-backed ***TerraPower*** "nuclear startup" has apparently decided to switch focus from its sodium-cooled "traveling wave" concept to some sort of super-secret "chloride" reactor. *Richard Martin. "TerraPower Quietly Explores New Nuclear Reactor Strategy". Technology Review. Retrieved 2015-11-30*. Since there isn't enough spent LWR fuel or "excess" ^{239}Pu & ^{235}U bomb material to start up 30,000 isobreeders of any kind, we'd initially have to run some of them as genuine breeders until steady state is achieved. An advantage of the MCFR concept is that its core could be in the middle of a tank which could either contain a molten salt containing a fertile isotope (it could then breed extra fissile) or a bismuth (or lead) reflector material which would convert it to an isobreeder when steady-state is reached.

[y] John Rawls, "Implications for Waste Handling of the Multiplier Module, June 29, 2010 http://www.nwtrb.gov/meetings/2010/june/rawls.pdf.

[z] Even some of the USA's "lead nuclear engineering laboratory's" technical experts seem to feel this way.

reactive/caustic chemical much more likely to harm both the environment and anyone handing it than is powdered basalt. Finally, simple calculations and readily available data (GOOGLE it) indicate that about an order of magnitude more energy would be required to calcine limestone and sequester the resulting CO_2 than to grind an equivalent amount of basalt.

"Your proposal is impossible because it would require a sea change in how the world's decision makers behave."
Answer. General Grove's "Manhattan Project" during the 1940's, Admiral Rickover's nuclear submarine propulsion program during the 1950's, and NASA's accomplishments a decade later - all performed under different political administrations - demonstrate that properly inspired/educated/chosen/funded/managed people can quickly solve any "big" technical problem consistent with Nature's laws and limitations. This proposal is so-consistent and our leaders can/will change their behavior if/when their constituents and/or especially compelling outside influences/circumstances[aa] convince them to do so.

Aren't breeder reactors (or any sort of nuclear reactors) evil?
Answer. Man's creations can only do evil that dysfunctional people or governments allow or direct them to do. For example, "big science" often commits evil by ignoring inconvenient truths (e.g., the characteristics of most of today's "renewable" energy systems); being more concerned with immediate funding issues, current projects, and "fitting in"[bb] than with solving problems; and, of course, by refusing to consider anything that its leadership does not currently support[15].

Isn't reactor radwaste management impossible?
Answer. This is another political, not technical problem[cc]. Either of the recommended nuclear fuel cycles would generate far less long-lived transuranic radioactive waste per kWhr than does today's. The disposition of the 5-10 m^3/GW_e year of "best demonstrated available technology" (glass) waste forms[16][17] that either would generate each year could be cheaply/competently affected by storing them at the USA's Nevada Test Site until their FP have decayed away[dd].

[aa] A good example is the USA's response to the bombing of Pearl Harbor. It not only quickly won WWII, but also immediately swept away most of the attitudes/rules responsible for the persistence of the Great Depression.

[bb] "Big Science" is like most big businesses in that the people who do most of the work are neither tenured nor wealthy and therefore must continuously seek the good will of their superiors. Since lobbying for a paradigm shift within any institution/discipline suggests that whatever its managers are currently supporting is "wrong", few people so-employed are willing to do so even when a problem is obvious. This is one of the reasons why so many of the US federal government's "nuclear initiatives" have failed to achieve their goals.

[cc] Alvin Weinberg, the long time ORNL Laboratory Director and staunch advocate of molten salt-type reactors downsized during the Nixon administration for not being a "good team player", coined the term "transcientific" to describe such issues.

[dd] The NTS already safely and naturally "manages" the radioactive residue generated by 828 (more?) underground nuclear "events" most of which were instigated with plutonium cores. After they've cooled off, a good place to "temporarily store" the first couple of centuries worth of glass "logs" generated by this paper's recommended nuclear fuel cycle(s) would be within the ~460,000 m^3 of space generated by the tunnel-boring machine employed during the US Department of Energy's (DOE's) ~30-year/~ $15 billion Yucca Mountain study. There they would be safe, do no harm, and easily retrieved whenever anyone wishes to study them (please just don't call YM a "repository").

The USA's consistent failures[9] in this nominally "technical" arena are entirely due to the political way that its technical employees, contractors, and program reviewers are managed [ee].

Why not put the basalt (or lime) into the ocean instead?
Answer: While ocean acidification is often characterized as the "worst" problem that we have created, significantly raising the pH of the oceans by adding anything to them would be almost impossible. There are three reasons for this: 1) the oceans already contain roughly 13,400 GT of carbon (total dissolved inorganic carbon (DIC)≈0.0023 M , ~ 88.5% of which is present as bicarbonate anions, ~11% carbonate anions, and ~0.55% "carbonic acid" [ff]). Bicarbonate & carbonate anions constitute their chief pH buffering system via carbonic acid's second dissociation constant.

i.e., $[H+] \approx K_{2a}$ (about 1E-9)$*[HCO_3^-]/[CO_3^=]$.

Straightforward calculations suggest that to shift that equilibrium enough to generate a pH increase of 0.1 unit (from 8.06 to 8.16) would require the addition of ~9500 Gt of basalt dust or ~2300 Gt of lime (too much!). 2) Human nature: nobody "owns" the oceans – they are a "commons" that each individual user benefits most from by not doing anything that might benefit anyone else (poor countries/people?) more than it might him/her/it. 3) More rock grinding energy/power would be probably be required because "big" particles would settle to the bottom & become buried in existing sediments before they could completely weather. Finally, 4) the "rainbow warriors" apt to be dogging ships dumping anything into the oceans - especially a dangerous/caustic material like lime - might inhale dust "known to the state of...." to be injurious & thereby raise the possibility (certainty?) of legal repercussions. Well-connected scientists, program managers, and politicians tend to be risk-averse.

Conclusions

We are the first generation possessing detailed knowledge of how humanity's activities influence the Earth, and therefore the first with the responsibility to change our relationship with it. Big changes are rapidly happening and business-as-usual cannot continue. Responsible stewardship requires radical transformation in how we go about doing whatever is necessary to live in harmony with each other & the environment. In particular, we must become willing to take action to solve "big" problems – not just "study" them. The main reason that geoengineering is usually written-off is that implementing even the most reasonable scheme on a scale large enough to make a real difference would be impossible with today's politically-correct "renewable energy". No combination of wind and solar power (either "towers" or panels) represents a realistic solution to our energy-related conundra because of their intrinsically high cost[gg], environmental impact, and unreliability[hh]. While a number of

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[ee] Descriptions of two ongoing USA reactor radwaste management boondoggles may be found at http://www.nwtrb.gov/meetings/2013/april/siemer.pdf and http://www.nwtrb.gov/meetings/2014/aug/siemer-pc.pdf.

[ff] C speciation calculated at a pH of 8.06 using equations found in Chapter IV of Emerson and Hedges', Chemical Oceanography and the Marine Carbon Cycle, Cambridge University Press, 2008, *see* http://courses.washington.edu/pcc588/readings/EH_IV_CarbSys.pdf

[gg] Wind power is much more expensive than its champions usually admit, see http://instituteforenergyresearch.org/wp-content/uploads/2013/10/Giberson-study-Final.pdf

technically astute environmentalists (e.g., James Hansen, Patrick Moore, Ansel Adams, Carol Browner, James Lovelock, Barry Brook**,** Tom Wigley, Ken Caldeira. and Kerry Emanuel.)[ii] feel that a nuclear renaissance is necessary, they remain a tiny minority in a world dominated by "market forces", political correctness, social/religious/political/institutional tribalism, and "good team players".

Straightforward calculations will convince anyone willing to perform them that any such renaissance must be much larger than current nuclear decision makers seem willing to admit and implemented with breeder-type reactors - not more of the same. While my proposal's geoengineering application of such power would certainly require some "optimization" (process specific study), it is likely that achieving substantial "negative emissions" is just another thing that only a properly implemented nuclear renaissance could accomplish. A "barrier to science" confronting anyone who wishes to do anything concrete in this arena is that very little of the research funding devoted to either new/better nuclear reactor development or climate science is spent upon the experimentation required to work out the "details" of implementing any specific proposal[jj]. To solve a big problem, the majority of available resources must be focused upon that goal and the most realistic approaches to reaching it, not upon "identifying (more) issues" or adding yet another gee whiz "what if" to "all of the above". The R&D required to determine if this paper's geoengineering proposal would work might best be performed at an "ag school's" experimental station because its personnel spend most of their time performing the real-world experimentation required to generate process-relevant (e.g., enhancing food production) information, not developing models.

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The author thanks the University of Tennessee's Prof. Ondrej Chvala for volunteering to do the neutronics modeling of Fig 5's MCFR iso-breeder. I also thank the U of Utah's Professor Nicholas Tsoulfanidis who while serving as "Nuclear Technology's" Editor, decided to accept my first retirement-hobby paper. Finally, I thank the internet's legion of selfless "technical nerds" whose volunteer work has rendered that pastime possible.

[hh] In 2014 the USA's 66 GW's worth of wind turbine "capacity" generated 170 billion kWhrs of energy www.renewableenergyworld.com. Together, these figures indicate a capacity factor of 29.4% - the latter, that ~48,000 utility-scale wind turbines provided only about 1.4% of the USA's "energy services".

[ii] https://en.wikipedia.org/wiki/List_of_pro-nuclear_environmentalists

[jj] e.g., "how much rock grinding is necessary"? "How long should we expect our new molten salt reactor's core-wall to last? What is the stoichiometry of CO_2 fixation (measuring only calcite accumulation rate in a well-drained soil ignores bicarbonate in any water leaving it)?.

Figures

Figure 1. Observed vs various IPCC model-predicted CO_2 emission (en.WIKIPEDIA, org)

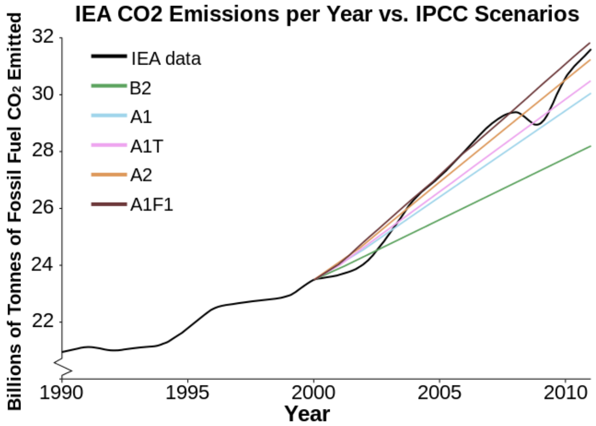
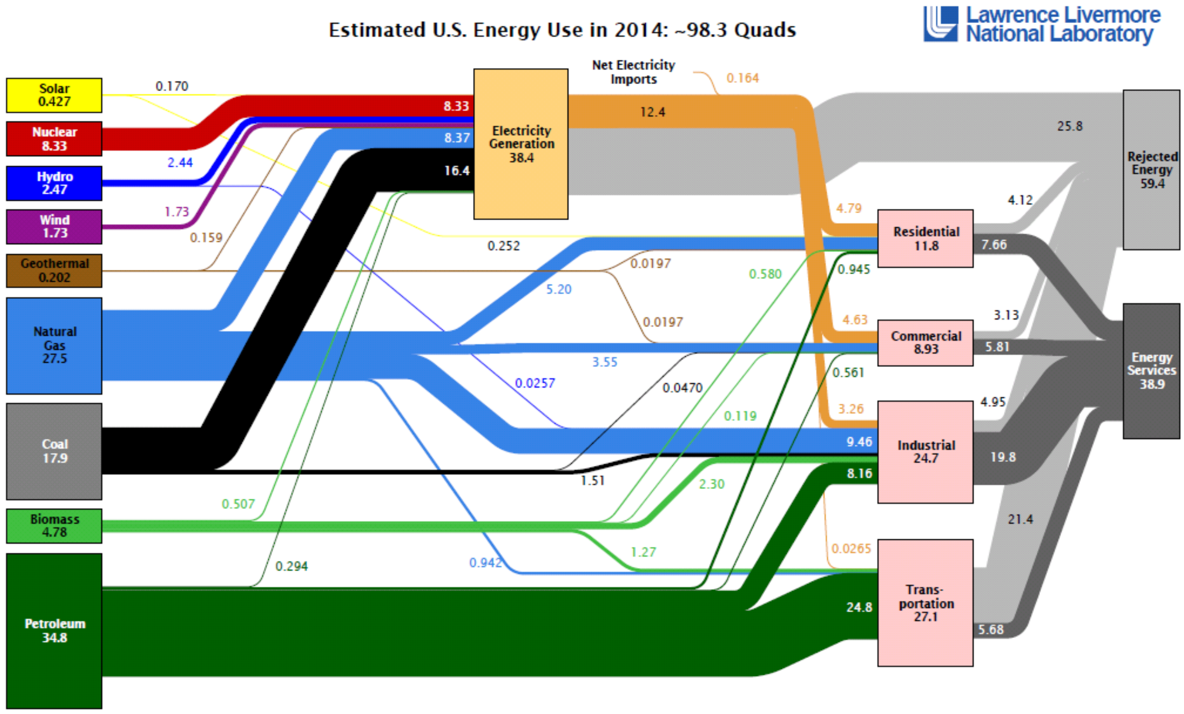


Figure 2. how a technological civilization uses energy https://flowcharts.llnl.gov/



Source: LLNL 2015. Data is based on DOE/EIA-0035(2015-03), March, 2014. If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant "heat rate." The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 65% for the residential and commercial sectors 80% for the industrial sector, and 21% for the transportation sector. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

Figure 3 Germany's real-time total wind power throughout 2014 -red line depicts total nameplate capacity http://www.vernunftkraft.de/85-prozent-fehlzeit-windkraftanlagen-sind-faulpelze/

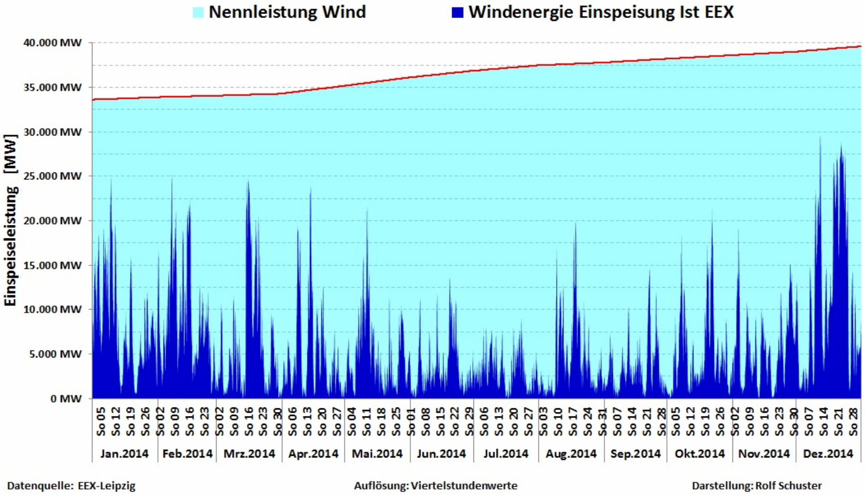


Figure 4, EVOL's basis MSFR (thorium-fueled, blanket equipped 3GW$_t$, (from [12])

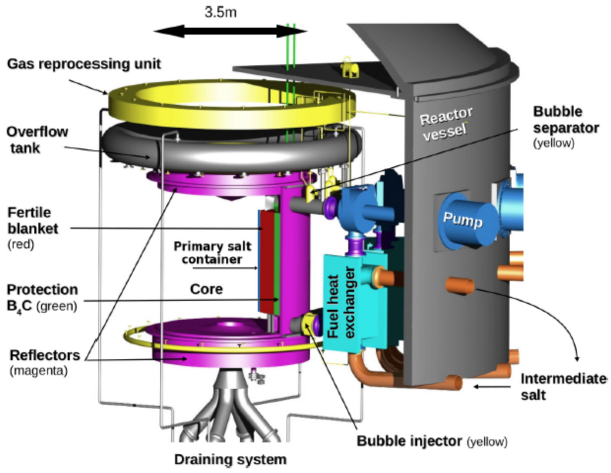


Figure 5. hypothetical 2.5 GW_t, no-blanket, MCFR isobreeder (from [13])

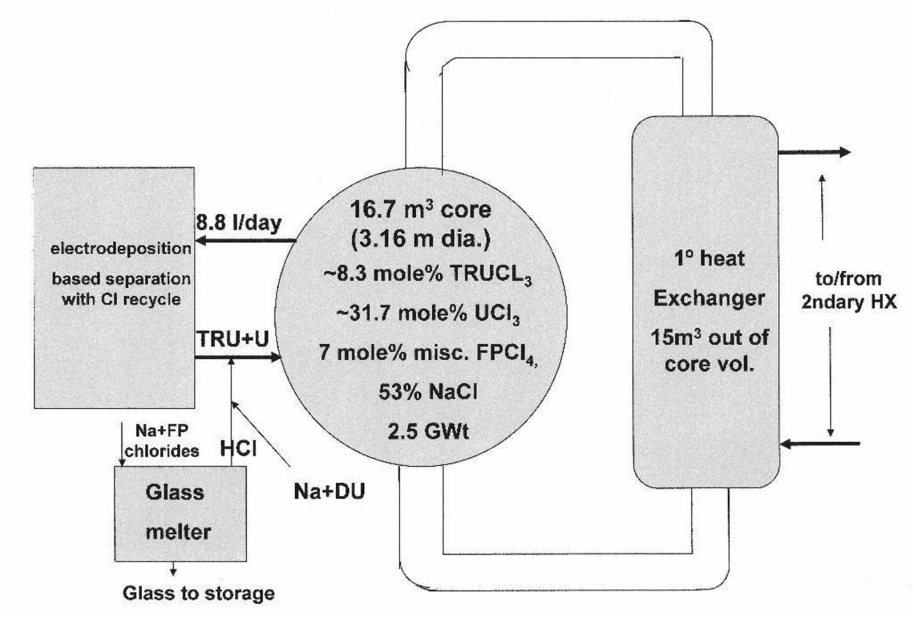


Table 1. key numbers

what?	amount	unit	Ref.
Total anthropogenic C emissions, 1870 to 2014	545	Gt	g
Total world grain production 2015	~2.5	Gt/a	h
Total world bone-dry wood production 2015	~1.9	Gt/a	i
Total C emissions from fuel combustion & cement-making	~9	Gt/a	WIKI
Total C emissions from unsustainable land-use	~1	Gt/a	WIKI
Total organic carbon (SOC) in top soils	~1550	Gt	c
Total inorganic carbon (SOI) in top soils	~950	Gt	c
Total soil CO_2 respiration rate (as C)	60-77	Gt/a	d,e,f
Total atmospheric C (almost entirely CO_2)	~800	Gt	WIKI
C_t oceans (≈0.0023 M ~0.55% CO_{2aq}, 88.5% HCO_3^-, and 11% $CO_3^{=)}$	~13,400	Gt	WIKI
Total C in remaining fossil fuel reserves	~1190	Gt	g
Total mass of land-based “flood basalts” (assumes 3g/cc)	~6.9E+7	Gt	a
C fixation potential average Earth mantle basalt	~7.5*	meq/g	b
Total volume of the oceans	~1.35E+9	km^3	WIKI
Mass of atmosphere (mean molecular wt=29 g/mole)	5.15E+18	kg	WIKI

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* 2 X wt. fraction of all alkaline earth oxides divided by their molecular weights. (In compounds or minerals, alkaline earth elements are divalent - each mole of leached oxide generates two moles of “alkalinity”).

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