K45: Strategies - Technology

Attempting to Reduce / Halt / Reverse Climate Change Through Techno-changes (but large-scale Geo-Engineering Covered later, in K46)

Part 1

FRAMING THE PROBLEM PROPERLY

Technological Strategies vs. GeoEngineering – What's the Distinction?

- Agreed – it's not a sharp border
- I consider "technological strategies" as those which have other value besides climate, including power generation or energy efficiency improvements.
- GeoEngineering is large scale modification of the planet completely intended for modifying climate.
- If your favorite idea isn't in this chapter, perhaps it's in the K46: GeoEngineering chapter, or… I haven't put thoughts down on it yet.

Strategy… to Accomplish What?

- **1.** Is our goal to return to a state of stable sea level close to today's? Stable temperatures, and a stable climate? *This is either impossible, or will require MASSIVE, IMMEDIATE and wrenching change far more severe than the populace believes. This goal is incompatible with long term global economic growth*. *Review the Thermodynamics of Civilization*
- **2.** Or, is our goal to do what we can to slow our descent into climate chaos, but not at the price of economic growth or population freedom? *This is more do-able, still requires very large political and economic changes. It still results in a crippled future for thousands of years*
- *My students: You decide – it is more your world than mine: Alas, you will inherit what my generation and those before have left you.*

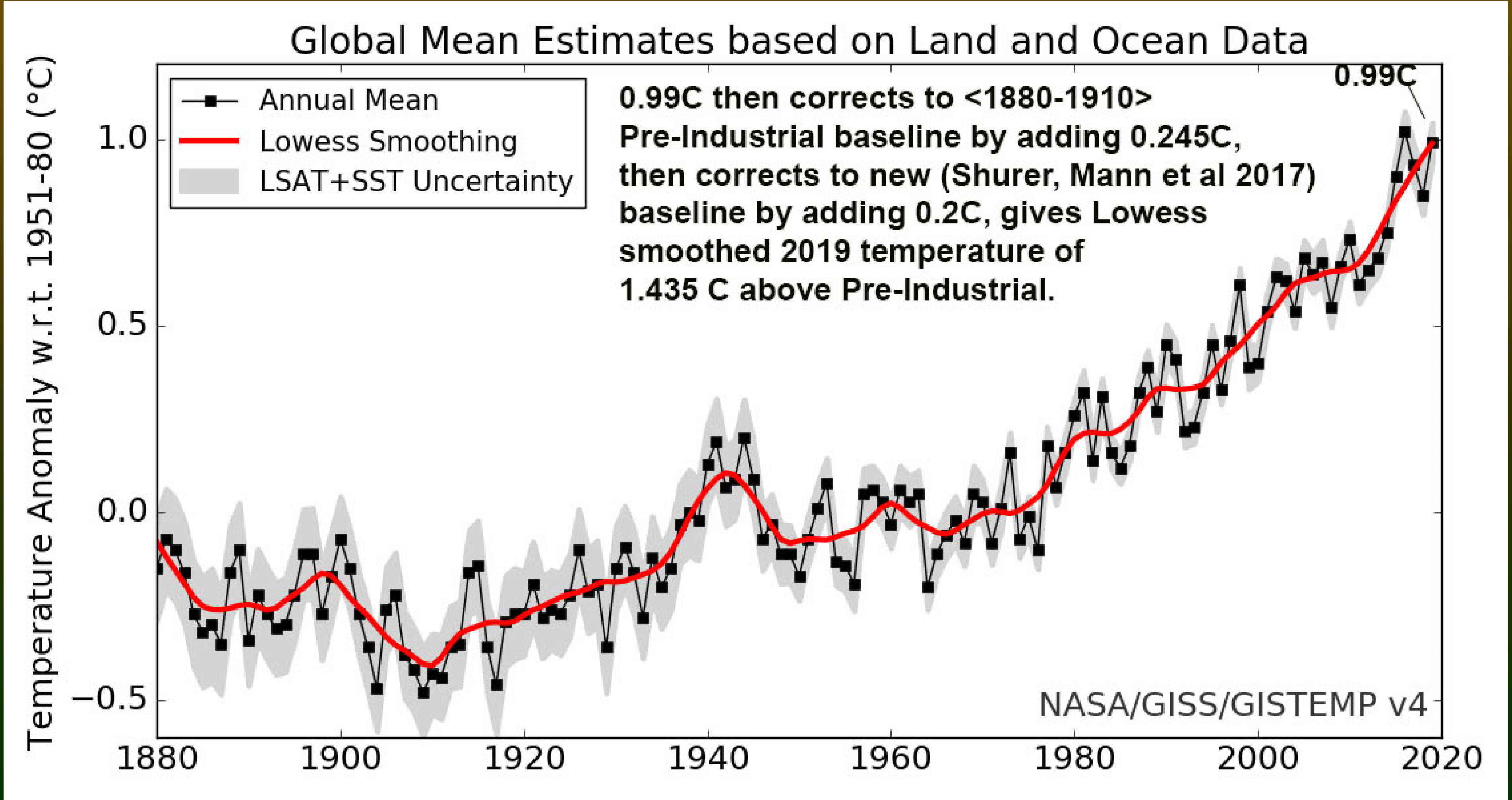
To Identify Technologies, We Need to Appreciate the Scale of the Problem

- 93% of greenhouse heating has gone into the ocean
- The ocean has 700 times more thermal capacitance than the atmosphere.
- And, we're out of thermal equilibrium by 0.83 watts/square meter. And we're forcing climate 3 watts/square meter above what we're emitting.
- Together, these will prevent the low thermal mass atmosphere above from cooling off – for thousands of years – even if we halt ALL CO2 emissions and somehow re-freeze Arctic permafrost and halt other carbon releases.

The Arctic permafrost will continue to thaw since global temperatures will not go back down

- …contributing greenhouse forcing at significant but poorly quantified levels, even if we end industrial civilization overnight.
- +1.5C above pre-industrial, maintained, could be enough to thaw most of the Siberian permafrost, and the rest of the Earth's permafrost (Vaks *et al.* 2013*, although his later data suggests the +1.5C may not correspond to global avg. temperature) and here, and Lawrence et al. 2008. It's already begun).*

As of 2019, we were already at ~+1.44C above pre-industrial temperatures using the new Schurer, Mann, et al. (2017) baseline for Pre-Industrial temperature. **+2C is inevitable, soon, and climate negotiators even in 2012 said only a complete cessation of all industrial civilization will prevent +2C. Scientists are even less optimistic than that. Especially today.**



From UK Climatologist Dr. Peter Cox, Commenting on the Paris COP21 and IPCC Scenarios…

- IPCC statement: *"Global Surface Temperature Change for the end of the 21st Century is likely to exceed +1.5C for all scenarios"*
- **Cox**: *"…but this is the understatement of the century!... and scientists are not allowed in the negotiations (at least not scientists like me, who might say something)…and I went there thinking 'we've got to TELL them; 1.5?? we're nowhere near +2, we're nearer +3C!'. And we all got side-tracked, as they put this shiny thing up (waving a key fob) '1.5 is over here, don't look at the 3, don't look at the 2'. There was an optimistic BUBBLE. But it needs to become…REAL."*

From former Head of NASA/Goddard Space Science Institute Prof. James Hansen…

- *"The paleoclimate record makes it clear that a target to keep human-made global warming less than +2°C, as proposed in some international discussions, is not sufficient - it is a prescription for disaster."*
- *"Assessment of the dangerous level of CO_2, and the dangerous level of warming, is made difficult by the inertia of the climate system. The inertia, especially of the ocean and ice sheets, allows us to introduce powerful climate forcing such as atmospheric CO_2 with only moderate initial response. But that inertia is not our friend - it means that we are building in changes for future generations that will be difficult, if not impossible to avoid."*
- *See 2011* http://www.giss.nasa.gov/research/briefs/hansen_15/

GeoEngineering is Now Not Just an Option. It's Required.

A 2016 peer-reviewed version of Hansen et al.'s evaluation of future ice sheet collapse and super-storms is described and linked here And in 2017, Hansen's latest paper declares climate disaster is assured unless we artificially pull substantial CO2 out of our atmosphere.

Our past inaction has now FORCED us to include GEO-ENGINEERING if we want a stable future climate. Not INSTEAD of, but rather in ADDITION TO – emissions elimination.

Even With Little or No Further Human-Caused CO2 emissions (which is impossible)… +2C will Happen Soon

- At 400ppm CO2, sea levels rise inexorably for many centuries, rising eventually ~80 feet or more (we're at 415 ppm in 2019), says paleo data.
- **Merely to halt rising atmospheric CO2 and hold at current levels, given the Macdougall *et al.* (2012) permafrost work, requires ending 100% of GHG emissions (Matthews and Weaver 2010, and even that assumes ECS (Equilibrium Climate Sensitivity to a doubling of CO2) is only 3C, which is increasingly looking far too low)**

To Halt Climate Change…

- Requires immediate end to all carbon emissions, including those from livestock and tropical and Arctic methane sources
- Requires reversing the tipping point thawing of the Arctic carbon sources (impossible without massive Geo-Engineering).
- Requires re-freezing the West Antarctic so that the major glaciers may re-anchor to the grounding line. Might be impossible.
- Requires pulling heat from the oceans to the atmosphere where it can radiate to space. That heat direction has been the reverse so far.
- Requires not only a cessation of all carbon emissions, but massive commitment to developing and deploying a technology for rapid CO2 removal from the atmosphere, far above that naturally due to oceans and plants, and finding somewhere to put it which is stable long term, regardless of cost.

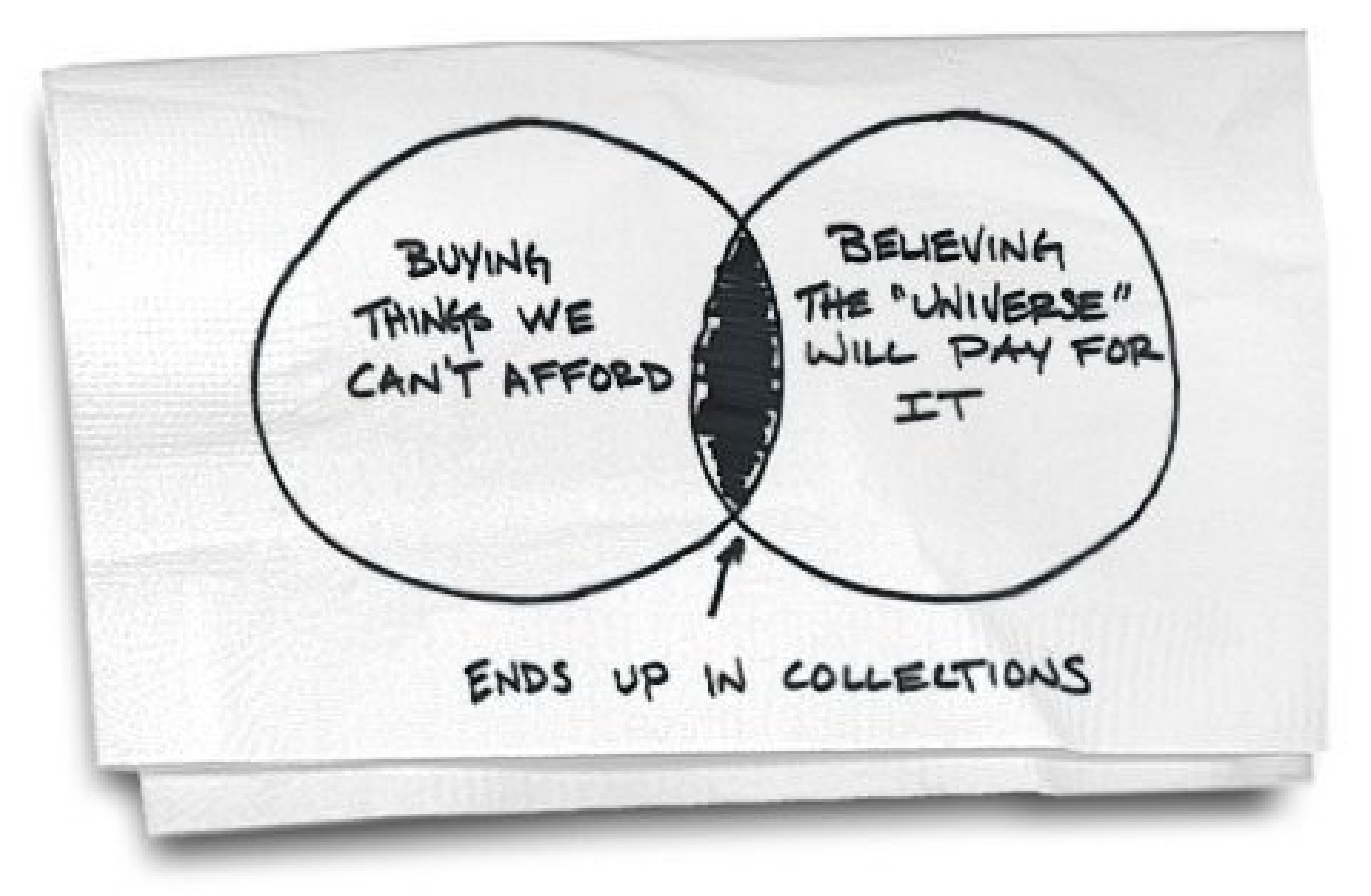
If We're Serious About Preserving the Stable Climate Human Civilization Evolved in…

- *…"It's not enough to pull the excess that's in the atmosphere at that time — we'd also have to pull out what went into the oceans," he said. "If we want to undo this, we would have to artificially pull out **all** of the cumulative emissions since preindustrial times." – Dr. Pieter Tans at NOAA's Greenhouse Gas Reference Network (source)*

At This Late Date, it Requires Inducing a COOLING World

- …to halt polar thaw.
- But it is climate change *per se*, which is so damaging to ecosystems and human civilization, in either warming or cooling direction.
- Think of the danger in engineering this - Climate change now in the cooling direction
- Think of the political and social resistance that such a climate shift would cause, and ask whether you think we will do it, for the sake of future generations unborn and un-cared about.
- When the great coastal cities are underwater, it will be too late to matter whether we lower sea levels by re-freezing the poles in order to save them.

So it's a VERY tough reversal that is needed. At a time when politicians are crippling basic science research in all fields, but especially Earth Sciences. How should we judge technology ideas out there for helping us in that direction?



Framing Techno-Solutions <u>Efficacy</u> and <u>Safety</u>:

<u>First Key: Efficacy:</u>

- There are only TWO solution categories. I'll summarize in the next three slides, then explore in more detail…

A. <u>Reduce</u> the influx of solar radiation reaching the ground and troposphere globally.

- Also called the "SunShade" or "SRM" category (SRM=<u>S</u>olar <u>R</u>adiation <u>M</u>anagement)
- Enhancing low clouds, sulfate aerosol dispersion, sunlight reflectors in space, lots of white paint, raising the albedo of darker areas of Earth's surface… all fall into this category; they're saved for the Geo-Engineering chapter

B. Raise the ability of Earth to re-radiate its heat to outer space.

- Lowering greenhouse gases strategies are in this category.
- **If a proposed strategy reduces the ability of Earth to radiate its heat to space, it would have to also reflect incoming sunlight even more effectively than it reduces Earth re-radiation, and do so at a continuously increasing rate in order to offset the increasing solar heat storage due to reduced re-radiation. I can find no strategies in this category that work.**

Anything else, is sweeping our excess heat under the rug.

- Excess heat MUST be dumped to space, since there is nowhere else that heat can be deposited for the long term. It can't be sequestered into the Earth because the geo-thermal gradient is HOTTER as we go deeper.
- Sweeping heat under the rug, by current studies, is a long term loser. It re-emerges later, making things even WORSE than doing nothing.
- Such ideas are in the "**Loan Shark**" category. And we know how that ends. **Badly. More later.**
- ***That's Our Choices.*** Keep that in mind

2rd Key – Safety

- There are two criteria which should both be satisfied to be optimally safe…

Safety Criterion #1: Induce No Hysteresis in the Earth System Trajectory

- This is an important aspect I've not seen discussed at all.
- No hysteresis means; the strategy backtracks the Earth System back along the ~same trajectory that took us to today's bad place.
- Profit strategies which instead make significant changes entirely novel to the Earth system, and over which we have very limited understanding, are the most dangerously unpredictable to all ecosystems, weather patterns, and civilization

Safety Criterion #2: Leave the SURFACE of the Earth as Pristine as Possible for Current Ecosystems

- The overall goal of halting climate change is to preserve the livability of the planet for all living things. The vast majority live on the Earth’s surface.
- Techno-changes should seek to NOT modify the Earth’s surface except in ways that take it back to their natural state

"White Paper" Promises? – Beware of Strong $$$ Conflicts of Interest

- This is one of the key real-world facts students of this course need to be wary of!
- Wall Street-savvy observers have noted: Overly rosy announcements are regularly made to attract venture capital.
- They accentuate, even exaggerate, the positive, and minimize or cover-up the problems.
- This is how Wall Street works, tragically.
- A great example is the absurd (but "catchy") SolarRoadways hype. Here's a well-deserved bucket of cold water, from an astronomer.

The Conflicts of Interest extend to the journalists who publish the announcements you read

- …And the engineers promoting the idea, who want to look good, naturally, and make money too (and we saw what the Thermodynamics of Civilization shows about that).
- They spin the idea to the journalists who interview them, who rarely ask the skeptically appropriate questions, because…
- … then they might not get the interview (or else they don't understand the science/engineering well enough)
- …the journalist wants to look good for his editor (including free-lance journalists looking for someone to buy their writing)
- …and the editor wants to look good to the publisher, who wants a sensational article promising to revolutionize the world. Smiling faces, for $$, is the goal. Truth? is secondary.

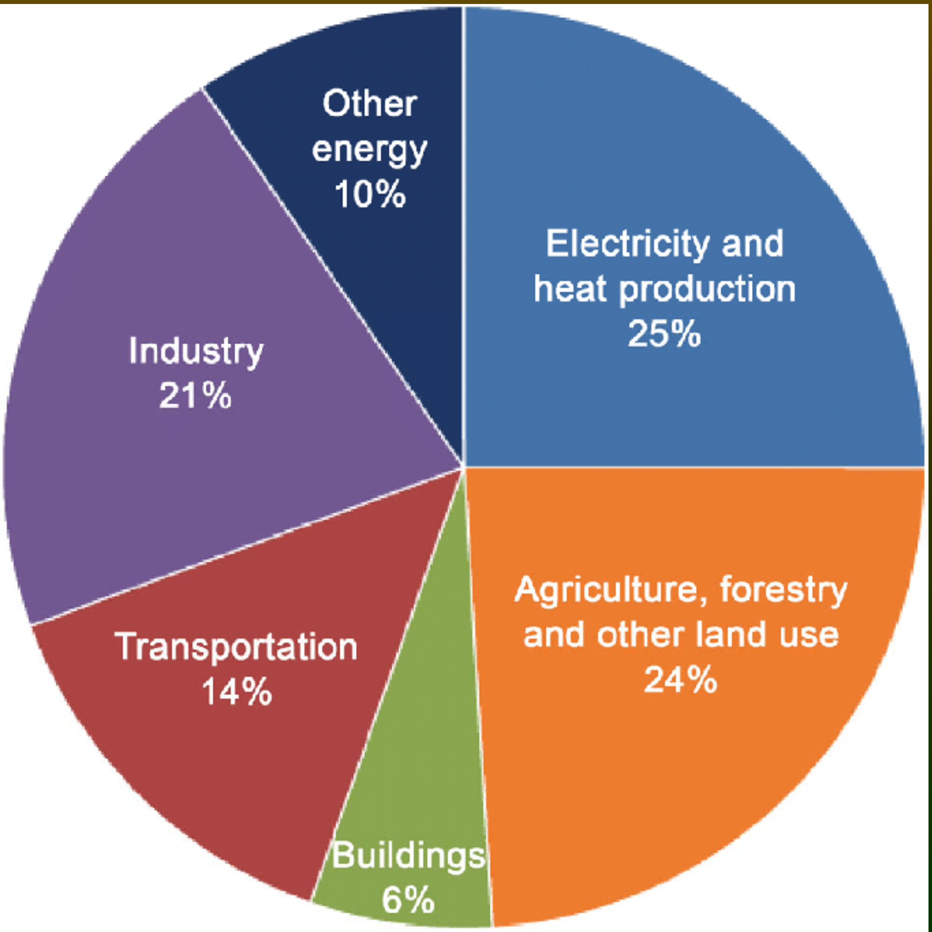
Instead – Focus on Peer-Reviewed Science Journal Papers, Refereed by Competing SCIENTISTS

- Do not blindly trust "white papers" issued by financially "interested" parties and organizations, no matter how eco-friendly or well-meaning they may appear.
- <u>Especially</u> don't trust white-paper proposals that have been out there for many years and STILL have no legitimate science journal articles to back up claims
- Whether innocent, or instead financially incentivized… they may be deeply flawed with major blind spots.

A Final Framing Point

- Invest no trust in any "solution" which avoids the real problem – that physical and economic, growth must end on a finite planet.
- Anything less, is just a Band-aid, another needle-to-the-vein "fix" for a species addicted by the hormones Nature gave us, urging us to ruthlessly grow eternally. Feel no enthusiasm for strategies which ignore this.
- **Remember – Growth and Domination: The tragedy is when you WIN (unfortunately - we did!).**

Here is Where Global Greenhouse Gases are Coming From…



- Soil carbon loss, deforestation, meat-centered lifestyles, other land use … is only ¼ of the total. Also, transportation of all kinds is only 14%. And half of all GHG's come from non-transportation heat and power generation.

Part 2
Low Carbon
Energy

This is in Solution Category 2: Raising Earth's ability to radiate back to space by Reducing CO2 and other GHG's (but only if they REPLACE, rather than ADD TO, fossil fuel energy as they are today)

Wind, Hydro, Solar, Nuclear, Geothermal Energy Sources

- Astrophysicist Frank Shu argues (Shu 2008) that the most promising energy sources which can compete in the sheer volume of energy which our society currently requires, are…
- --- solar photovoltaics
- --- nuclear power

Neglecting Nuclear, Solar Energy Dwarfs Other Renewables, Wind Next. In 2020, Global Energy Consumption Rate = 19 Tw

Maximum Available Energy:

- Sun 173,000 TW
- Wind 1220 TW
- Plants 166 TW
- Waves & currents 65 TW
- Geothermal 44 TW
- Human use today 15 TW
- Tides 4 TW
- Hydroelectric 1.9 TW

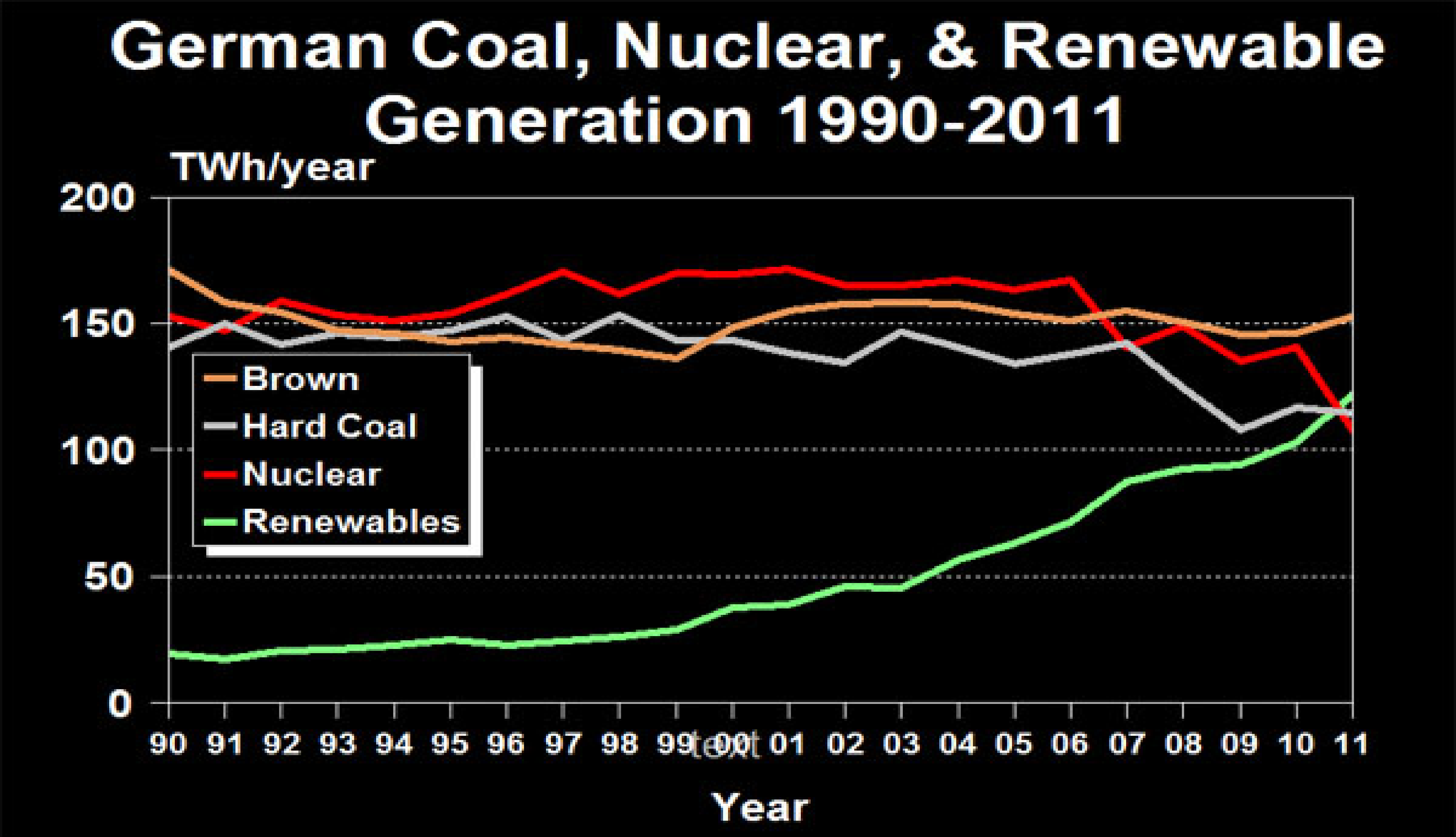
A. Solar Photovoltaics

Solar Photovoltaics: Good…

- **<u>Solar PV's Advantages:</u>**
- --- rapidly getting cheaper
- --- carbon nanotube-based solar may provide slightly improved power/cost ratios
- --- rooftop panels allow distributed systems "off the grid" and therefore
- *** provides no easy targets for terrorists (cyber-terrorism threatens all, but individual rooftop PV least)
- *** allows energy independence, and are the ultimate in "local", motivating their care by owners
- --- few if any moving parts to break, only occasional further investment (batteries, transformers mainly) once purchased. Degradation is slow, useful life per panel perhaps 30yrs? Some worry about toxics in recycling (Cd)
- --- in warm climates, rooftop systems also lower heat load to structures, lowering air conditioning costs. As the Earth warms, more and more of us will be in "warm climates"

Solar rooftop system in Germany. Large subsidies helped get solar going in this cloudy northern country

Getting Off Fossil Fuels? Cost gets much steeper once solar PV becomes larger than 20% of the total power, for today's grid. That may improve with better storage.



Potential Rooftop PV? Less than half of what's needed (Gagnon *et al.* 2016)

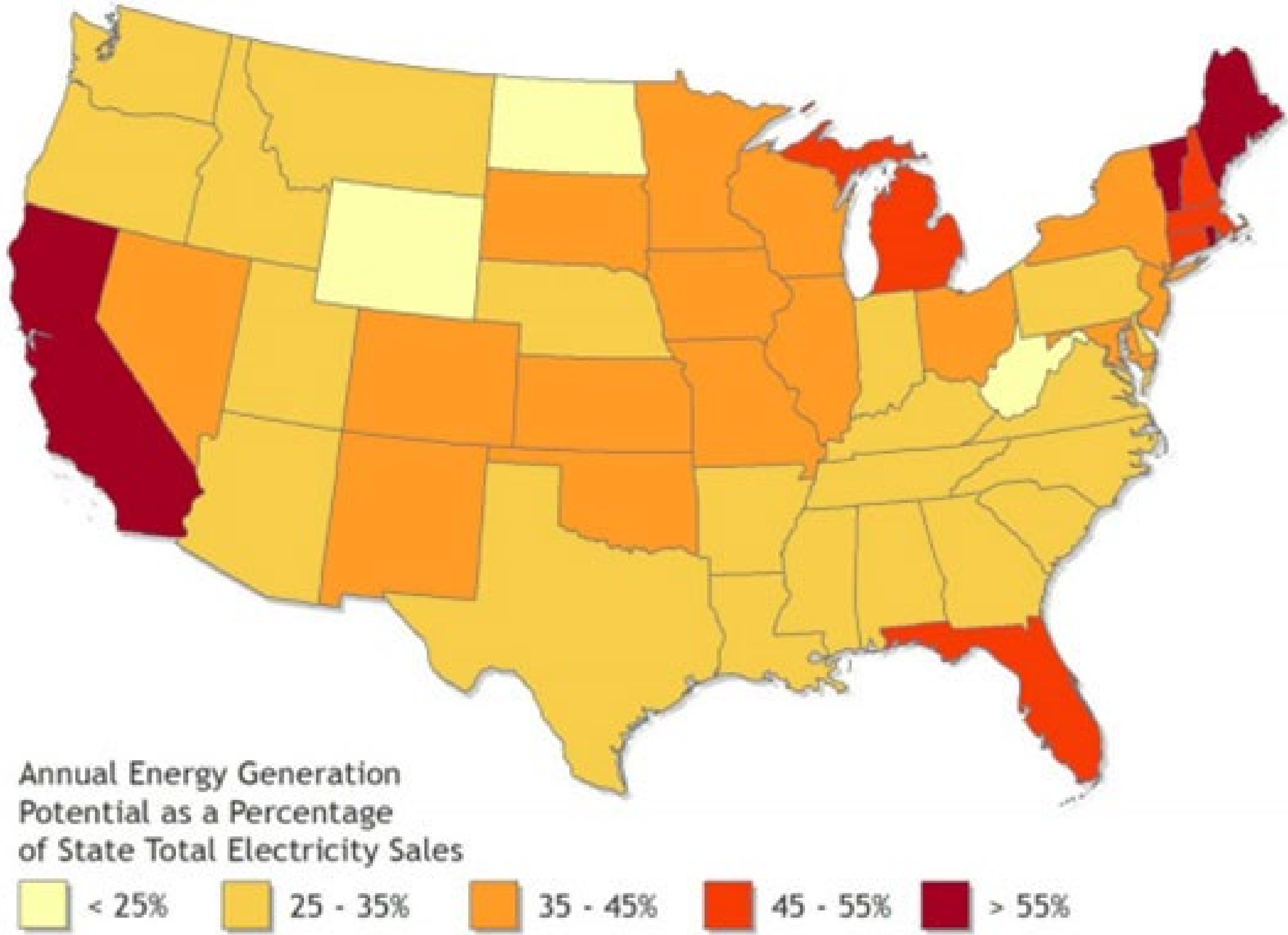


Figure ES-2. Potential rooftop PV annual generation from all buildings as a percentage of each state's total electricity sales in 2013

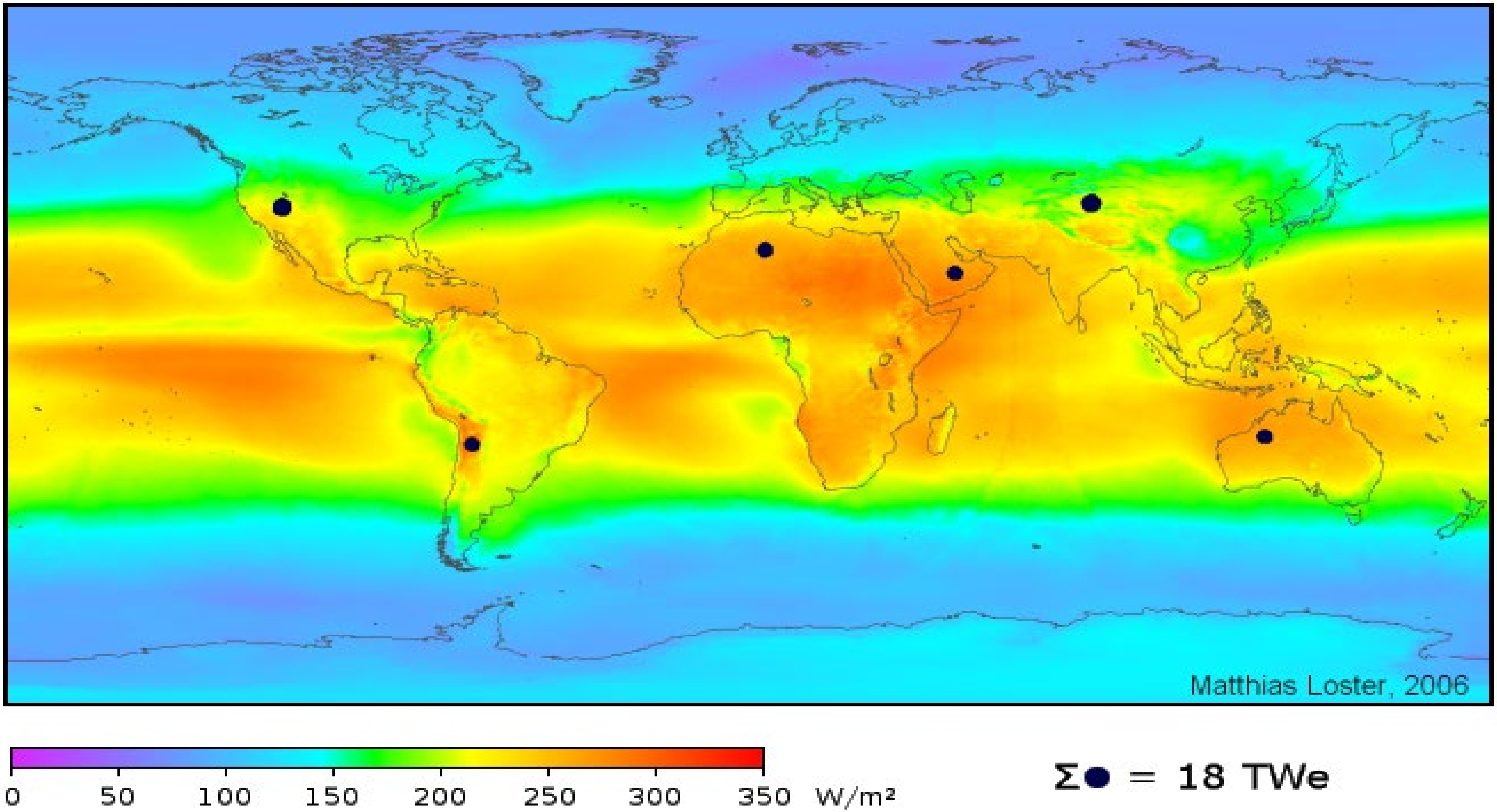
In Europe, while there's room for adding to rooftop Solar…

- …But only enough to provide a fraction (25% as of 2019) of Europe's power, and that assumes the other problems with solar can be solved (see later).

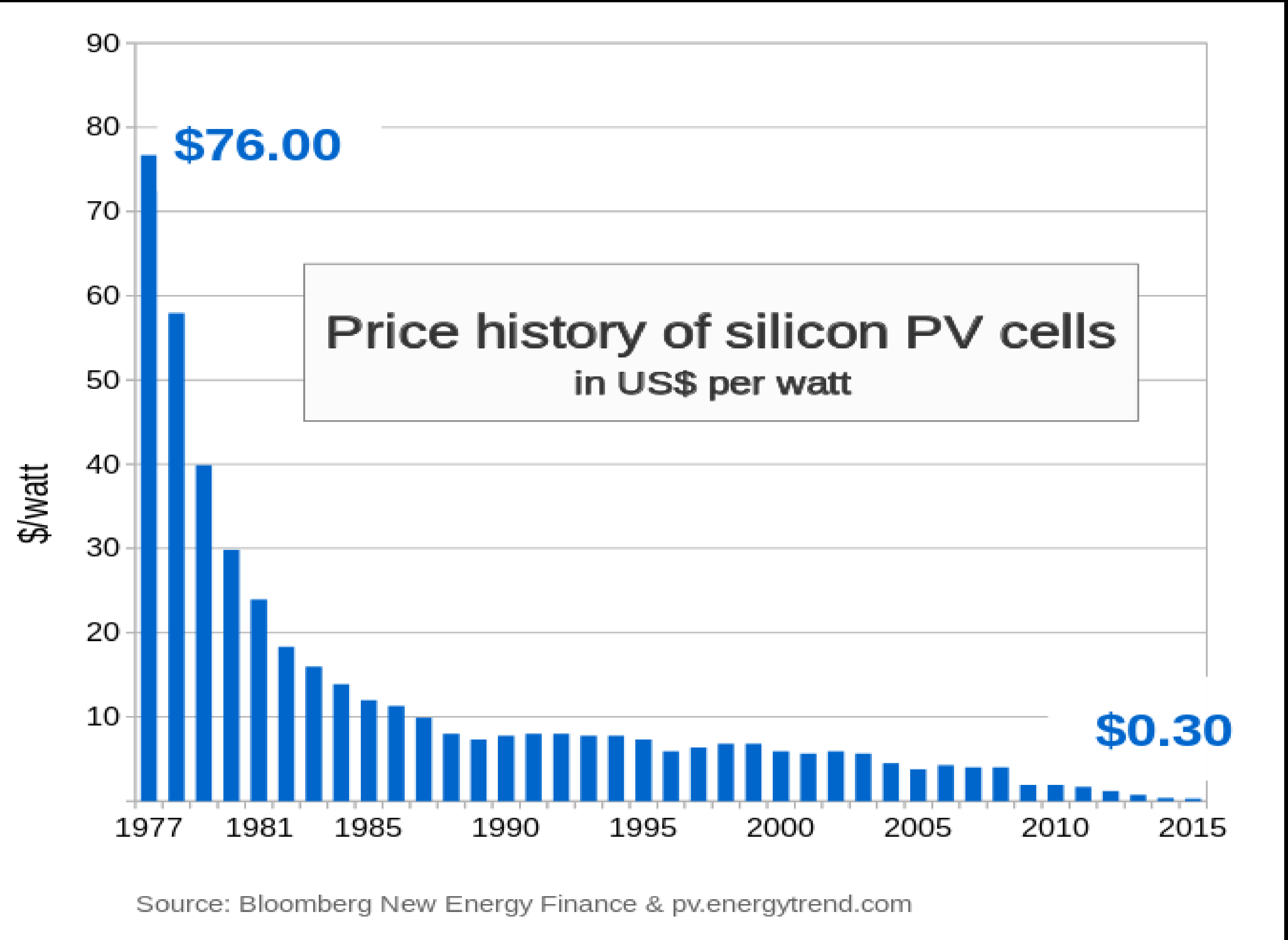
Rooftop Solar is Appealing

- In the US, if every building had rooftop solar, it might supply up to 39% of our 2013 electricity. Gagnon *et al.* 2016 (but in a "white paper" from the National Renewable Energy Lab). Sunny CA better: ~400% of CA power (*Nature: Climate Change* , and discussed here)
- However, even uber-optimist Mark Jacobson sees rooftop solar only giving 7% of the US power by 2050, and that is with "enormous, heroic assumptions about social and political change" (source quote)

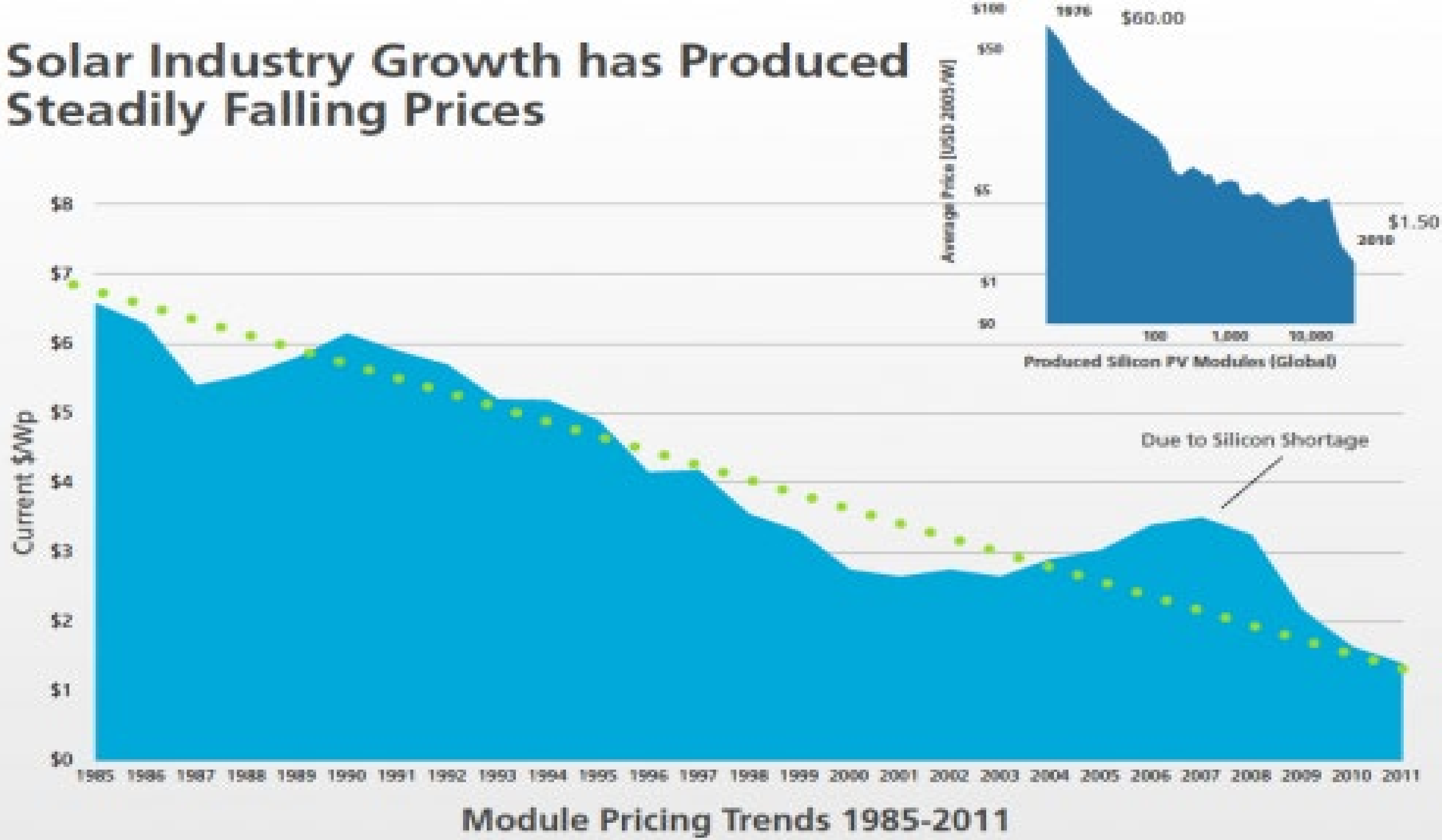
Solar PV Accessible Power Potential, Including Cloud Cover. Sum of black dot areas = total global power needs. More like 20 TWe in 2021



Silicon PV Cell costs falling (but not the same as entire PV Installation)

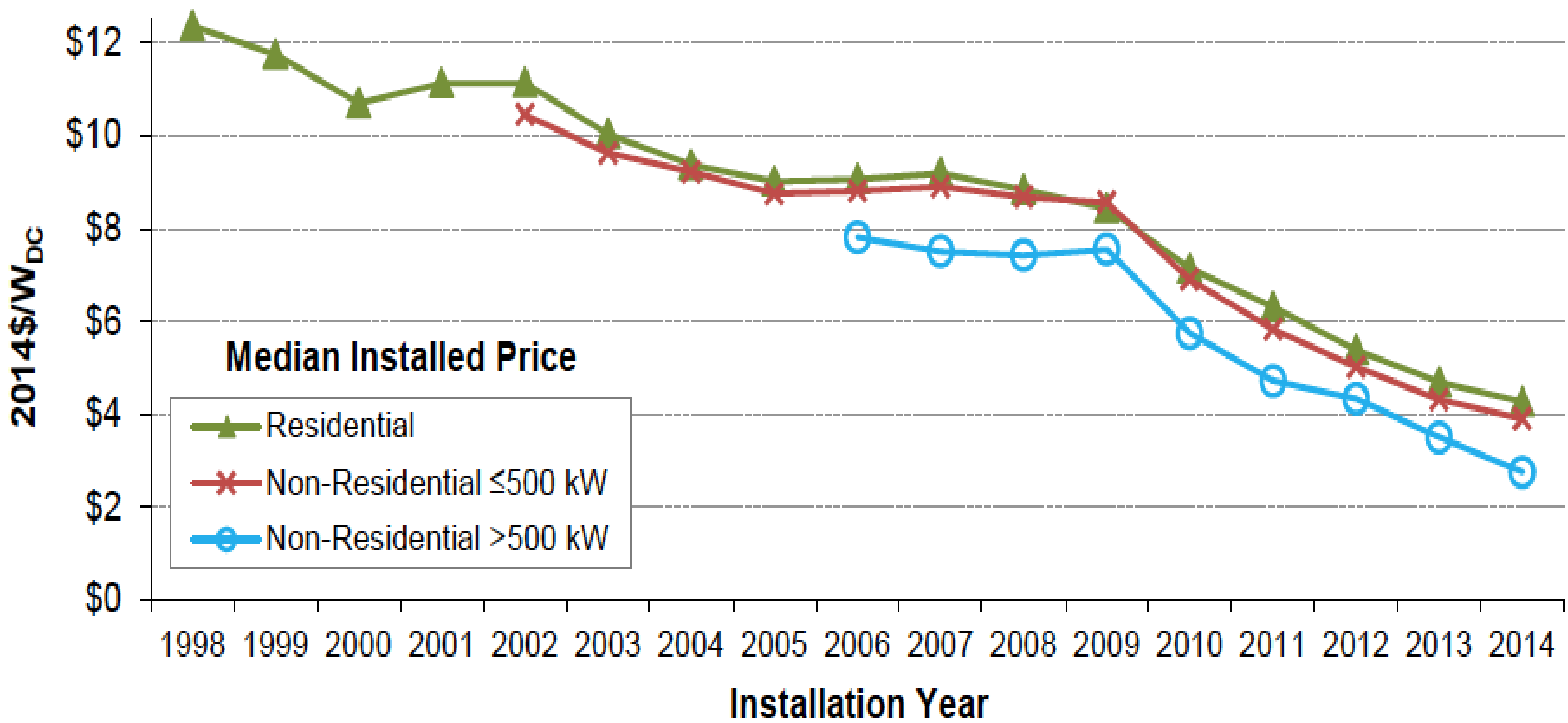


Solar PV module costs: 1985-2011



Sources: 1976-1985 data from IPCC, Final Plenary, Special Report Renewable Energy Sources (SRREN), May 2011; 1985-2010 data from Paula Mints, Principal Analyst, Solar Services Program, Navigant; 2011 numbers based on current market data

In the US, Solar PV Installed Prices Continued to Drop for Both Residential and Utility-Scale



Note: Median installed prices are shown only if 20 or more observations are available for a given year and customer segment.

Total Cost of Solar PV in the U.S. Continues to drop

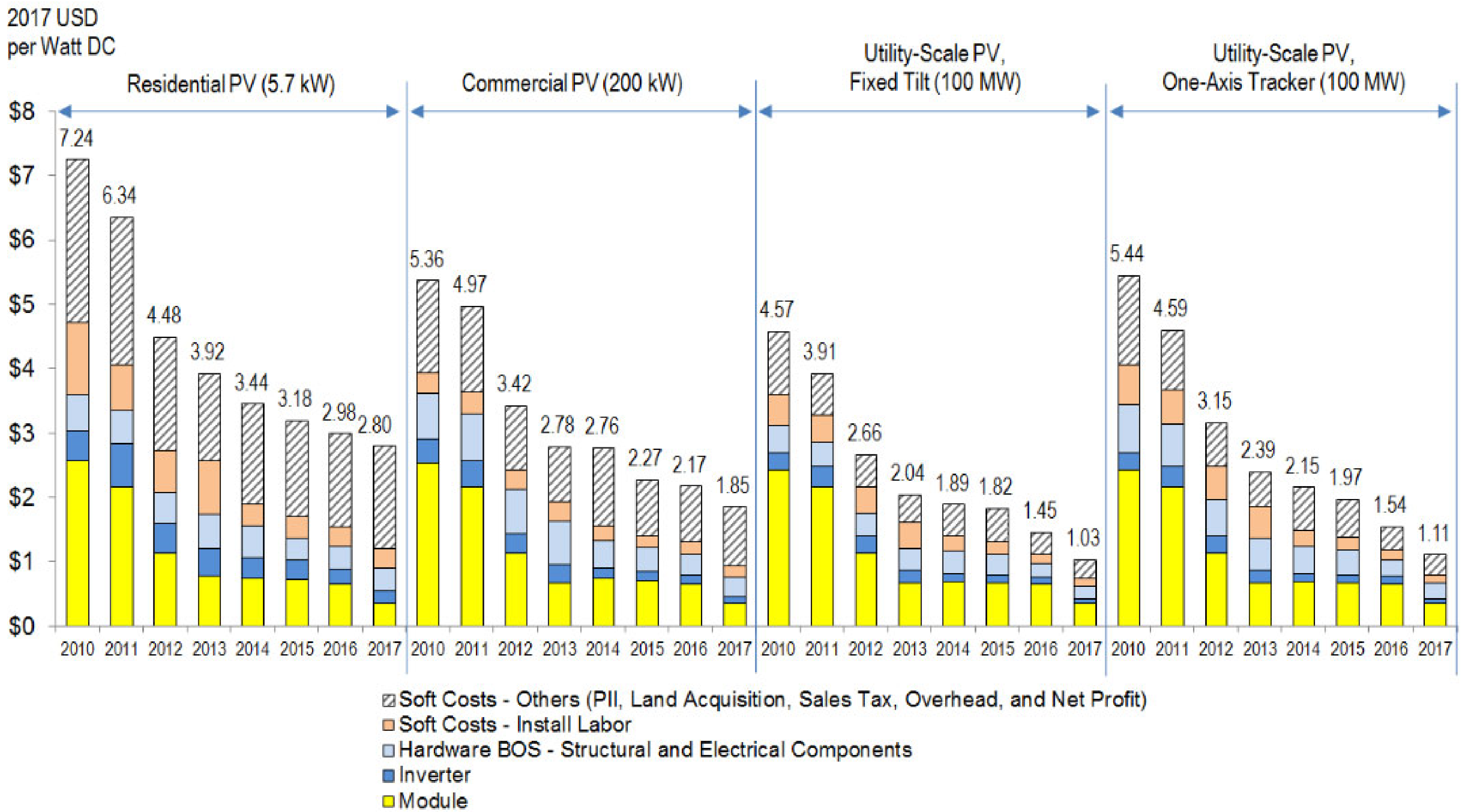
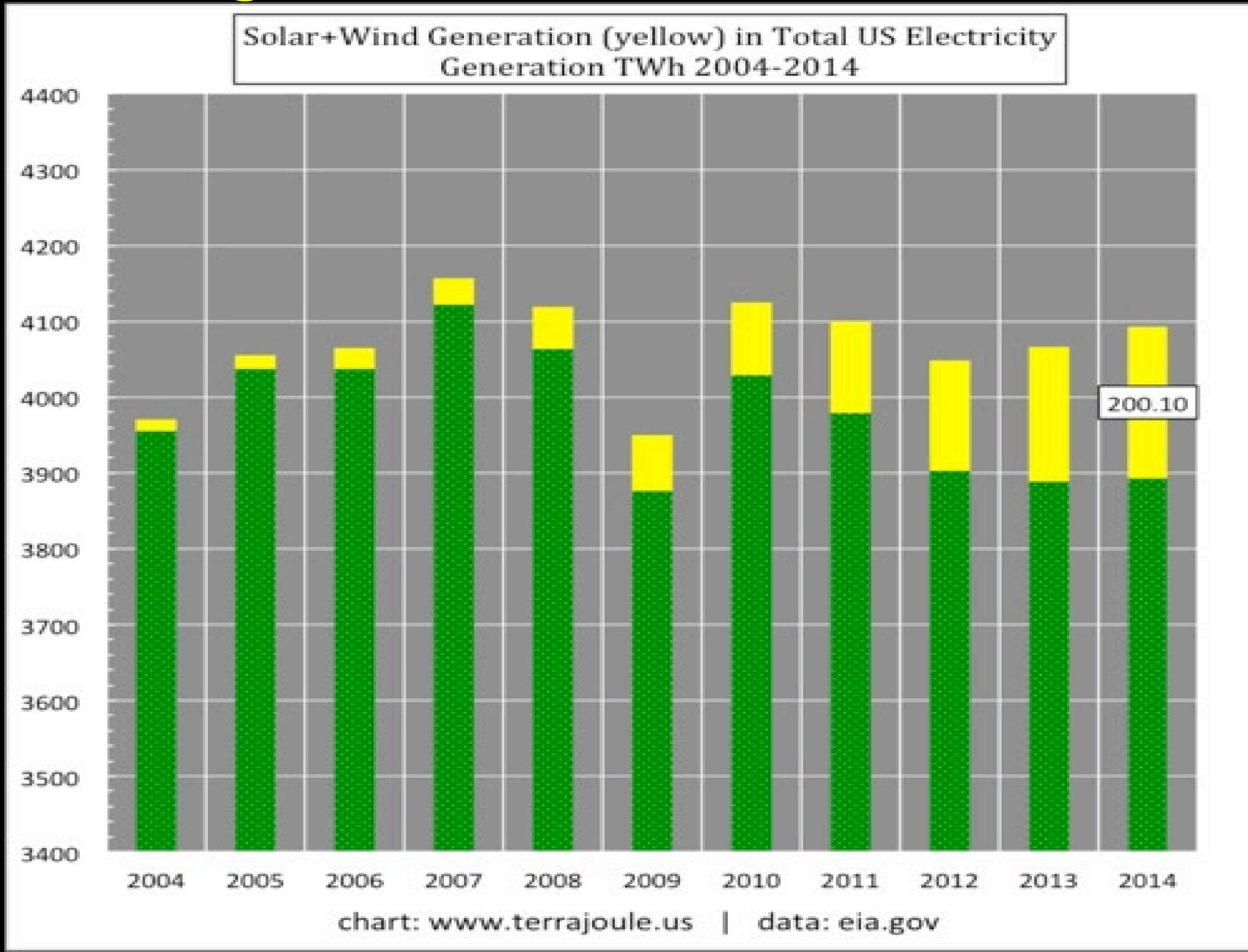


Figure ES-1. NREL PV system cost benchmark summary (inflation adjusted), 2010–2017

Solar and Wind (yellow) are Rising as Percentage of US total Power. 5% in 2014

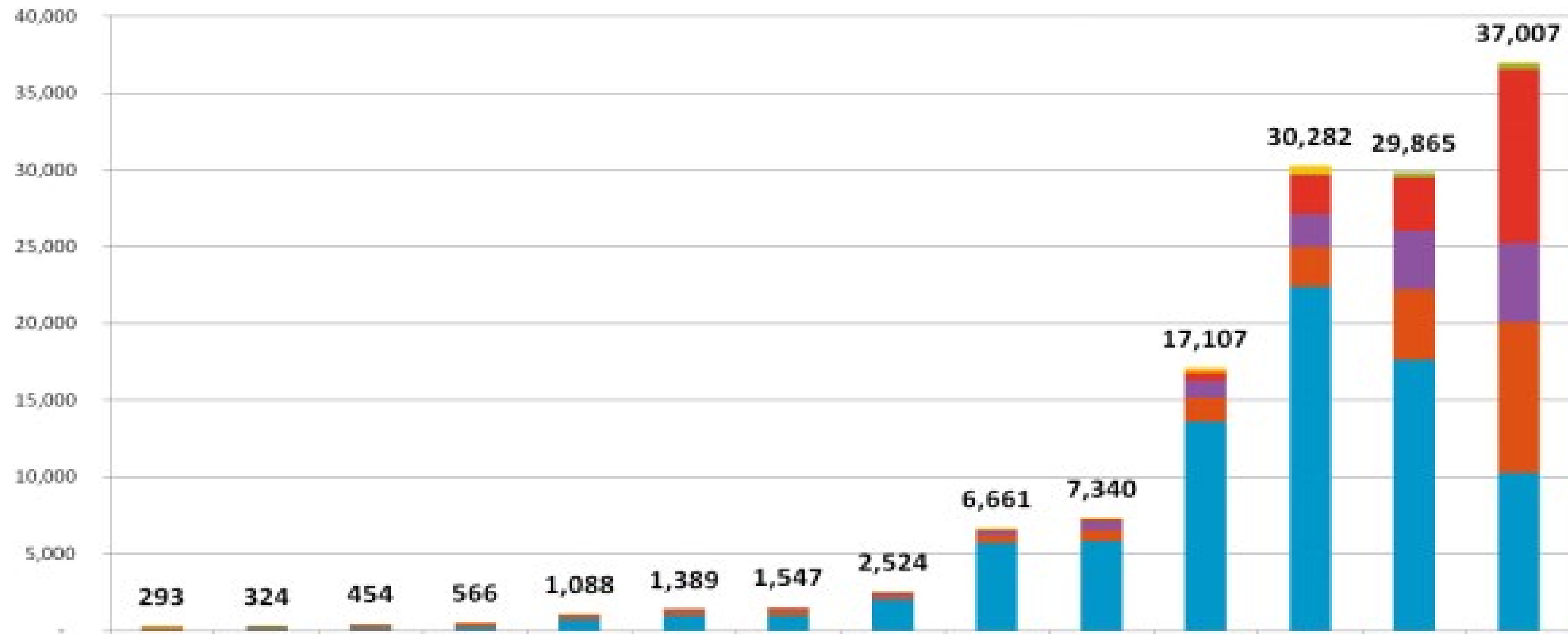


But Govt. Subsidies Have Given a Strong Boost to the Spread of Solar Energy

- Nothing inherently wrong with this, especially given the huge subsidies ongoing for fossil fuels
- The Solar Investment Tax Credit , was scheduled originally to end in 2016 but now extended as part of the appropriations bill voted on at the end of 2015.
- The end of solar subsidies in Europe clearly had a major detrimental impact on spread as we saw a few slides back, and next. Subsidy loss in the U.S. was predicted to cause 80,000 jobs lost here.
- Meanwhile, in the U.S. The Trump administration proposes slashing research funding for renewable energy by 72%, nearly ¾ gone.

With subsidies and govt support, global solar installations growing. But Europe (blue) scaled back subsidies, severely hurting solar deployment, as this graph shows

Evolution of global annual installations 2000-2013 (MW)

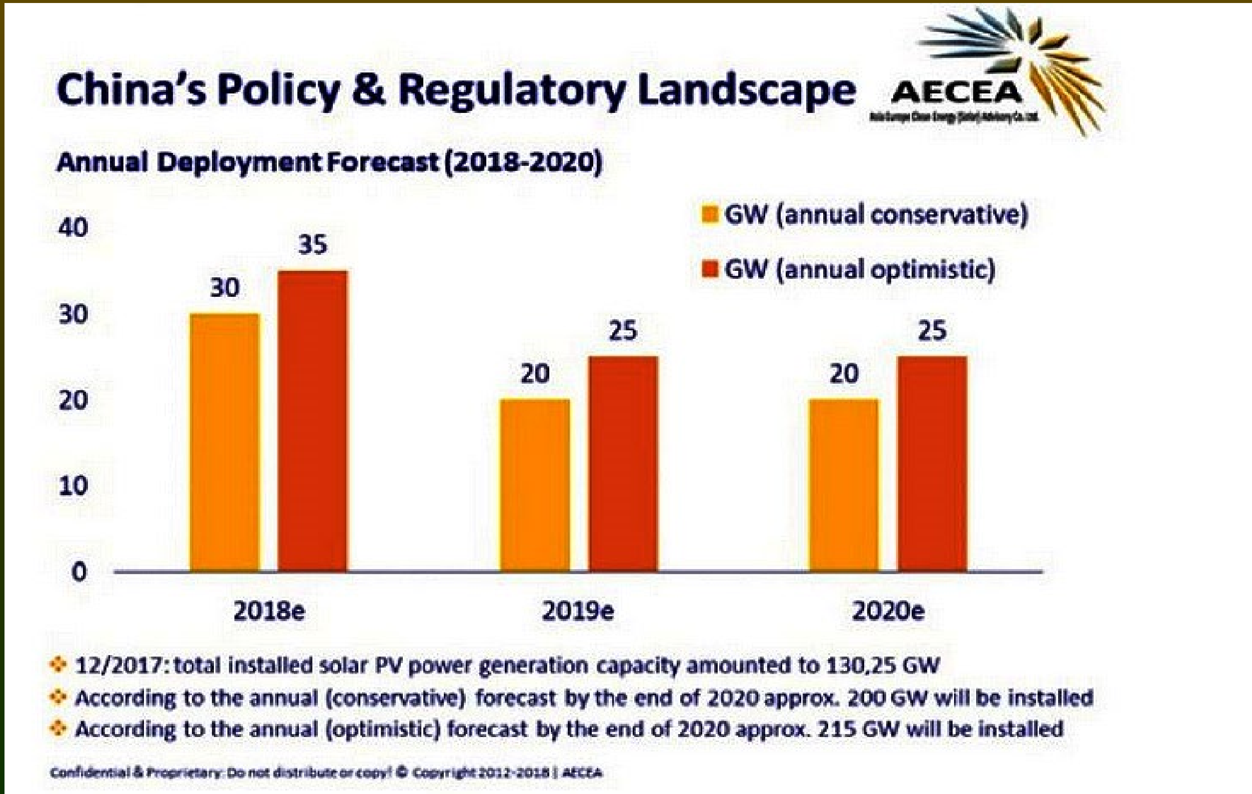


	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
ROW	88	56	80	77	29	10	105	42	76	80	284	508	-	85
MEA	-	-	-	-	1	0	0	1	1	22	46	125	365	383
China	19	5	19	10	10	8	10	20	40	160	500	2,500	3,500	11,300
AMERICA	2	3	30	48	61	82	110	166	306	500	1,082	2,181	3,774	5,153
APAC	126	128	190	230	282	304	325	271	530	745	1,578	2,562	4,646	9,833
Europe	58	133	134	202	705	985	997	2,023	5,708	5,833	13,616	22,407	17,580	10,253
TOTAL	293	324	454	566	1,088	1,389	1,547	2,524	6,661	7,340	17,107	30,282	29,865	37,007

Source: EPIA

As of 2018, China too is strongly cutting back support for Solar PV, as Demand can't justify Supply

- China deployment of solar PV to be 30% lower in '19 and '20 *vs.* '18.

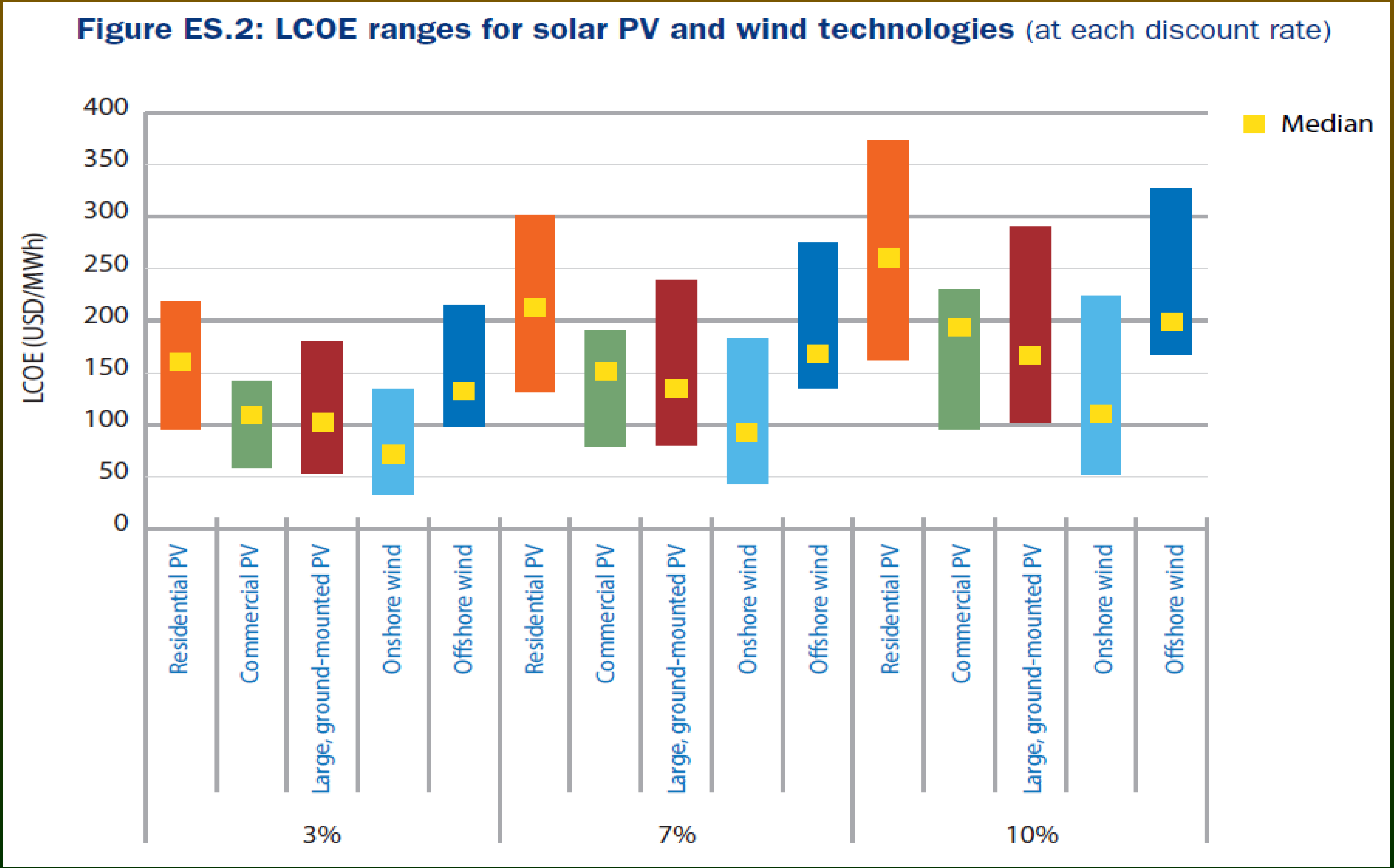


AECEA noted that total cumulative deployments could reach between 200GW to 215GW, targeting only annual deployments in a range 20GW to 25GW over the next two years. Image: AECEA

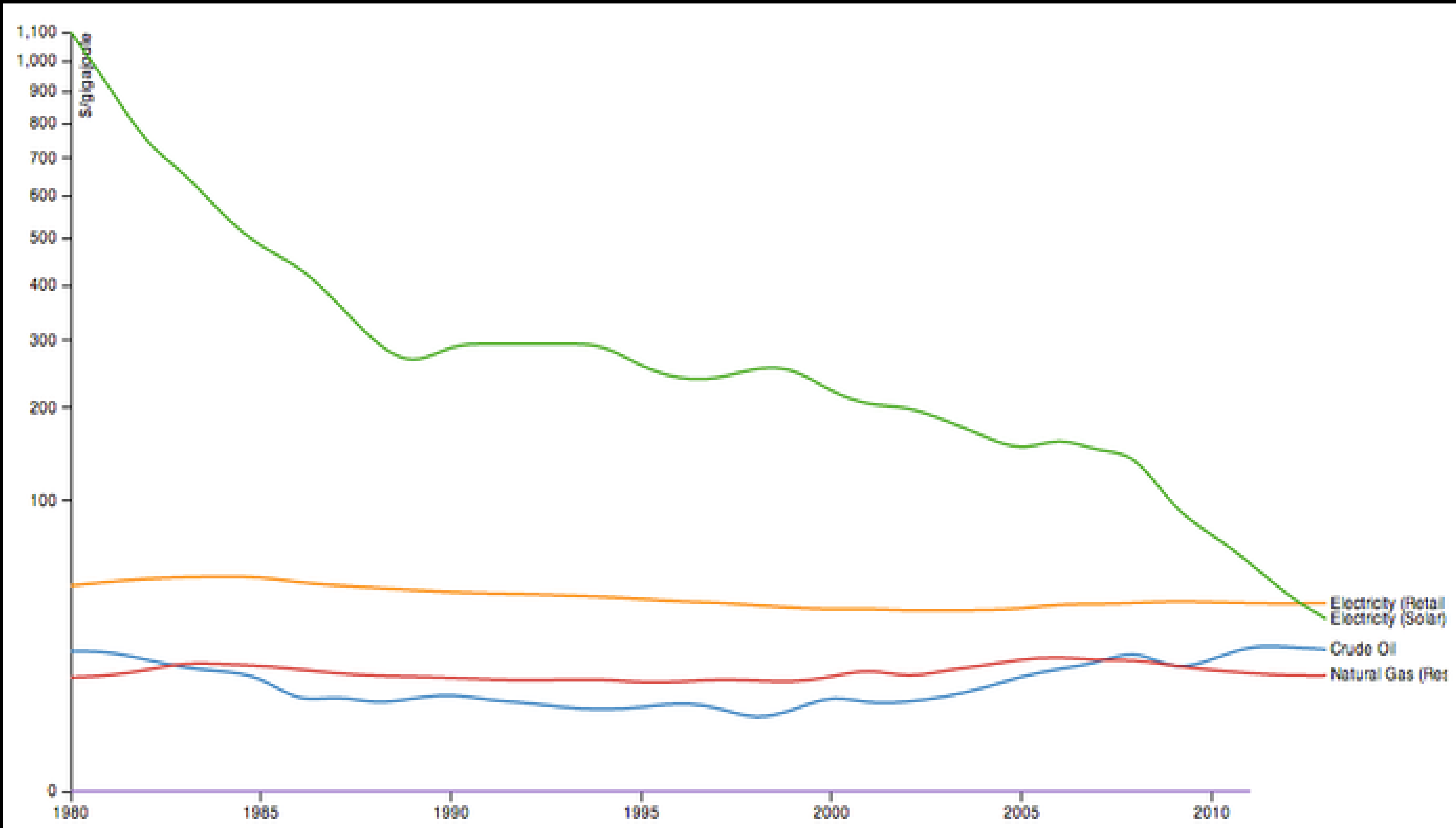
Levelized Cost of Electricity: LCOE

- "**Levelized cost"=LCOE =** The average total cost to build and operate a power-generating asset over its lifetime, divided by the total energy output over that lifetime.
- The LCOE can also be regarded as the minimum cost at which electricity must be sold in order to break-even over the lifetime of the project
- Quite sensitive to uncertain assumptions (the future!), so figures vary widely.

LCOE's: The latest (2020) again from Lazard. Residential PV is expensive



Cost For Solar *vs.* Fossil Fuels: Improving Every Year through 2014.



Projected levelized costs ($/MWh) for power plants entering service in 2020?

- **$48 – Geothermal ($44 with subsidies), but in rare locations**
- $74 -- Land-based Wind
- $75 – Conventional Nat Gas
- $84 -- Hydroelectric
- $95 -- Advanced nuclear (online date 2022, not 2020)
- $100 – Nat Gas with Carbon-capture
- $100 -- Biomass
- $125 -- Solar PV ($114 with subsidies)
- $144 – Coal with Carbon-capture
- $197 -- Off-shore wind
- $240 -- Solar Thermal
- Source: IEA Data on next slide (note however that the IEA has tended to underestimate the cost drops in solar in the past) . The LCOE costs for solar thin-film and crystalline PV now appear to be much less, according to this new (2017) **Yale 360 Climate interview**

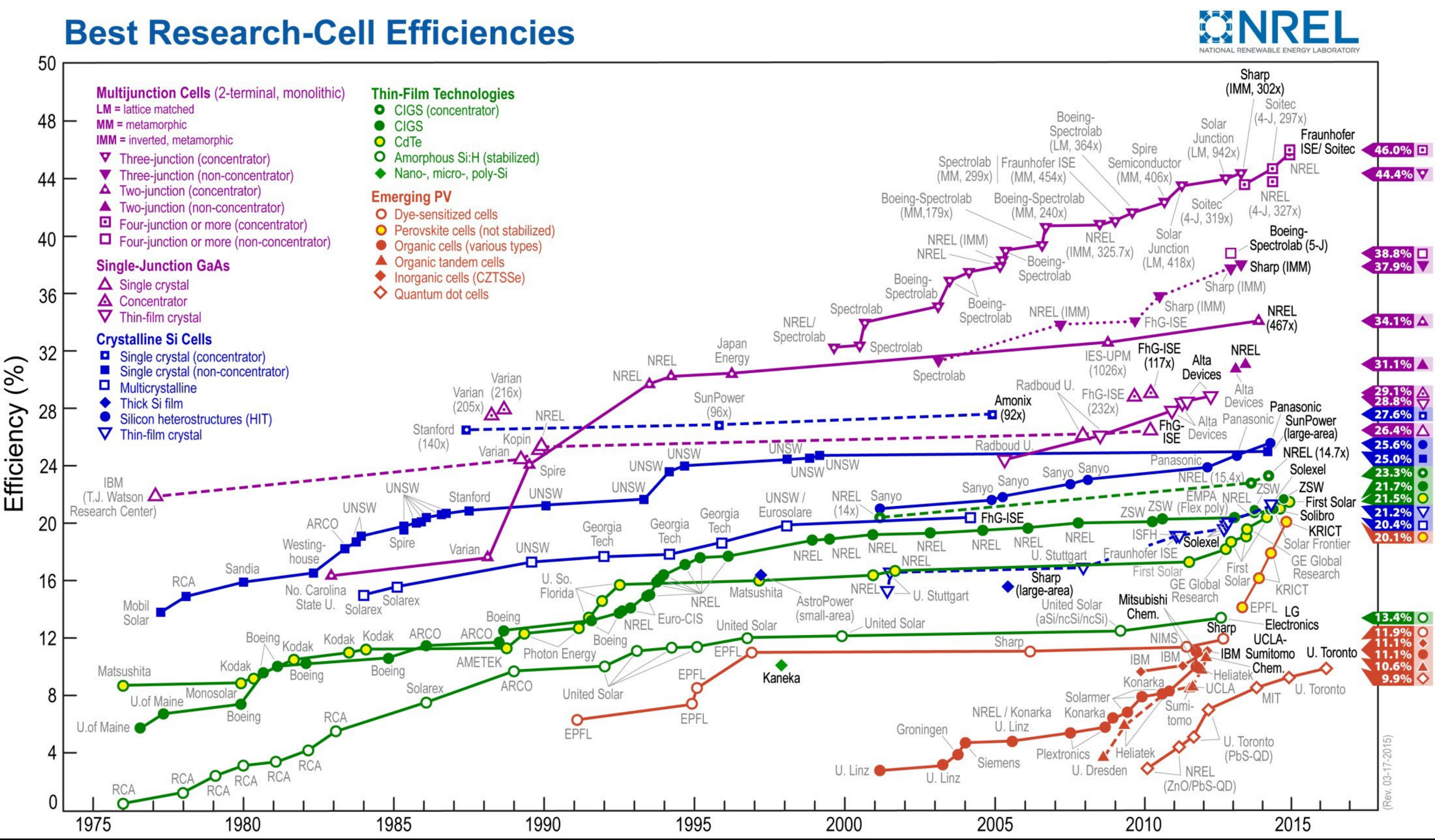
Solar PV costs likely to fall going forward, but not as fast…

- Technology advances have wrung most of the theoretical efficiency out of solar PV already. The theoretical maximum for a single-junction cell is **34%**
- Modern PV cell efficiencies range from the high teens to 44% for the most advance (non-commercial, very expensive) multi-junction cells, very close to the **theoretical ~50% maximum**.
- However, these multi-junction cells cost ~100x more than the cheaper cells, while delivering only ~4x the efficiency. **NOT cost effective to deploy**.

A Recent Advance May Increase Solar Cell Efficiency

- … to closer to the theoretical maximum of 50%, by taking the sunlight fraction which does not currently get absorbed into making electricity, and converting it to shorter wavelength light which does.
- Cost per power is the real determiner, though, so this is not necessarily as encouraging as initially you may think
- Manor *et al.* 2016 described here
- And…

…Unlike computer power and Moore’s Law, Solar’s future efficiency gains will be slower. The dilute nature of incoming sunlight will always limit the energy density available

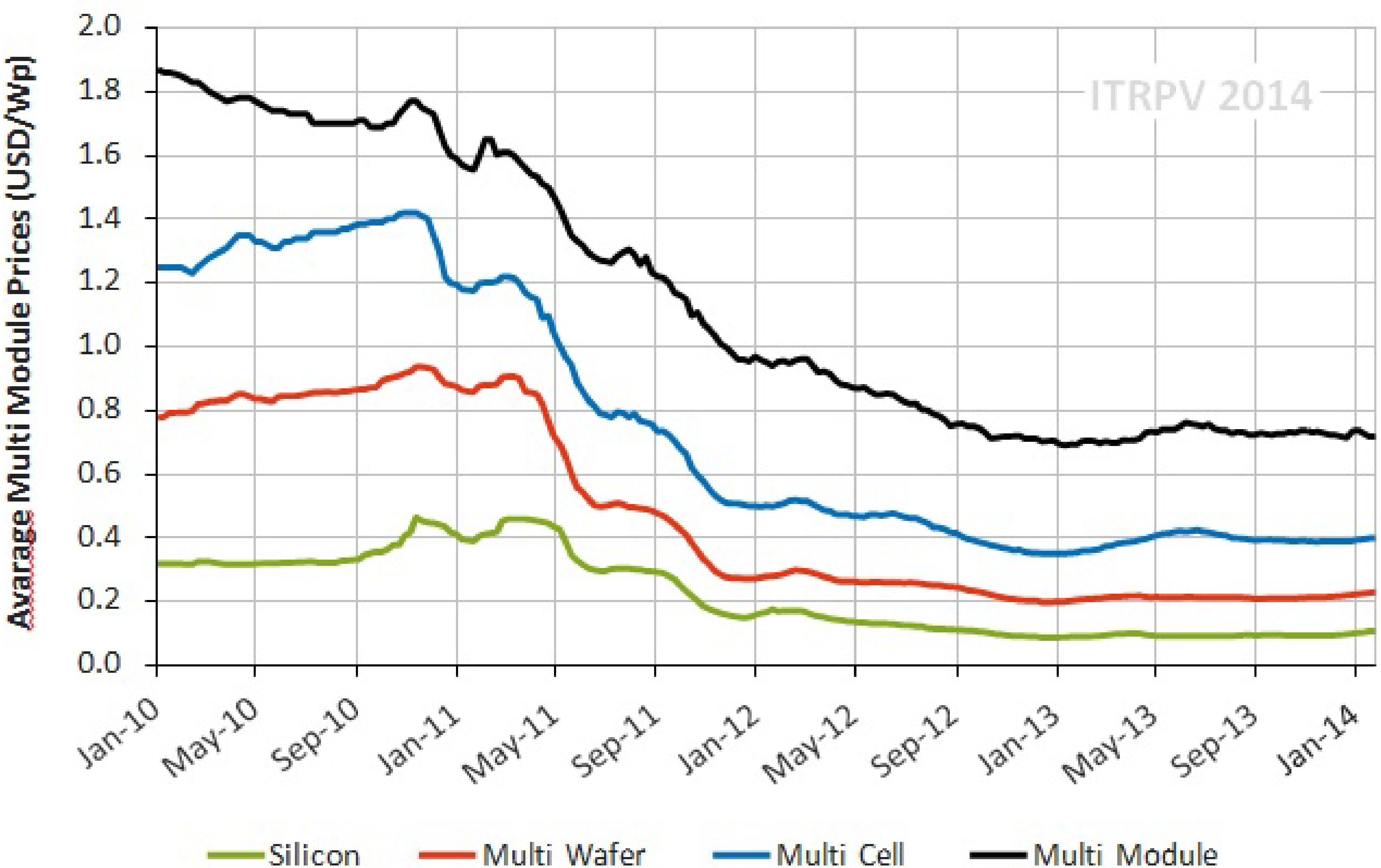


More important for cost…

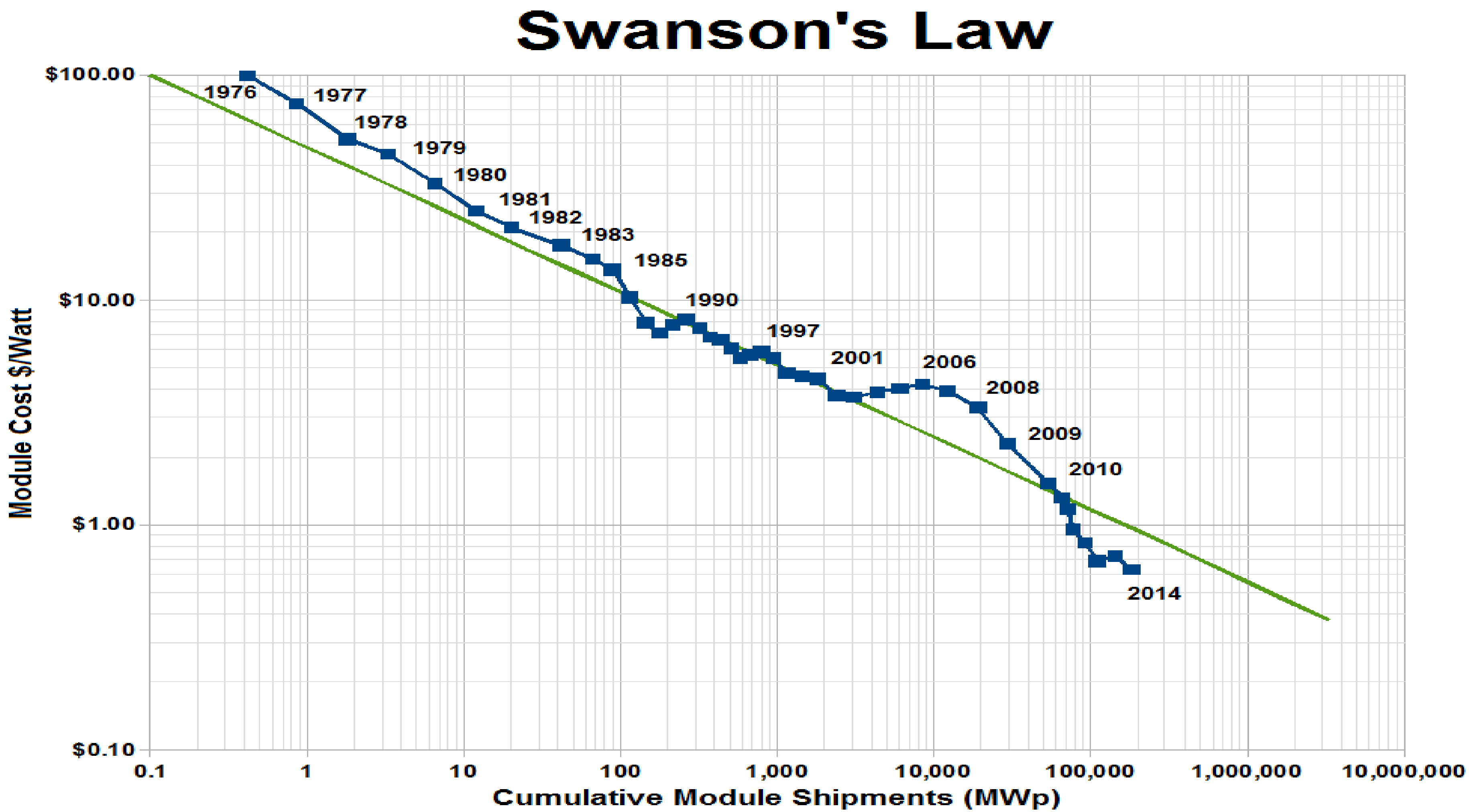
- The technological gains in cell efficiency are mostly already accomplished, as are the gains due to economies of manufacturing scale.
- Solar is already a significant industry, with scaling cost reductions mostly accomplished, especially by the Chinese.
- Gains will likely continue, but be slower.
- BEWARE of promoters who simply extrapolate past curves into the future, ignoring the true, evolving source of future costs (next slides).

Polysilicon Prices – Past Decade. Price spike due to shortage, then a glut, then stable, then declining since 2018

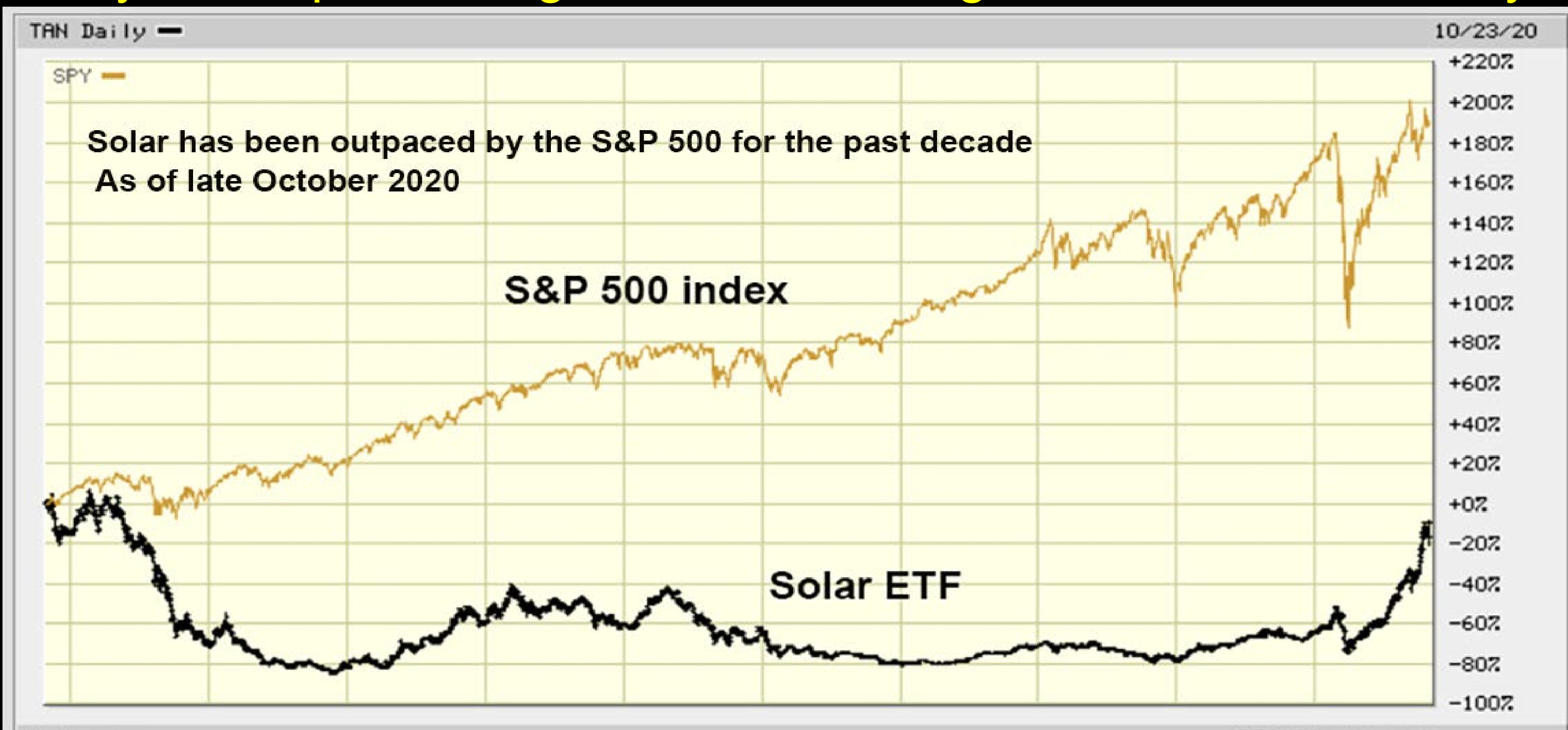
Solar PV Module price declines appear to be episodic. Post-2014 prices dropping again (not shown here)



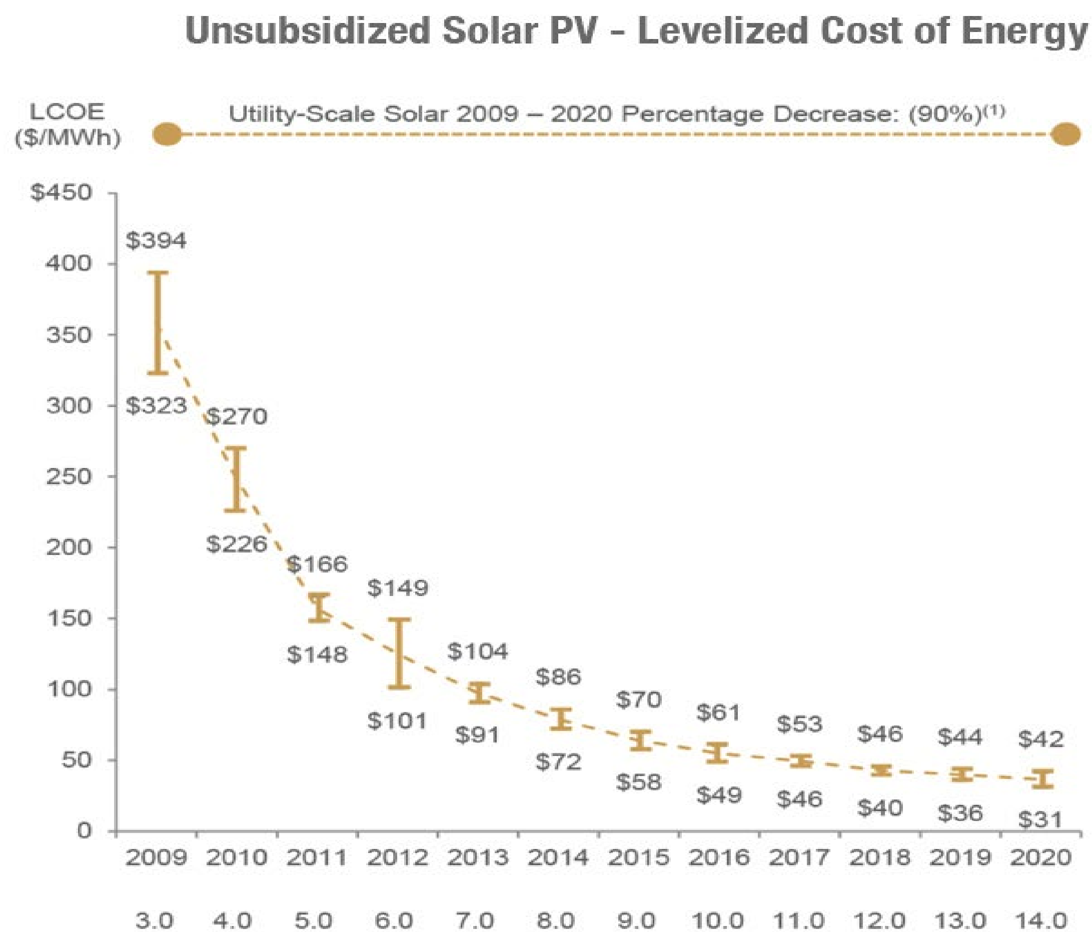
This is also seen in the past decade's deviation from Swanson's Power Law, note the steepening lately – falling module costs are not leading to increased shipments at same rate as earlier, as more of the costs are not in the modules, but other costs which are not falling at nearly that rate…



Another way to see the slowing gains in solar PV cost and efficiency is from the profitability of solar PV companies as reflected in their stock charts. Today's largest solar PV manufacturers: First Solar, Sunpower, JK Solar, Canadian Solar… all peaked in 2008. Below; price chart for **TAN** – the largest solar ETF, a combination of many solar companies. Badly under-performing the S&P 500. Signs of a mature industry



Even Utility-Scale – the most cost-effective, is slowing gains.



Source: Lazard Levelized Cost of Energy - October 2020

Most remaining solar PV costs…

- … are in labor and materials, electronic components like inverters, and other segments which have already matured and are not plummeting in cost as fast.
- For the panels alone, residential solar PV panels are about $1.00/watt, from a 2018 google search. But the total installed cost is about $4/watt, or 4 times higher
- These facts argue that the large drops in solar costs have already largely occurred, and future drops will be more incremental

In fact, all hardware, including the silicon cells, is already less than half the total cost of solar installations

- **Permits, labor, marketing, profit, etc. are 56% as of 2014**
- And even the "Hardware" includes items which are already mature technology; supporting structures, wiring, metal fab…
- And photo-voltaic cell chips, where rapid hi-tech advance was possible, increasingly are only a minor part of the costs.
- Add in, that most theoretical efficiencies are already accomplished, and the conclusion is clear: Solar costs are not going to follow "Moore's Law" like silicon computer speed has. But what about adoption rates?
- **The one positive** is that a legitimate case can be made for a "tipping point" here, where the costs for new installation, with all disadvantages included, is cheaper than alternatives. Then adoption rates can spike upward – The S Curve

Tech-heavy module prices get the media splash, but the cost-heavy “soft” portion is hardly improving at all, and is now most of the total costs

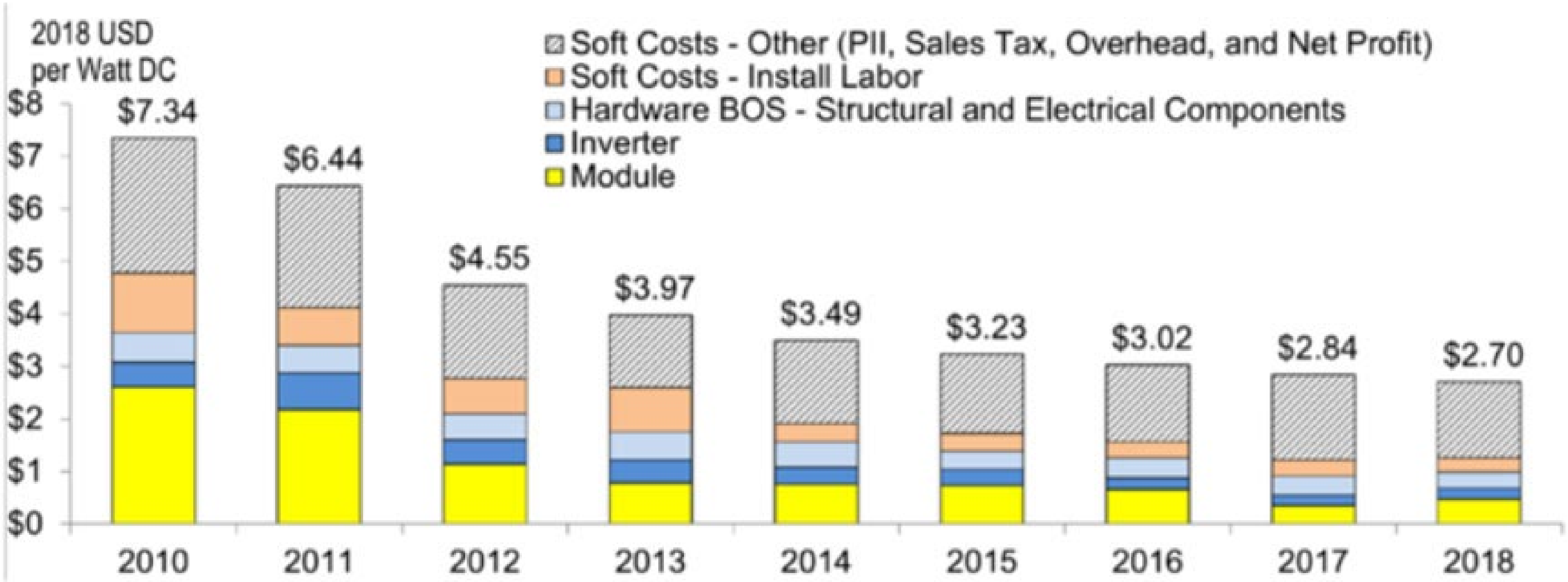


Figure 17. NREL residential PV system cost benchmark summary (inflation adjusted), 2010–2018

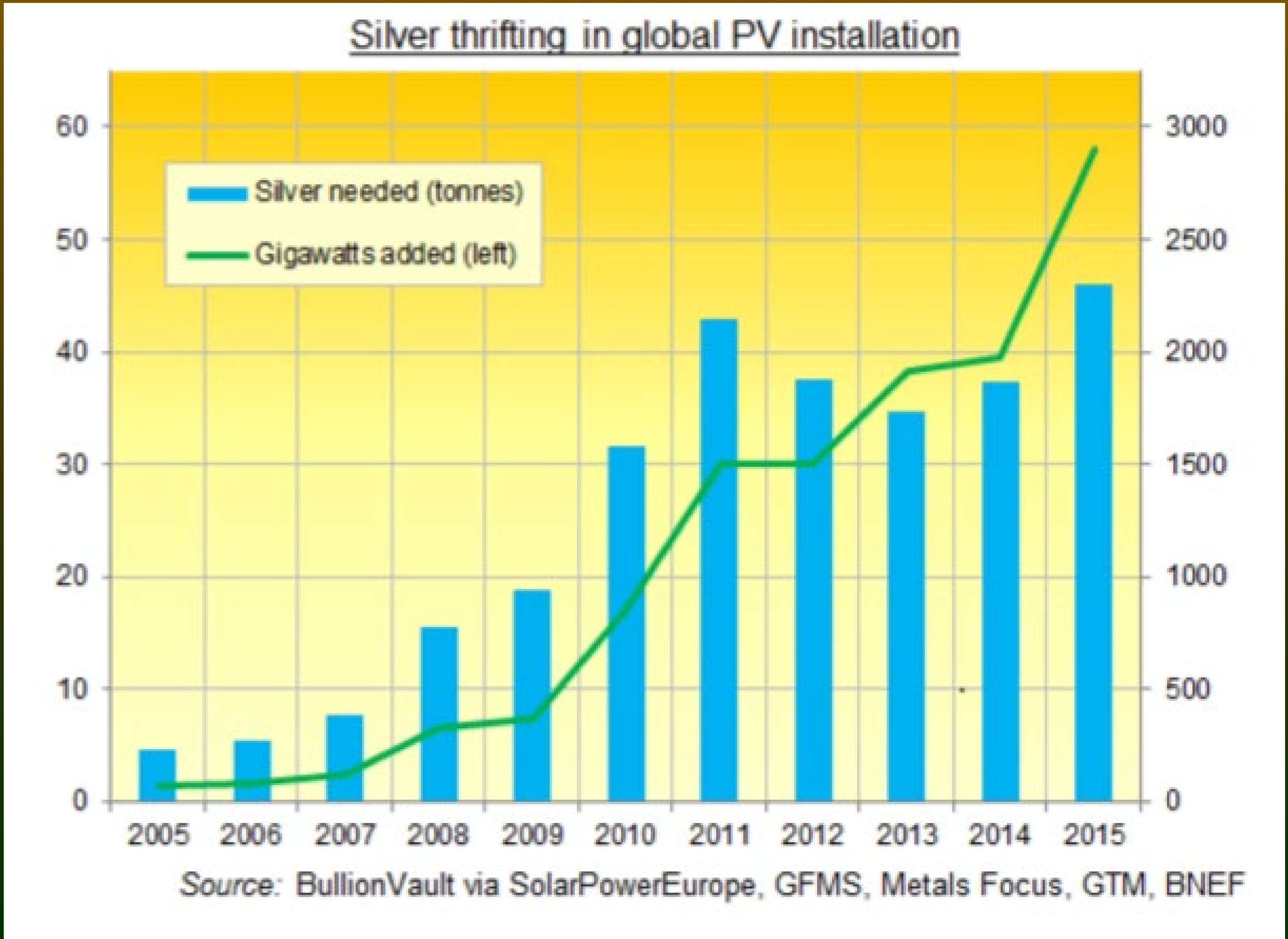
But Even the Very Optimistic SolarCellCentral.com Acknowledges

- *Having "More than 20% (of our energy mix) of solar and wind would require major investments in transmission lines. Not only are transmission lines expensive, but they are hard to permit because of the NIMBY (not-in-my-back-yard) factor. Transmission lines also require three to four years to build, versus solar or wind plants which can be easily built in two years. If, by 2040, 20% of our electricity comes from solar and wind, almost everyone will be happy with the situation."*
- **Everyone - except Planet Earth and Future Generations. It's just not fast enough.**

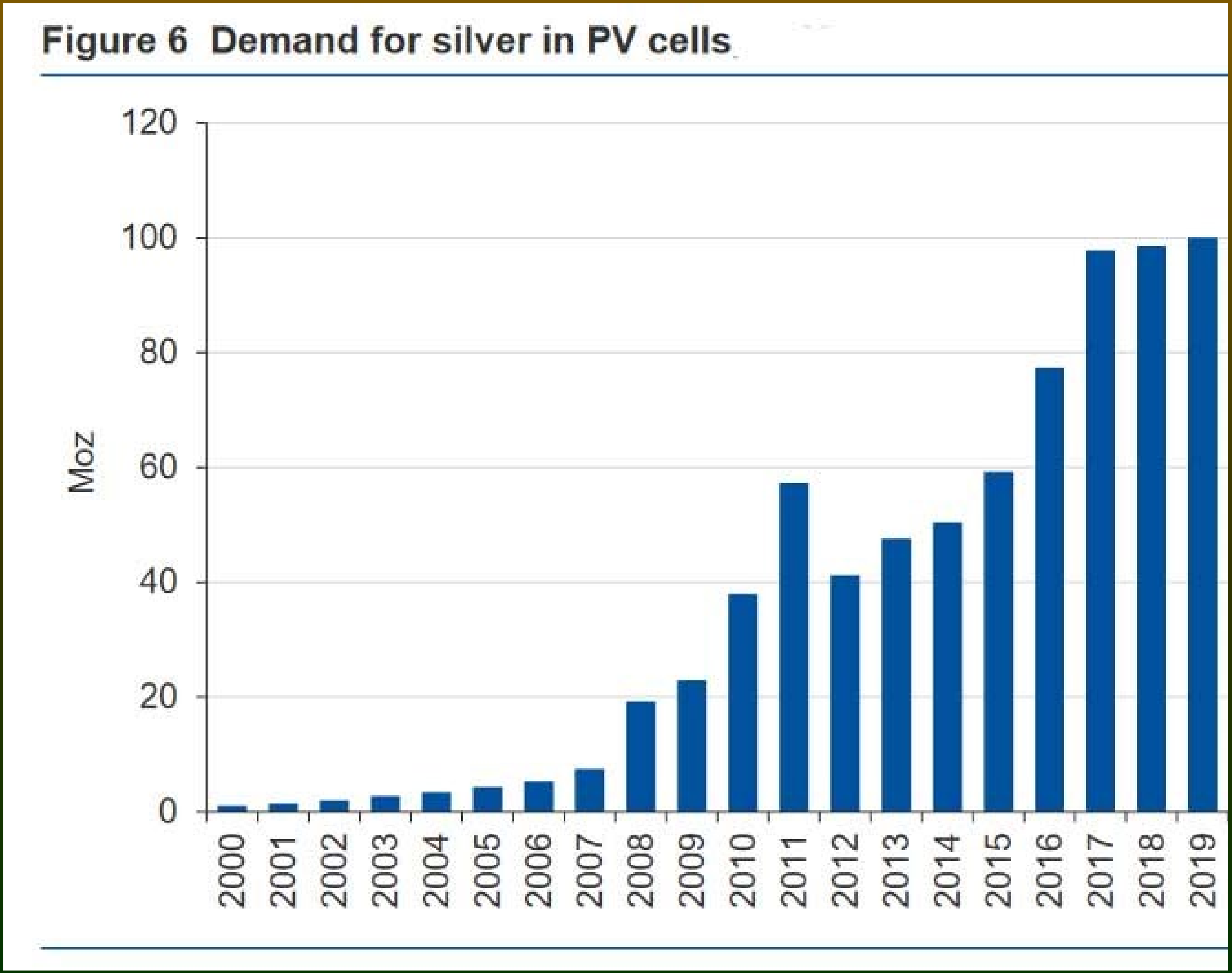
There's Another Problem: Available Silver

- As of 2016, solar panels (1.8 square meters) require 20g of silver.
- That's 11.1 tons of silver for 1 square km of solar PV panels.
- **In order to power the world with solar PV panels, it would take 5.62 million tons of silver.**
- **If we instead assume silver per GW of power will drop to only ¼ of today's), that's still 1.4 million tons of silver needed.**
- Today's panels already use far less than they did 10 years ago, motivated by high silver cost. So this hypothetical drop may not be easy.

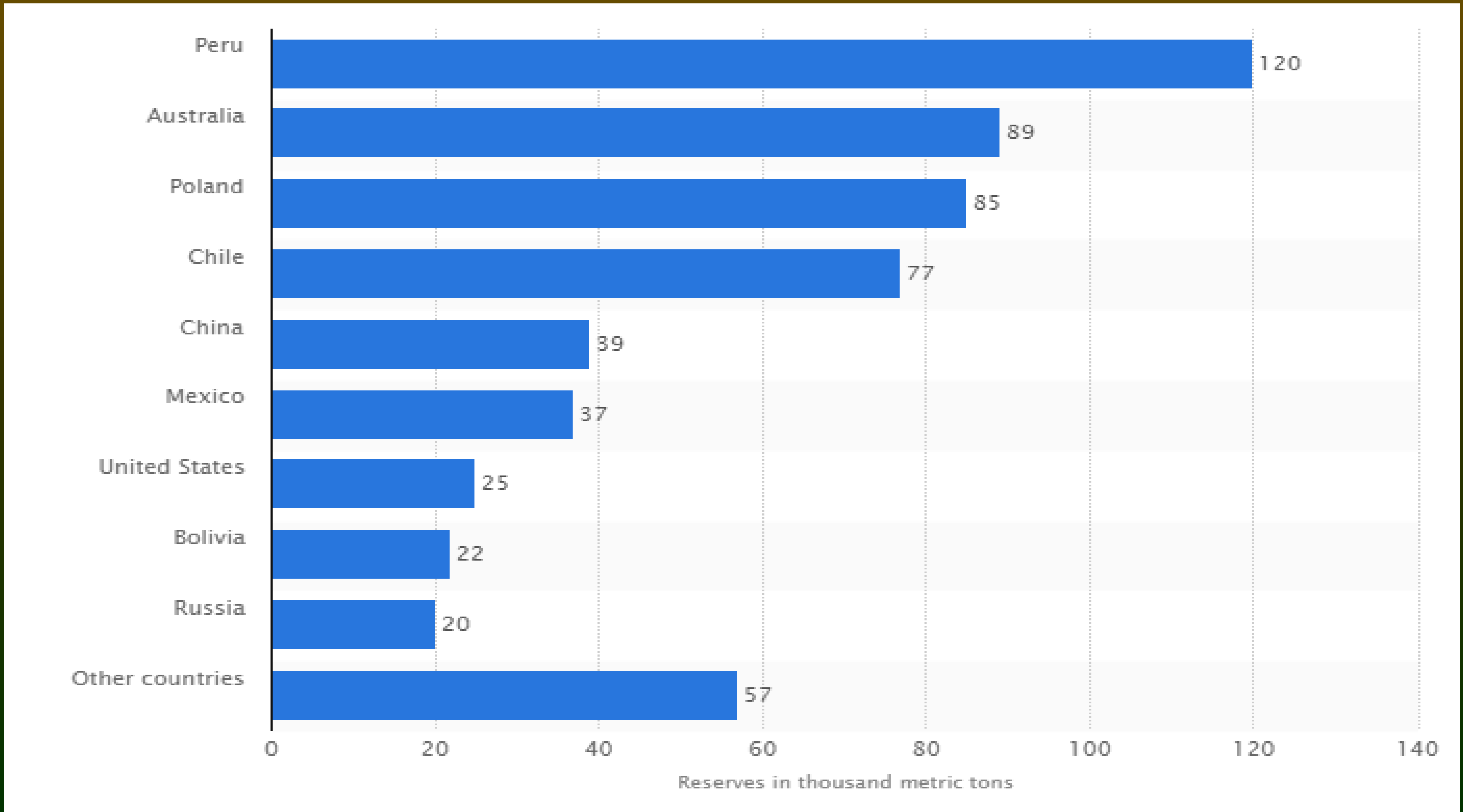
While silver needed per unit of power is falling at 5%/yr, the total silver required keeps rising as solar deployment continues



2019 Update: Demand Still Rising



What's required is more than 2x the estimated silver reserves on Earth. While above-ground stores (*e.g.* old coins) can be put to use here, only at sufficiently higher prices and on only a small fraction of it.



- Solar panels lose efficiency at a rate of 0.2% to 1% per year, requiring ongoing new silver even at constant global solar power use (even with recycling).
- Other industrial processes require silver, which would then not be available for solar panels.
- Merely adding to energy needs at standard global 2% growth rates would consume almost double the current rate of silver mining today.
- **As of 2020, silver content has been sharply reduced in panels, due to cost. Yet silver demand still rising.**

Can’t we just replace silver with aluminum or copper, in solar PV panels?

- Some makers are doing this, for example with copper, but copper prices are rising rapidly too.
- Silver has the highest reflectivity and the highest conductivity of any available metal, so price compromises will also become panel efficiency compromises.
- Lower efficiency means more solar panels to produce the same power. Substitution is not necessarily a killer, but is a problem.

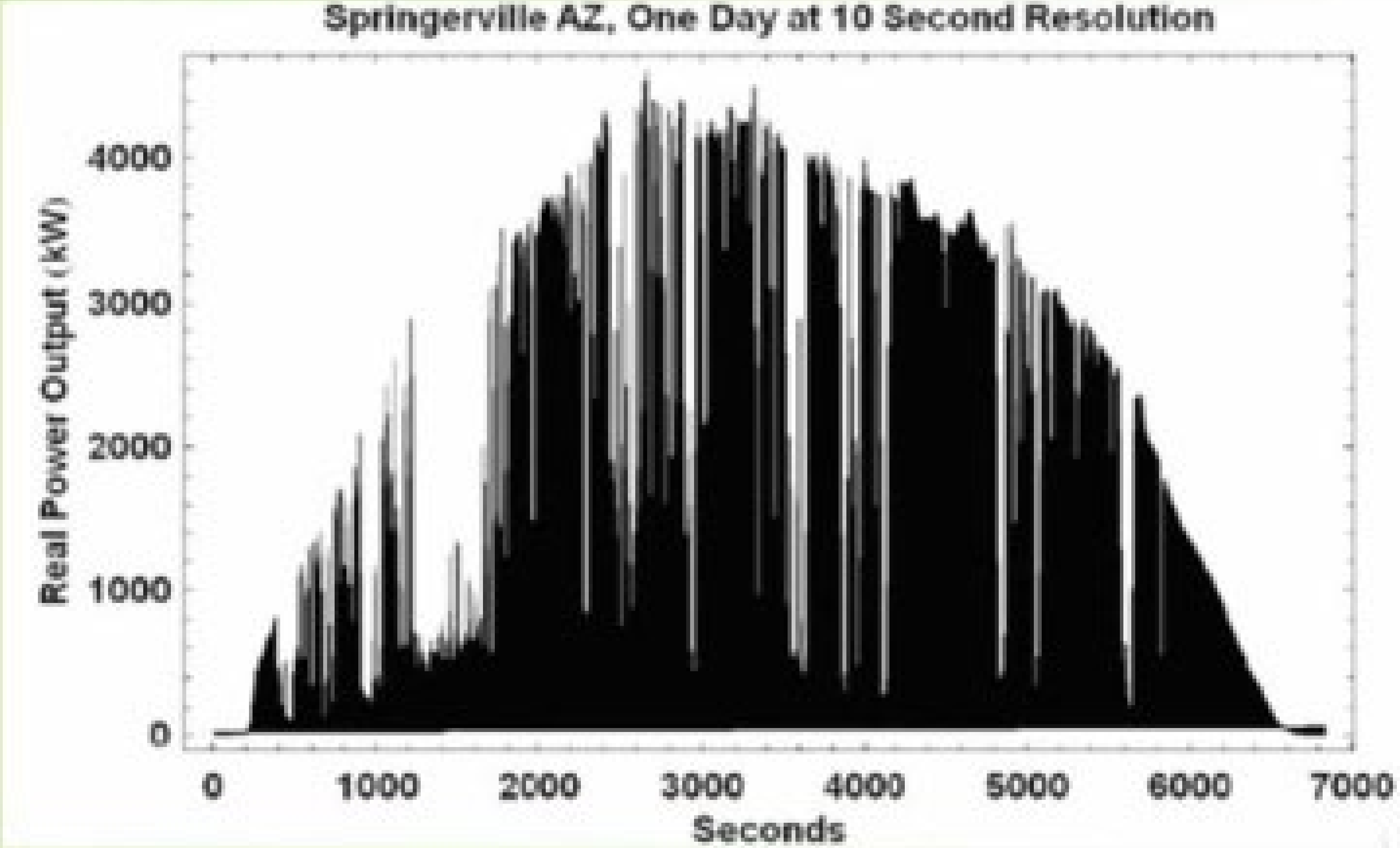
The Political/National Boundary Problem with Solar…

- For a given country - when it's after dark, it's dark for the whole country (although less so for one country: Russia).
- Having distribution lines which must cross national and even continental boundaries to connect sunny places to dark places is very unlikely to be politically possible, especially in the kind of fox-hole bunker'd world into which we've been heading.
- Need much better energy storage methods.

The Inconsistent Sun

- PV Power generation is at the mercy of weather, and completely unavailable at night
- Power needs are greater in cold climates, but those are also where the sun is weakest
- Typical duty cycle means a “1 GW solar plant” is actually only able to deliver ~20% of that 1 GW, when averaged over a year which includes night time, weather, cleaning, etc.
- Said another way 20% is the “capacity factor” for solar PV power

Intermittent Solar



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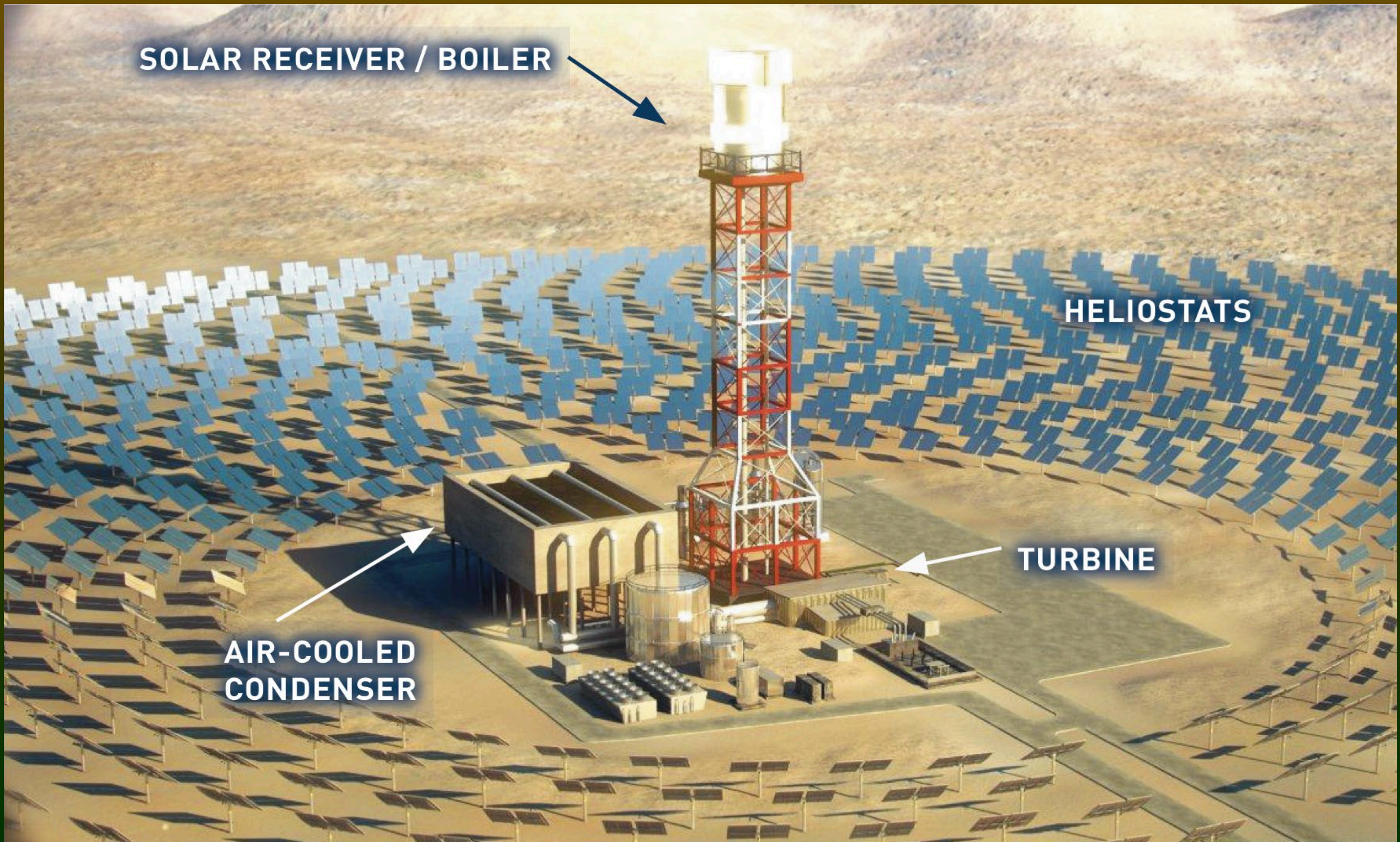
Requires better storage technology to be feasible. But progress is happening

- **But it requires a very different grid based on the highly variable and unpredictable outputs of solar (and wind). Expensive to re-build such infrastructure**
- Still, even given the existing power grid, rooftop solar can be a no-brainer for feeding energy into the grid and lowering carbon footprint and lowering personal utility bills. And empowers individuals, and we all feel better when we feel “in control”, in all areas of life.

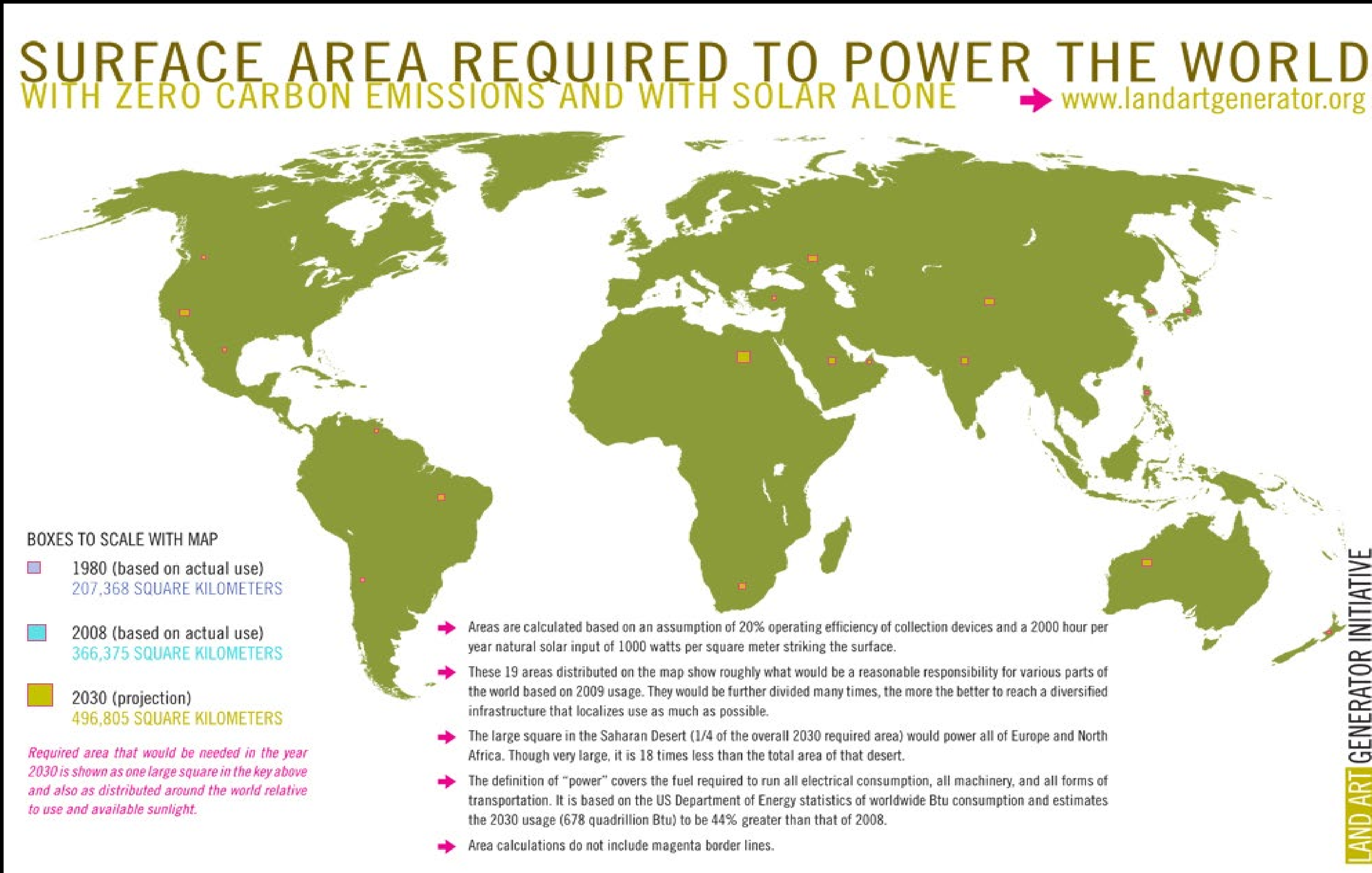
Always On Solar: Using solar power to heat a molten salt solution to far above the boiling point of water, store it in a well-insulated lining, and use it to boil water to drive power turbines after the sun has set

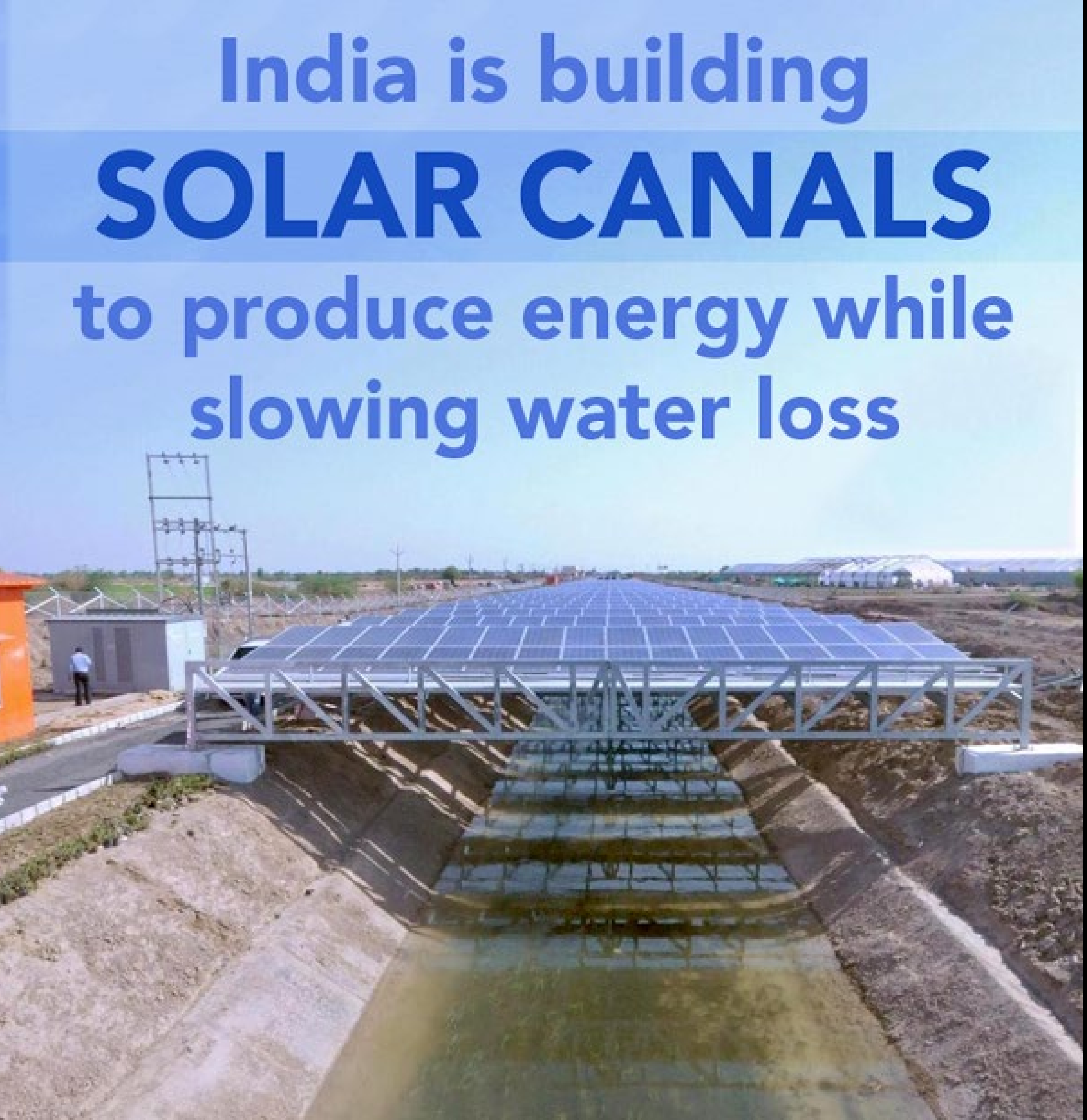


But Solar Thermal Can't Compete

- Solar PV prices dropping faster than solar thermal's.
- Result: the big expensive solar thermal plant built on the CA/NV border is now bankrupt.

Going 100% Solar PV: Area Required Today is “Small”. A PV panel area the Size of Spain or 497,000 sq km (2015) in a sunny low latitude location, could supply the World today, but need 40% more by 2030 (Dept of Energy). Larger for the solar infrastructure surrounding it. – an area the size of Kentucky just to power the U.S.





Solar panels covering canals. More surface area put to good use, cutting evaporation as well

Utility-Scale Solar Farms

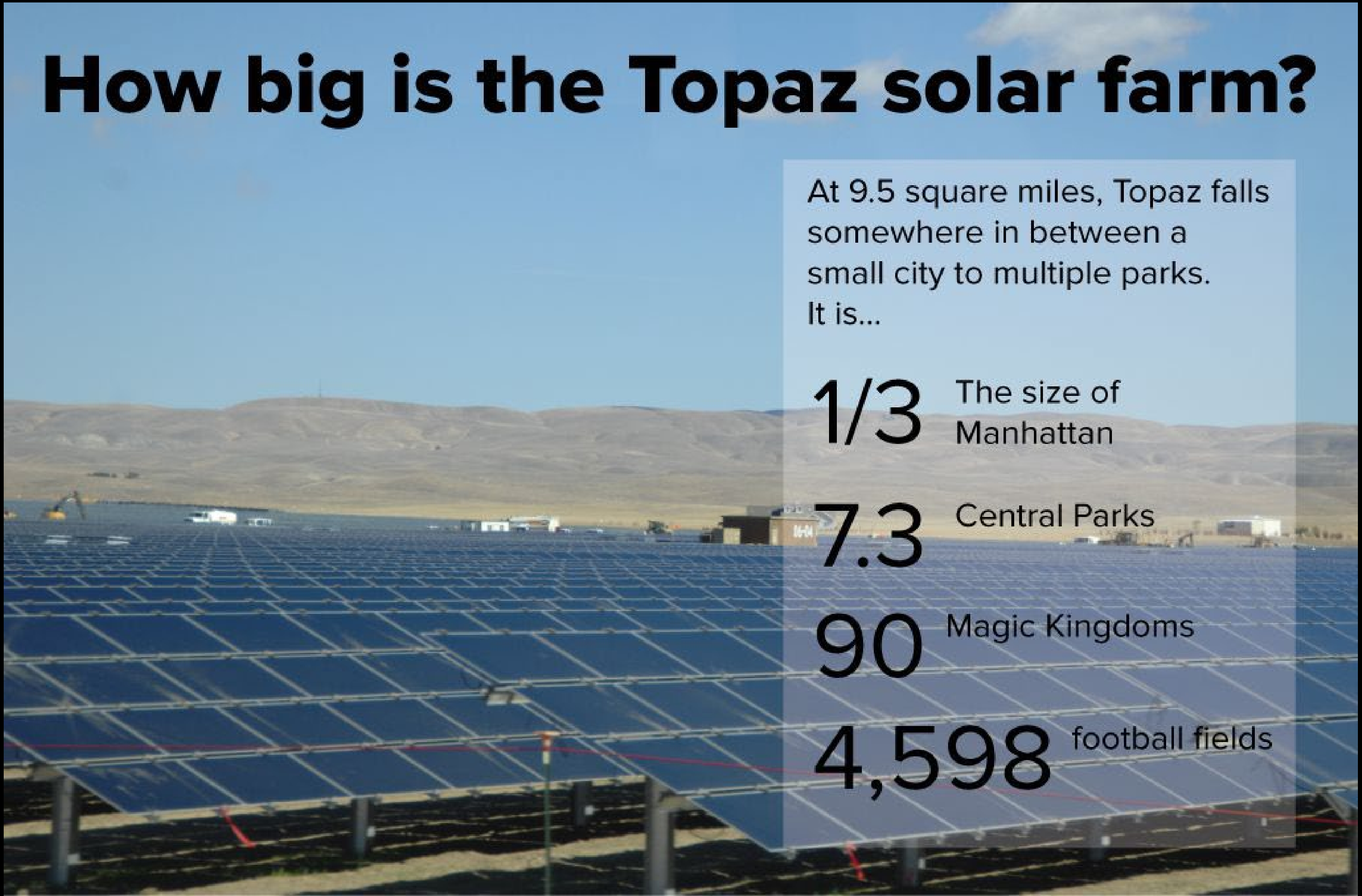
Is Utility-Scale the Way to Go?

- Utilities are trying to take advantage of subsidies and cheap desert land leases, and also keep control of the electric power supply by building vast solar farms.
- But these impact sensitive habitat, are ugly, and require expensive transmission line losses compared to local solar.
- Local (rooftop) solar seems far more attractive, but it is less efficient (~twice the cost per kwh) as it needs its own power conditioners, and… not near enough rooftop area to power the world

Utility-Scale Solar Farms: Shadowing Local Flora

- This is a problem with current massive solar farms… they are tough on the local ecology
- There is research at UC Santa Cruz on solar cells which are transparent at wavelengths needed by plants, and placed much higher, minimizing local ecological damage
- See local news

Topaz Solar Farm: in Carrizo Plain, home to the last large tract of native California Great Valley ecosystems and endangered species.



Here's a visual from 2023 on the most obvious footprint of solar PV on Nature

- **The new power plant save 2.4 million tons of atmospheric emissions of CO2-equivalent greenhouse gases annually.**
- ***This is less than 1% of annual emissions by the energy sector alone, of the UAE.***

Combining Utility Solar + Wind

- Home-based wind systems not as efficient as utility-scale wind because wind velocities are much lower near ground level. Although perhaps is still worth doing in some places (like nearby Salinas Valley?).

Solar Roadways and Bikeways?

Heavily criticized as too expensive and fragile

- …when first announced, the company SolaRoads was hoping for some success in their testing of a solar bikeway. The road/bike way has solar panels protected by thick shatter-proof glass.
- Tempting; It's a lot of ground area otherwise wasted, but it's a tough environment and ultimately this was discontinued.
- The power was far too expensive, and durability failed.

Solar Windows

- In places where tinted windows are desired, why not use the rejected sunlight for power, just like solar PV's?
- Los Alamos labs has been having some success in this direction (description and links here)

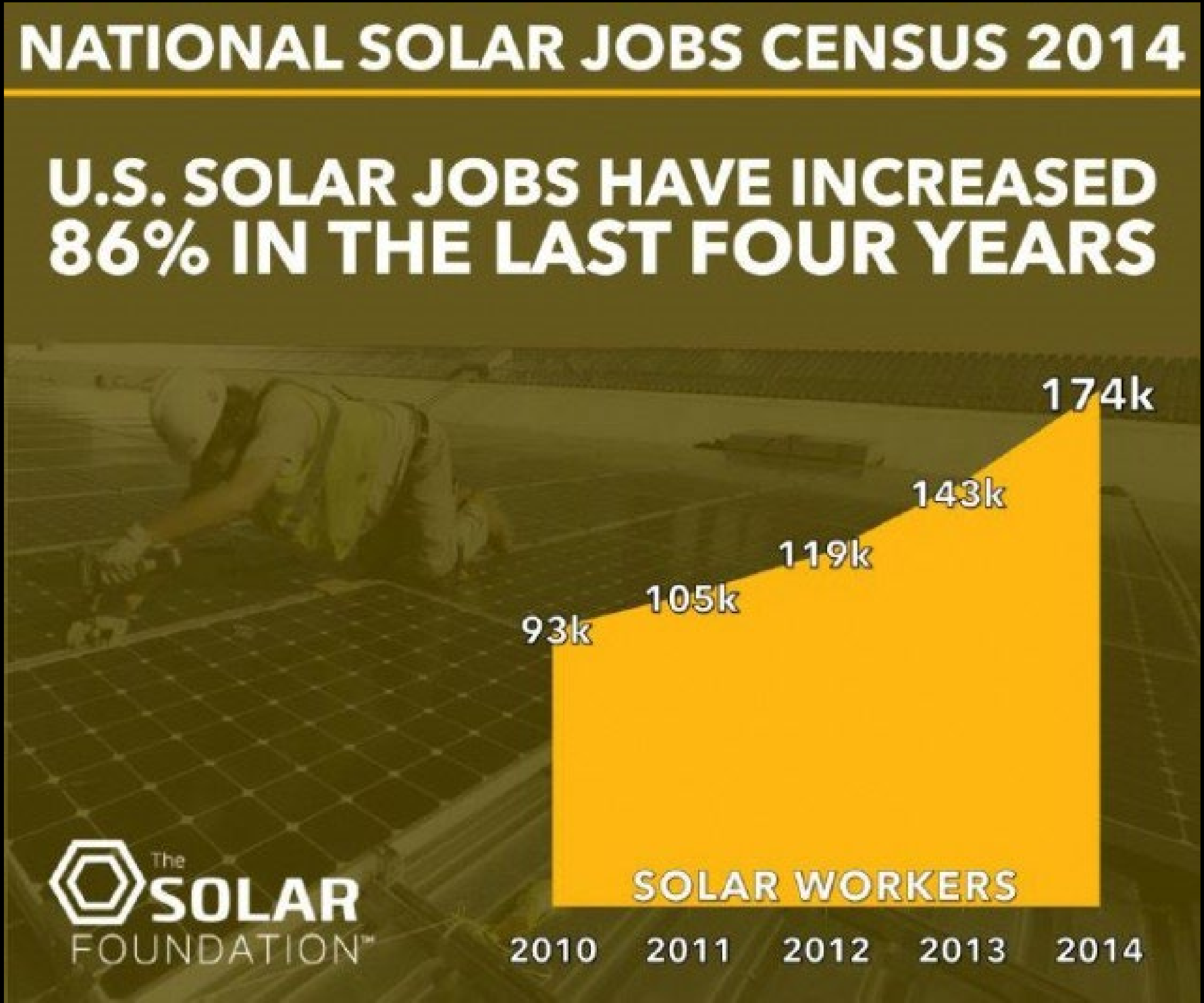
Solar Manufacture: Carbon Cost

- 2008 study found 280 kwh input energy is needed to produce 1 square meter of solar panel
- Some more recent advertising claims are of 1.4 years to pay back carbon footprint.
- 2-3 years payback is more the average seen in 2015 literature.
- ~25 year life of a panel (but remember solar is so new that no modern panel has, or can be, observed for so long. Others argue they may last longer, or shorter), so roughly 10x carbon value in solar *vs.* fossil fuel
- 280 kwh/m^2 means about $2.2x10^{14}$ kwh needed to make enough solar panels to power the world

1 Kwh of Energy, generated by a mix of fossil fuels, generates about 1 kg = 2.2 lb of CO_2

- So that's 2.2 x 2.2 x 10^{14} lb of CO_2 to make enough solar panels to power the Earth
- That's 2.4 x 10^{11} tons of CO_2
- That's 240 gigatons of CO_2 , or about 7 years of total current global emissions of CO_2 from all sources. That's a lot.
- And likely a significant underestimate - you'd have to first build the infrastructure to make all those factories before powering them. And the supporting industry (inverters, etc) and the power to run them as well.

Jobs in Solar are Rising



California has been aggressively deploying Solar for power

- And as of mid ‘17, now half of California’s power comes from renewables, especially solar.
- This is encouraging. What would be much more encouraging, is to see perfectly well-functioning fossil fuel power sources being de-commissioned, *vs.* merely new power being renewables

"Revenge of the Duck!"

- Variable and semi-unpredictable output from solar and wind translate into high costs once they make up more than 20% of the power generation, in today's grid.
- The low-hanging fruit of initial deployment of solar and wind… that fruit's been pretty much picked, especially for solar-friendly places like California and southern Europe

The Duck Curve – Demand *vs.* Supply of Power During the Day. Cost inefficiency rises with increasing adoption of solar and wind

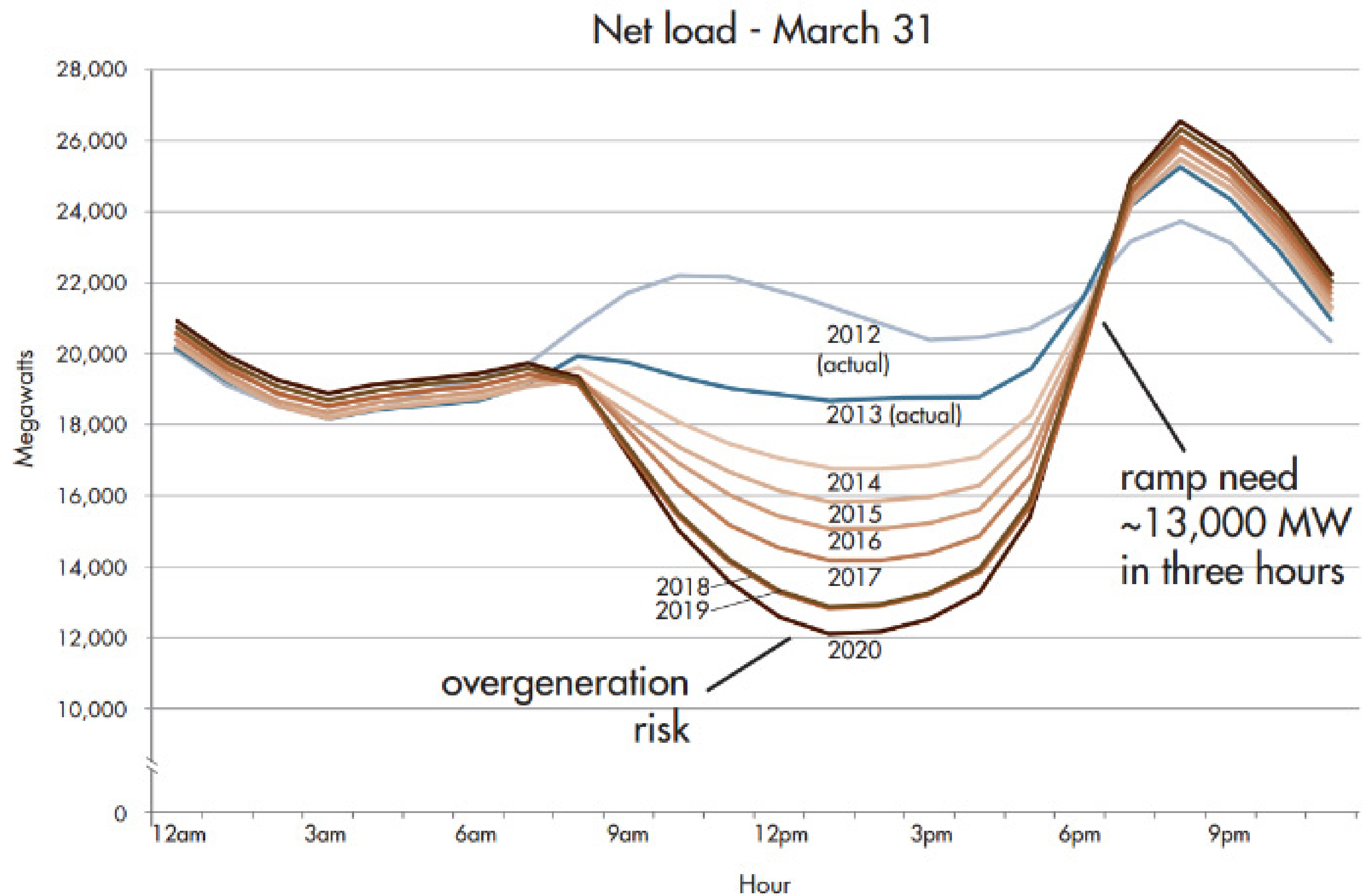


Figure 1. The CAISO duck chart

Source: CAISO 2013

Investing in 22% added capacity in solar plus wind (equally), yields only a 9% reduction in base capacity needed, in this typical optimistic example from sunny California

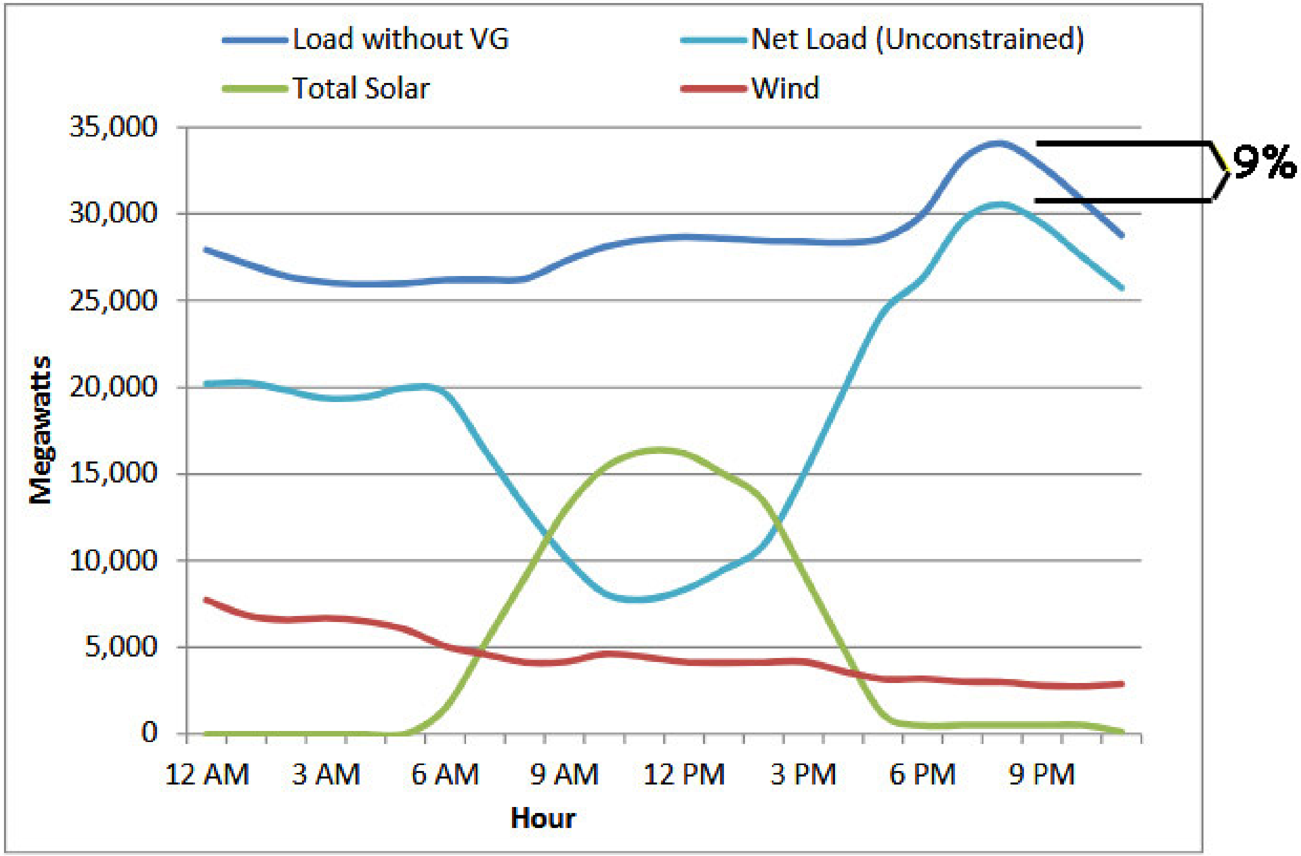


Figure 7. Load, solar, and wind profiles for California on March 29 in a scenario with 11% annual wind and 11% annual solar assuming no curtailment

The more renewables (RPS) we add, the more of its power must be wasted ("curtailed") to avoid danger to the grid and its users, especially costly for the marginal (*i.e.* newly added) renewables being costed out (National Renewable Energy Labs 2016)

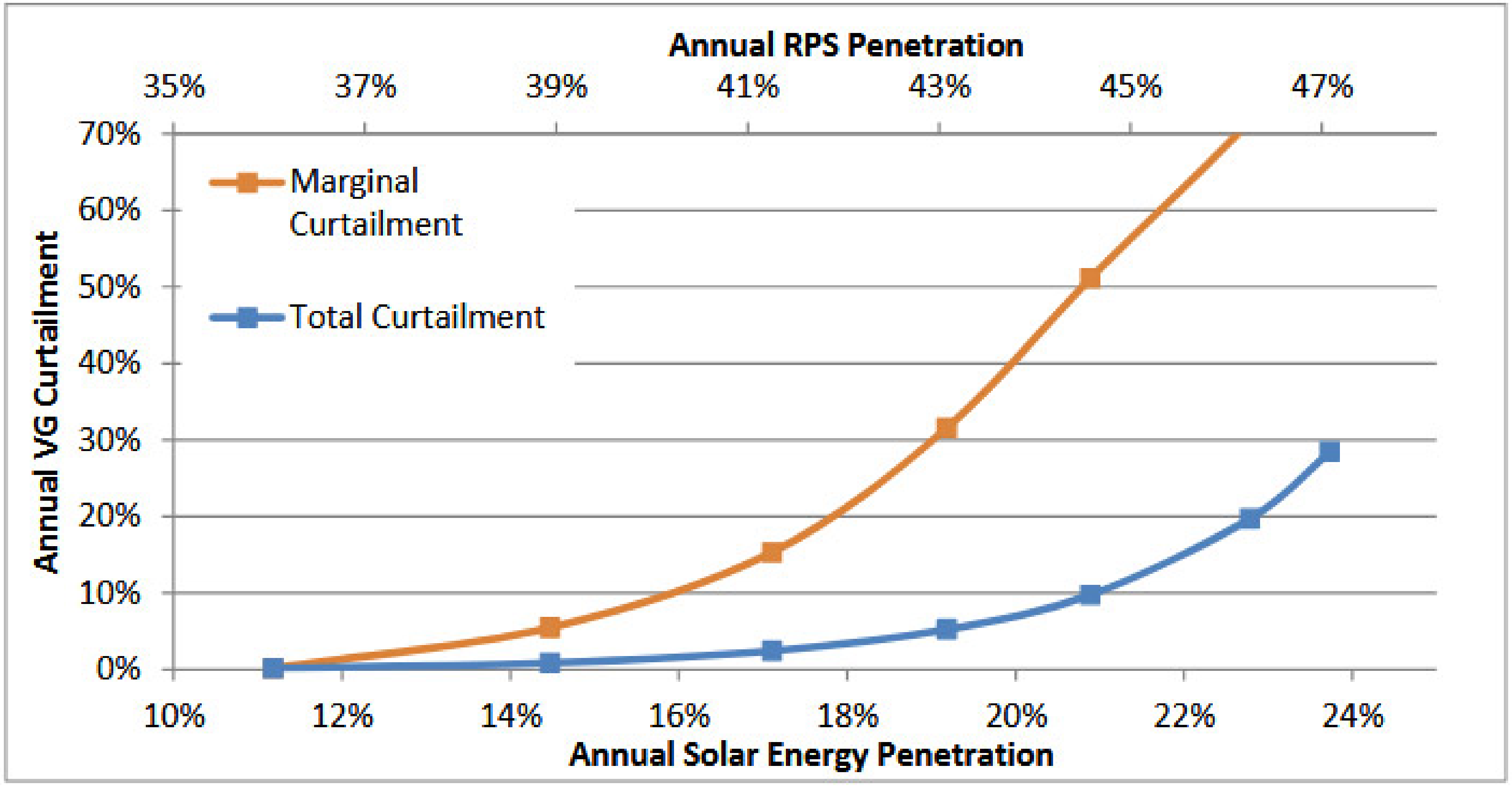


Figure 17. Marginal and average curtailment due to overgeneration under increasing penetration of PV in California with a 60% instantaneous penetration limit

Therefore, even with only ~20% penetration of solar power to the grid today, it becomes economically uncompetitive to add more (orange curve)

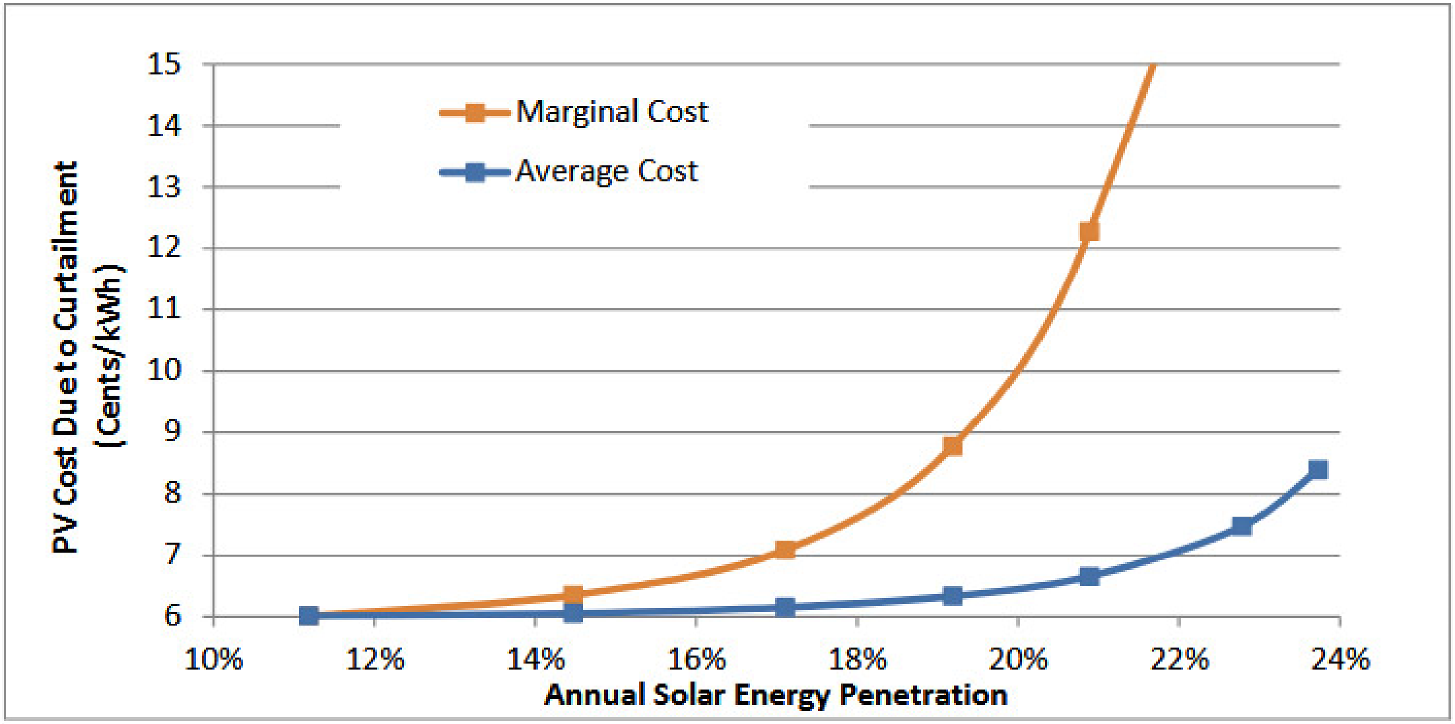


Figure 18. Marginal and average PV LCOE (based on SunShot goals) due to overgeneration under increasing penetration of PV in California with a 60% instantaneous penetration limit

Figure 18 shows the importance of examining marginal curtailment rates. While average rates can remain relatively low, marginal rates determine the cost and value of adding the next unit of solar to the grid. Actual investment decisions may be driven by these marginal values.

"In the longer term, grid operators will need non-traditional resources to supply reserves and grid stability services. This shift in operating practices will in turn require system operators to have visibility and control of distributed PV (i.e. your rooftop), storage, and load, and it will likely require new market mechanisms to incentivize these resources to participate in providing grid services. Without utilizing PV or other distributed resources to provide grid services—which is technically feasible—excessive curtailment of PV could occur at penetrations well below 20% on an annual energy basis."

There is plenty of solar energy falling on Earth, so with enough spending on these problems, its power will likely come to dominate in time

- …But beware of biased claims. Calculating the Energy Return on Energy Invested EROI for solar can be spun to make it look cheaper than it is (Tverberg 2016)
- Calculating EROI is not straightforward, so it's good in general to be somewhat skeptical and pay close attention to the agendas of the source of the data.

Finally, a Troubling climate problem with Solar PV … Albedo.

Solar panels are dark. Only about 1/6 of the incoming sunlight is converted to power. The rest mostly turns to heating the surrounding air.

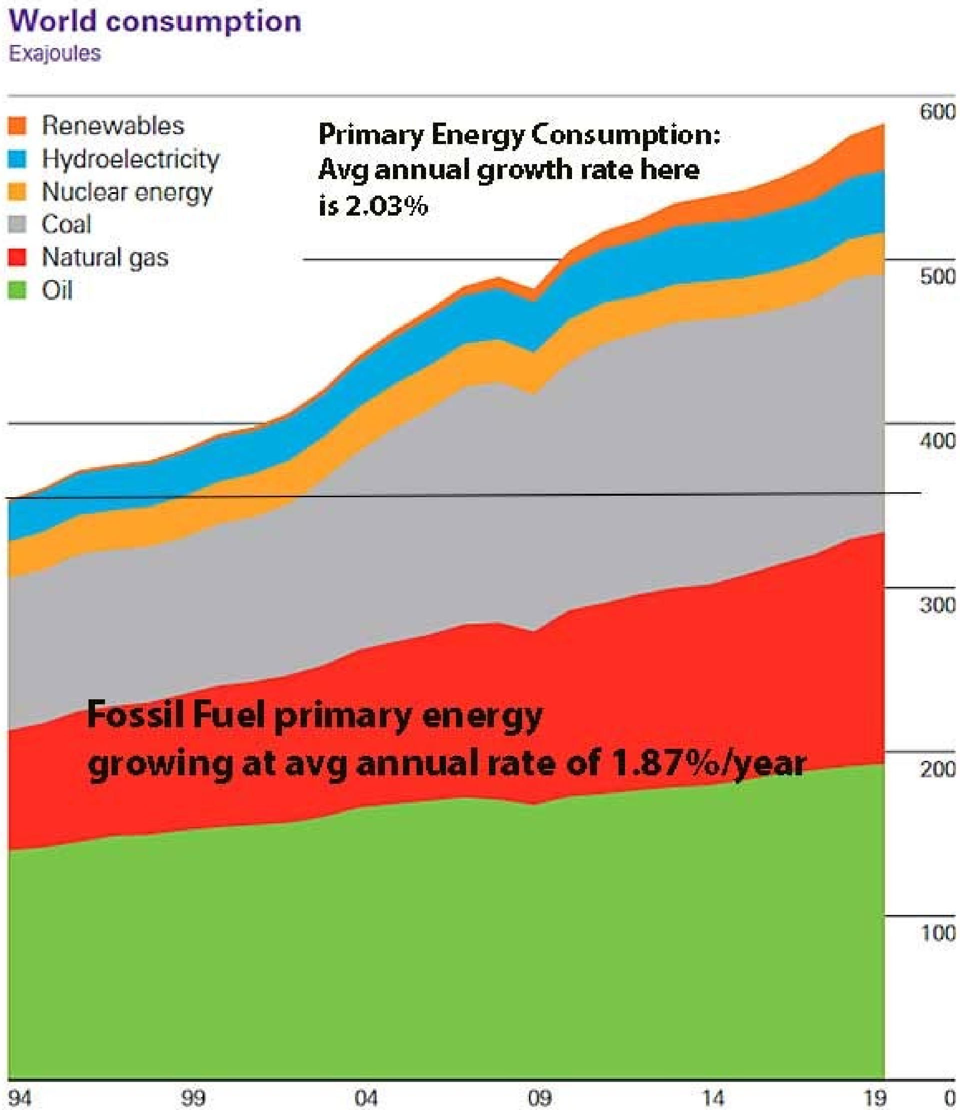
If solar comes to cover millions of square miles, as some dream it will, this may be a significant climate warmer.

The effect depends strongly on what surface they cover up.

- It's especially bad for Utility scale solar built in deserts, such as the Topaz Solar Farm in Carrizo Plain, CA, where the light colored ground normally reflects much more energy back to space.
- Few things are as dark as solar panels, and this albedo effect is not negligible.
- They cause a net heating of the Earth, while hopefully lowering CO2 emissions but only <u>if they replace fossil fuels… Do they?...</u>

But DO they replace fossil fuels?

- …Or do they merely improve civilization's ability to grow, and thus require yet more net power, while they provide their niche in the power mix…?
- We showed in K43 "The Thermodynamics of Civilization" that indeed solar PV is merely helping us grow faster for all energy sources, including fossil fuels.
- However, if they ever truly do REPLACE rather than merely AUGMENT fossil fuel power, the lowered CO_2 effect does generally beat the albedo effect



Primary energy consumption rose by 1.3% last year, less than half its rate in 2018 (2.8%). Growth was driven by renewables (3.2 EJ) and natural gas (2.8 EJ), which together contributed three quarters of the increase. All fuels grew at a slower rate than their 10-year averages, apart from nuclear, with coal consumption falling for the fourth time in six years (-0.9 EJ). By region, consumption fell in North America, Europe and CIS and growth was below average in South & Central America. In the other regions, growth was roughly in line with historical averages. China was the biggest individual driver of primary energy growth, accounting for more than three quarters of net global growth.

Renewables are not replacing Fossil Fuels. They're only growing on top of a fossil fuel growth rate which is almost as high as Total Primary Energy Consumption growth

B. Wind Power

Wind Turbines: Good Energy Return on Investment

- For commercial wind turbines, it is only ~7 months to recover the energy of manufacture and operation
- Wind produces a tiny ~12g of carbon per MWh (million watt-hours) of power over the life of the turbine.

Some Features of Wind Power

- Blades need to be high above ground to access better wind speeds, which allows ground below to be used for e.g. farming – not true of solar.
- Farmers, in fact, are quite happy to earn royalty income by allowing turbines built on their land
- Wind is essentially solar power in degraded form, from pressure differences caused by differential heating of land, and therefore less concentrated therefore (efficiency loss in conversion of incoming solar radiation through the steps to wind power)

The “Wind Turbines Kill Birds” Issue

- Fossil fuel interests complain commercial wind turbines kill unconscionably large numbers of birds.
- Even granting for the moment that the fossil fuel corporations and their paid promoters which make these claims actually care about birds, the claim is a vast distortion...
- Wind turbines kill 0.27 birds/Gwh, (Gwh = billion watt hours) while fossil fueled power plants kill 9.4 birds/Gwh, or 50x greater Sovocool (2012).
- Sovocool claims even nuclear kills more birds (0.6 per Gwh) than wind – however this number is highly disputed as it relies on kills at mine sites which are not nuclear-related and should probably be disregarded.

This study (Smithsonian), using Web key word searches and statistics…

- ….finds ~230,000 birds/year die in wind turbines. Highest estimates elsewhere are 3x higher.
- Let's do the math…
- Wind generated 706 TWh of electricity in 2014 (more in 2015), that's 706,000 GWh
- That equates to 230,000 birds/706,000 GWh or about 0.33 birds per GWh of energy. That agrees with earlier cited work of Sovocool (2012).

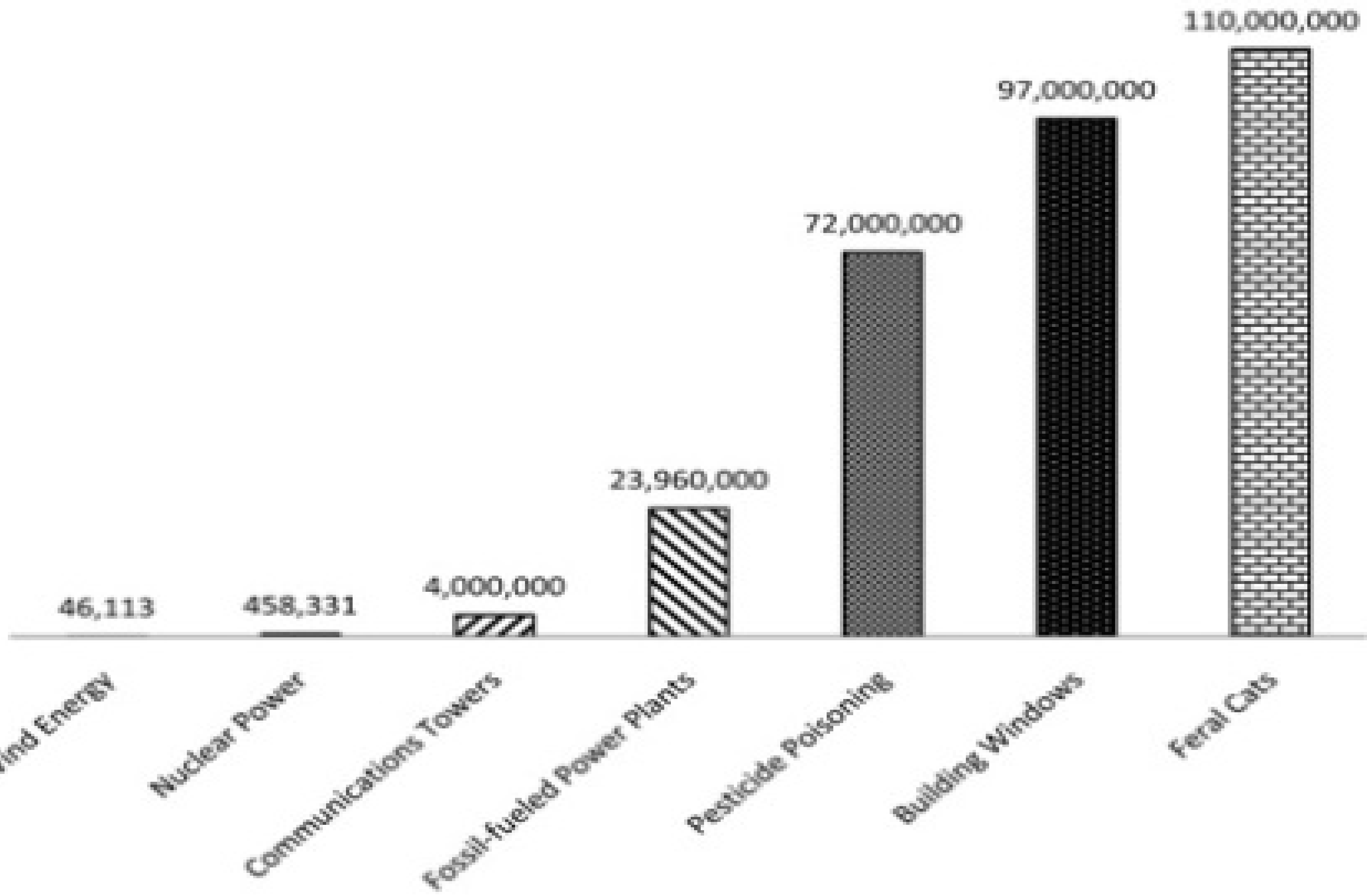
Eagles and Wind Turbines

- The other claim is that wind turbines preferentially kill eagles. I can find no reputable evidence that wind turbines preferentially kill eagles *vs.* the eagle kill fraction from fossil fuels
- Right-wing apologists for fossil fuels regularly lie about this, as PolitiFact documents on Donald Trump's claim that wind turbines kill "hundreds and hundreds of eagles" (source).
- **Predictable: There's nothing like a dying bald eagle to bypass the facts and go straight to the RightWing emotional outrage button**
- Here's the facts….

This <u>Article</u> says 7 Golden Eagles Killed at NorCal's Altamont Pass per Year

- However, Altamont Pass, CA has the densest net of wind turbines – 3,000 - in the country, generates 1/3 of California's wind power and *"which has one of the densest nesting populations of big raptors in the world"*
- It's by far **<u>the</u>** deadliest spot in the country for wind turbine bird kills - **<u>It is hardly typical</u>**.
- Replacing the smaller, aging, lower to the ground turbines with larger turbines much higher above ground, and siting carefully after mapping bird flight paths, has cut bird deaths by ~half

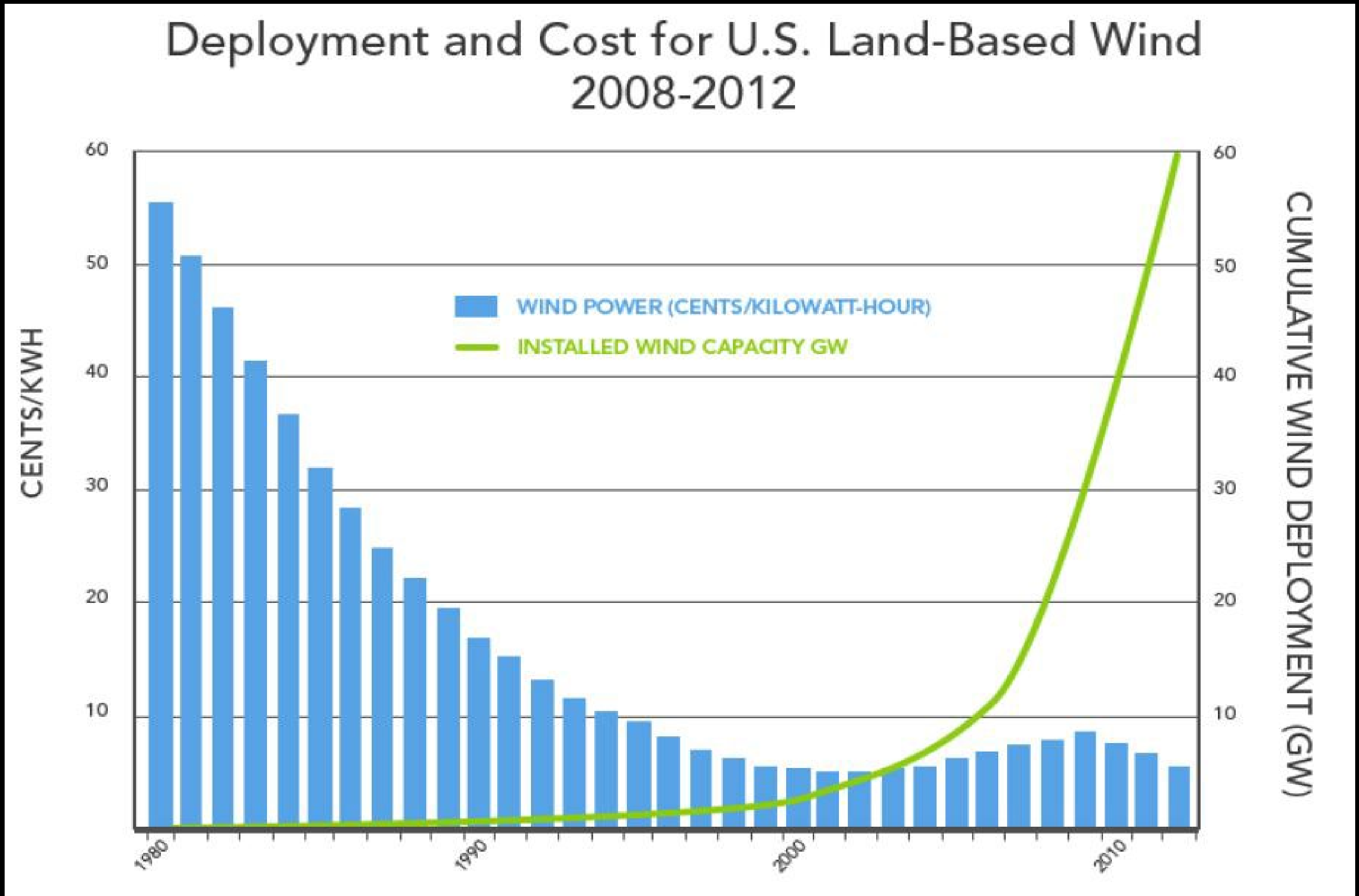
And For Birds, Wind Farms are the Least of their Worries



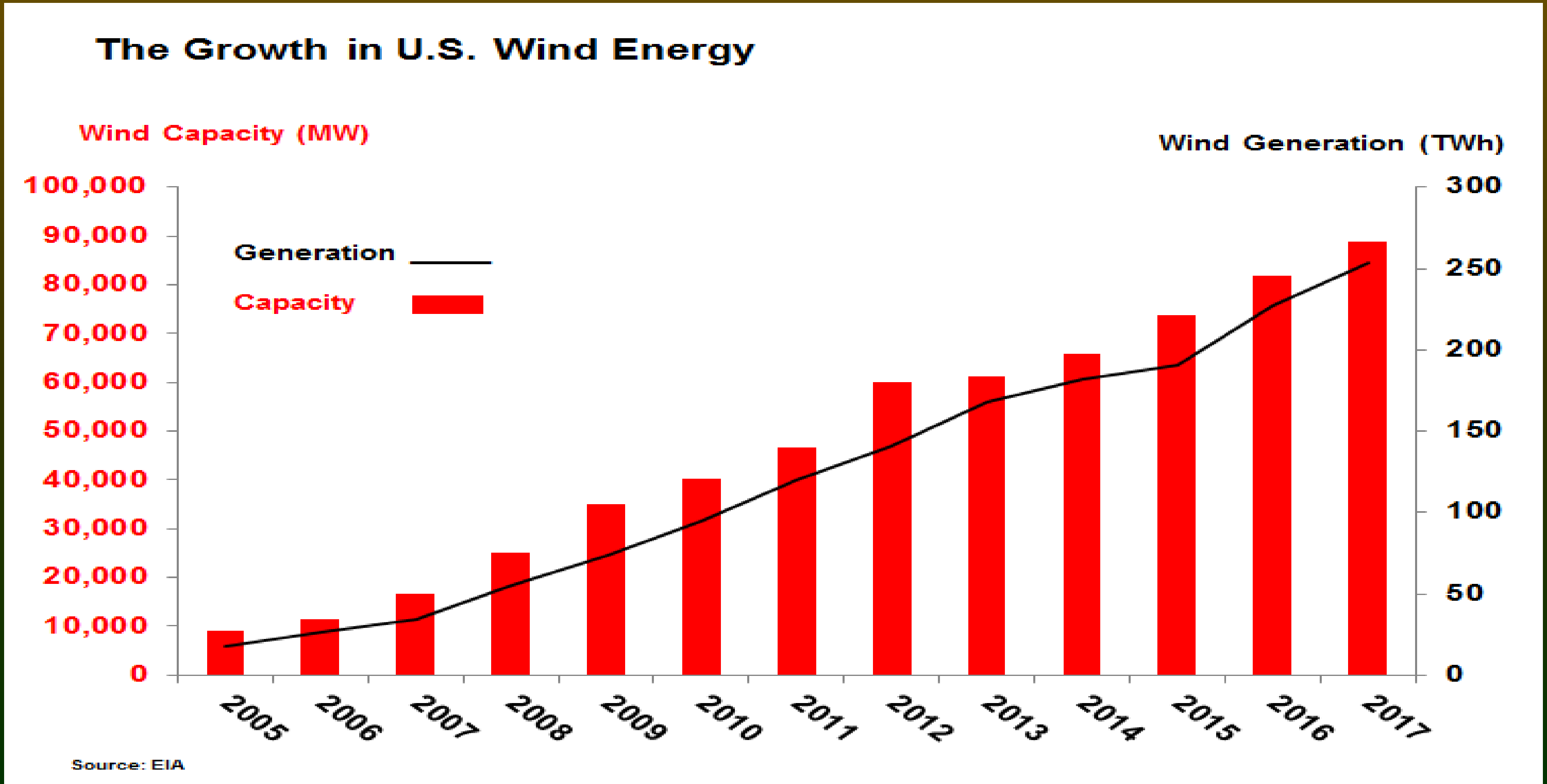
A Few Claim Nearby Wind Turbines Make them Sick

- But there is no evidence of physical causation.
- Instead, seems most consistent with the "nocebo effect"
- "They list another possible reason for the sickness as Somatoform Disorders which is 'the unconscious expression of stress and anxiety as one or more physical symptoms."
- The American Psychological Association also conducted a study and came to the conclusion *if people think physical problems are caused by the turbines, they will have them (physical problems)*.' (source)
- No doubt this will remain a favorite theme for the anti-renewable energy lobbies to use

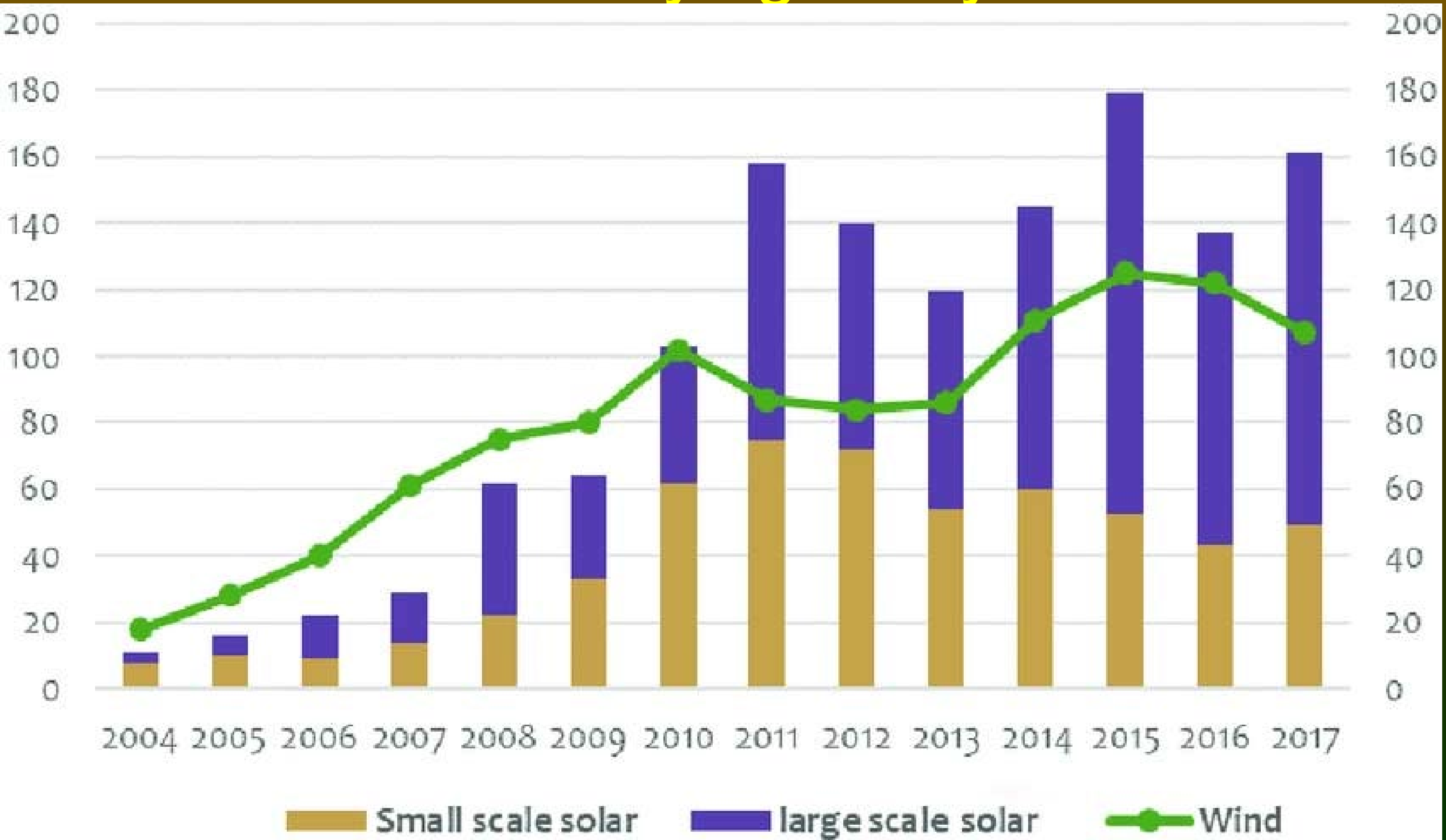
The big technology and cost advances were in the early days, leading to exponential deployment. Cost improvements ~ceased 15 years ago, and dropped onto the linear deployment rate still seen today (green curve). The best, windiest, most concentrated sites were built out first, of course



Updated through '17. Now, capacity is still growing at merely a linear rate. It's the economics, not the politics - prime spots mostly built early, leaving less economically favorable sites, and declining rate of cost improvements. It's becoming a technologically mature industry.

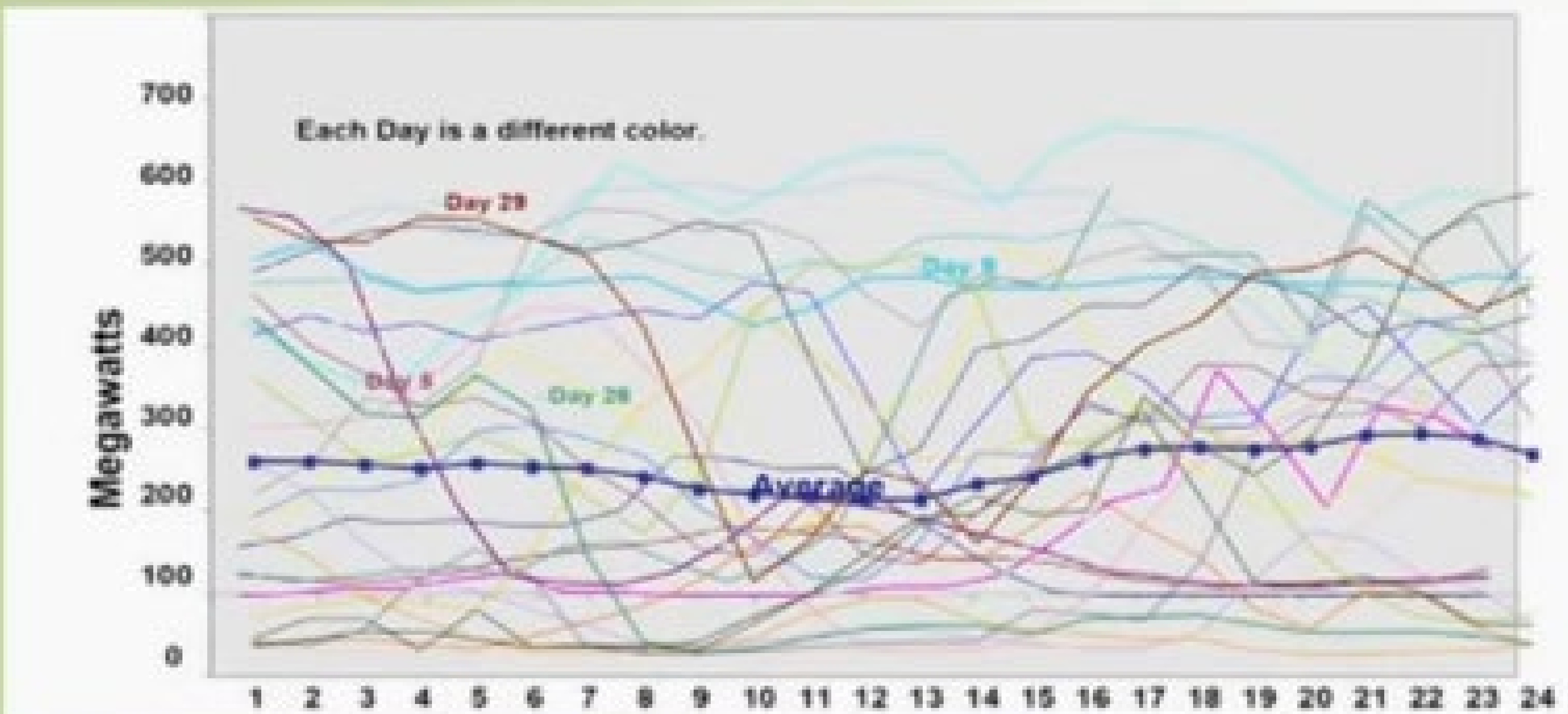


Global Renewables: Small scale solar declining, and wind is uneven. Most growth is in Nature-destroying Utility Scale Solar



Wind Unpredictable. Tough on our current grid, which was built for predictability

Unpredictable Wind



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While wind for a given turbine will be variable…

- But only the average over a single collected area is really what matters to grid operators.
- The turbine-to-turbine power output is uncorrelated enough that it tends to average out well enough to not be a huge problem
- This white paper (admittedly not necessarily unbiased, but it does have quantitatives) argues wind power is less affected by downtime than fossil fuel plants, since the power per turbine is much less than for a single fossil fuel plant which may be go down for maintenance, accidents, etc.
- It finds in Texas that wind variability will impose negligible additional cost for required additional capacity

But Wind Turbines Cause a WARMING at Earth's Surface

- Say what? (Miller *et al.* 2018, discussed here)
- Yes, by mixing the boundary layer near the ground, studies and observations confirm that cooler denser air at ground level is mixed out with warmer air aloft.
- A "massive deployment" of wind turbines could warm surface temperatures by +1C.
- On balance, wind power is good…. But not as good as many would have you believe

But – Wind Farms are HUGE compared to equivalent Nuclear Power

East Anglia One – the World's Largest, Most Advanced Wind Farm

- North Sea offshore wind farm, and offshore wind looks to maximize efficiency.
- Still, EA1 would require more than 50x the land (sea) area as Diablo Canyon Nuclear Plant for equivalent power, and even that's using Diablo Canyon's 35 year old technology
- Modern LFTR (liquid fluorine thorium reactors) would be far smaller in all aspects.

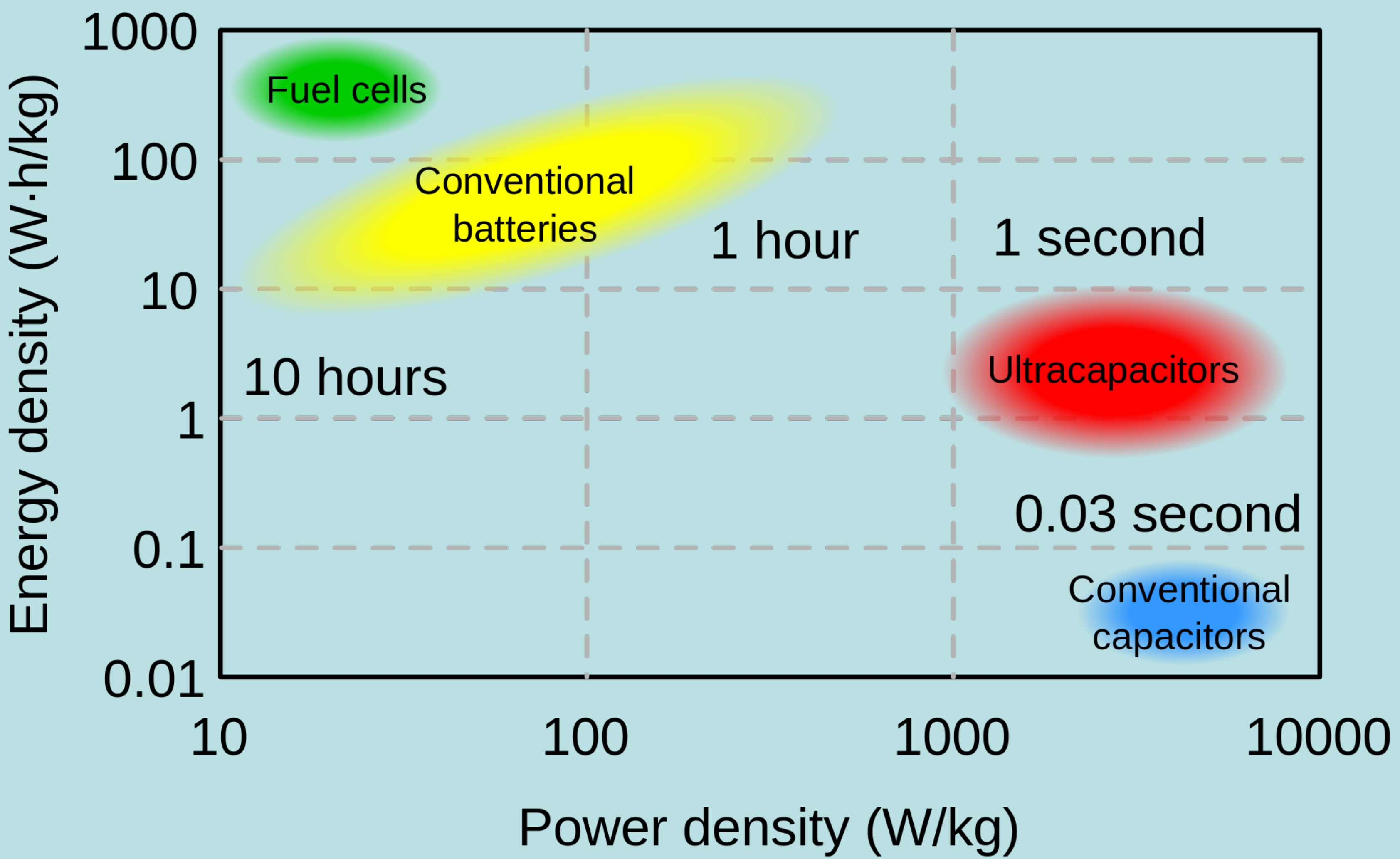
A Nice Idea for Local Unobtrusive Wind Power Generation

- "Sky-brators", avoid the big turbine blades
- Power generation is lower, but they are much more suitable for deployment along highways and even in backyards.

C. Energy Storage Technology

- How to power our transportation – cars, trucks, rail?
- "liquid electrolyte" (**Duduta *et al.* 2011**) **advance in battery technology made at MIT** is a hopeful sign. If it works as hoped, it may double the energy density of current batteries, and also make possible the ability to "fuel up" at the pump with an oil-like rechargable electrolyte much like we do with gasoline cars at the moment. Read about it **here.**
- A new **all-liquid-metal battery** technology suggests the possibility of very high storage densities at relatively low cost. "Flow batteries".
- Other battery technologies here
- **But, so far the electrolyte liquid doesn't stay charged long enough. A "deal killer" unless solved**

An Ideal "Battery" would have high Energy Density (compact) and also high Energy RATE (the "zoom" factor, and quick re-charge) capacity (upper right corner). So far, we have to compromise…



Load Balancing When Renewables Are Included

- Our grid requires precise 60 hz current be always available. It is controversial whether load balancing with totally renewables energy sources can be successful. Even more than this, Delucchi and Jacobson (2011) claim it is theoretically possible to power the entire U.S. by 2050 with solar+wind dominated renewables. A number of recent published paper disagree, but as I write this, it's not clear where the truth ends and opinion / hope begins, from my readings. It's certainly true there's plenty of solar energy falling on Earth. The problem is the grid/storage technology to utilize it. That's a problem – it doesn't yet exist.
- Nuclear: always on, full tilt
- Coal, hydro, can easily ramp up/down as needed
- Solar, wind can only ramp down. Not up. Not good.

A few highlights of what's needed to power the world with renewables, according to Delucchi and Jacobson

- 90,000 solar power plants of 300 MW size. Today (2018), we have about 30.
- 5 MW wind turbines - that's the largest possible size today, and only a few exist. We'd need 4 million of them
- Every family of 4 on the planet would also need a 3 kw solar rooftop system.
- Energy storage in the form of hydrogen (which is highly corrosive to metals).

Energy Storage…

- Because the sun sets every night, and clouds can come in daylight, and because wind is unpredictable, and because energy demand cannot realistically accommodate frequent brown-outs and black-outs….
- We need better energy storage!

The Promise of Graphene

- Graphene is a two-dimensional structure of carbon – *“thin, transparent, about 200 times stronger than steel and conducts electricity better than copper. When it comes to storing energy, ‘It is about seven times better performing than lithium-ion’ Monaghan said.*
- *Graphene is lighter, more conductive, does not need cooling, charges faster and has a long life cycle, he added, adding that it is also cheaper than lithium-ion, costing about $300/kW compared with about $1,000/kW for li-ion”.*

Graphene Capacitor Cars?

- Ultra Capacitors as energy storage are far safer than high-capacity batteries in an accident, but energy density hasn't yet been competitive.
- Worse, we've been unable to design them so that they hold their charge instead of leak it away. Shelf life is far too low.
- 2016 prototype car from Edison Electric proposes graphene capacitor energy storage to enable ~300 mile range, and hopes can charge in only 5 minutes, making it very competitive with gasoline cars. Very speculative (even, perhaps, just hype?)
- … similar claims and promise for ultra-capacitor powered cars came from EEStor over a decade ago in 2006… promising delivery by 2007. In 2019 - still waiting.
- UltraCapacitors have been the future of storage for a many decades now… Perhaps they will always remain in the future?

Glass Electrode Sodium Batteries

- These promise high energy density (3x Lithium Ion), cheap materials (sodium vs. rare lithium), and safety (glass electrodes).
- They’re all solid-state, using no liquids
- They can operate at very low temperatures, like -20C, making them promising for EV vehicles
- Their development is promising so far (Braga *et al*. 2016)

Molten Silicon Energy Storage?

- In 2017, an Australian startup called "1414" is promoting a new technology which stores energy by melting pure silicon at a temperature of 1,414F, and using the heat later to power a turbine. Claims it can store the same energy as equivalent Lithium-Ion at ~1/10 the cost as Tesla's entry.
- Silicon is cheap, plentiful, non-toxic.
- But that was now 3 years ago; Since then, I've heard nothing about this promotion.

Spanish Firm Working on Solar Thermo-photovoltaic System

- Energy again stored as molten silicon
- Power is tapped by using special “solar cells” sensitive to the infrared light coming off the molten silicon.
- Patent pending. I’m wondering how long thermo-PV cells can survive so near to the 1500C = 2,700F extreme temperatures of this environment. High heat accelerates destruction of just about everything
- Announcement here . Let’s be hopeful…

Lithium Sulfide and Lithium-CO2 Batteries

- Promise ~15x the energy densities than Li-Ion, and might provide a path to an electric car that has comparable range and refill-the-tank time as gasoline cars.
- Will it come true? Let's hope.

However, I've seen <u>"Wonder Breakthroughs"</u> Announced for Batteries and Storage for Many Years

- But, still not much has happened commercially. Instead, incremental improvement in older technologies like lithium-ion.
- Elon Musk agrees – his massive battery factory being built in Nevada and on which he's basing his battery technology for many, many years – **<u>is still Lithium-Ion.</u>**

As One Example:

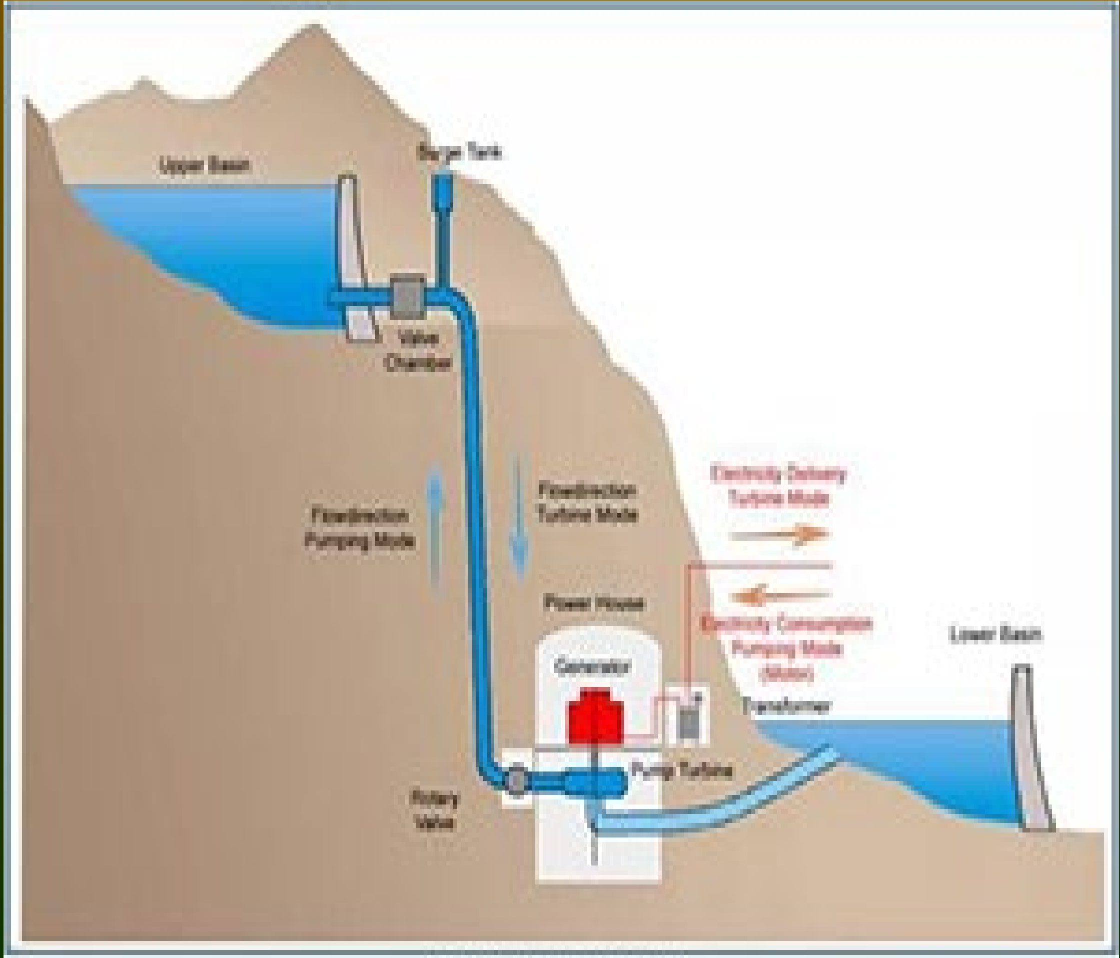
- Michigan start-up Sakti3 made big claims of the invention of a battery with 2x the energy density of Li-Ion and all solid-state, and that it was very close to achieving the Holy Grail: a battery which could provide a 300 mi driving range and cost $100/Kwh or less.
- High-profile photo-ops with President Obama followed…
- Then, it turns out its claims, even on the micro-level, could not be verified or replicated. Before the story got worse, it was sold for a mere $90 million to a larger company. On Wall St, $90 million is low even to buy a company producing just a marginal improvement in some obscure area of life. For a battery technology supposedly going to overturn the transportation power market – it's a confession that it was all hype, as indeed the experts have concluded.

Another: Dual Carbon Batteries

- First invented in 1989, in 2014 Japan announced their advanced version, claimed to be able to discharge 20x faster than Li-Ion batteries, and made of common carbon and not rare Lithium.
- That was 5+ years ago. Since then? Silence…. And Li-Ion technology still rules the commercial battery world.

Pumped Hydroelectric Storage

In locations with usable elevation, this is a long proven way for storing large amounts of energy. Excess power is used to pump water up hill to a storage basin, and then when power is needed (*e.g.* at night if solar was your main source), simply run the water downhill through a standard hydroelectric generator setup. Nice efficiencies, up to ~80%..



Source: Alstom Power

Adding in pumped storage (using excess solar energy to power pumping water uphill to a reservoir, then generating hydro power with that when needed), helps some with "variable generation (VG)" sources of power in the mix by avoiding wasted renewable power.

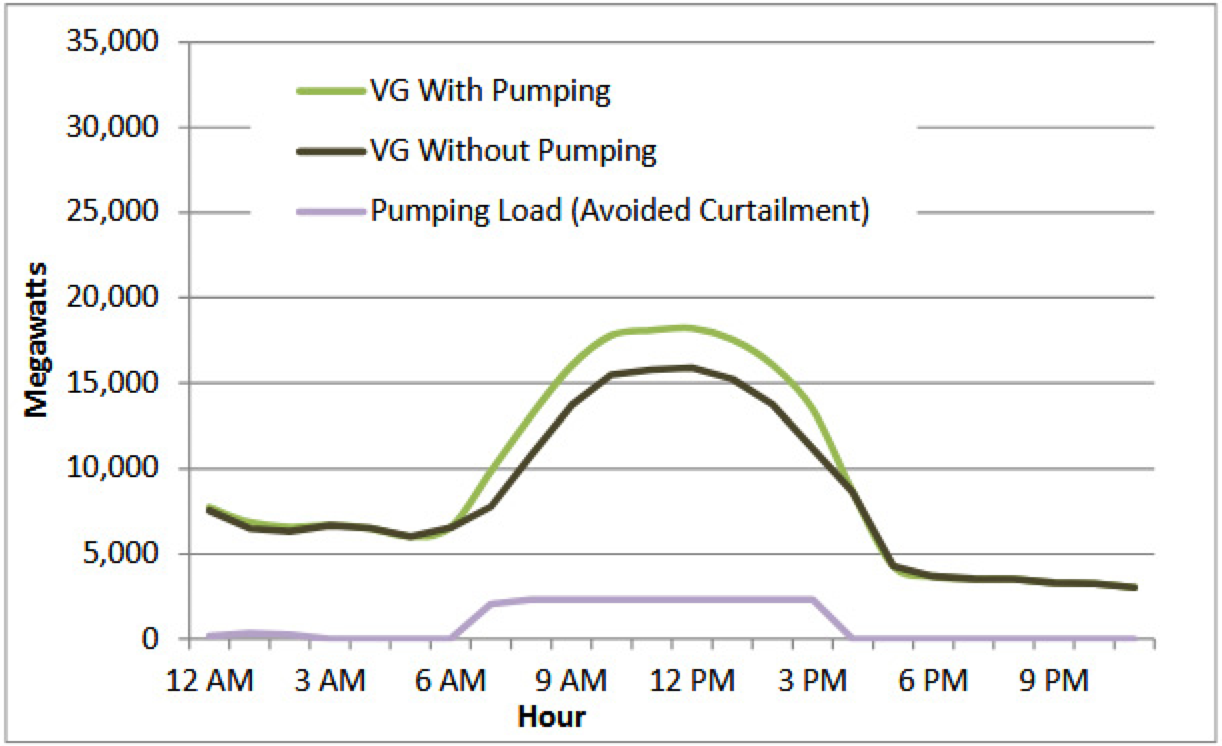
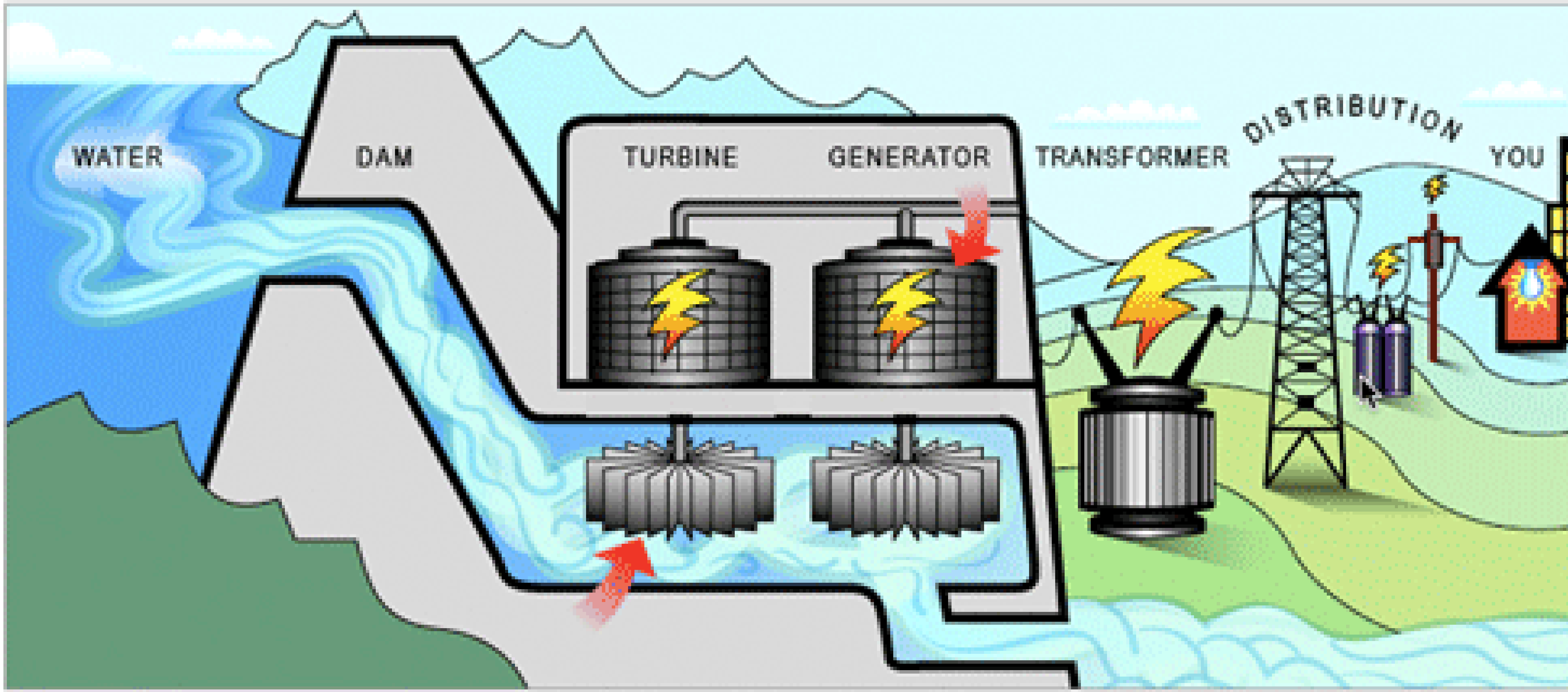


Figure 11. Increase in VG use resulting from schedulable pumped storage in a scenario with 11% annual wind and 11% annual solar

Capacity Still Small. Not clear it can be more than a small part of the solution

- Though pumped hydro has been around and in use for a hundred years (!), it still provides storage for only 2% of the U.S. power generation capacity. 5% in Europe, only 10% even in mountainous Japan.
- Considerations for expansion ultimately may double this. Good… but still small.

D. Hydroelectric Power



1. **Water** backs up in a river...
2. then falls through tubes in a **dam**...
3. to turn the blades of huge **turbines**...
4. which spin **generators** to create electricity.
5. A **transformer** increases the voltage to send electricity over...
6. **distribution** lines. Then local transformers reduce the voltage...
7. for **you** to use.

Hydroelectric is very cost effective; high EROI

- But, most of the usable and economical sites are already dammed; it's not scalable, is costly to local ecologies, and expensive and damaging to remove dams once they silt up.
- Also, climate-caused drought will hurt mid-latitude river flows going forward.
- But power can be constant <u>on</u> (unlike wind, solar)…. (at least until reservoir runs dry, or silts up… then constant <u>off</u>!)

In 2013 hydroelectric accounted for fully **50%** of U.S. renewable energy

- …and 6.8% of electricity generation in the U.S.
- Globally, hydro supplies 16% of total electricity generation (not the same as total energy generation)
- And has been expected (hoped?) to grow at about 3% per year for coming years, but in fact it has not been growing significantly for decades

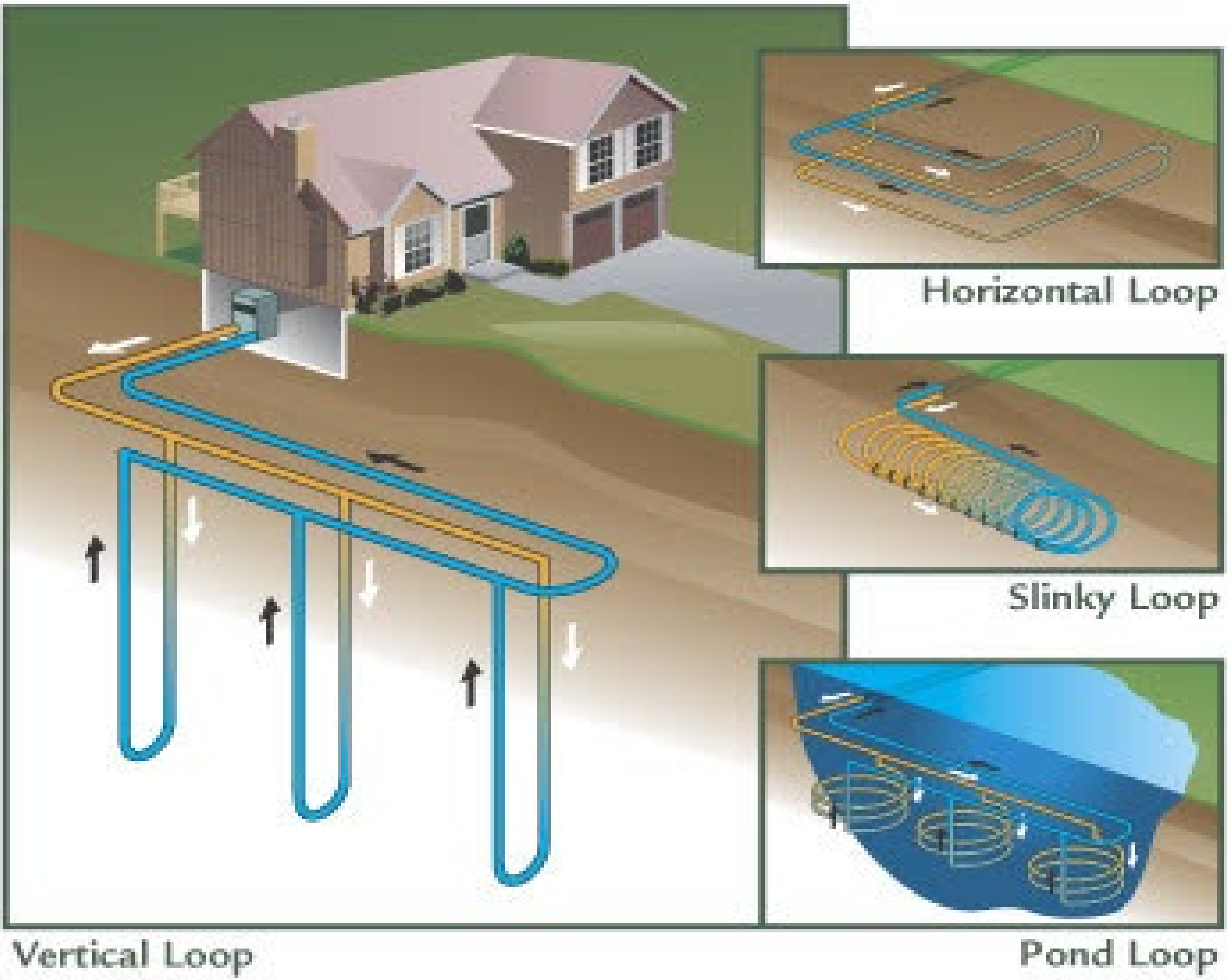
The Downside of Hydro-Electric

- Most hydro plants are in tropical or mid-latitude areas, and flooding upstream land drowns trees and plants which, when now deprived of oxygen, generate methane on decay.
- **The greenhouse gas emission rates, in many cases, are equal to that of a large oil-fired power plant**. So, you get "clean" electricity at the dam, at the expense of comparable GHG emissions from the backed-up water behind the dam!
- Global methane emissions are still dominated by tropical wetlands as of today
- Globally ~60,000,000 people displaced by dams

E. Geothermal Energy

- **I**n rare places it is high grade and very cost-effective (like Iceland), but most places you can only access average annual temperature, via digging many meters down with pipes and access low-grade thermal energy which is slow to replenish, given low conductivity of soils.
- This is still quite useful to do for heating and cooling homes and should be more adopted than it is.

Geothermal Energy for the Home



The Problem with low-grade Geo-Thermal is Cost

- It’s up to $25,000 for a single-family home sited on the ground. Govt. credits can help.
- Techno- improvements in installation, and using heat pumps, is showing promise
- Typical payback time is roughly 10 yrs.
- System life ~15-25 yrs, so it can eventually pay off.
- However, it limits landscaping and other land-use options and that may lower home values, depending on buyers.

Urbanization Doesn't Favor GeoThermal

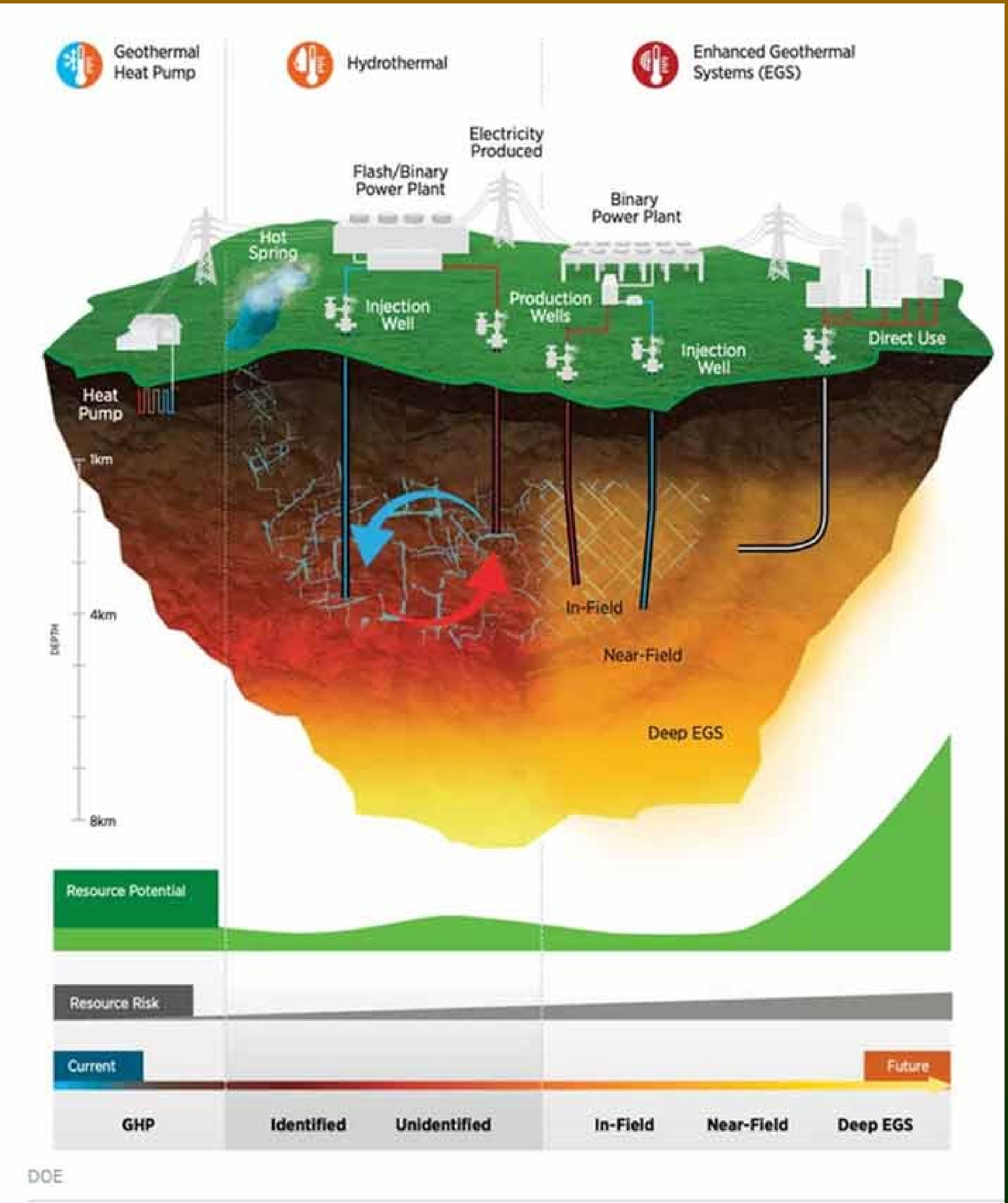
- With rising housing cost driving more housing going into high-rise and apartment dwellings, geo-thermal for multi-family will be much harder.
- Low-cost natural gas already has an in-place pipeline infrastructure and geo-thermal will likely only begin to win when fossil fuel alternatives get much more expensive.

Recent Advances are Promising

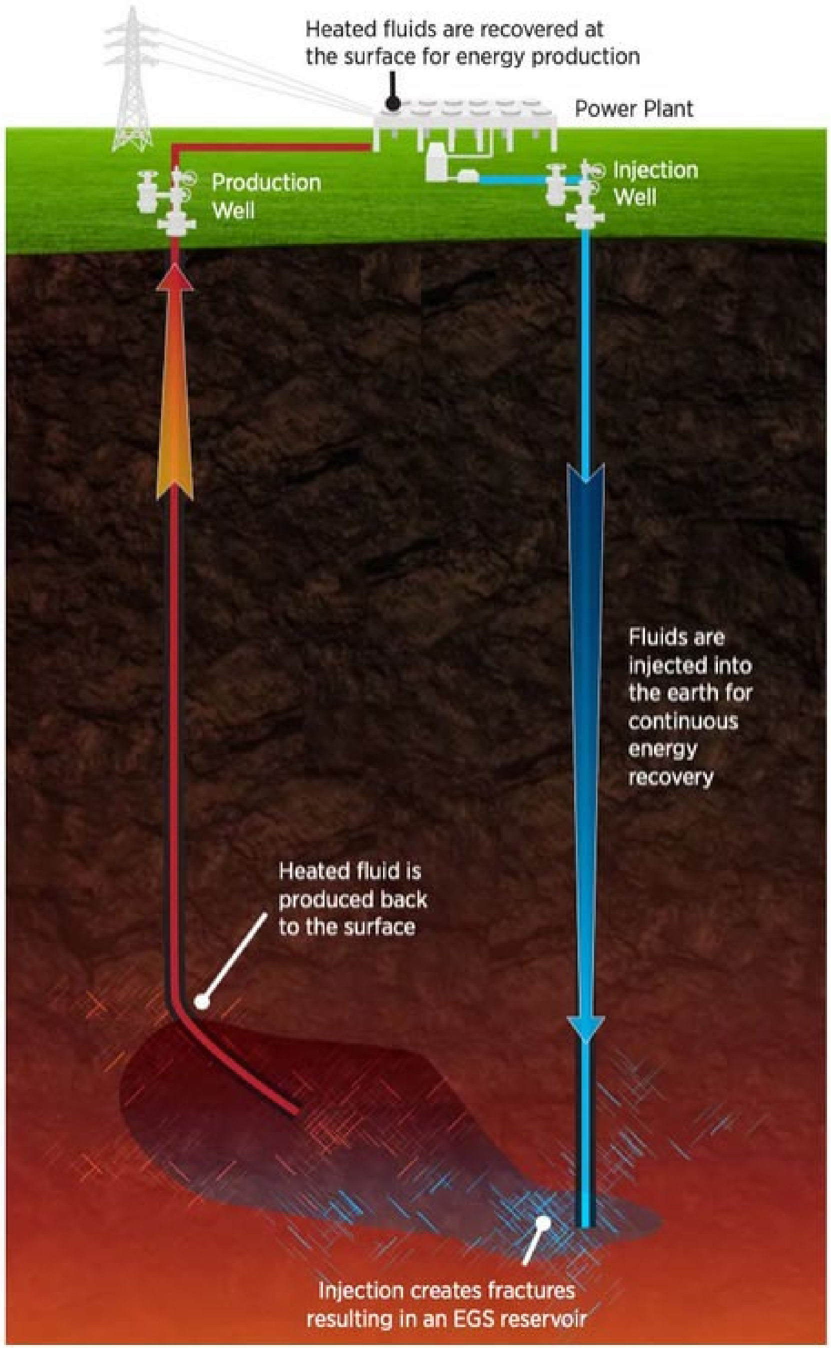
- First – let's realize that geothermal has some great characteristics…
- #1 – It's always on, and easily dial-able as needs change. This beats solar and wind.
- #2 – it meets our first safety criterion; it doesn't spin the Earth into new Geo-Engineered states
- #3 – it meets safety criterion #2; it leaves the surface of the Earth where life lives, pretty much untouched.

But to optimally meet these, it must be high grade (hot!) Geothermal

- *"You can't economically produce geothermal energy at 90°C," Beard says. "150, yeah, you're getting there. 250, oh yeah. 300, you're solid." – Jamie Beard, Geothermal Entrepreneurship Organization*



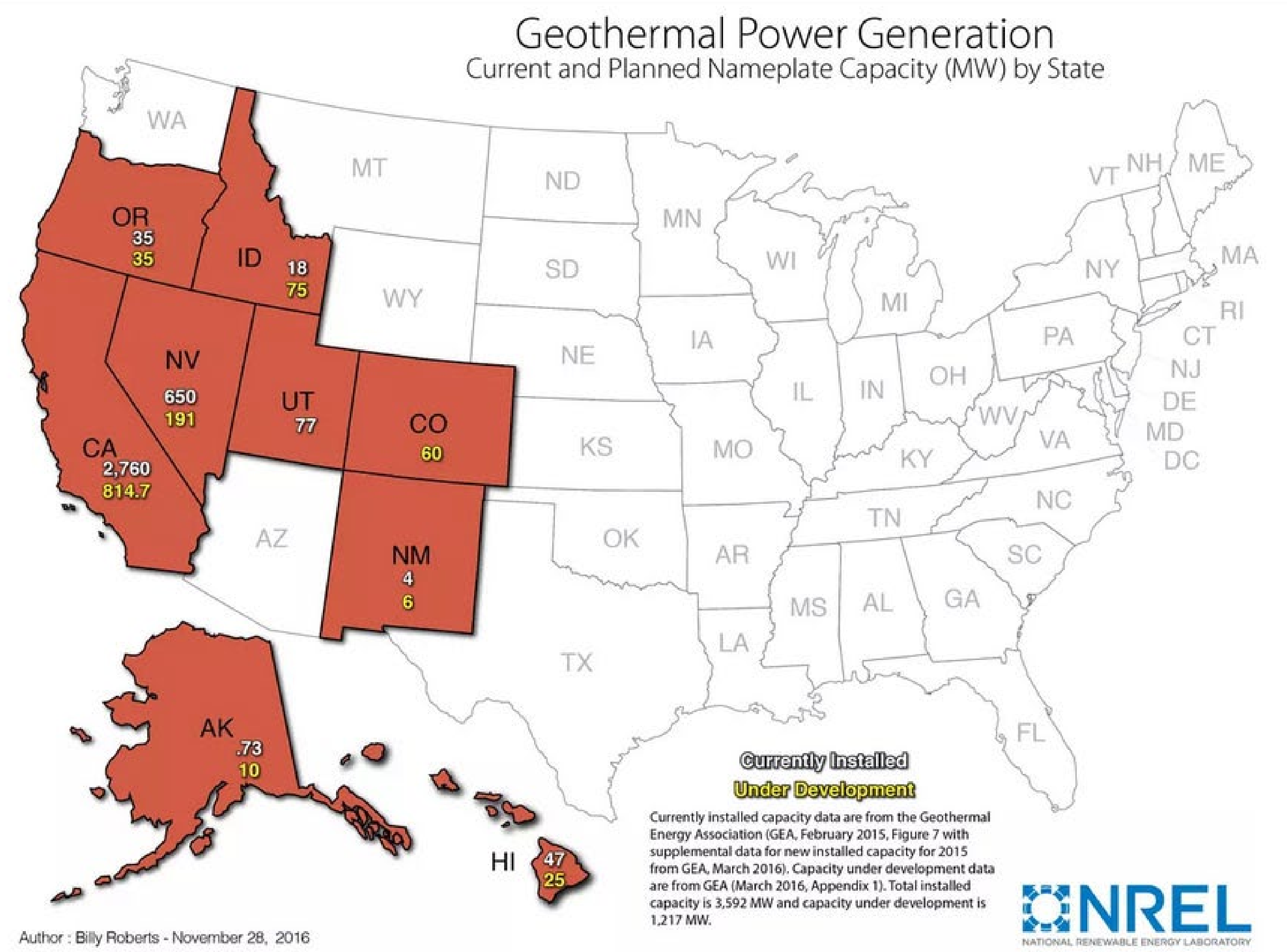
Geo-Thermal. The deeper, the hotter, and the more power-efficient.



DOE

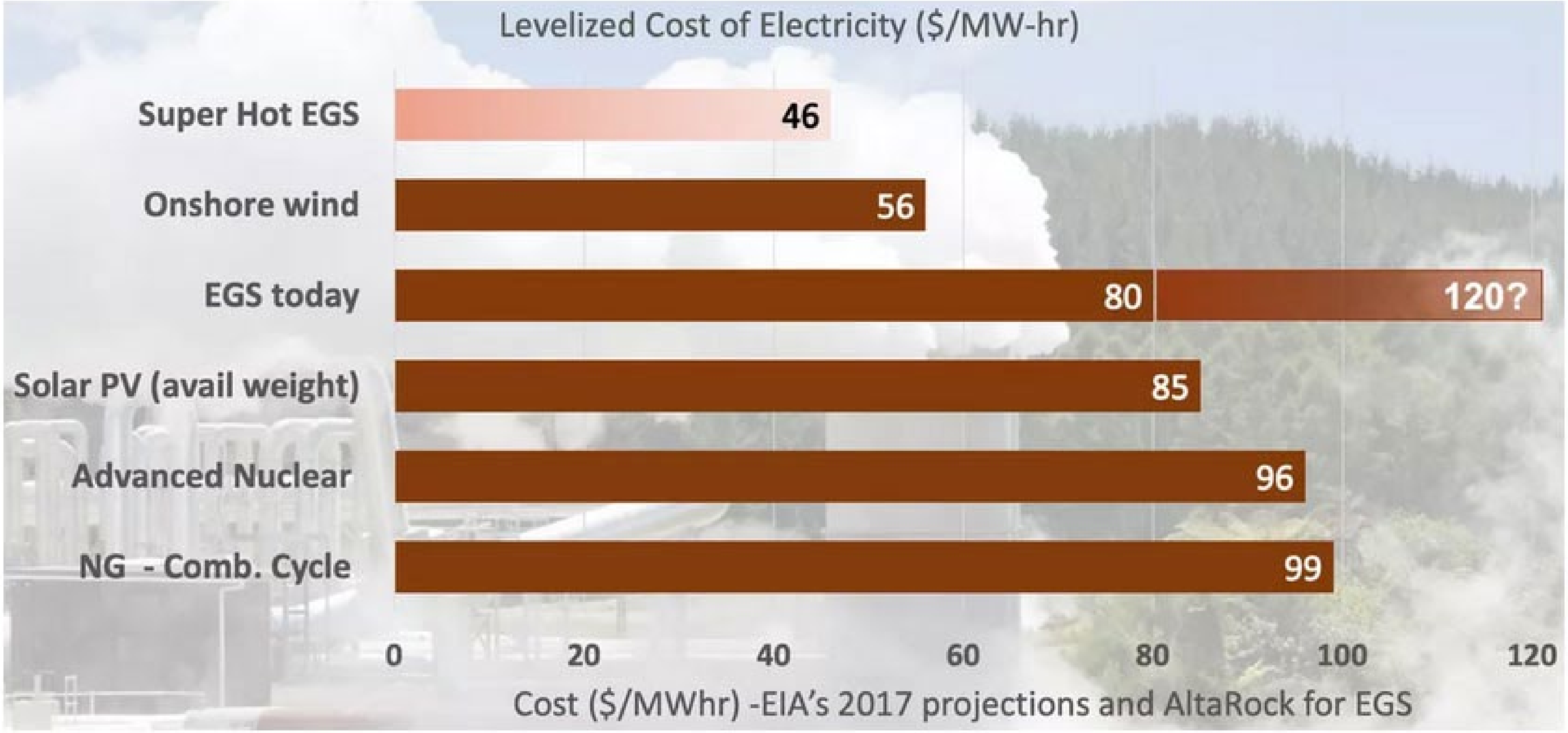
One idea: “fracking” for GeoThermal artificial hot springs. Lose a lot of power in doing the pumping, limited by volume. Borrowing gas fracking technology.

Without fundamental new technology to access deep heat, geothermal is very limited. In the U.S., almost all is in California and Nevada.



NREL

EIA projects super-hot enhanced Geothermal (EGS) could beat all others, and w/o their pollution side effects



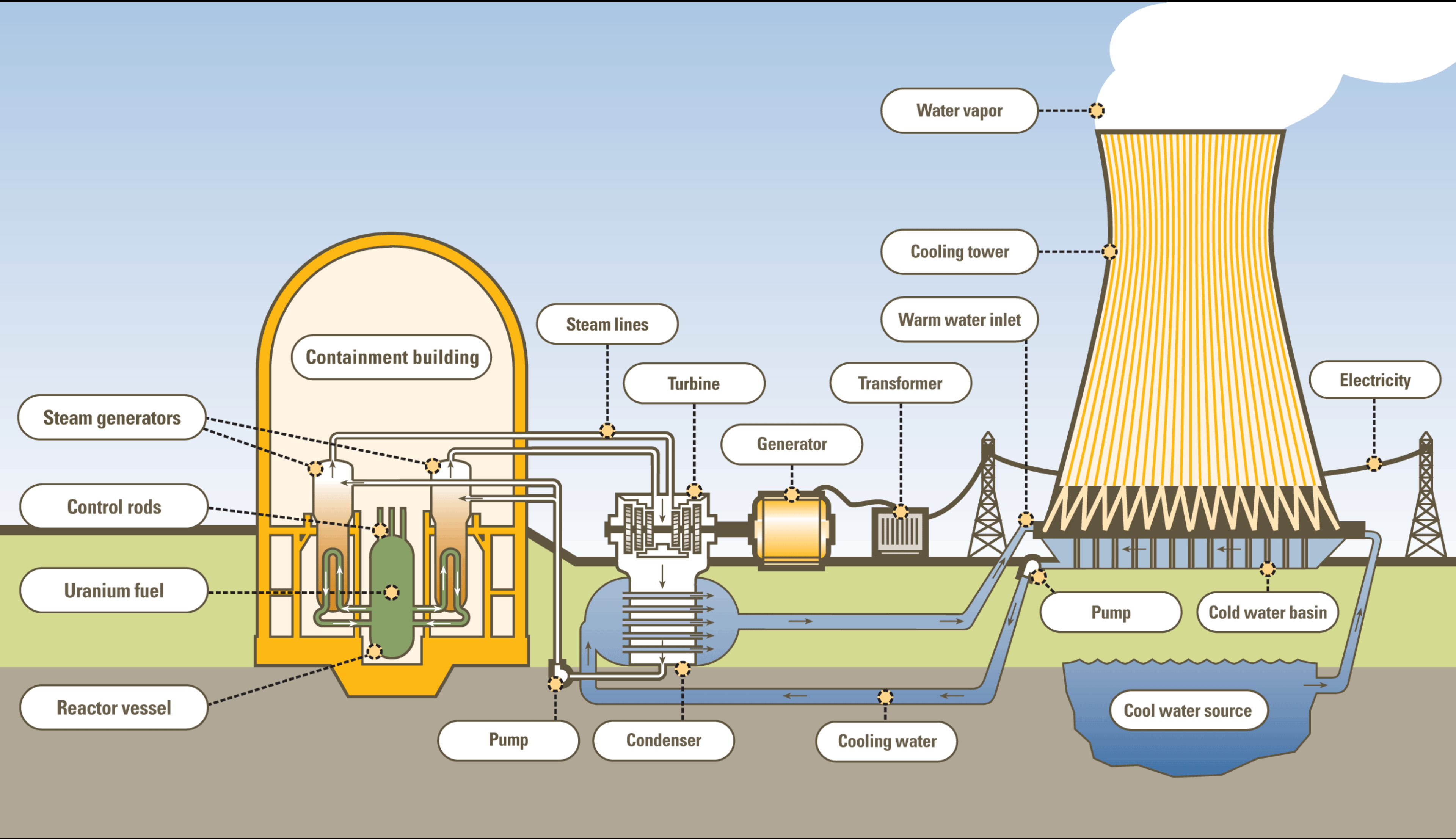
My Take on GeoThermal

- Here's a good article on the current overview of GeoThermal and its promise and problems, from Vox.
- If this cost curve can be realized, and deep, high efficiency high capacity EGS can be realized globally, it could take the lead in my favorite technologies for Earth-saving / environmentally safe technologies.
- So far, my favorite has been molten salt thorium breeder reactors. Let's re-look at nuclear power…

But there's a big "IF" in Deep Geothermal…

- The RATE at which energy can be extracted from the deep Earth ultimately is constrained by the conductivity of the rock.
- Conductivity is a very slow heat transfer mechanism, especially in rock. Metal? Much better. But we're dealing here with rock.
- I've yet to see the poor conductivity of rock mentioned in write-ups I've seen. I"ve seen the hype of "infinite energy" (just like the sun), but not the fundamental RATE issue.

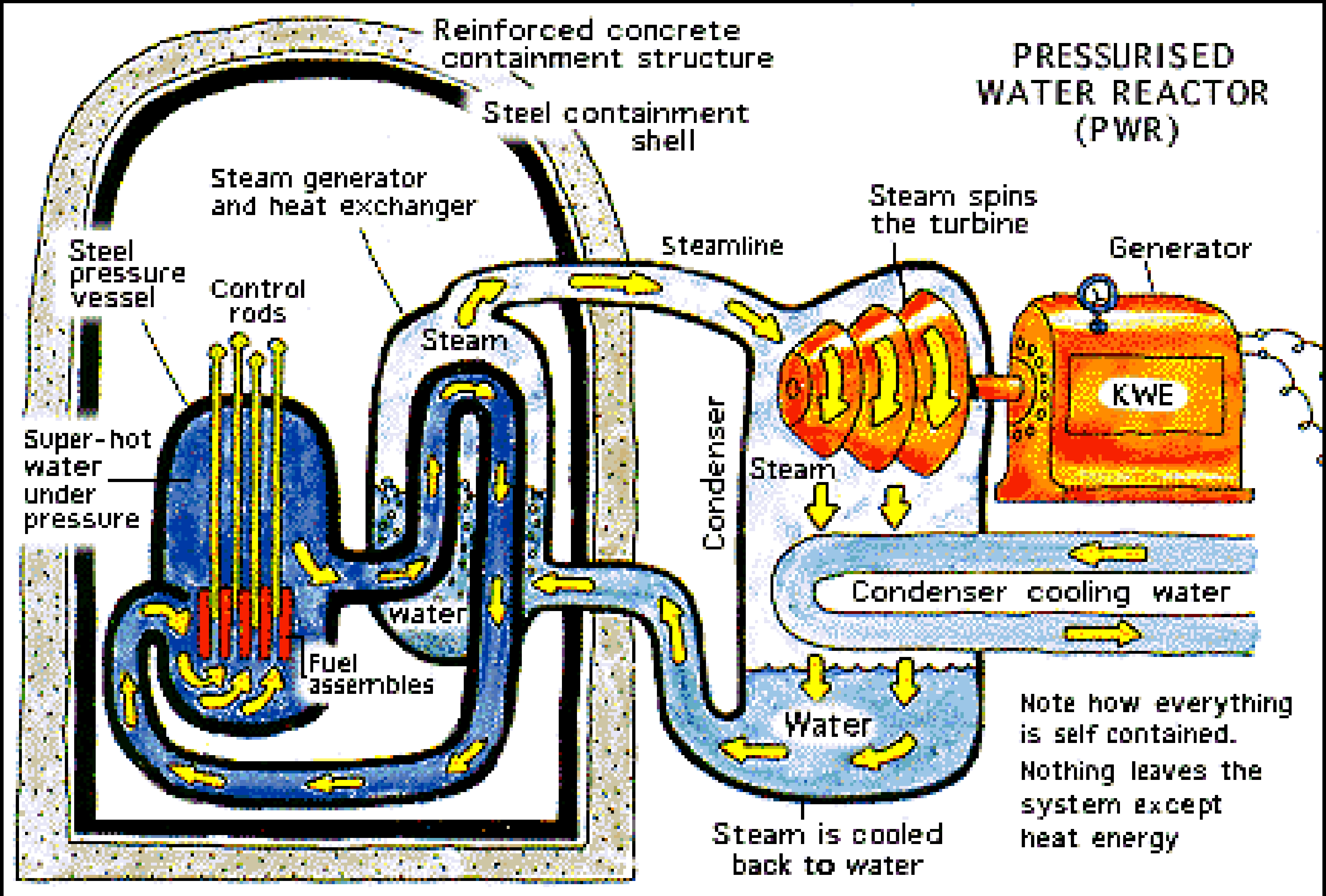
F. Nuclear Power



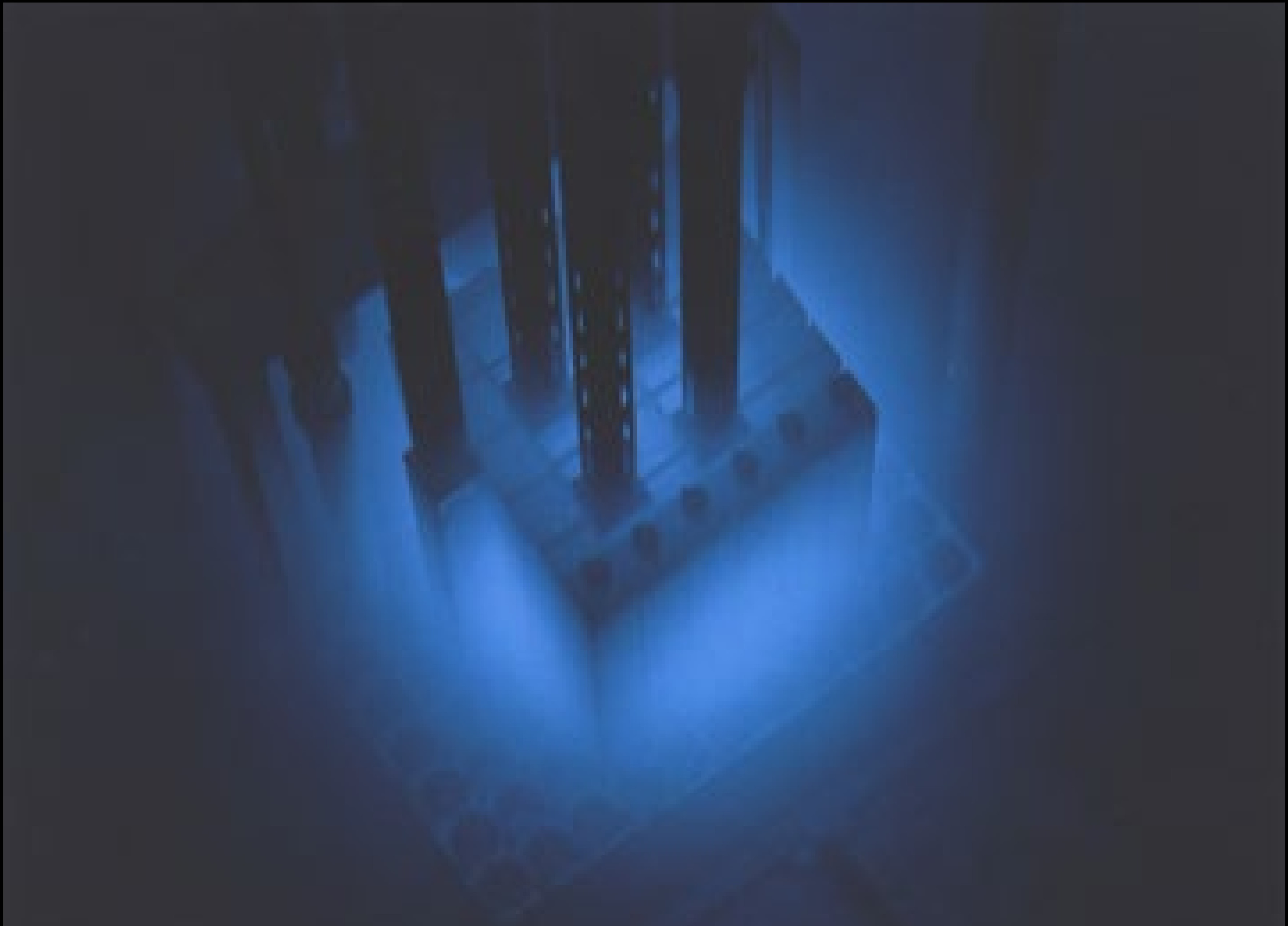
Nuclear Reactors are Just Steam Engines

- Nuclear reactors are just steam engines that use something other than wood or coal to stoke the boiler. They use the heat generated by nuclear fission reactions of certain heavy elements.
- Nuclear has some advantages:
- --- it's "always on", unlike solar.
- --- its carbon emissions are minimal (even including mining the uranium or thorium currently)
- --- its very energy-dense and can supply a lot of power in a small area, so is especially intriguing for use in certain technologies for pulling CO_2 out of the atmosphere. As a fan of undisturbed natural land, it's a very attractive feature in general

Conventional Light-water Pressurized Nuclear Reactors



Cerenkov Radiation from high energy electrons and other sub-atomic particles slowed by water



Cooling and condensing steam back to liquid, using cooling towers

Nuclear Fusion?

- Fusing hydrogen into helium, as the sun does, releases 8x more energy per pound than even standard fission, and the ocean has plenty of deuterium. Sounds promising…
- Easier to fuse **deuterium (D)** and tritium (T), two heavy hydrogen isotopes.
- Incredibly attractive: inexhaustible D fuel, and hybrid fission/fusion ideas can destroy otherwise long-lived nuclear waste while generating energy from this process.
- Incredibly difficult to confine D,T to high density and millions of Kelvin at the same time. So *"Fusion is the energy source of the Future… and always will be",* is the standing joke.
- Tritium can only be obtained by fission reactors. That's a problem if your desire is to totally abandon fission in favor of fusion.

Doc Brown to the Rescue? Not Quite

However, Lockheed-Martin is working on a compact fusion reactor which they say will work. We shall see…

But Fusion Shares Many Drawbacks that Fission does…

- Jassby (2016) points out…
- **1.** Radiation damage to materials in the structure
- **2.** Radioactive waste – radiation damaged materials often end up radioactive.
- **3.** Radiation shielding necessary for workers.
- **4.** Tritium; danger of release from corrosion of heat exchanger or breach of vacuum ducts

- **5.** Nuclear proliferation – easy to produce bomb-grade Pu-239, and tritium could be fairly easily stolen from outside the main reactors as well.
- **6.** Massive coolant demands, needing water which can be heated then returned to environment eco-safely.
- **7.** Operating expenses will be extremely high, and yet even fission reactors are shutting down because, given NRC's politics, they cannot produce competitive electricity prices given solar's dropping prices. The killer drawback?
- **8.** Political pressures will be there, just as for fission, once these radioactive aspects get more public exposure. So far, fusion has been sold on not needing radioactive uranium as fuel, instead inexhaustible deuterium from the ocean.
- Hacking – nuclear plants now the target of foreign computer hackers. The consequences could be… bad. This would be harder for distributed power like roof-top solar and local wind

Nuclear – the Advantages over Solar/Wind

- It's "always on", just like current carbon-fueled power plants. This means minimal change to an existing grid built with this assumption
- They can be sited almost anywhere, weather not relevant (cooling water needed for current designs though)
- They take up VASTLY less land than equivalent solar and wind installations. Costs discussed later
- Carbon footprint is very low, although on-going fueling and enrichment/security costs are significant *vs.* <u>no</u> fuel costs for solar, wind, geothermal, hydro

Nuclear: Eco-Efficient. Virtually ALL species need sunlight. Only ONE species can use Thorium, Uranium

- 33 square miles of PV panels + support area around them, would be needed to replace one 12-acre nuclear power plant (Diablo Canyon Nuclear Power Plant, even with its ancient design), and that's not including the needed storage due to intermittency of solar PV.
- That's a lot of Mother Earth's incoming energy to commandeer for ourselves.
- Plants, animals… all need sunlight. Yet no other species can use thorium except us. Maybe we should consider doing so and leaving the sunlight to the rest of Earth's species (when we can climate-afford to)?

Nuclear – the Disadvantages *vs.* Solar/Wind: Safety

- All conventional reactors are necessarily too big for transportation except big ships, and ~expensive. No car-sized "Mr. Fusion" is on anyone's horizon
- Safety - When they go wrong, conventional nuke can go VERY wrong. In the real world, bad engineers get jobs too.
- They were economically viable only when the government stepped in to insure them. Are they economically viable when they must be privately insured? Any Libertarian wanting to support nuclear should consider that.
- Is no private company willing to insure a nuclear power plant? If there are premiums to be collected over/above the claims to be payed out, why are private insurance companies not looking to exploit this opportunity? …or have they in fact run their own risk/reward numbers and decided it's not worth it? (this is not sarcasm, I'm genuinely wondering).
- There may be solutions to some of these… read on.

One More Slide on Insurance

- I'm continually badgered by a certain person who shall remain nameless…
- ***I'm in favor of ALL power plants being strictly privately insured – renewables too – PROVIDED that <u>true externalized costs</u> are included, and damage to future generations are fully included in all cost models!***

Nuclear – the Disadvantages: Waste

- **Nuclear Waste** – conventional waste is radioactive for tens of thousands to hundreds of thousands of years. Stolen waste can provide the material for a "dirty bomb" with no technological savvy required. A "dirty bomb" can spread radioactivity packaged around dynamite (for example) far and wide and which can be much more damaging and expensive than the dynamite alone can do.
- Merely the threat of using such a bomb can apply great political leverage. Even low grade nuclear waste therefore provides a very tempting target for terrorists. In 2016 Belgium, this is proving to be more than a theoretical threat
- There may be solutions to these problems. Read on…

- These problems do not exist for wind, solar, geothermal, and most likely also wouldn't for modern thorium nuclear designs.

Don’t worry about “The China Syndrome”, worry about the “Homer Simpson Syndrome”

- Nuclear Regulatory Commission employees caught surfing the web for porn while on the job (Washington Times article)
- Regulators sleeping with the industry people (literally) that they’re supposed to be regulating.

How Many Reactors Are Operating Today?

- As of 2021, there were 445 operating nuclear power reactors spread across the planet in 47 different countries [source]. The number has been ~constant since 1986.
- In 2009 alone, atomic energy accounted for 14 percent of the world's electrical production. Break that down to the individual country and the percentage skyrockets as high as 76% for Lithuania and 75% for France [source: NEI].
- In the United States, 104 nuclear power plants supply 20 percent of our electricity overall.
- To run the world on nuclear, it's estimated to require 16,000 nuclear power plants.

MSR (molten salt) Breeder Reactors – The Solution?

- Breeder reactors convert long-lived radioactive waste products into power and into short-lived radioactive waste – requiring storage for ~several centuries, rather than tens of thousands of years as with conventional reactors. They produce nuclear fuel as they run, and so are also extremely fuel-efficient.

- Capital costs are only ~25% higher than for conventional reactors. With the abundance of Uranium, breeders were not thought economical, however with the worries about radioactive waste storage and uranium not abundant enough to completely power the world, they are now more interesting.

Thorium *vs.* Uranium

- U^{235} supplies will exhaust with current designs in a matter of ~century, but with breeders, using Thorium could last for well over 1000 years at current power needs (Shu 2011).
- There's enough thorium lying around already in mine tailings to power the globe.
- Uranium reactors require large starter of U^{235} for fast neutrons for fissioning other nuclei. U^{235} is only 0.7% of natural uranium. Thorium is 400x more abundant

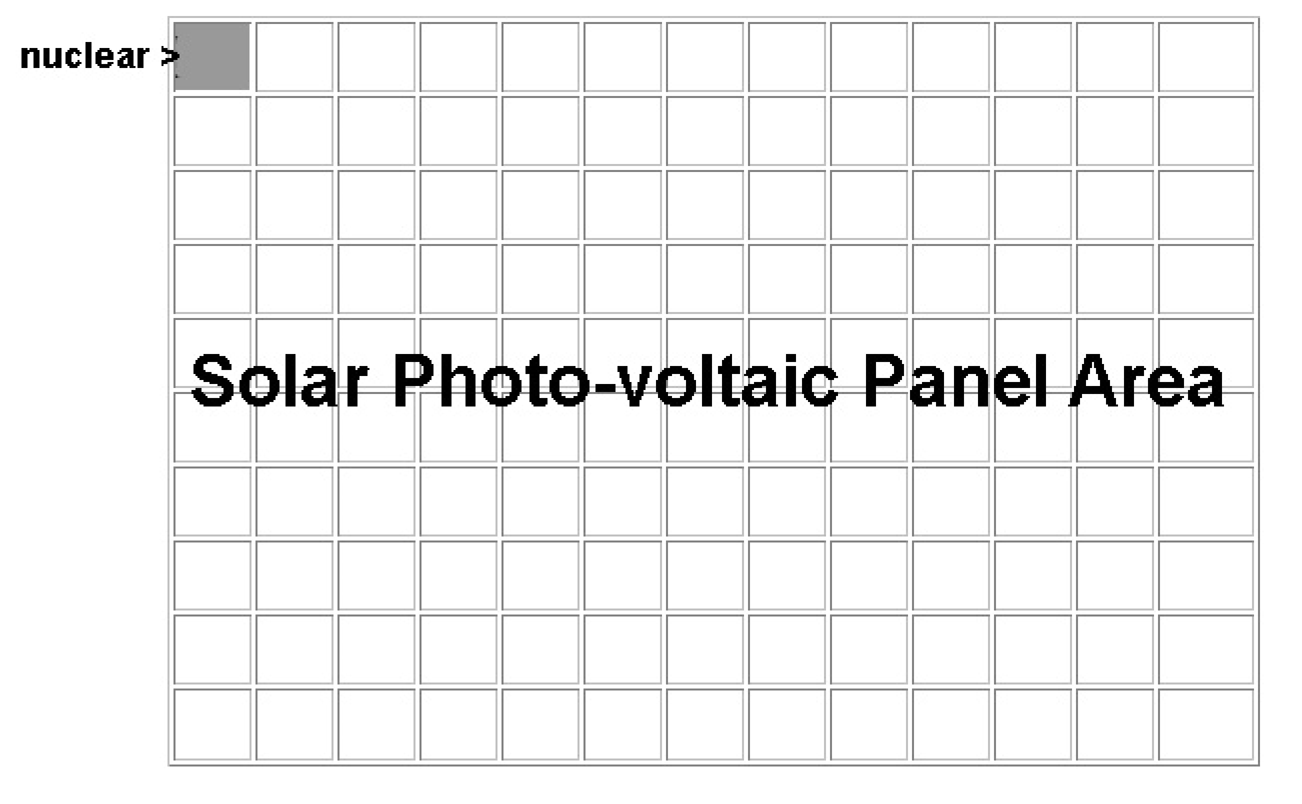
Using existing U^{235} originally purified for weapons, but now for peaceful power, is the logical choice for the fast neutron starter source

- But then, Trump/"Dr Strangelove" nuclear war plans may say otherwise
- For the waste to be safe after just a few centuries, requires very high grade separation of actinide series chemical elements.
- From the Yale 360 forum, this article argues in favor of Breeder technology, and this is a rebuttal. Here is a debate on nuclear for our future, at Stanford University June 2016 (start 12 min in)

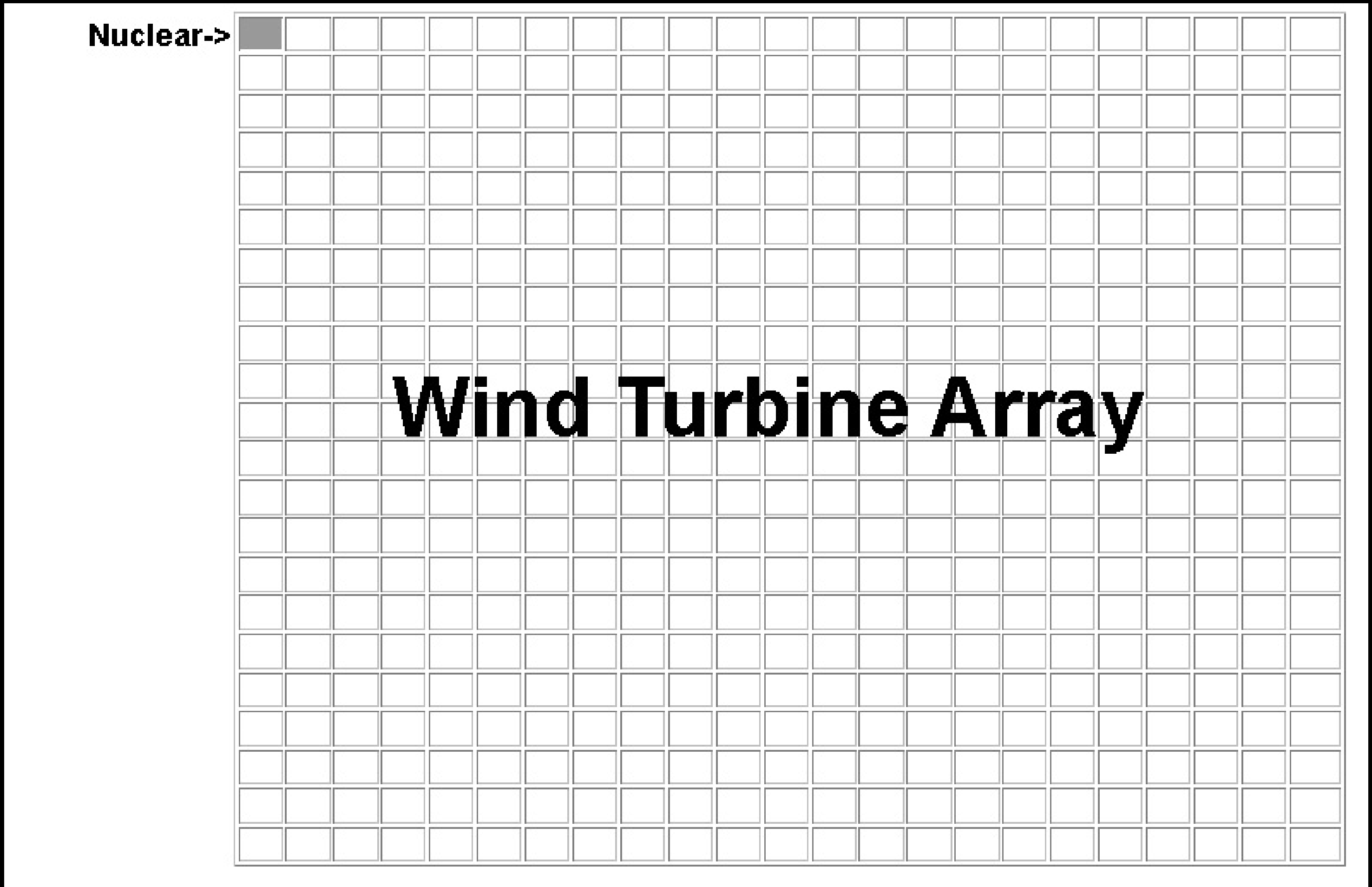
Land: Nuclear Wins Dramatically

- The value and cost of land is almost never explicitly considered by the anti-nuclear people. Wilderness is valued as worthless economically. Yet in a world where un-trampled nature is disappearing fast and faster due to climate change… consider the land needed for equivalent power generation (2.2 billion watts electricity, or 2.2GWe): 67 min into this talk
- Nuclear: 750 acres (at most; consider Diablo Canyon, whose power plant sits on only 12 acres)
- Solar PV: 100,000 acres (more if include storage)
- Wind: 400,000 acres (more if include storage)
- To summarize with images…

The land footprint of a nuclear power plant is less than 1/125th that of the panels alone for an equivalent rated Solar PV plant



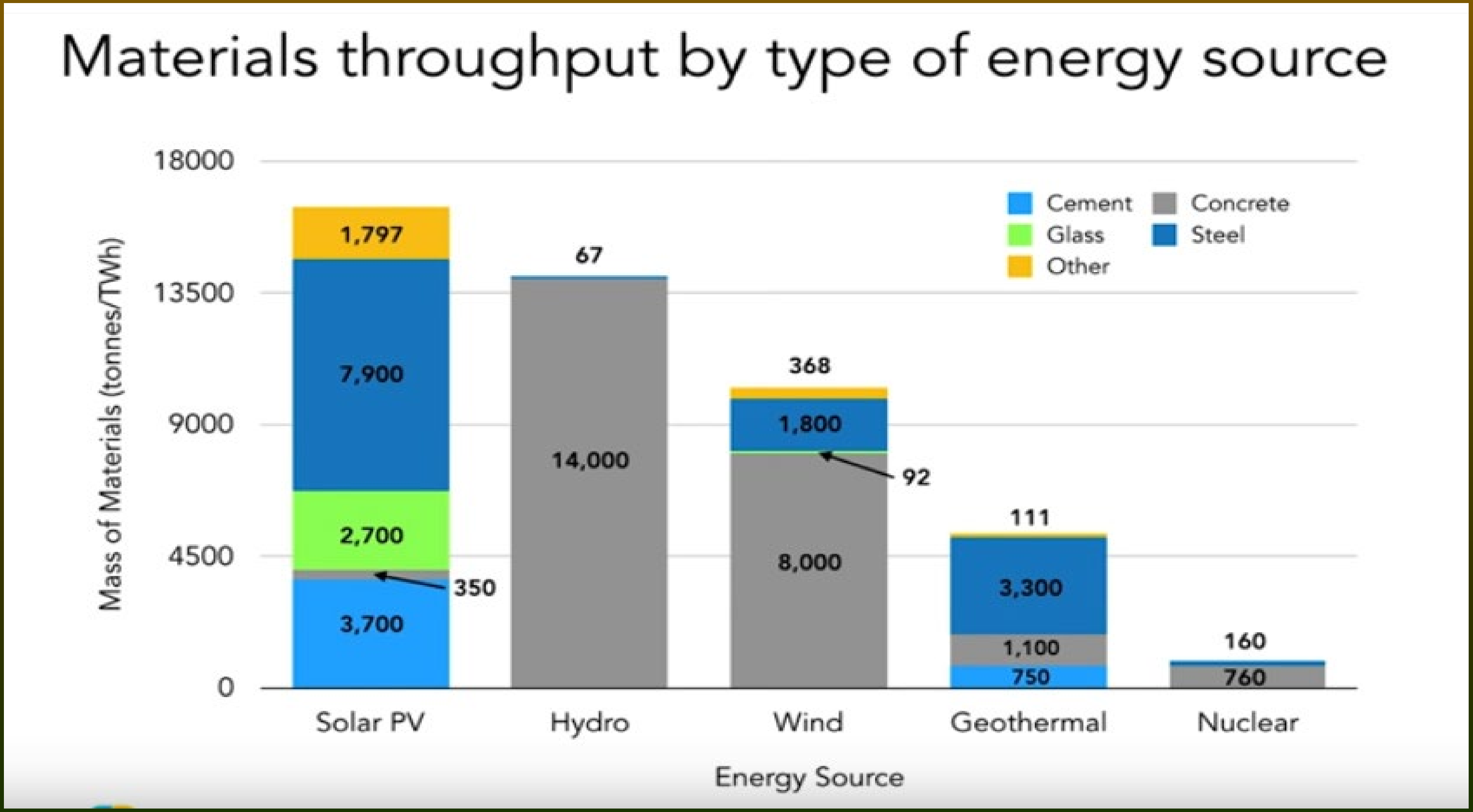
Required area for equivalent wind turbines is even larger: 500 times that for nuclear. But with the important caveat that the land underneath can still be used; *e.g.* agriculture, roads…



The Integral Fast Reactor (IFR)

- Was developed in the 1990’s. A design which made its own fuel with fast neutrons (a “breeder”), produced far less waste than conventional reactors, and was meeting its design criteria very well… when cancelled by Clinton when he came into office.
- A book on the story – written by nuclear engineers involved in the project - is here.

The ecological cost of the mining and materials strongly favor nuclear.



"Throughput" means, at what rate are materials mined and used up, taking into account the replacement time scales.

Source: 2015 DOE Quadrennial Technology Review

This is a Key Point Avoided by Pro-Solar Advocates – The Huge Impact of Mining and of Material Extraction

- Solar PV requires 18x more material throughput than does old style conventional nuclear power, per unit power delivered.
- And over 3x higher than for Geothermal.
- The newer molten salt designs are much better still, in this regard.

Nuclear Safety; a Saner look

- Nuclear has been given an unfair knock from a few media-splashed accidents. Safety/kwh is excellent, but still need private insurance, It was, at one time, realized as a clean and low-cost new power source…. before Chernobyl
- Chernobyl killed only 31 people directly, but estimates of excess cancer deaths from the radiation cloud range from 9,000 (U.N. and Atomic Energy Commission) to 25,000 (Union of Concerned Scientists) to ten times higher (Greenpeace) - it's easy to see the correlation with "green"ness. But is that also "truth"ness?
- Japan's Fukishima disaster in 2011 was the only other "Level 7" nuclear disaster. Direct excess cancer deaths here are expected in the hundreds. Lurid stories of radiation crossing the Pacific to the U.S. are an example of unreasonable paranoia.
- Uranium mining / radon exposure. In early years, this was unappreciated and resulting death rates were high. But conversion of mining to leaching and better air safety standards has reduced radon exposure to about the same as non-miners experience (source)

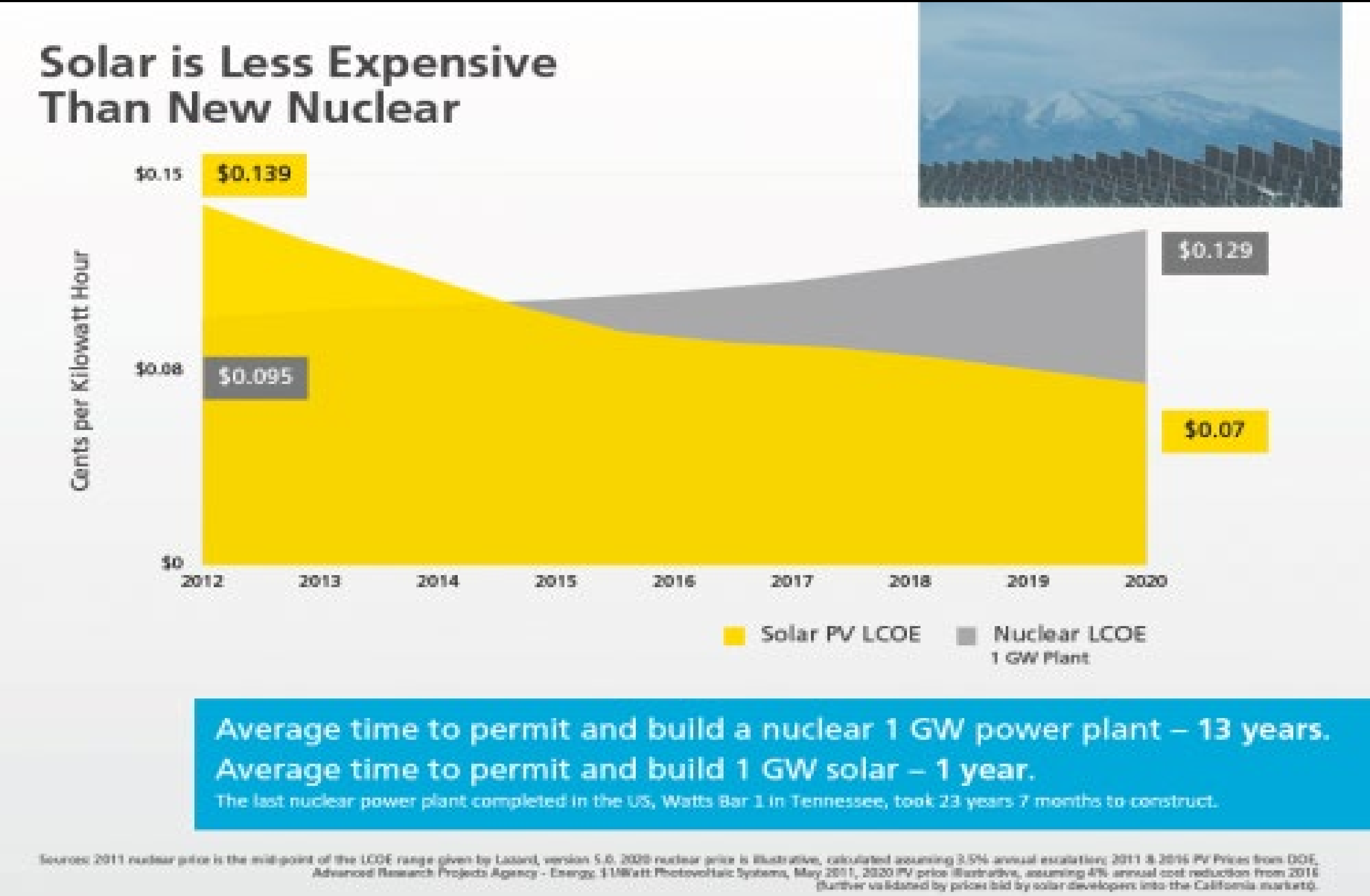
However ALL these death rates *Pale…*

- … in comparison to deaths caused by fossil fuels, even without global warming's future casualties
- Black lung, emphysema, cancer, heart disease, and air pollution's many other health effects.
- 13,000 deaths per year in the U.S. alone from coal dust
- Even hydroelectric has a worse record than nuclear… A string of dam failures in China once killed 230,000 people.
- **Fossil Fuels kill 320 times more people per unit power produced than solar + nuclear combined…**
- **Adding in the deaths global warming will cause show that arguments about nuclear safety, by comparison, are a non-issue**

Energy Source	Death Rate (deaths per TWh) CORRECTED
Coal (elect, heat,cook -world avg)	100 (26% of world energy, 50% of electricity)
Coal electricity - world avg	60 (26% of world energy, 50% of electricity)
Coal (elect,heat,cook)- China	170
Coal electricity- China	90
Coal - USA	15
Oil	36 (36% of world energy)
Natural Gas	4 (21% of world energy)
Biofuel/Biomass	12
Peat	12
Solar (rooftop)	0.44 (0.2% of world energy for all solar)
Wind	0.15 (1.6% of world energy)
Hydro	0.10 (europe death rate, 2.2% of world energy)
Hydro - world including Banqiao)	1.4 (about 2500 TWh/yr and 171,000 Banqiao dead)
Nuclear	0.04 (5.9% of world energy)

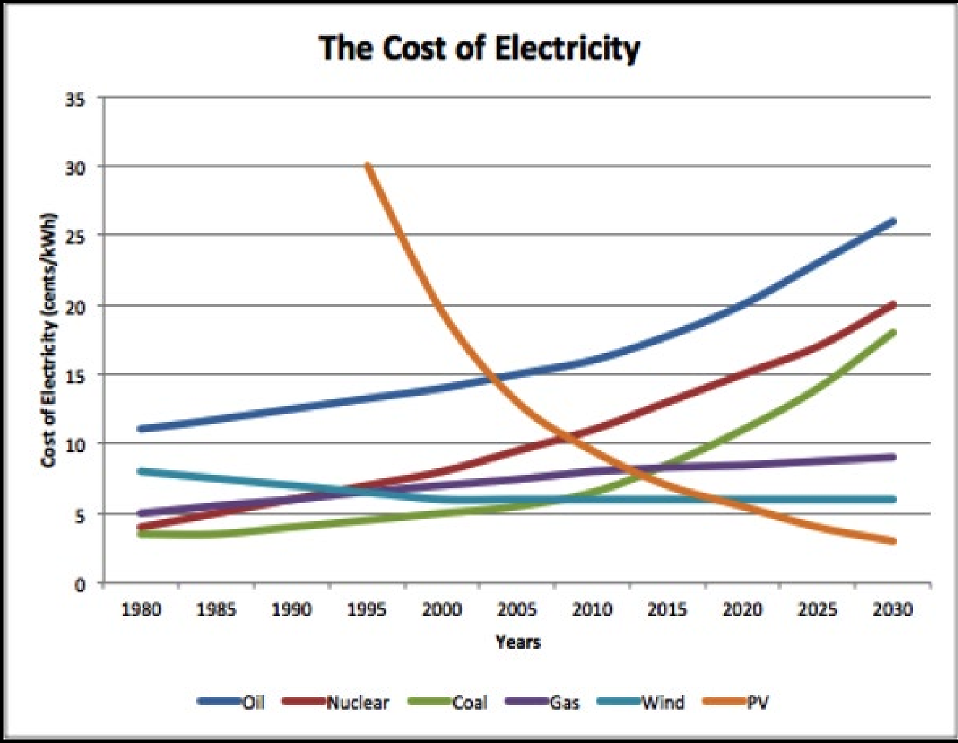
- Fossil Fuels = 164 human deaths/TWh
- Solar = 0.44 deaths/TWh
- Nuclear = 0.04 deaths/TWh = 1/4000th of fossil fuels, but only includes direct short term deaths. Highly contested estimates using the LNT model are higher

The Problem with Existing Nuclear Designs is Escalating Cost: But it's Mostly for Licensing



Most of the cost is political - the time to get permits for a 1 GW conventional power plant: 13 yrs for Nuclear vs. 1 yr for solar (pre-Trump)...

- It will take political will to change this, and shift to MSR (molten salt reactors – which are inherently safe from meltdown or pressurized explosions) technology as well
- Meanwhile, solar costs are projected to continue to fall



Old Style Conventional Lightwater Reactors are Clearly a Loser

- A study commissioned in Germany in 2011 (**here**) finds that insurance would cost at least as much as the electricity produced; $0.20/KwH at a bare minimum, on up to 15 times the price of the electricity produced ($3.40/KwH)
- An amazingly high 50% of the cost of nuclear power is just paying interest on the loans while the plant waits for years to be approved and licensed by the (anti-nuke) Nuclear Regulatory Commission (31 min into this interview of energy expert Saul Griffith) (!)

But There's an Even Bigger Problem with Going Nuclear…

- We won't solve climate change unless we eliminate nearly all carbon emissions GLOBALLY.
- The rapidly rising CO2 emissions are coming from the 3rd world, not Europe and the U.S.
- **So…** here's the big question:

Will the U.S. and Europe and their engineers provide the technology, knowledge and nuclear materials…

- …to countries like Iran, Syria, Egypt, Yemen, Somalia, Libya, other African dictatorships, etc, to help them transform their energy system to nuclear, as they envy American wealthly lifestyles and energy footprints?
- **Seems unlikely**, especially in a world entering an era of climate chaos, desperation from "have not" countries, rising tribalism, and walls going up on national borders, and the very real possibility of societal breakdown this century.

My Thoughts

- The danger of climate change catastrophes rises with every new day of research that comes in, and every new day of institutional foot-dragging.
- Beyond replacing fossil fuel energy currently, we must remove our portion of existing CO2 from the atmosphere. Carbon-neutral alone will not save us from serious and permanent climate change.
- It may be that the best way of powering the large energy needed to pull CO2 out of the atmosphere and sequester it, is modern MSR breeder nuclear power.
- Breeder technology makes the most use of available isotopes, insures the long term smallest and safest nuclear waste. Recent issue of the APS and articles on nuclear fission and fusion prospects

Ideological Blinders!

- Ideological emotions cloud both sides of this pro/anti-nuke debate, in my experience. I’ve been attacked for being pro-nuke. I’ve been attacked for being anti-nuke. Unless I have respect for their judgment, I’ve learned to not care much about people’s emotional reactions to my thoughts, beyond heated frustration, but instead to follow the advice in my own Chapter 0…
- **Mother Nature doesn’t care about my opinion, nor yours. Only about the unchangable Laws of Physics. We either obey HER laws, or there’ll be HELL to pay**

As an Example of Blinders

- Conventional uranium nuclear reactors use less than 1% of the available nuclear energy in the fuel, the rest being left as radioactive "waste". This waste could be used for power in modern breeder reactors, which could extract as much as 100x as much energy from uranium or thorium (wikipedia).
- Otherwise, we need sequestration sites (like Yucca Mountain, NV) which must be geologically stable, and kept from ground water for hundreds of thousands of years
- Yet I've not heard a single anti-nuke person advocate making at least a few breeder reactors simply to "burn" the waste from old-fashioned nuclear reactors and turn it into useful power; solving much of this nuclear waste problem.
- Isn't that interesting? Isn't that telling?

From Award winning and very pro-environment journalist George Monbiot

- *"You will not be surprised to hear that the events in Japan have changed my view of nuclear power. You will be surprised to hear how they have changed it.* ***As a result of the disaster at Fukushima, I am no longer nuclear-neutral. I now support the technology.***
- ***A crappy old plant with inadequate safety features was hit by a monster earthquake and a vast tsunami. The electricity supply failed, knocking out the cooling system.*** *The reactors began to explode and melt down. The disaster exposed a familiar legacy of poor design and corner-cutting. Yet, as far as we know, no one has yet received a lethal dose of radiation. (400 are projected to die in the future)*
- *Some greens have wildly exaggerated the dangers of radioactive pollution. For a clearer view, look at the graphic published by xkcd.com. It shows that the average total dose from the Three Mile Island disaster for someone living within 10 miles of the plant was one 625th of the maximum yearly amount permitted for US radiation workers.*
- *This, in turn, is half of the lowest one-year dose clearly linked to an increased cancer risk, which, in its turn, is one 80th of an invariably fatal exposure.* ***I'm not proposing complacency here. I am proposing perspective."***

What should power the grid into which your rooftop solar pumps its power?

- There's a strong case for nuclear. If it can be insured and safety from radioactive material theft is insured. That may require continued Federal govt insurance as we have today.
- Given the fact of night-time, it would seem that (absent very large storage capability) stable power would have to be transmitted over vast international distances – and given the growing isolationism as climate chaos begins, this is tough to imagine as a secure power system.
- My biggest problem with solar/wind to power the world is the **huge footprint on Nature**

Molten Salt Thorium Reactors – Melt-downs are Impossible

- A de-centralized power grid, minimizing high tension lines from juicy terrorist-target big power plants, is a worthy goal, with power generated by rooftop solar as much as possible, and electric vehicles for transportation.
- But for the needed safe, constant-on power, with minimal footprint on Nature, I find the argument for molten salt thorium breeder nuclear power to be very strong.

I, Like Many Environmentalists (and Other Species on this Shared Earth) Value Un-trampled Nature

- Unfortunately, at this very late date. We need a political reversal that streamlines modern nuclear designs rather than let them collect dust in “in-baskets” at the NRC, too timid against the ill-informed knee-jerk anti-nuclear public.
- Solar and wind are now cheaper, safe, and faster to approve, permit, and build.
- **Alas, this means vast tracts of land covered with solar PV installations, and giant wind turbines blighting the horizons.**

But is Solar / Wind Climate-Scalable?

- In 2020's new work is showing that the vast materials needed, when energy storage is included, makes an exclusively solar/wind powered world unfeasible (e.g. see Michaux 2023), GTK 2021, recent talk w/slides.
- Michaux argues that realistic intermittency requires ~4 weeks of energy storage. With available technology, this is impossible. E.g. 180 years worth of current copper production to enable. Worse for many rare metals.

Long Term: A Nuclear Always-On Grid with Supplemental Solar Rooftop and some Wind?

I personally hope that some day, if, against all odds, we stabilize climate through a combination of deep cuts in Civilization and massive decarbonization, that we can gradually replace hundreds of thousands of square miles of solar arrays on otherwise virgin land, with safe breeder reactors, and reclaim 99.5% of the land which went for utility scale solar and wind

In 2017: At the Bonn COP23 Climate Talks, an Interview…

- With Dr. James Hansen and Dr. Michael Shellenberger (founder of "Breakthrough Institute" and "Environmental Progress" Institute) give sober science and data on nuclear power and renewables, making a strong case that nuclear needs to be part of the solution, and that it has been the victim of unwarranted knee-jerk fear from science-ignorant environmentalists.

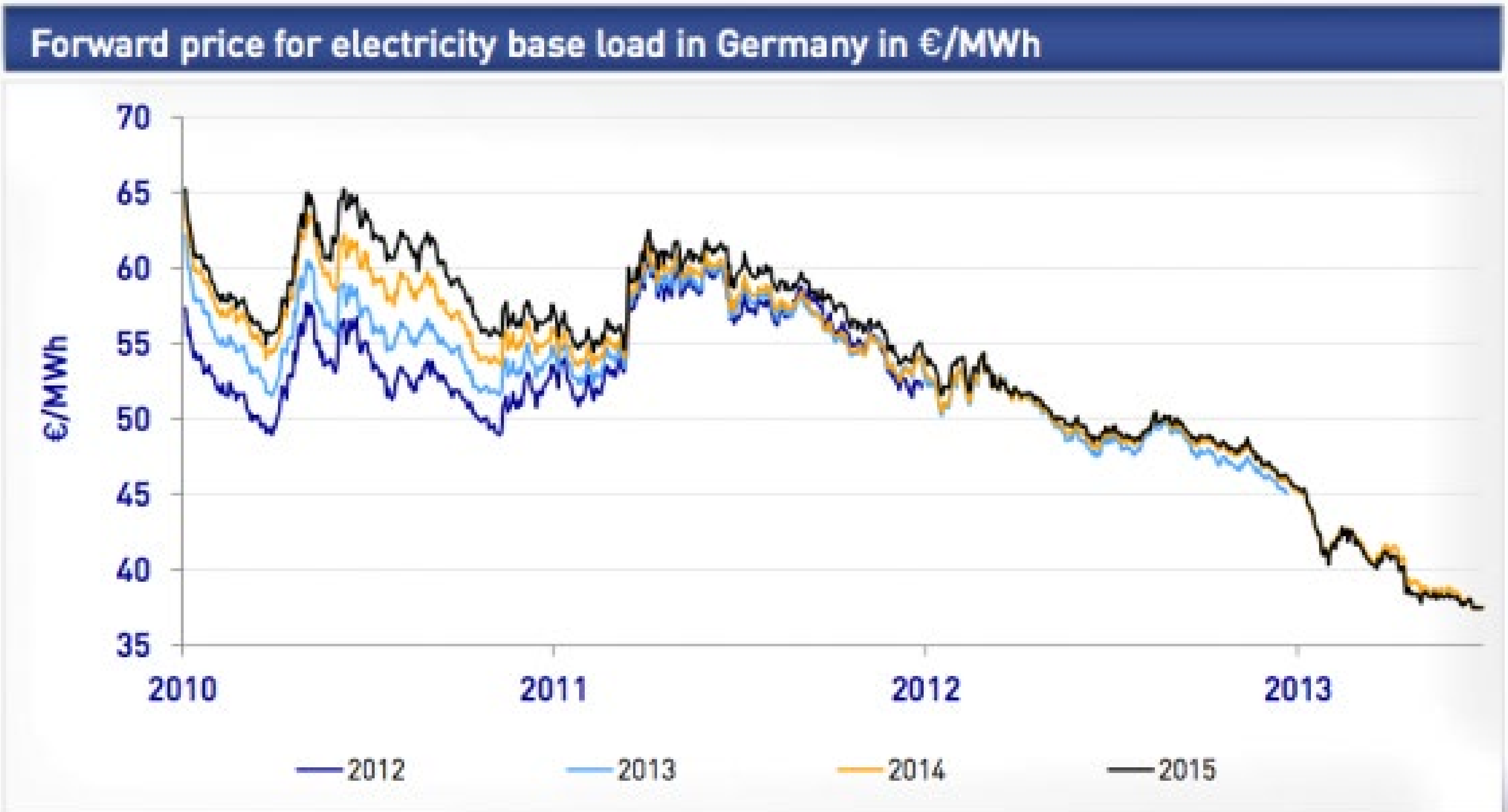
G. Shifting from Conventional Utilities to Distributed Energy Ownership and Generation – Issues…

- Good article (2014) here. Summary:
- *"Vattenfall, a Swedish utility with the second-biggest generation portfolio in Germany, saw $2.3 billion in losses in 2013 due to 'fundamental structural change' in the electricity market. The problem is well documented: high penetrations of renewables with legal priority over fossil fuels are driving down wholesale market prices -- sometimes causing them to go negative -- and quickly eroding the value of coal and natural gas plants. At the same time, Germany's energy consumption continues to fall while renewable energy development rises."*
- All it took is strong legal framework. Government commitment to a renewable future.
- Will it continue? Uncertain, as political resistance continues

Germany's War on Fossil Fuel: Cross Fire from Industry, Customers

- *"To make matters worse for (conventional fossil fuel) utilities, their commercial and industrial customers are increasingly trying to separate themselves from the grid to avoid government fees levied to pay for renewable energy expansion."*
- According to the *Wall Street Journal*, 16 percent of German companies are now energy self-sufficient – *vs.* 10 percent from just a year earlier. Another 23 percent of businesses say they plan to become energy self-sufficient in the near future." Again, to avoid govt fees levied to pay for renewables

Rapidly Dropping Energy Costs are Making an Impact in Germany. But heavy subsidies helped greatly, and manufacturing from the 1st world has been rapidly exported to 3rd world, whose carbon emissions have skyrocketed)



But Look Closer at the German Miracle…

- Germans pay over 2x as much for energy as their neighbors in France. Why?
- France is powered mostly by nuclear power.

The Staggering Impact on Natural Resources for these High-Tech Solar/ Battery / Storage Needs

- Herrington *et al.* 2019 show that to meet… "*electric car targets for 2050, we would need to produce just under two times the current total annual world cobalt production, nearly the entire world production of neodymium, three quarters the world's lithium production and at least half of the world's copper production.*"

While You Let That Sink In…

- … these vast resources are not what's required to satisfy GLOBAL electric car demand for zero emissions.
- No, this amount of mining, even if possible…

- **…is just to meet the EV car promises for zero emissions in the tiny <u>United Kingdom alone.</u>**
- **Also, China controls nearly all rare Earth supplies at mine-able ore quality.**

Part 3

Reducing Carbon from Existing Energy Sources, and Using Plants to Capture Carbon

Reducing Carbon from Existing Energy Sources

- **We produce ~37 billion tons of CO_2 per year… ideas for capture:**
- Using microalgae to remove CO_2 from coal flue gas. Acidic flue gas reduces CO_2 uptake greatly.
- **The Economics of CO_2 Separation and Capture (Herzog MIT, late '90's)**
- Other processes have been considered to capture the CO_2 from the flue gas of a power plant -- e.g., membrane separation, cryogenic fractionation, and adsorption using molecular sieves – but they are even less energy efficient and more expensive than chemical absorption. This can be attributed, in part, to the very low CO_2 partial pressure in the flue gas. Therefore, two alternate strategies to the "flue gas" approach are under active consideration – the "oxygen" approach and the "hydrogen" or "syn-gas" approach.

Herzog estimated that by 2012…

- CO2 removal from coal flue gas would cost as little as 1.5 cents per kWhr (but it hasn't worked out that way… **at all!**).
- Gasify'ing coal allows up to 65% of the CO2 to be captured, according to industry sources. Are such "industry sources" to be trusted? Skepticism is warranted.
- IPCC Report on Carbon Capture
- Again, strong flavor to "rosy up" the projections by policy people, *vs*. energy analyst Vaclav Smil who estimates scrubbing 20% from our emissions would take 70% more than the entire capacity of the petroleum industry flow rate.

Despite Continued Talk from Fossil Fuel Advocates that CCS is the Answer

- The truth appears otherwise. Here's the CEO of the largest private coal miner in the U.S. saying – "Clean Coal and CCS doesn't work"
- It's too expensive compared to renewables.
- A new study (Rosa *et al* 2020) also finds that almost half of the coal fired power plants do not have enough accessible water to enable CCS.
- Worse: A new study (Mountain 2020, discussed here) finds the cost of CCS is 6 times higher than Wind+Storage

What About Ideas from the Coal Companies Themselves?

- Our naivete, our trusting respectfulness to those destroying the future, our "pillow fight" refusal to engage fully, has encouraged more of the same nonsense we've always gotten…
- Marketing-as-solution: Rename coal?!
- and…

Disregard the ***Clean Coal Carolers***

Carbon Capture by Soil, Grassland

- Alan Savory promotes reducing overgrazing by judiciously confining and moving cattle around on rangeland can make a healthier grassland, sequestering additional carbon in the root systems and helping against desertification.
- But topsoil is on average only 8” deep (and getting thinner), and once filled with roots, it’s very slow to build new topsoil (1 to 2 cm per thousand years) unless the soil is already there. So, how widely applicable?

- This proposed livestock strategy is labor-intensive and such costs are not adequately addressed. There's nothing particularly new about this sort of basic cattle raising, and if it hasn't already been done by ranchers, it's the cost, especially on a global scale.
- The COST of food; rising food costs globally causes famine and revolutions.
- Merely advocating "Go Organic" is not enough. Need better insight into why it hasn't happened.

- A new study finds there is a definite positive effect on net carbon by using the ideas of intelligent movement of cattle on rangeland. (Stanley *et al.* 2018), approximately neutralizing the negative effect of beef from so high up the food chain
- However, this study was done in the American mid-west – famous for its very deep topsoil, which therefore has a larger capacity to sequester additional carbon. In the famously thin and poor soils of the tropics and other places, we should expect less.

Tropical Reforesting with Sugar Palms?

- This project would re-forest degraded areas of Borneo by planting sugar palms, which can produce optimally 36 tons of sugar per acre per year.
- Can convert to 19 tons of bioethanol
- These trees require no fertilizer or pesticides, and basically are solar energy converters *via* biology. But photosynthesis has notoriously low efficiency, of 0.3%– **you get only 1/30th of the energy than if same area were covered in solar PV**.
- How will this affect local ecologies *vs.* simply letting degraded land re-forest naturally. Very likely - badly

Organic Farming and Carbon Sequestration in Soil

- Soil can hold more carbon in roots, but only until the topsoil has a climax community above it
- Claims that organic farming can sequester enough carbon to halt CO_2 rise (**Rodale white paper**), neglect this key fact and are at strong variance with nearly all authoritative studies cited by the IPCC.
- Note: Rising soil temperature increases carbon oxidation and returns soil carbon to the atmosphere as CO_2, and cooler soil temperatures do the opposite (Post *et al.* 1982). Note the rich carbonaceous soils of the rain forests of the Pacific Northwest, for example, and the famously poor soils of the tropics.
- Therefore global warming will be taking carbon OUT of the soil INTO the atmosphere, independent of soil management. We saw this, strongly, in 2015-2016 especially in the Amazon.

Potential Carbon Uptake with Best Ag Management Practices

- A good review paper (Stockmann *et al.* 2013) with comprehensive links on soil organic carbon (SOC) and soil carbon sequestration (SCS)
- Returning cropland to forest or pasture has the most potential for increasing SCS (Post and Kwon 2002) (but then, where to grow crops??)
- *The IPPC (Smith et al., 2007) AR4 digestion finds an annual sequestration potential of 1.4–2.9 Gt of CO_2-equivalents through global agricultural soils, where soils would reach C saturation after 50–100 years.* (sec. 5 of Stockmann *et al.* 2013)
- **Great. But this is only ~5% of annual global anthropogenic CO2 emission rates**

Best Organic and "No Till" Soil Practices: Still, Potential Soil Carbon Sequestration Rates are Small *vs.* Human Emissions

- Stockmann *et al.* 2013 sec. 5 continued…. (NT="no tillage of soil")
- *"In contrast, a recent publication by Chatterjee and Lal (2009) suggests a sequestration potential of agricultural soils of up to 6 Gt of CO_2-equivalents per year by 2030* (=about 15% of human emissions)*. In this regard, Table 7 summarizes potential rates of SOC sequestration by adoption of best management practices for principal biomes whereas Table 8 compiles actual measured rates of SOC sequestration."*

"No Till" Has only Limited Effect on Soil Organic Carbon

- *"For instance, most meta-data analysis (Table 8) suggest that if NT farming is adopted, there is a slight overall increase in SOC in the surface soil compared to full-inversion-tillage (FIT) and that this increase improves with time (Angers and Eriksen-Hamel, 2008, Luo et al., 2010a and Virto et al., 2012). However, when considering the whole soil profile, there seems to be a limited effect of NT on SOC stocks (Luo et al., 2010a). Virto et al. (2012) found that some of the variability (up to 30%) in response to NT can be attributed to differences in yield and C inputs. As seen in Table 8 there are some case studies where NT does not increase SOC (e.g. Loke et al., 2012) or where NT results in SOC increase at very great depth (Boddey et al., 2010)."*

<u>So, No-Till Helps SOC, but amount is likely small, and in dispute. And…</u>

- Can we do this and still feed 7 billion people affordably? We have put our soils "on steroids", stripping them of natural nutrients and force-feeding nitrogen chemical fertilizers, and used today's massive monoculture Ag practices <u>**precisely because this is the most cost-effective way**</u> to get crops out of the soil with the least labor cost.
- Selling price minus cost means everything to a farmer. We see riots when basic staple crops rise in price even by just 20-30%, (*e.g*. "Arab Spring" revolutions)
- <u>Worse, modern Ag practices are causing topsoil loss of 1%/year, leading to estimates we have only ~60 years of topsoil left at current trends.</u>

Faulty Measuring Has Overestimated the Speed of Soil Carbon Uptake

- He *et al.* (2016 and discussed here) use radiocarbon dating of over 150 global soil 1m depth samples to measure the age of their carbon, to determine that Earth System Models relied on by the IPCC in their summaries have overestimated the rate of carbon uptake by ~40%.
- They conclude that *"it will take hundreds or even thousands of years for soils to soak up large amounts of the extra CO2 pumped into the atmosphere by human activity – far too long to be relied upon as a way to help the world avoid dangerous global warming this century."*
- …the prospect of adapting soils so they suck up more carbon is "unlikely", especially in the short-term, according to He.

Agenda-Oriented "Cowspiracy" Film has Sidetracked Some

- This rather strident film starts by claiming that 51% of greenhouse emissions come from animal agriculture. This is just bad-math false. The claims come from 2 people in a non-peer-reviewed article. Their big boost to CO_2 accounting comes from counting the exhaled breath of the animals, and ignoring that plants also "breathe out" CO_2 at night.
- Proper accounting says much less. IPCC AR5 summary of peer-reviewed science finds the figure is about **18%.**
- At my own public talks, I can attest that this film, hyped by a certain local gadfly, has deflected some attention and efforts away from the real culprits, which is the global fossil fuel industry.
- **Beware of agenda-driven false claims, even among climate-friendlies.**

Related: The Republican Meme "CO_2 is Plant Food!"

- This is a popular come-back from Republicans in favor of laissez faire fossil fuel burning
- It's refuted by the data. A 700 year long study of trees in Canada shows that since 1850, when CO_2 levels really began rising due to fossil fuel burning, right up to today… that the added CO_2 has not aided tree growth (Giguere-Croteu, et al. 2019)

BECCS = BioEnergy with Carbon Capture and Sequestration

- The UN, through the IPCC, has promoted this idea. But it has major flaws…
- The idea is to grow trees specially for burning as power sources, but doing the burning in such a way as to capture the CO2 and then sequester the carbon somehow.
- Looks phenomenally expensive; requiring re-purposing an area 150% of the size of India just to stay within the (overly rosy) IPCC scenarios to keep to +2C using weeds.
- Or much worse – an area 3x the size of the U.S. to capture the 38 billion tons of CO2 we emit annually.

BECCS: A Contradiction

- The problem is that forests sequester carbon far too slowly, and would take ~4x India's area for tree-growing and then burning, to sequester our annual CO2 output.
- Weeds grow up to 4x faster. Still, that's **An India size area of weeds to be repeatedly burned. Do we have a spare India's worth of land for weed-growing? Obviously not.**

- *“Once you create a demand for biomass, this demand usually increases to a point where local biomass does not suffice, or competes with other types of biomass, such as food crops. I have seen these schemes come into being AND fail in my country every single time in the last 4 decades precisely because of that reason. Every time, they had to start importing biomass from abroad. When there is a price spike for whatever reason (storm at sea, lower price of competing energy plant) these businesses fail, and that is even without the negative impact they have on biodiversity. They always require the introduction of monocropping to guarantee a predictable production and burn rate, because 'mixing' never works. Beyond very local small scale schemes, they lead to environmental tragedy.”*
- *-J. Luypaert here*

At least, we do know how to burn trees and weeds. We see them on fire more and more these days

BECCS and Soil Health

- BECCS removes carbon, but also nutrients and minerals from the soil, impoverishing it, accelerating erosion and desertification.
- Plenty of experience on the soil implications of grow/remove from our decades of tropical deforestation.
- Artificially fertilize denuded soil? Then what about the NOx greenhouse gases that result, and that we're trying to get rid of by "going organic" in the first place?

BECCS Causes MORE, not LESS Environmental Damage

- The Potsdam Institute for Climate Impact Research (#1 rated institute by U. Penn) has published in *Nature: Climate Change,* finding that BECCS is dangerous to several planetary boundaries (Heck *et al*. 2017)…
- *"We show that while large-scale BECCS is intended to lower the pressure on the PB's (**p**lanetary **b**oundaries) for climate change, it would most likely steer the Earth system closer to the PB for freshwater use and lead to further transgression of the PB's for land-system change, biosphere integrity and biogeochemical flows.*

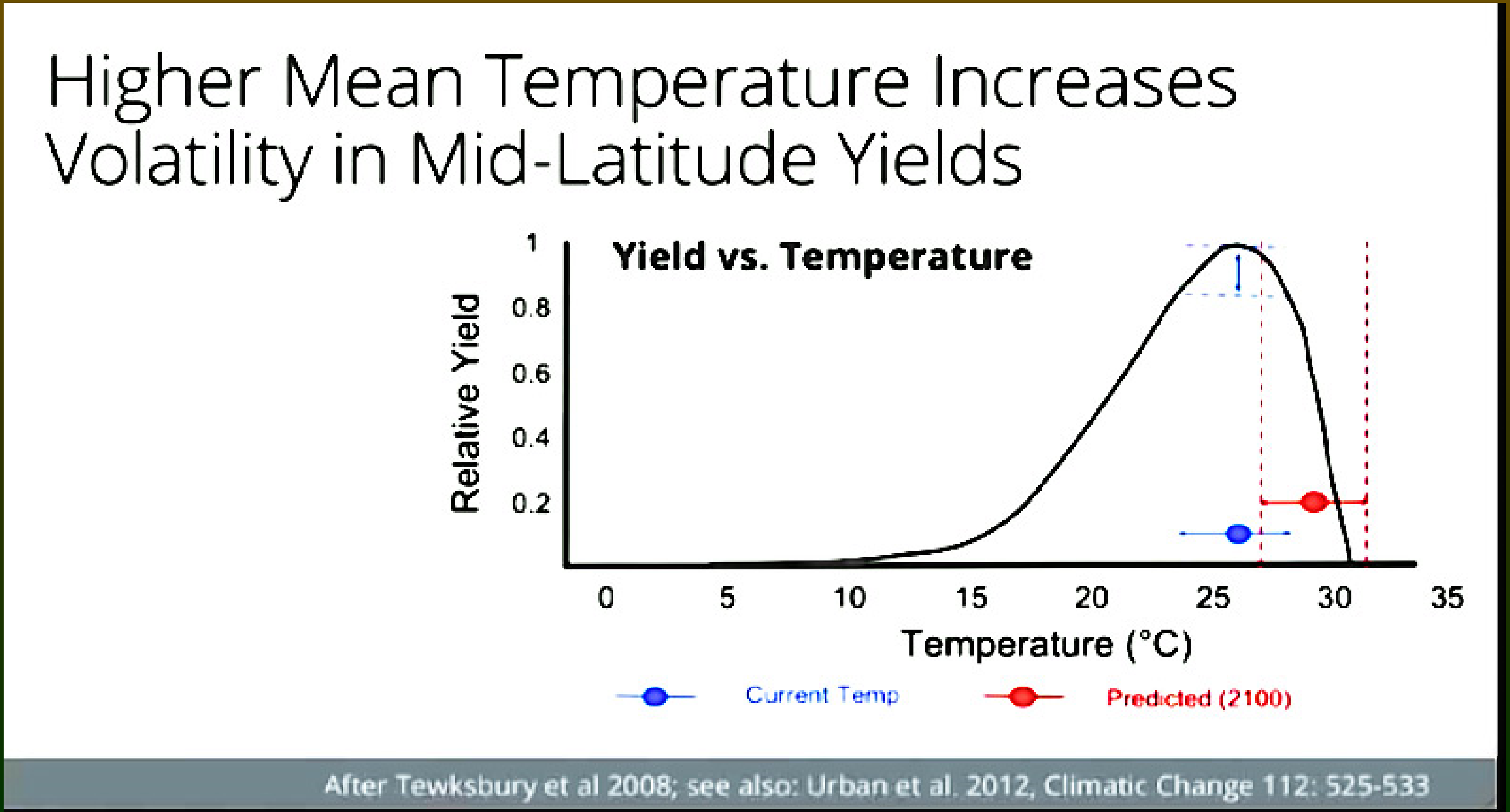
Crop Yields Peaked a Decade Ago. However….

- Young scientists (winners of the 2014 Google Science Fair) appear to have made a significant advance:
- Irish teenagers Ciara Judge, Émer Hickey and Sophie Healy-Thow, all 16, won the Google Science Fair 2014. Their project, Combating the Global Food Crisis, aims for a solution to one cause of low crop yields by pairing a nitrogen-fixing bacteria that naturally occurs in the soil with cereal crops it does not normally associate with, such as barley and oats.
- The results were encouraging: they found their test crops germinated in half the time and had a dry mass yield up to 74 percent greater than usual.
- Maybe we'll again GMO our way to another few years, further stripping Nature, before it all catches up with us?

But the Real Killer of crops is Temperature

- The big staple crops – corn, wheat, rice, grains - grown to feed the billions in the tropics and lower-mid latitudes, are already living above their optimum temperatures
- Why not just breed GMO heat-tolerant staples?
- We've been trying to do this for over 30 years now – **with no success**. Biological processes are EXTREMELY temperature-sensitive (last 20 min of this lecture by Prof. David Battisti)

As temperatures rise, even mid-latitude crop yields (and also carbon sequestration in soil), plummet. One heat wave can completely kill vast areas, later this century



Stopping Tropical and Mid-Latitude Deforestation.

- Deforestation adds carbon to the atmosphere in two ways – by ending the sequestering happening in living trees, and by letting the carbon they have already sequestered, slowly or rapidly (slash/burn) return to the atmosphere.
- Also, hurts low cloud formation (climate coolants), and doesn’t raise albedo enough to compensate for these warming forcings.
- New initiatives in tropical Africa may replant trees on millions of acres of land.

Boreal (far North) Re-Forestation: Not at all Clear That Helps Us

- It's not clear whether deforestation in the far north hurts, or instead actually helps climate, since deforested land here reflects <u>more</u> sunlight, even though it doesn't sequester the same amount of carbon. Bala *et al.* 2007 find albedo heating effect of trees dominates their carbon sequestration effect. (see Part 3 starting a few slides later here).
- Remember that carbon can only be removed from the atmosphere by a tree until the tree reaches full adult size.
- But, brighter more reflective treeless landscape is a permanent cooling forcing to climate, by reflecting more sunlight.

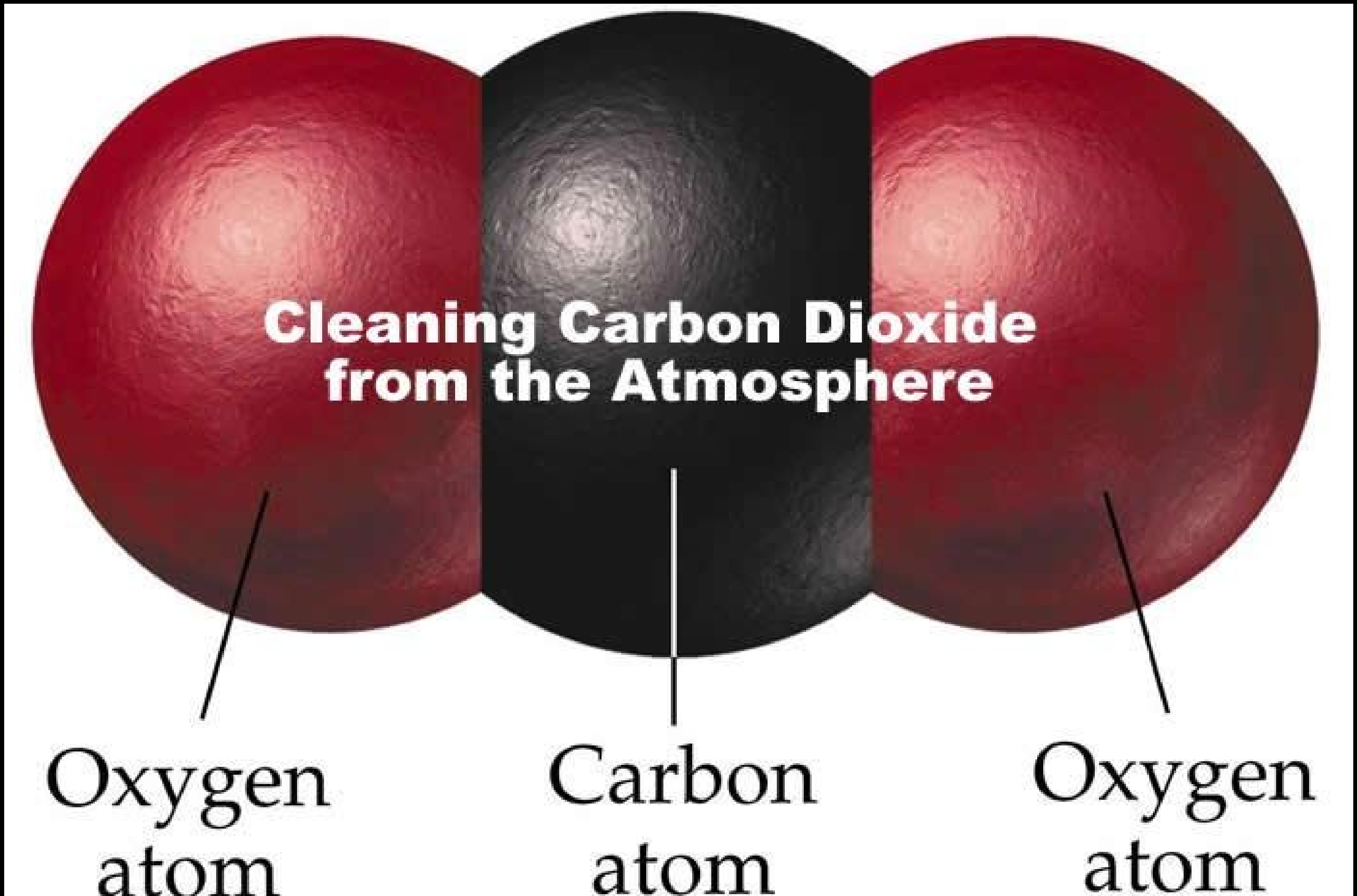
… Rebuttal from Nelson *et al.* 2010

- However, unlike tropical forests, boreal forests sequester 85% of their carbon underground, and tree loss will cause much more carbon release than just the tree mass Bala assumed.
- Also, climate change is already reducing snow coverage in spring and summer, when albedo matters, so albedo changes may not be as significant.
- They conclude preserving Boreal forests is a necessary part of combating climate change

If Yours is Goal #1 – To Halt Climate Change…

- We'll have to do all of the above, and much more – we'll have to quickly undo the damage we've done, and reverse the existing climate forcing.
- A. Removing carbon from the atmosphere
- B. GeoEngineering strategies to cool the Earth (chapter my K46)
- C. Population Control, Other Policy Strategies (review my K44)

Part 3: Atmospheric CO2 Removal



Strategy: Plant Trees – They've evolved over millions of years to extract CO_2 and sequester it as hydrocarbons

<u>Advantage:</u>

Low tech. Given the political will, millions of people could be employed immediately to plant trees with minimal training. This is important – we need IMMEDIATE solutions in order to avoid long term disaster. But, they'd better be happy working for free.

- New initiatives in tropical Africa may replant trees on millions of acres of land

Planting parties – fun! Build a sense of shared effort towards our future

But, Tree Planting Looks to be Too Little and Too Late

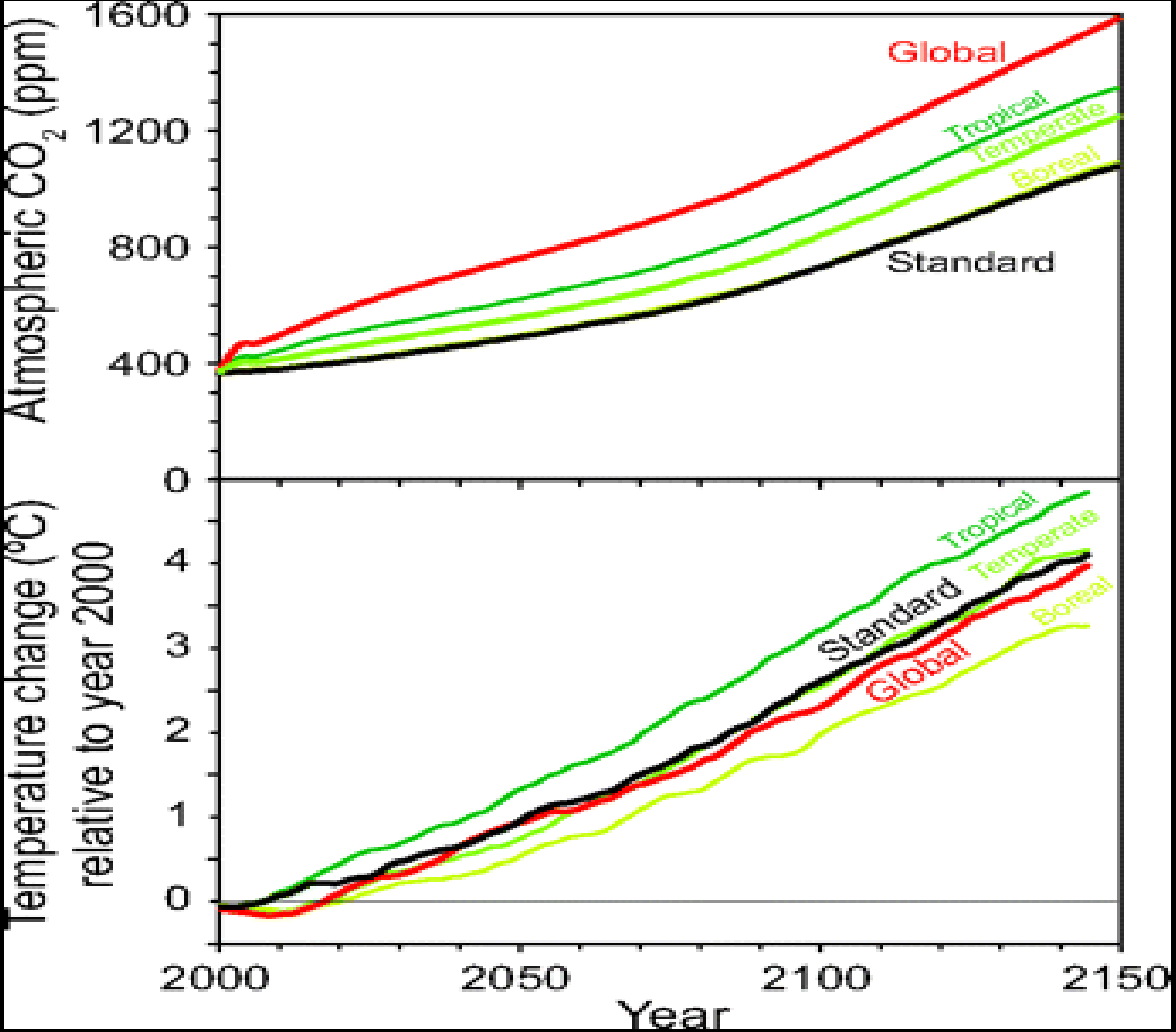
- --- Where do we plant them? The reason most of our forests are gone is that we wanted that land to grow crops and feed stocks, and pave it over for cities and houses. Over 90% of all arable land on Earth has already been converted to agriculture and other human use.
- --- In a rapidly changing climate, can we plant trees in a place where they will thrive for decades to come?
- --- Worse, tree planting will only help a little: This IPCC report, described more digestably in this article, finds that planting trees will only sequester about 1.4 gigatons of CO_2 per year; *vs* 38 gigatons of human-generated CO_2 emissions per year as of 2015.
- In other words, only ~4% of current emissions.
- It turns out to be even trickier…..

Trees: Albedo *vs.* Carbon Uptake

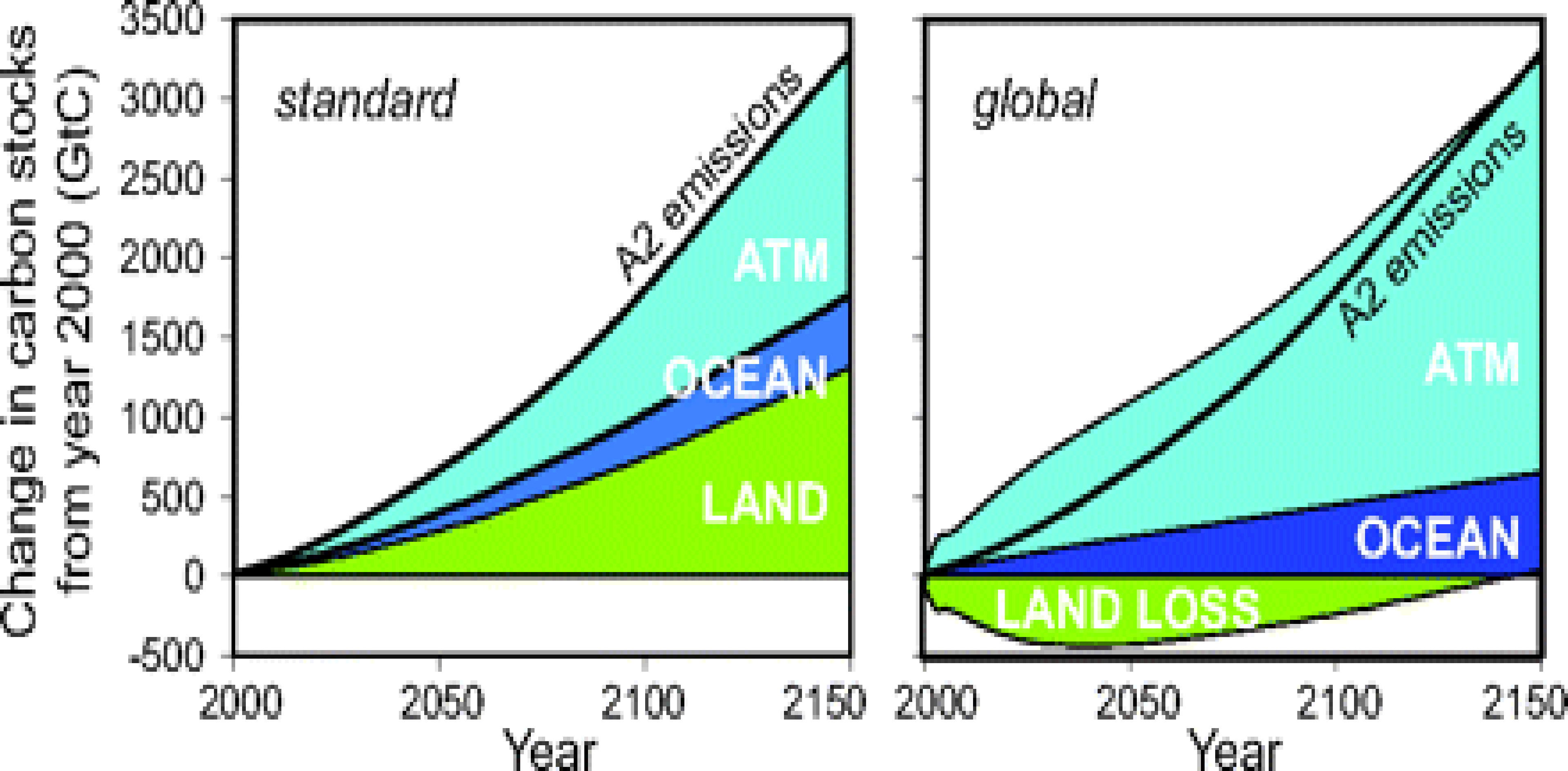
- The dark color of forests means they absorb more solar energy than the grasses that would replace them, and according to one study, actually heat the Earth, with the effect stronger at higher latitudes. (Bala *et.al.* 2007)
- Especially true in the far north, where winter snow is highly reflective while dark conifers absorb sunlight. In the tropics, there's ~no snow so the difference in albedo is much smaller – thus the dominant effect is the longer term sequestration of carbon that trees provide.
- There are three other effects of trees that both cool climate:
- --- 1. Evapo-transpiration; taking water from the ground and evaporating in leaves into the air absorbs the latent heat of evaporation from the environment
- --- 2. This evaporation also promotes the formation of low clouds, which also cool climate
- --- 3. Trees take up CO2 out of the atmosphere to build their tissues

Trees: 3 cooling effects, and one heating effect

- Finding out the net of these was the subject of the Bala *et al.* study. See summaries here Lawrence Livermore Labs 2006 study, and also here.
- Lee *et.al.* (2011) claim that the cooling effect of clearing high latitude forests is not just theoretical, but shown in real data. Still, the issue is very complex and other studies find losing boreal forests will warm climate, not cool it.
- **Bottom Line: Reforestation is best in the tropics to lower middle latitudes. From latitudes of the northern U.S. northward, reforestation's effect on climate is controversial**



Simulated time evolution of atmospheric CO2 (*Upper*) and 10-year running mean of surface temperature change (*Lower*) for the period 2000–2150 in the Standard and Deforestation experiments. Warming effects of increased atmospheric CO2 are more than offset by the cooling biophysical effects of Global deforestation in the Global case, producing a cooling relative to the Standard experiment of ≈0.3 K around year 2100. Bala *et.al.* 2006.



(Bala *et al*. 2007) Simulated cumulative emissions and carbon stock changes in atmosphere, ocean, and land for the period 2000–2150 in (A) Standard and (B) Global deforestation experiments. In Standard, strong CO2 fertilization results in vigorous uptake and storage of carbon by land ecosystems. In the deforestation case, land ecosystem carbon is lost to the atmosphere. Most of this carbon is ultimately reabsorbed by grasses and shrubs growing in a warmer CO2-fertilized climate at year 2100.

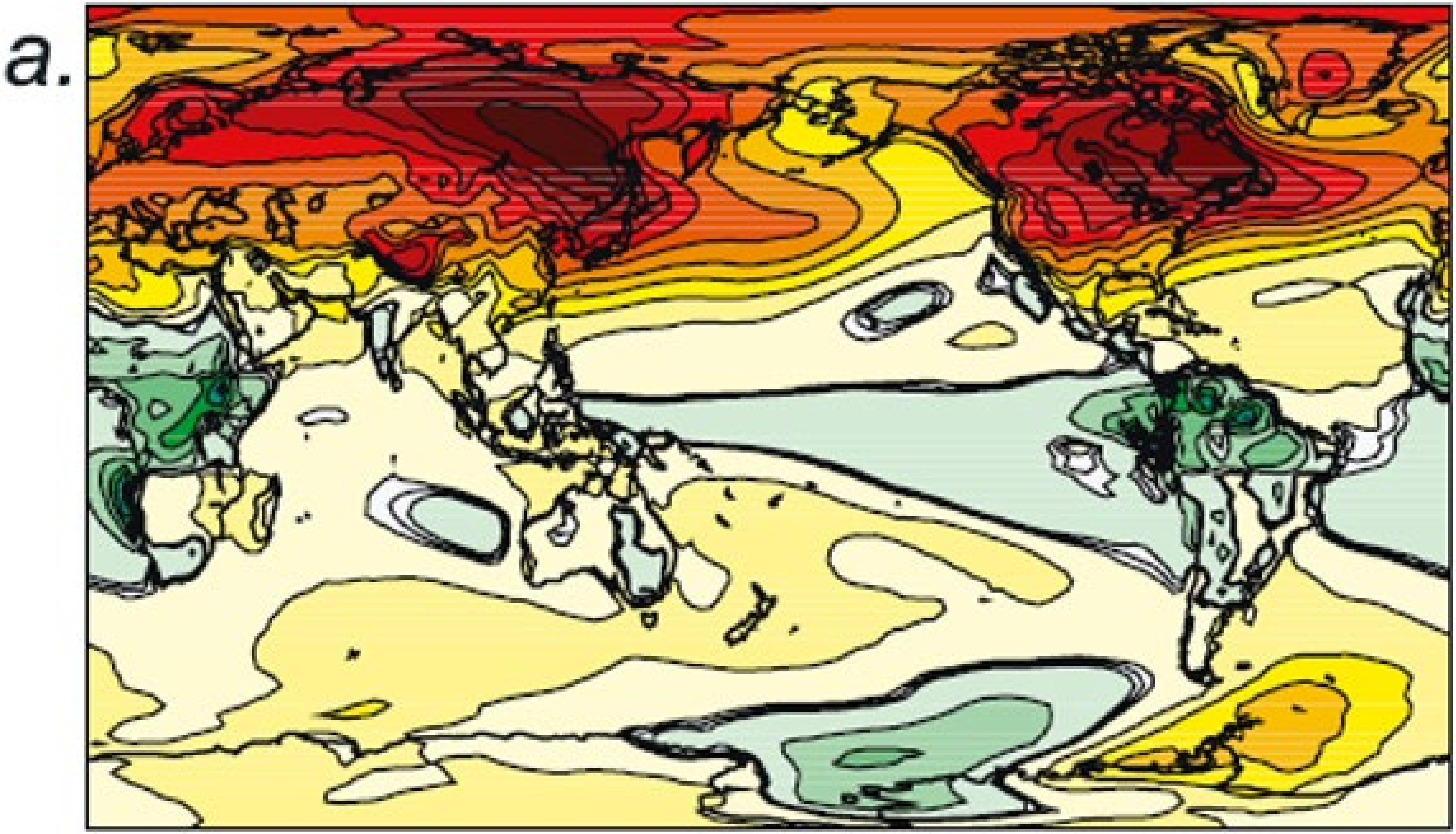
Of the land eco-system carbon in the Standard simulation that is not present in the land biosphere in the Global case at year 2100, 82% resides in the atmosphere and the remaining 18% in the oceans.

- Kirchbaum *et al.* 2011 basically confirm Bala *et al.* that albedo dominates over carbon sequestration, so Boreal re-foresting may well be a problem.
- They measured the albedo of a pine forest *vs.* meadow w/o trees in mid-latitude New Zealand over time, and find that carbon capture of trees rises with their age, but still, the net climate effect is that the warming due to reduced albedo overwhelms cooling due to CO2 sequestration.

Let's Ponder The Implications of this Debate

- Before the loggers out there get excited about clear-cutting boreal forests, note that the released carbon goes into the atmosphere and the oceans.
- The resulting greenhouse heating effect in the atmosphere is slightly less than is the expected <u>cooling</u> due to the more reflective grasses (and seasonal snow) that replace trees.
- However, from reading the papers, it's not clear that they have included the fact that there is little or no snow to be reflective in spring and certainly summer, especially as temperatures soar in the Arctic.
- Also, cutting Boreal trees would involve more carbon going into the ocean, worsening acidification.
- Hard to think that we'd come to this as a cooling strategy; politically un-sellable as well, no doubt.

Warming *vs.* Cooling: Net Climate Effect of Planting Trees (Gibbard *et al.* 2005). Only in the Tropics does tree carbon capture and cooling dominate



Natural Vegetation Changes due to Rising CO_2 Levels

- Port *et al.* (2012) model the expected rising CO_2's effects on vegetation for 300 years.
- Find fertilization due to rising CO_2 causes boreal forests to spread north, deserts to migrate away from equator and slightly shrink as Hadley Cell rains extend north too.
- By including the rise in carbon sequestered by CO_2-fertilized plants, the reduced greenhouse warming is 0.22 C
- 0.22C is only a tiny fraction of the net ~7 C rise in global temperatures.

From Port *et al.* 2012. But does not include thawing permafrost which will raise GHG emissions

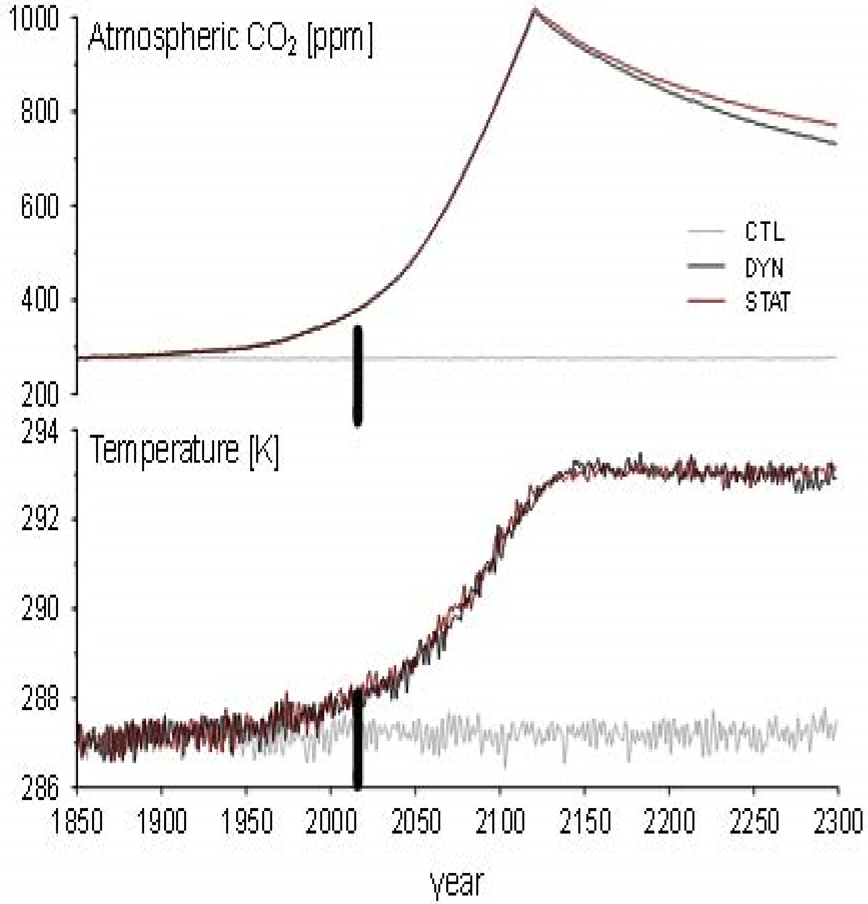


Fig. 2. Time series of annual mean atmospheric CO_2 concentration and global annual mean temperature in the CTL (grey line), the DYN (black line), and the STAT (red line) simulation.

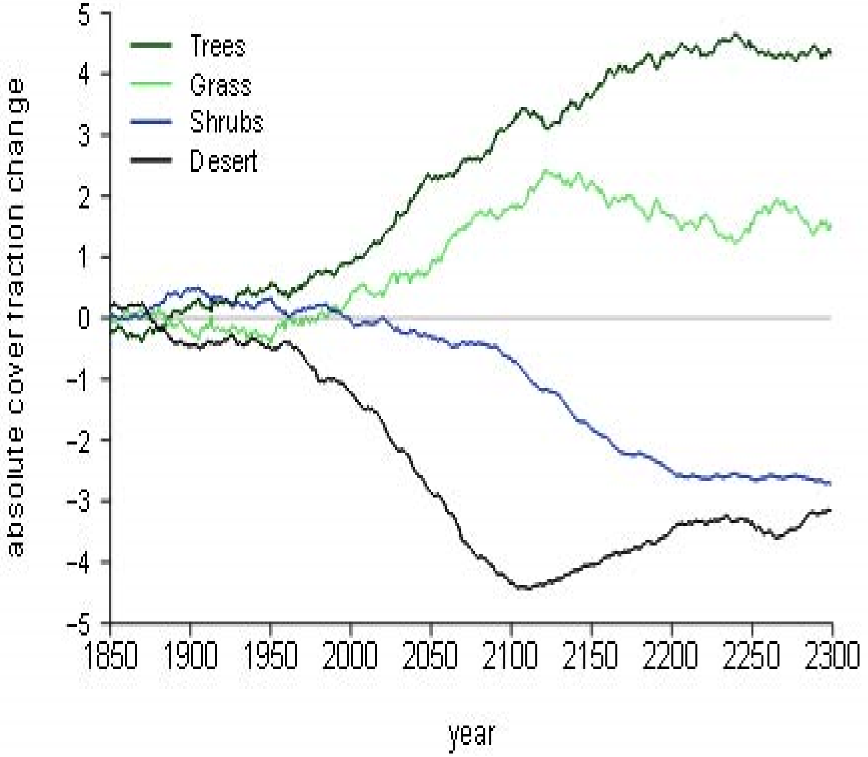


Fig. 3. Time series of changes in absolute global mean vegetation cover (DYN – CTL) in [%]. Forest includes tropical evergreen and deciduous trees as well as extra-tropical evergreen and deciduous trees. Shrubs contain cold and rain green shrubs and grass includes C_3 and C_4 grass.

U.S. forests are currently taking up carbon in excess of releasing it. This is as expected on land that has had most of its forests already cut. Halting further tree cutting would sequester carbon even more than currently. This is even more true in the tropical rain forests where clear cutting has been rampant

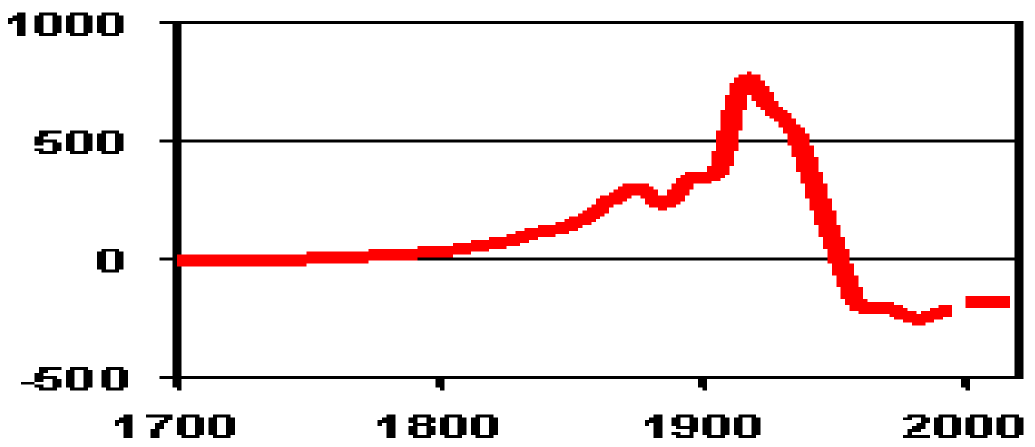


Figure 1—Carbon balance of the U.S. forest sector in millions of metric tons of carbon per year. The large flux of carbon from forests to the atmosphere (from logging and deforestation) peaked in 1915 at 760 million metric tons of carbon per year. Currently forests take up about 250 million metric tons of carbon per year. From Birdsey et al. (2006).

Another Way to Show How Hard it is for Tree Planting to Be Our Solution

- Stanford's Ken Caldiera points out that each American causes the emission of 100 lb of CO_2 per day. Large trees only sequester carbon vigorously for their first ~30 years. He estimates it would take about 10 new acres of tree-friendly land and climate to sequester the CO_2 of a family of 4, and after ~30 years they'd have to not only keep the original 10 acres tree-healthy, but find 10 more to plant more young trees to take up their next 30 yrs of carbon
- The point is, we just don't have that kind of land available to do this.

Deforestation and the Ocean

- Other vegetation change simulations give similar results
- Note in the previous graph that in the global deforested case, the ocean takes up much more CO2 than in the ‘standard’ case. While global temperatures may not change much by 2150 between the ‘standard’ and ‘global deforested’ cases, **the oceans suffer much more by deforestation, and that CO2 must further acidify the ocean.**
- Planting mid and high latitude trees to take up carbon should perhaps be seen more as a strategy for minimizing ocean acidification and its dire consequences, and not as much a direct global warming solution, because trees darken the landscape and so absorb more sunlight and heat the surrounding air.

Part 4

Artificial Capture of CO_2 from the Atmosphere – “Air Capture” of GHG’s

Ideas…

- Klaus Lackner's resin-based "artificial trees"
- Bioenergy with carbon capture and sequestration (BECCS)
- Greg Rau's bicarbonate via limestone
- Greg Rau's bicarbonate via silicates
- Artificial photosynthesis
- Making calcium carbonate from atmospheric CO2
- Arctic Ocean re-freeze via pumped seawater

As of 2014, Klaus Lackner's conception of an Air Capture Installation

Some Early Resources on this Idea

- Klaus Lackner video lecture on our Carbon dilemma (53 min) at SUNY Stonybrook
- Video interview (5 min)
- Good quantitative overview of the carbon dilemma, from DOE and Lackner
- Demonstration video of artificial tree, BBC 2009
- NovaScienceNow video 2008 (12 min)
- Yale Environment 360 op/ed

Some Bullet Points on the CO2 Capture ideas of Lackner *et al*.

- **Need 7 typical (real) trees just to pull out of the air the CO2 generated by one breathing human being (476 lb/yr)**
- **We're injecting the equivalent of 130 billion people's worth of out-breathing of CO2 into the atmosphere**
- Pulling CO2 by Lackner's resin is very energy intensive. This is why I suggest nuclear may be the way to power them.
- Since CO2 rapidly moves through air, can pull it out from anywhere. The resin idea works poorly at low temperature and in high humidity; Therefore, site them in deserts at mid latitudes for best results.

Pack the “trees” around nuclear power plants above underground carbon sequestration sites?

- …if that’s feasible or possible (it’s my speculation; no more info on this).
- Now – the American Physical Society’s evaluation (2011) and a summary: Bottom line, uneconomical until all large point-source carbon emitters are already thoroughly scrubbed.

Lackner's early and (now clearly) overly optimistic quantitative evaluation of the artificial tree idea…

- Claimed can remove CO2 a thousand times faster than real trees (!)
- Emits only 200g of CO2 for every kg of CO2 removed from the air
- Claim: Each "tree" costs about the same as a new car, and removes 90,000 tons of carbon per year (to be put where??).

Compare Lackner's Artificial Trees to Real Trees (as of 2009)

- Real trees: 7 trees needed to remove 1 human's worth of CO_2 production (476 lb/yr)
- Lackner's "tree": claimed - 1000x more efficient than real trees.
- Would need 100 million Lackner trees to remove as much CO_2 as we are emitting at current rates
- Would need 100 billion real trees to do the same.
- Source for these figures is here

Let's Run Some Simple Figures…

- 100 billion additional trees (spaced 33 ft apart for a large tree, seems reasonable in average climate) would require:
- At 33 ft x33 ft = 1000 ft^2 per tree as a ballpark rough number, means
- 1000 ft^2 /tree x 100×10^9 trees = 10^{14} ft^2
- = Area of United States = 1.06 $\times 10^{14}$ ft^2
- In other words, we'd need to plant additional real trees on a tree farm as large as the United States to soak up all our CO2 emissions. That sounds very hard to do.

Another estimate for tree planting is worse

- …cited here, says covering an area the size of the United States in trees and sequestering their carbon upon burning the trees, would only pull enough CO2 to reduce net global emissions by 1/3 of what they are at present. Another estimate is “7 Australias” of area.
- Does the Earth have a spare “U.S.” of area waiting to be put to this use?? (no).
- If Lackner’s claims are correct, we’d need only 1/1000 of this area, or about ¾ of the area of Los Angeles County, if we still allow 1000 ft^2 per artificial tree. This sounds do-able… IF Lackner’s claims are correct (keep reading)
- Note that his business venture in this direction folded up in 2012.

2014 Update on Air Capture

- MUCH less rosy estimates of air capture are now being acknowledged…
- Lackner now estimates the cost at $1,000/ton of CO2 captured (order of magnitude higher than his original estimates of a few years ago).
- Still, it's ~15x more efficient than real trees at CO2 capture. (His early estimate was 1000x more efficient) And we need efficiency!
- What's our planet worth, after all? $Infinity, isn't it?

2017: The First Commercial Air Capture CO2 Installation

By Climeworks, Inc. in Switzerland. Very small scale, and CO2 is sold for fertilizer, not sequestered. Their ambitious goal is build 250,000 air capture plants by the mid 2020's. As of '22, they've built … **18.** But even if they succeed, that would capture only 1% of our current emissions. Estimate $400/ton CO2 to capture and $20 to sequester, except feasibility of climate-scale sequestration is highly speculative at present. **How expensive is $420/ton?**

Let’s do the Math…

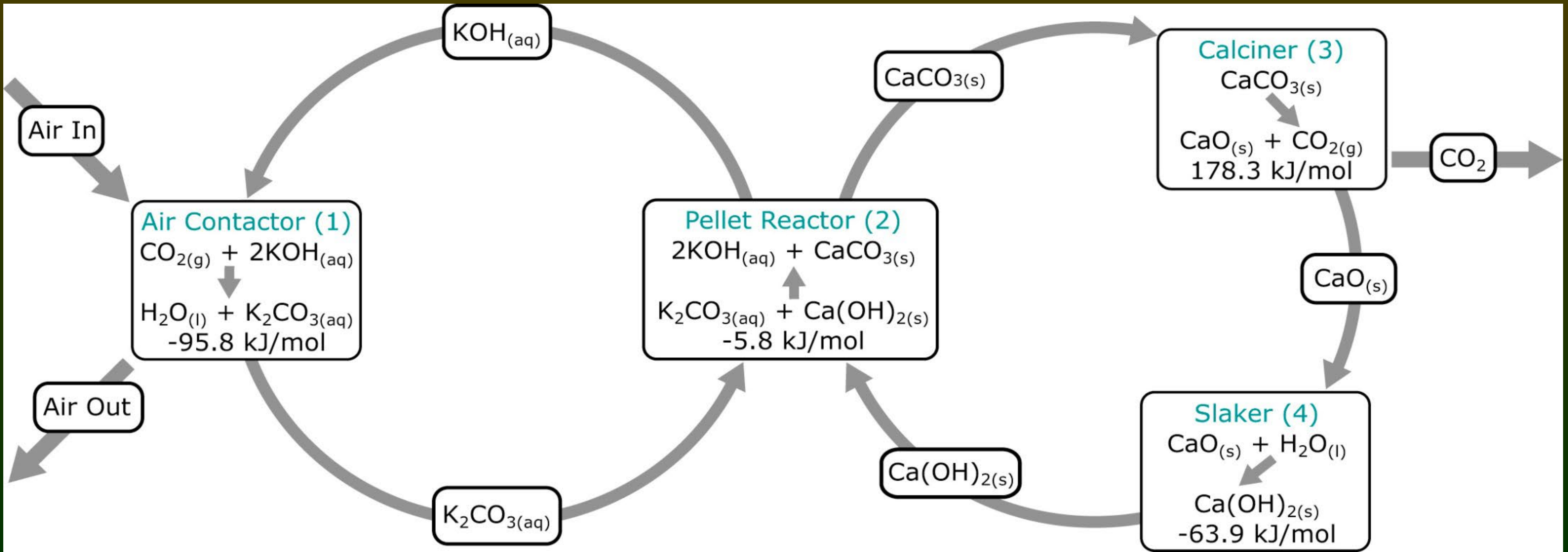
- Each part-per-million of CO_2 in the atmosphere is 7.81 gigatons of CO_2.
- Assume we somehow drop emissions to only 30% of today’s rate so that atmospheric CO_2 concentration remains constant.
- The even assuming 350.org’s goal of 350 ppm is where we should aim (climate scientists say now it needs to be 280 ppm), still, 350 ppm means dropping from today’s 410 ppm down to 350 ppm…
- 60 x 7.81 Gt = 469 Gt CO_2, and at $420 per ton, that’s $197 trillion, which is…
- $26,200 for every man, woman, and child on the planet… the vast majority of whom don’t have anywhere near that kind of cash. Most AMERICANS don’t have that in savings. **Average wage of half the world’s population: under $3/day**

Carbon Engineering, Inc

- …now in 2018, claims they should be able to capture CO2 from the atmosphere for $94-232/ton CO2, based on modelling and experience from their small pilot plant. (Keith *et al.* 2018)
- This improves on earlier cost estimates of roughly $550/ton (American Physical Society (APS) 2011)
- The main improvements being in design, in using a lower pressure process, and importantly – in siting only where renewable energy to power the process is plentiful, since "avoided emissions" from grid power figure prominently.
- Estimating Life Cycle costs for a full scale commercial plant were "beyond the scope" of this paper, however.
- Will it really scale and work out like this? We shall see…

The Carbon Engineering Direct--Air-Capture Process schematic

- Improved efficiency by using a steam slaker *vs.* water, at higher temperature for greater thermodynamic efficiency
- Also using horizontal bed, which was rejected by the APS study as being to risky for caustic leakage to the environment.



Transport and Storage of CO_2

- IPCC estimates vary widely, depending on pipeline transportation length to sequestration sites
- Storage \$2-\$30 / ton CO_2 but does not include cost of storage site monitoring, well maintenance, nor liability costs. (IPCC Chapter 8 p. 345)

CO2 Transport costs given per 250km of pipeline, after pipeline constructed.

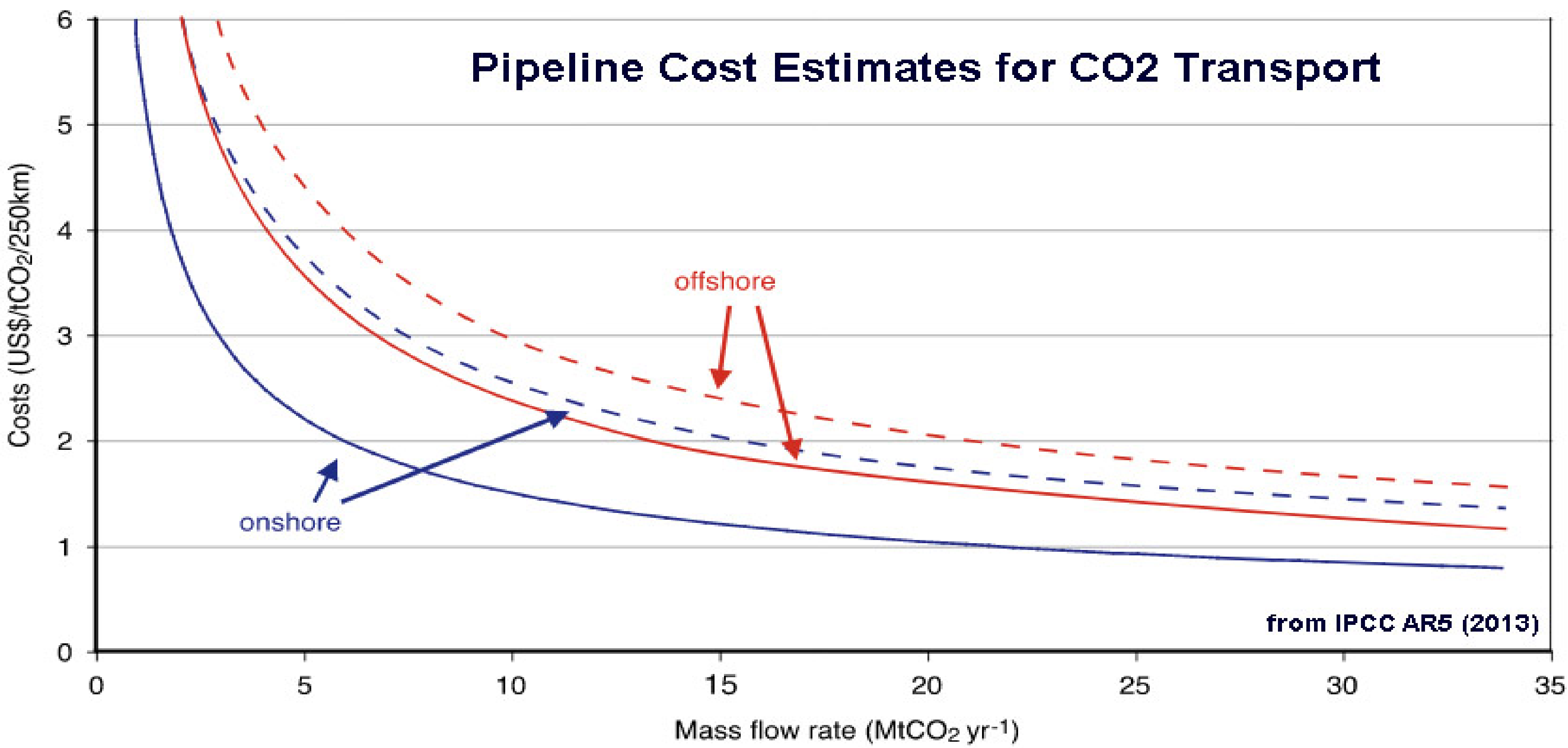


Figure 8.1 CO_2 transport costs range for onshore and offshore pipelines per 250 km, 'normal' terrain conditions. The figure shows low (solid lines) and high ranges (dotted lines). Data based on various sources (for details see Chapter 4).

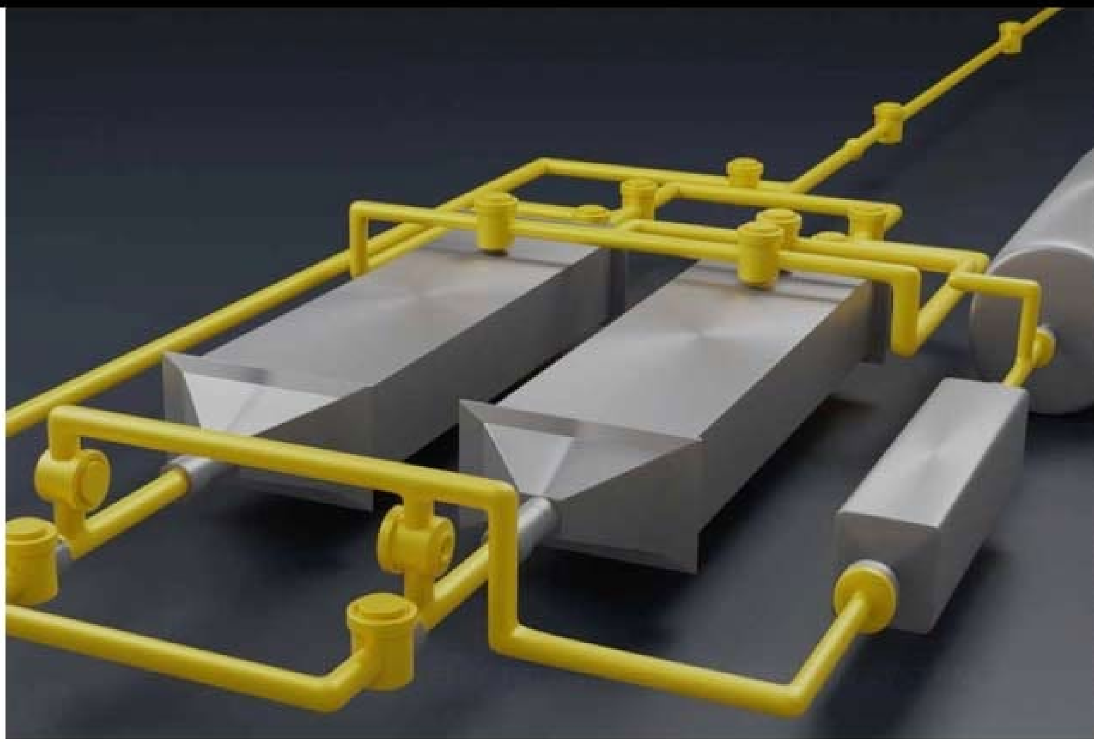
How much money is needed just to pay for the energy cost of atmospheric CO2 removal?

- House *et al.* 2011 estimate 400,000 joules of energy to remove and sequester a mole of CO_2.
- Converting this to the global problem, that's 2.6 x 10^{21} joules or $7x10^{14}$ Kwh to pull the atmosphere down to 280 ppm (pre-industrial level) .
- At ~$0.10 per Kwh of energy, that's $70,000 billion **just to pay for the energy alone**
- That's $10,000 for every man, woman, and child on the planet, the vast majority of whom have nowhere near that kind of cash. Almost half the world lives on < $3.00/day
- MIT's Jaffe and Taylor, in their 2019 book **"The Physics of Energy"**, calculate the energy cost alone of separating and sequestering underground the same amount of atmospheric CO2 we emit per year, **is 40% of total global electricity consumption.**

Direct Air Capture via Battery Technology

- MIT has developed a new process which looks promising. It uses an electrochemical process to grab CO_2 into carbon nanotubes, at an energy cost of about 1 gigajoule (=278 kwH) per ton of CO_2.
- At 10 cents per kwh, that's about $20/ ton of CO_2 for the energy of capture alone, or 200x the thermodynamic absolute minimum, but a 5-10x improvement over other technologies.

Still, by operating at ordinary room temperature and air pressure, it promises lower cost overall *vs.* other competitors (2019)



FULL SCREEN

In this diagram of the new system, air entering from top right passes to one of two chambers (the gray rectangular structures) containing battery electrodes that attract the carbon dioxide. Then the airflow is switched to the other chamber, while the accumulated carbon dioxide in the first chamber is flushed into a separate storage tank (at right). These alternating flows allow for continuous operation of the two-step process.

Image courtesy of the researchers

MIT engineers develop a new way to remove carbon dioxide from air

The process could work on the gas at any concentrations, from power plant emissions to open air.

Bio-Char as Sequestration?

- Lenton & Vaughn 2009 : "In the most optimistic scenarios, air capture and storage by BECCS, combined with afforestation and bio-char production claimed to have the potential to remove 100 ppm of CO2 from the atmosphere…". (with **very** optimistic and questionable assumptions)
- BUT – the biochar must be very pure or it'll give back its carbon to the atmosphere in a century or two, or less. We don't yet have the technology to make such pure bio-char, at scale
- I and James Hansen and other scientists remain highly skeptical of the promotions at this time.

Could biochar be sequestered deep underground?

- Let's do the math…
- James Hansen makes clear we need to get atmospheric CO_2 back down to 280-300 ppm to return to <u>stable</u> historical climate… What we've sown, so must we reap.
- So we're talking about reversing all the oil wells we've ever drilled and pumping back into the ground a pressurized biochar slurry, and hoping there's volume in the Earth to hold it. But there's every reason to believe that after the oil was pumped, the volume it came from is crushed by the weight of overlying Earth, *e.g*. causing the notorious earthquakes shaking Oklahoma, for instance. That's a lot of pressure (energy) needed to pump it. That was not true when we get the oil OUT, since we have the weight of overlying Earth to provide most of the working force.

- Some CO_2 was aborbed by the ocean, but if we drop atmospheric CO_2 this far, the ocean will outgas CO_2 (which relieves some acidification) so we'll need to re-sequester that CO_2 as well.
- How much pumped in volume do we need? the density of oil is about 0.9 g/cm3, while that of biochar is only about 0.2 g/cm3, and less if we water it down into a slurry for pressurizing.
- Take account we'd only need to sequester about 60% of what we mined, after roughly accounting for ocean/land capture over the century. Then we're asking for ~3x the volume you first pumped out (in the form of oil) in order to bury the biochar.
- **The feasibility therefore: highly questionable.**

Biochar: Good for soil?

- Biochar improves soil and if high quality stable, could be alternative to pumping of liquid CO2 underground.
- HOWEVER – if the biochar is used by plants directly for nutrients, it will be returning that sequestered carbon to the atmosphere *via* the "fast carbon cycle", a complete deal-killer!
- But what would seem to be the biggest problem is that carbon incorporation into biomass <u>is slow</u> – again, we'd need ~2-3x the size of the United States as a tree farm to pull CO2 out at climate needed scales. Biochar might some day prove out for sequestration, but <u>creating</u> it at climate significant scales at this late date when strong measures are necessary, may be the limiting factor in using this as a significant strategy.
- McLaughlin *et al.* 2009 give a good synthesis of what we know about bio-char and appears written in an objective way (*vs.* mere cheer-leading/fund-raising boosterism)

UCSC's Greg Rau Has Another Idea, Using Bicarbonate Chemistry

- Combine silicate minerals in electrolysis with salt water and CO2
- From (Rau *et al.* 2013) bench lab demonstration and rough calculations…
- *"Using nongrid or nonpeak renewable electricity, optimized systems at large scale might allow relatively high-capacity, energy-efficient (<300 kJ/mol of CO2 captured), and inexpensive (<$100 per tonne of CO2 mitigated. [RN: No; $172/ton w/o re-selling CO2] removal of excess air CO2 with production of carbon-negative H2. Furthermore, when added to the ocean, the produced hydroxide and/or (bi)carbonate could be useful in reducing sea-to-air CO2 emissions and in neutralizing or offsetting the effects of ongoing ocean acidification."*

But it's Very Energy Intensive…

- Using wind energy, they calculate that to power the process would require the total wind energy from 8% of the entire Earth's surface to remove our annual 41 gigatons CO2/year, which is physically impossible to achieve
- A typical basalt can convert 1/3 of its weight of CO2 into bicarbonate, so roughly <u>120 billion tons of basalt would be needed every year</u>

But, the Oceans and Soils Already Take up CO2, so that will help with the job, right?

- True, except that CO_2 into the ocean lessens its alkalinity and therefore its ability to absorb CO_2, as too does today's hotter ocean temps. Rising ocean temps does the same, compounding that problem.
- Also, recall that even if we end all CO_2 emissions, the thermal inertia of the oceans and the radiative imbalance we're already at, will prevent global temperatures from ever going back down, for millennia (short of GeoEngineering)
- So we do indeed need to force it down, quickly, before more permafrost melts, more runaway polar melt happens, etc. Perhaps not at $56,000 per capita, but even at ~1/4th of that the diversion of funds away from other spending will be a strong impediment to growth (but ultimately, worth it).

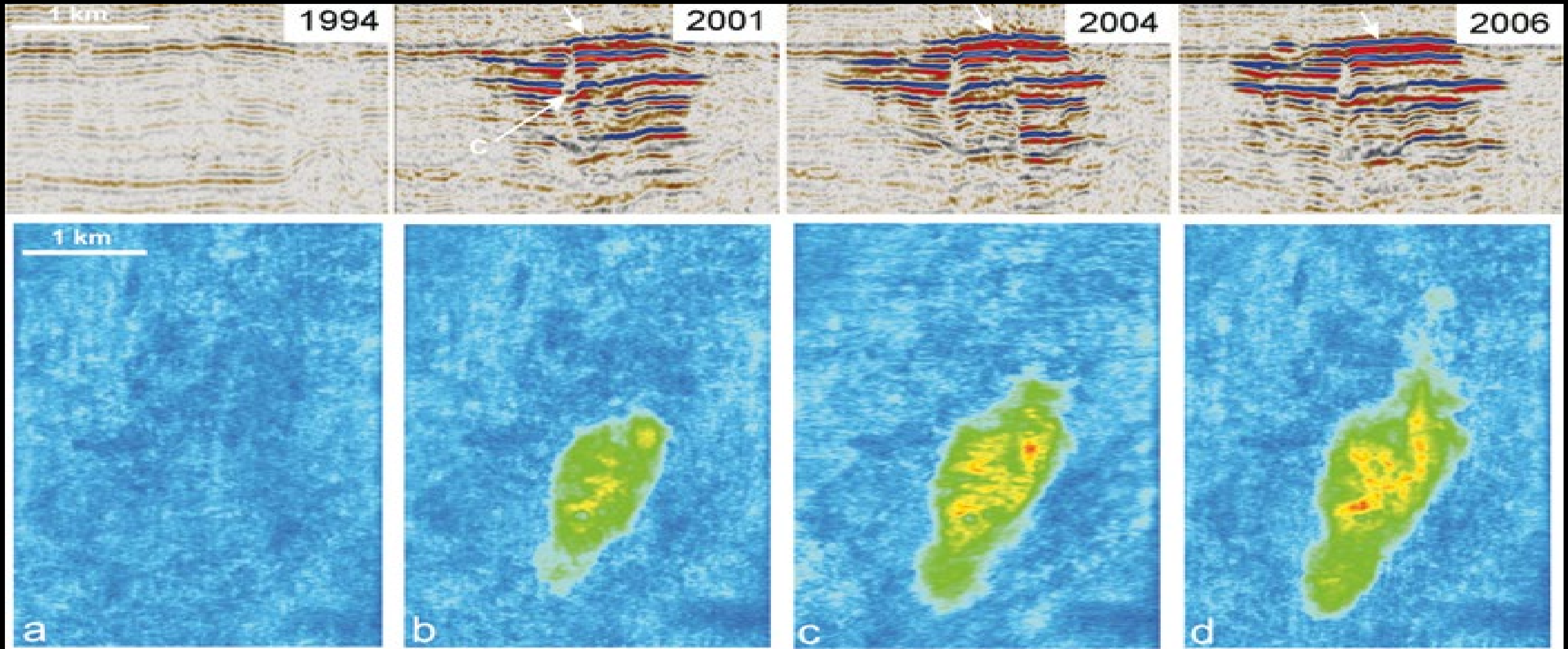
Ah! But You Recall from Our work on the Thermodynamics of Civilization

- …that an economic degrowth is exactly what we need if we are to keep CO2 levels from climbing further and forcing temperatures higher
- An engineered massive global Economic Depression of indefinite length, engineered by diverting money away from goods and services and instead to funding atmospheric CO2 removal – cleaning up after our century-long Carbon party
- Highly unlikely to be politically acceptable until climate pain has deepened much further, and progressed till far too late, as we argued earlier.

Where to sequester the carbon in climate-significant quantities is still an issue…

Injecting CO_2 into underground porous spaces

- Norwegians have been putting 1 million tons of CO_2 per year back into the ground undersea. (but, in 2015, that halted)
- The Utsira Sand has pore-space volume of ~600 km^3. 6 km^3 would be sufficient to store 50 years emissions from ~20 coal-fired or ~50 gas-fired 500 MW power-stations. Not remotely enough to be climate-significant.
- See "GeoEngineering" later



Estimates from Stanford University's Dr. Sally Benson

- Suggest there is enough suitable geological formations (porous rock overlain by dense layer of clay-based metamorphic cap rock) to sequester the CO2 needed, but rare in China and India, more in western U.S. and Russia.
- Need extensive new pipeline network, comparable to that of existing oil and gas pipeline network, to route the CO2 to the sequestering sites from where it is captured at the power plants. Very expensive!
- Prof. Kevin Anderson's conversations with CCS experts says they're much less certain climate-significant sequestration is do-able.

But Have We Already Ruined Many of the Safe Geological Storage Sites?

- Widespread fracking (using high pressure water/chem mixture to crack impermeable rock) to release natural gas, almost certainly ruins that formation for being able to safely store pumped CO2 for long term. The well-publicized scandal of fracked nat-gas seeping up into shallow well ground water testifies to this.
- Leakage rates of even ½% per year is a complete killer for sequestering CO2.
- I've not seen numbers quantifying this danger to the long term plan. Not good.

The industry buzz this decade: natural gas as the new energy source ("thanks" to fracking). With Trump, fossil fuels look to continue.

New Design for Natural Gas Turbine Power Plant

- A company called Net Power is building (2017) a demonstration plant which will burn natural gas and capture the CO_2 it creates to make a working fluid for running a more efficient power cycle.
- A portion of the power produced would capture the CO_2 created.
- The CO_2 would have to be contained in much higher pressurized vessels than traditional steam, and leakage or failure would release the CO_2.
- How to sequester, let alone in climate-significant quantities remains an issue and not part of the plant. However, costs of producing power could eventually perhaps be less than for non-CO_2 capturing traditional natural gas power plants.

Net Power's Cost Projections

- Hope that they can eventually get to $42/ Mwh which is about the same as for standard combined cycle nat gas power plants.
- No mention of how much CO2 could be captured or the cost. Not at all convincing that it's a "game changer" as the news copy terms it.
- The moral hazard is that this continues to motivate the extraction (fracking?) of nat gas to use for power.
- The cynical realists out there can wonder whether this is a ploy to make use of govt. funded carbon incentives while still mining carbon.
- **Burning Nat Gas is carbon-positive (bad!)**, but less bad if this idea is employed

Creating carbon fuels on-the-fly, rather than mining ancient carbon

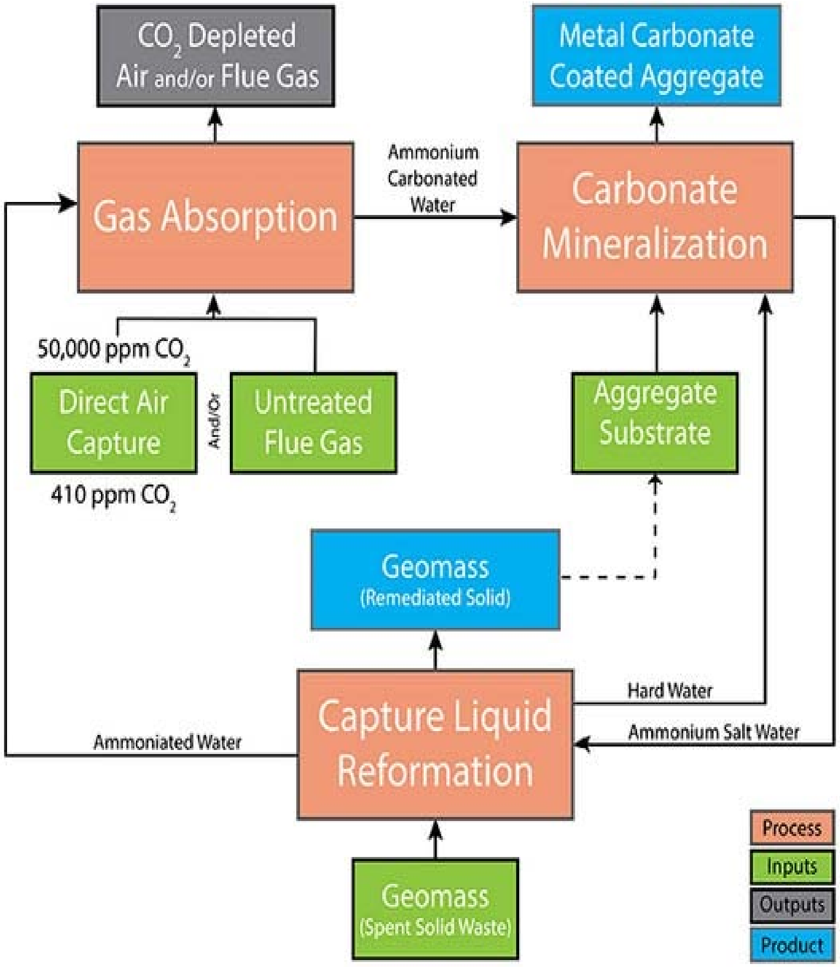
Gasoline and gasoline substitutes are considered attractive because…

- --- Transportation vehicles (trucks, cars, trains) require very high energy density power sources, and gasoline is hard to beat. (but with battery advances, EV's may very well have neutralized this)
- --- We have existing infrastructure to deliver biofuels
- --- Require little modification to existing vehicles to utilize

Using Captured CO_2 to Make Concrete

- A new company – Blue Planet – has a process for taking captured CO_2 and incorporating it into aggregate for concrete.
- Costs claimed to be small, once the captured CO_2 is available.
- However, even if all concrete globally is made with this process, it is only a few percent of the CO_2 we emit today

How it Works: Process Flow

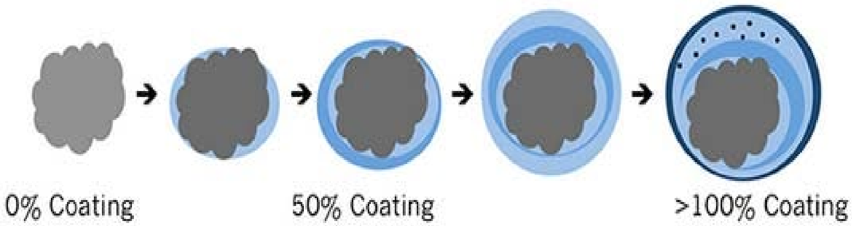


metal ions such as calcium, magnesium, and iron. "When the 'spent' capture solution reacts with the Geomass, reforming it, these metal ions are released and combined with the carbonate solution to form the carbonate mineral coating.

Blue Planet Process is Similar to Ooid Formation in Nature

A rock particle is coated with our synthetic limestone, forming a carbon-sequestering coating that is 44% by mass CO2.The coating can contain residual fine particles from the capture solution regeneration.

44% (by mass) of CaCO3 Coating is CO2



But….<u>biofuels, especially corn-based</u> make no sense.

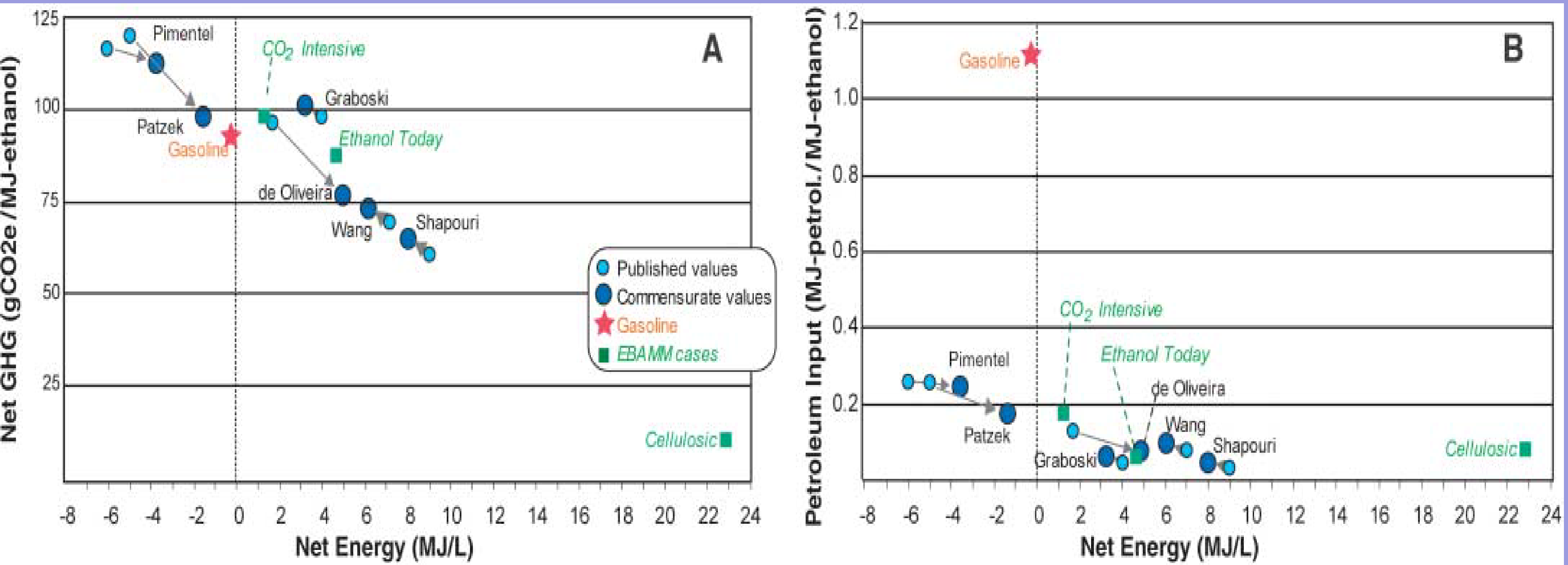
- They consume 30% more energy in growth/manufacture than they give. Other problems:
- --- They commandeer valuable farmland which could go to food
- --- Cause vast acreage of tropical forests to be cleared to produce sugar cane, palm oil, and cereal grains destined for ethanol. Clearing tropical forests adds both heat and CO_2 to the atmosphere
- --- And far worse, in this increasingly drought-stricken world, biofuels require between 80 and 1000 times more water to produce than does conventional fossil fuels (!) (*Mulder et al.* 2010)

- --- Biofuels leave soils poorer, are supplemented with artificial fertilizers, which add greenhouse gas nitrous oxide and other pollutants to the atmosphere in their manufacture, and are heavy water users.
- --- They nevertheless are being pursued, incentivized by government subsidies for farmers, whose lobbies line the pockets of the appropriate government decision-makers
- --- Accounting for carbon flows is deeply flawed on the part of the proponents of corn and sugar ethanol biofuels. **<u>This strategy is not carbon neutral (more later on this)</u>**

Cellulosic ethanol: at least better than corn ethanol

- A Berkeley study published in Science (Farrell *et al.* 2006) finds the cellulosic ethanol has significant advantages over fossil fuel in the making of gasoline
- Cellulosic ethanol many times more efficient and lower carbon footprint than corn-based or other ethanol's.

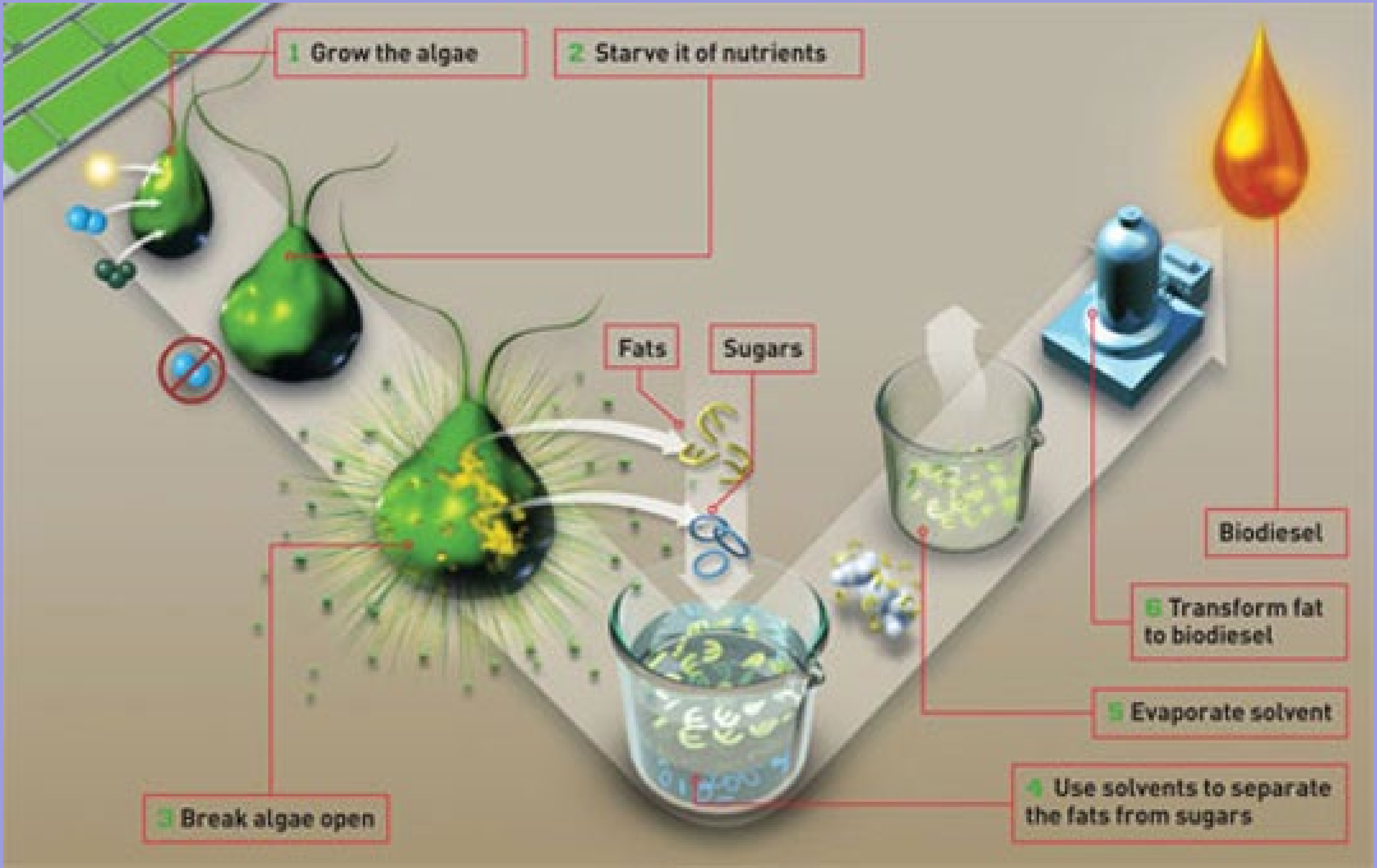
(A) Net energy and net greenhouse gases for gasoline, six studies, and three cases. (B) Net energy and petroleum inputs for the same. Small light blue circles are reported data that include incommensurate assumptions, whereas the large dark blue circles are adjusted values that use identical system boundaries. Conventional gasoline is shown with red stars, and EBAMM scenarios are shown with green squares. Adjusting system boundaries reduces the scatter in the reported results. Moreover, despite large differences in net energy, all studies show similar results in terms of more policy-relevant metrics: GHG emissions from ethanol made from conventionally grown corn can be slightly more or slightly less than from gasoline per unit of energy, but ethanol requires much less petroleum inputs. Ethanol produced from cellulosic material (switchgrass) reduces both GHGs and petroleum inputs substantially.



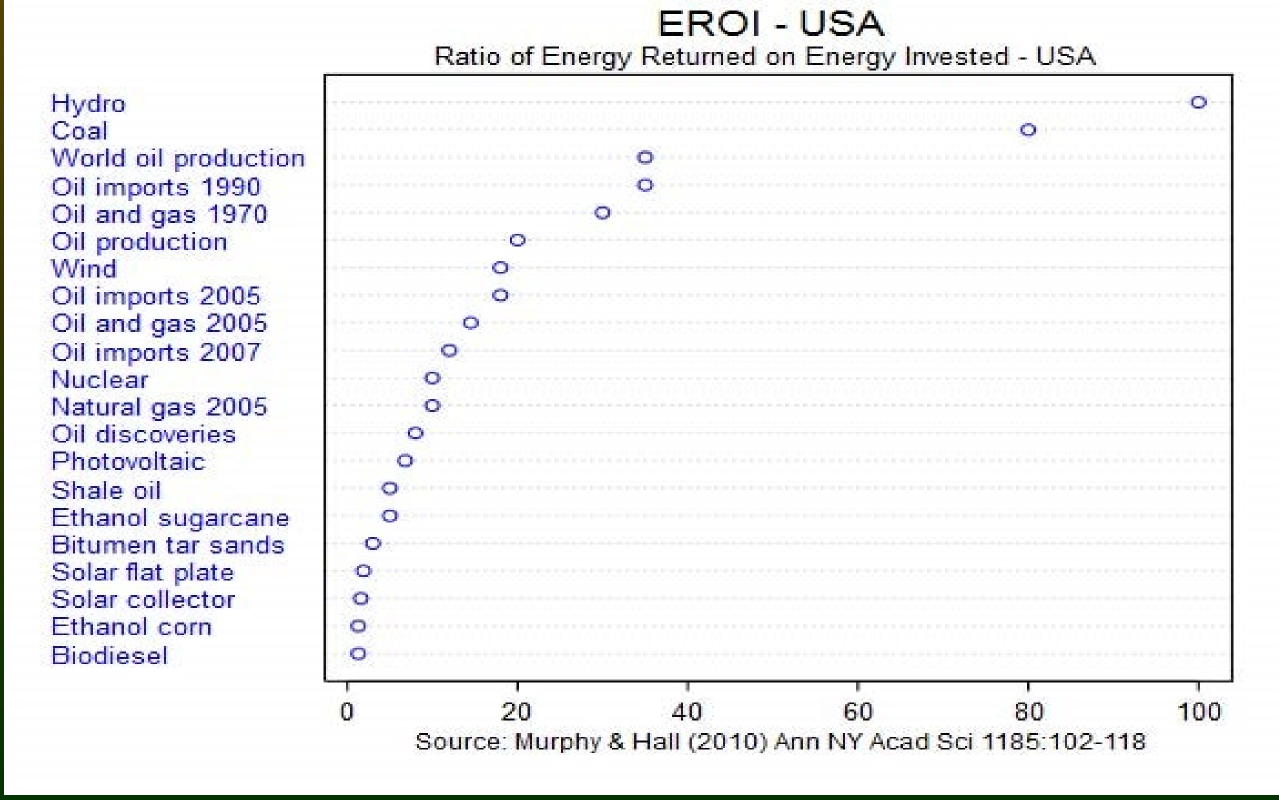
Better: Microbe-based fuel producers?

- Bio-engineered bacteria at MIT produce isobutanol – a burn-able fuel. It appears it may be feasible to scale this up to industrial scales.
- Algae-based diesel production. The company Algenol claims to be able to produce over 6,000 gallons of ethanol per acre per year, compared to corn's rate of 370 gallons per acre per year. That's 15 times more! (but still only good for ~200 fill-ups at the gas station for a decent truck)
- In 2015, Algenol plans to open their first commercial facility, for producing ethanol from algae

Biodiesel from Algae?



Energy analyst Vaclav Smil finds biofuels are completely cost/energy absurd. Their tiny EROI (below) makes them an extremely inefficient investment of solar energy and land. **<u>However, they are politically popular with the Farm Belt, which figured prominently in the 2016 Trump election</u>**, in case that may be relevant. EROI's, in fairness, are highly dependent on assumptions. While this graph is likely generally reasonable, solar and wind are getting better and oil/coal worse.



Think of Biofuels as Inefficient Harvesters of Currently Arriving Solar Energy

- The great advantage of fossil fuels is that they are the readily available concentrated solar energy of MILLIONS of years.
- The paltry arrival rate of CURRENT solar energy is all you can work with for biofuels.
- Why not skip all the chemistry inefficiencies and complex engines and go straight to solar PV and wind for high quality electric power? As time goes on, biofuels make less and less sense.
- In fact, the promotion of biofuels is a growing scandal, looking more like an financial boon for farmers and not for climate. The promo studies are seen to be based on deeply flawed accounting

We have TOO MANY people competing for TOO FEW resources on this finite planet

- However, a major point is that ANY method of producing significant quantities of biofuels are going to have a major impact on raising prices for competing resources.
- For ethanols, the dilemma is “food-*vs.*-fuel”, and for cellulosic it is (to some extent) “everything-*vs.*-fuel”…
- Cellulosic ethanol led to price rises in pulp such that Mexicans were unable to buy tortillas, and wood pellet factories pricing dairy farmers out of the market for sawdust.

All Biofuels Share a Big Problem

- **They emit CO2 back into the atmosphere when burned**
- At least, say their promoters, they are "carbon neutral".
- But in fact, research shows they aren't even close to carbon neutral (DeCicco *et al*. 2016), with re-grown plants only pulling 37% of the CO2 emitted by the burning of the derived biodiesel and ethanol.
- In fact, their study finds that the use of biofuels in place of gasoline actually cause a net **INCREASE** in CO2 emissions(!)
- *"When it comes to the emissions that cause global warming, it turns out that biofuels are worse than gasoline," DeCicco said. "So the underpinnings of policies used to promote biofuels for reasons of climate have now been proven to be scientifically incorrect. (source)*

Biofuels: their day is over

- The advent of Li-Ion and better auto technology has brought us to the brink of long-range EV’s. Much less expensive to run an EV than the complex machinery of a gasoline or biofuel powered engine.
- Biofuels last and best use was in transportation. Now, they’re losing that too.
- Biofuels convert current incoming sunlight to liquid form in inefficient ways. And now, solar PV/battery systems are making biofuels uncompetitive.
- Note that using bio for power plant fuels at least allows for at-scale carbon capture – a technology not applicable for small scale (*e.g.* transportation) biofuel use

Artificial photosynthesis?

An electrochemical cell uses energy from a solar collector or a wind turbine to convert CO2 to simple carbon fuels such as formic acid or methanol, which are further refined to make ethanol and other fuels.

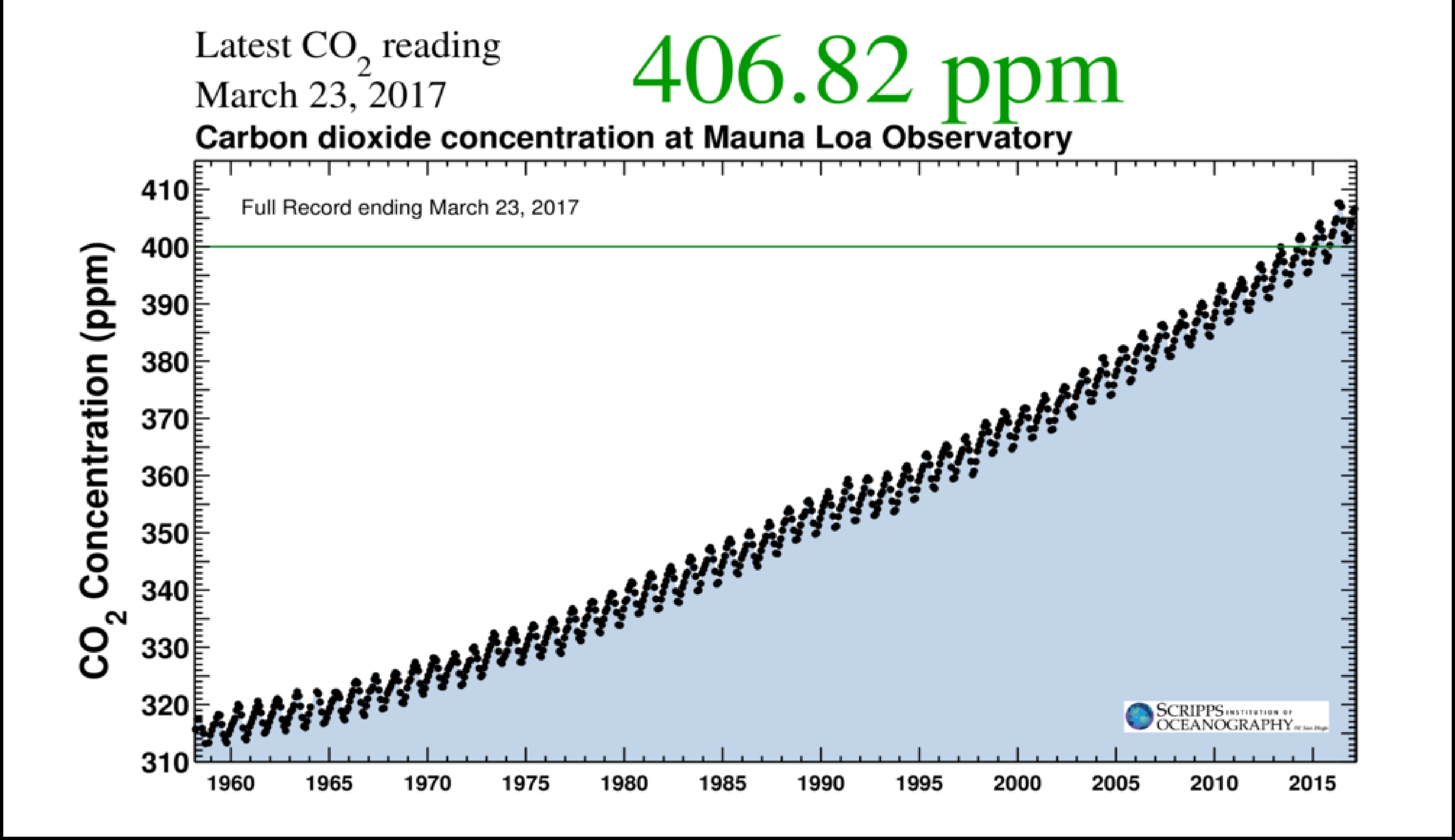
- Very energy intensive, but a catalyst – an ionic liquid electrolyte (Rosen *et al.* 2011) may make it energetically viable (but that was 7 years ago. Heard nothing since).
- Process involves converting CO2 into carbon monoxide (lethal!) as a first step. Safety issues?

Mortal Wounds to Artificial Photosynthesis (AP)

- Burning such fuel in conventional engines re-emits the CO2. Why not just go straight from solar PV to electricity?
- Solar PV efficiency ~20%, AP ~0.3%
- Fatal flaw: The amount of CO2 needing to be pulled from the atmosphere is vastly more than industry could ever use. **The Economics make no sense. We need to curtail economic growth, not make it bigger.**
- The only justification early on, was in making use of existing internal combustion engines, and the problem of storage for PV. With improving batteries, this logic is going away.
- **Bottom line: Biofuels and Artificial Photosynthesis are Non-starters.**

So, we've had solar PV and alternative fuels employed now for going on 20 years. How are we doing on reducing CO2 emissions?

Answer: We're Not. At all.



A Summarizing Quote on Carbon Capture and Sequestration (or "Negative Emissions Technologies - NETs")

- Professor Kevin Anderson, head of Tyndall Climate Centre, in this talk "Revealing the Naked Emperor – Paris, 2C, and Carbon Budgets"…
- *"If we rely on NETs to achieve +2C, and they prove not to be viable – and I know of only ONE modeller who thinks they are viable. The people who produce the models do NOT think they are viable… - then we'll have locked in +3C to 5C of warming."* (31 minutes into talk link above).
- This is because the IPCC Policy people have decided we'll kick the can down the road in order to not harm current economic growth. And this doesn't even consider the added CO2 we discussed from the permafrost thaw, ECS above 3C, and tropical methane amplification. So it's worse.

Here's Some Other Recent Ideas to Help GHG Emissions

- Cows fed kelp instead of grasses emit less methane. Is there enough harvest-able seaweed and processing / transport ability to make this effort significant? How does this affect ocean health?
- Better, is a possible vaccine to reduce cow methane. Much lighter footprint on ecologies
- Cerium oxide catalyst, with other rare earth elements, is seen to turn CO2-infused solution into carbon flakes, at room temperature. Questionable whether scalable to climate-significant scales, but interesting to follow (Esrafilzedeh *et al*. 2019)

More…

- In March '19, 500 Architectural firms pledge to design carbon neutral buildings (source).
- Good! But, the customer is always right, and how MANY such buildings? As always, economic growth will be the ruling consideration, so we run up against the Garrett Relation.

It's Business that would bring the technological changes from ideas to reality

- Are they on board with climate change?
- **No.** This survey (Phillips *et al.* 2019) showed stark differences between scientists, business people, and professional forecasters on what are the big changes by 2052…
- Business people don't even rate climate change in their top 3 change movers. So how much investment should we really expect?

We Need more Drastic Measures to Halt Rising Temperatures. Immediately. So, Next up is K46: Geo-Engineering

T. M. Lenton and N. E. Vaughan: Radiative forcing potential of climate geoengineering 5541

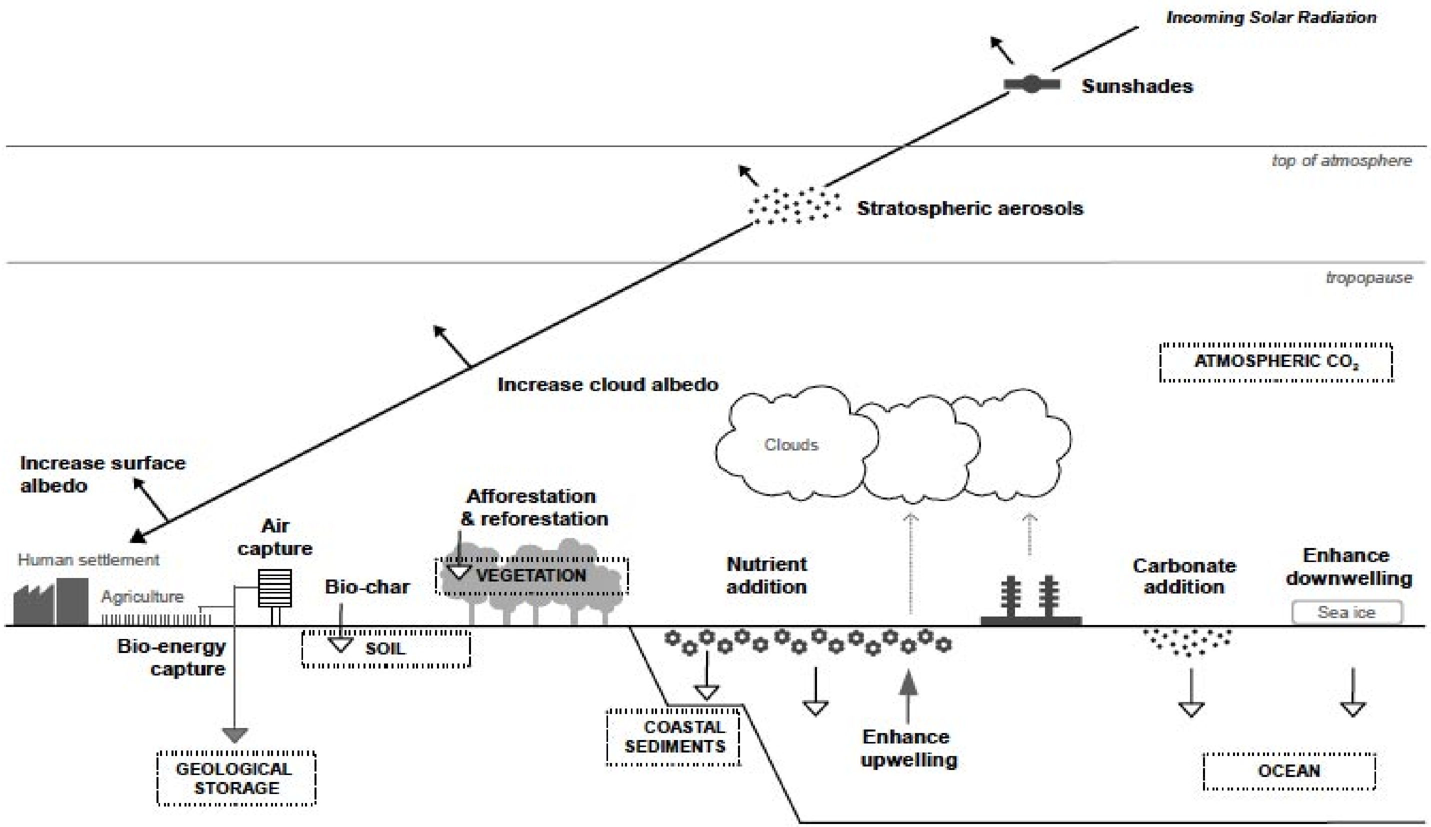


Fig. 1. Schematic overview of the climate geoengineering proposals considered. Black arrowheads indicate shortwave radiation, white arrowheads indicate enhancement of natural flows of carbon, grey downward arrow indicates engineered flow of carbon, grey upward arrow indicates engineered flow of water, dotted vertical arrows illustrate sources of cloud condensation nuclei, and dashed boxes indicate carbon stores. From Vaughan and Lenton (2009), not to scale.

K45: Key Points – Strategies: Technology

- Shu (2008); Solar PV and Nuclear can provide large-scale non-fossil power. Wind power rising rapidly as well.
- Solar requires high quality battery or super-capacitor, hi-tech E-storage technology to go “off grid”, but intelligent mix with wind can help.
- Solar has many advantages: know them.
- Solar cost goes up strongly and becomes uncompetitive with today’s grid and storage capacity when it passes 20% penetration
- Existing point-source CO2 emitters are more economical to scrub (~$30/ton?) than is the atmosphere (~$600-$1,000/ton CO2)
- CO2 and high temperatures are permanent, unless humans actively remove CO2 from the atmosphere, beyond what the land and ocean do naturally
- Artificial trees to scrub CO2 from atmosphere – must be sited in dry mid-latitudes
- Artificial trees; rapidly evolving, require high energy input, sequestration still problematic, but enough geological storage volume appears possible. Safety, permanence needs more study.
- CO2 must be removed from atmosphere before too much is absorbed by the ocean, else ocean life in peril and ocean CO2 uptake ceases, making climate change “permanent”.
- World energy supplied by fossil carbon in ’08 = 86%, rising to 87% by 2013 and 2015.
- Renewable sustainable present technologies can support world’s current population only at a standard of living equivalent to that of Ethiopia. Or, at current income distribution, can support about 2 billion people.
- Virtually no climate/engineering modellers think it is viable to succeed in capture/sequester CO2 at a level such as to halt warming at +2C.