K45: Strategies - Technology

Attempting to Reduce / Halt / Reverse Climate Change Through Techno-Fixes (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 absolutely incompatible with 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*
- *You decide, students – it is more your world than mine: Alas, you will inherit what my generation and those before have left you.*

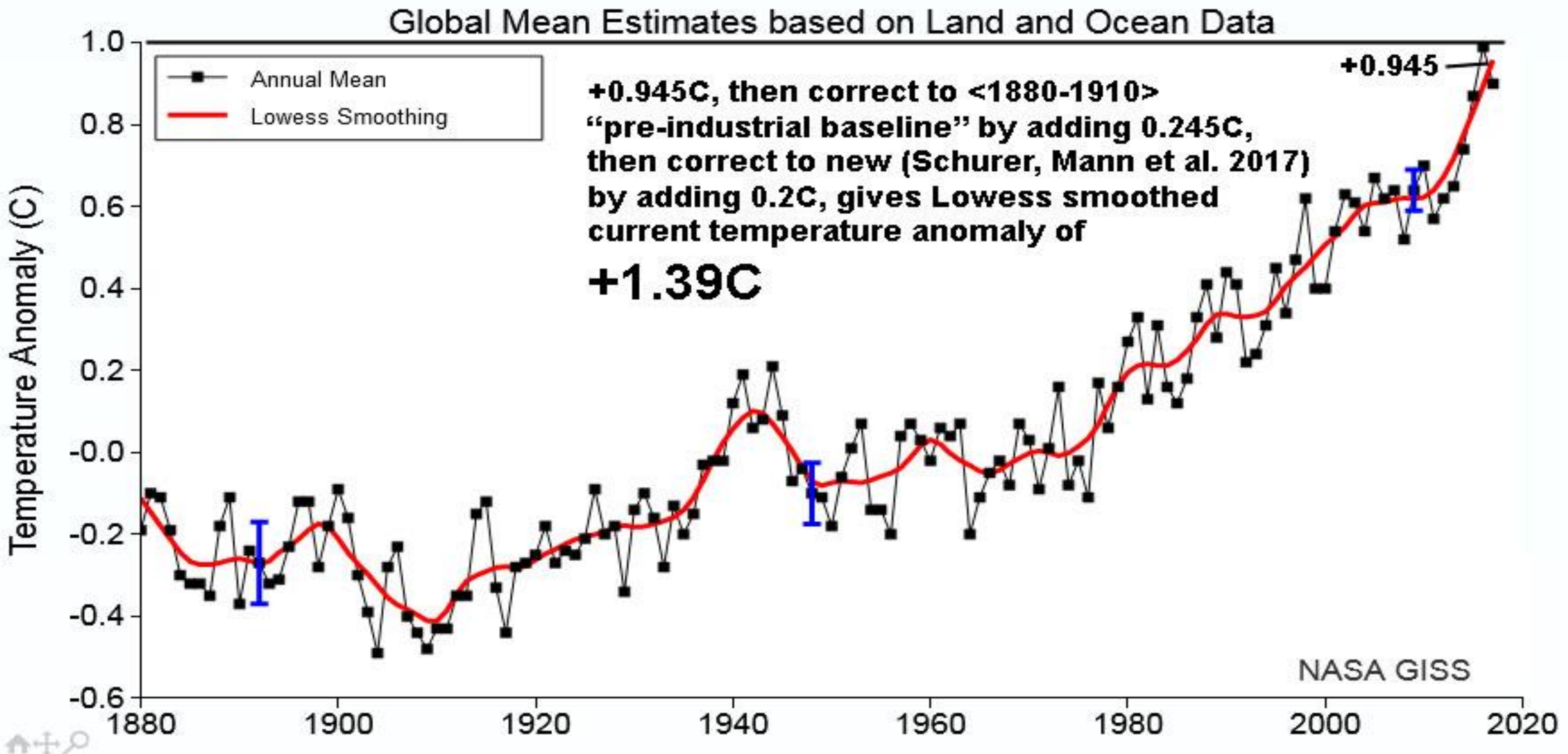
To Identify Technologies, We Need to Appreciate the Scale of the Problem

- 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.
- Together, these will therefore prevent the light-weight atmosphere above it from cooling off – for thousands of years – even if we halt ALL CO2 emissions and somehow re-freeze Arctic permafrost and halt other methane release

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 2017, we were already at ~+1.4C above pre-industrial temperatures using the new Schurer, Mann, et al. (2017) baseline for Pre-Industrial temperature. **+2C is realistically 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.**



Land-ocean temperature index, 1880 to present, with base period 1951-1980. The solid black line is the global annual mean and the solid red line is the five-year lowess smooth. The blue uncertainty bars (95% confidence limit) account only for incomplete spatial sampling. [This is an update of Fig. 9a in Hansen et al. (2010).]

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 an Option. It is Required

A 2016 peer-reviewed version of his evaluation of future ice sheet collapse and super-storms is described and linked here And in 2017, his latest paper declares climate disaster is assured unless we pull substantial CO_2 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 410 ppm in 2017), 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)**
- From Ice Age paleo data which had much milder forcing, there were pulses of sea level rise of ~+2 ft per decade, lasting for centuries, making it impossible to have ports or conduct international trade in any form resembling today.
- However, these pulses were from a time when the Earth had much more ice to melt than today, and the evidence suggests these pulses were from the Canadian Laurentian ice sheet (which no longer exists), so possible future pulses would have to happen from Greenland or Antarctica.

To <u>Halt</u> 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 <u>from</u> the oceans <u>to</u> 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 <u>*per se*</u>, 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

Efficacy and Safety:

First Key: Efficacy:

- 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

2nd 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 climate change trajectory that took us here.
- 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 neglect the problems.
- A great example is the absurd (but "catchy") SolarRoadWays hype. Here's a well-deserved bucket of cold water, from an astronomer
- This is how Wall Street works, unfortunately.

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 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, is what they all want.

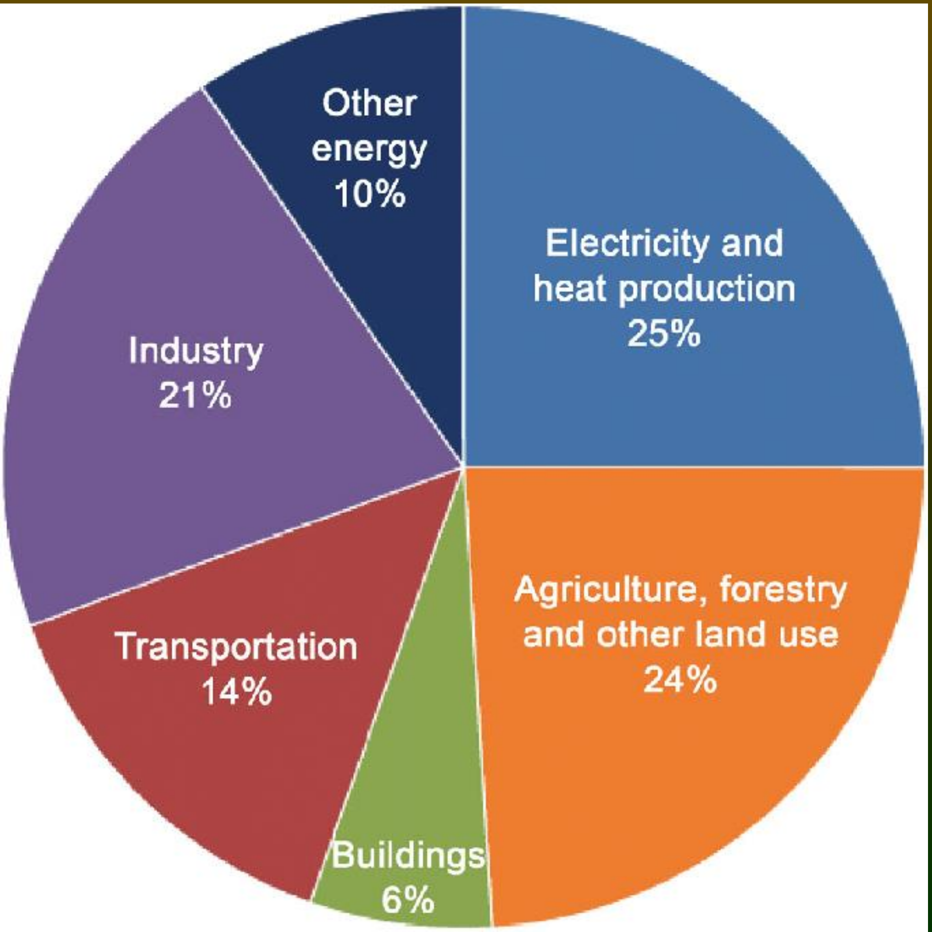
Instead - Trust Peer-Reviewed Science Journal Papers, Refereed by Competing SCIENTISTS

- 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 economic, physical growth <u>must end</u> 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.
- **<u>Remember – Growth and Domination: The tragedy is when you WIN (unfortunately - we did!).</u>**

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
Alternative Energy

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

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
- --- Others argue wind also makes sense. Wind is cheap.

Potentially, Solar Energy Dwarfs Other Renewables, Wind Next. (This slide is a few years old; human use=19 TW in 2019)

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

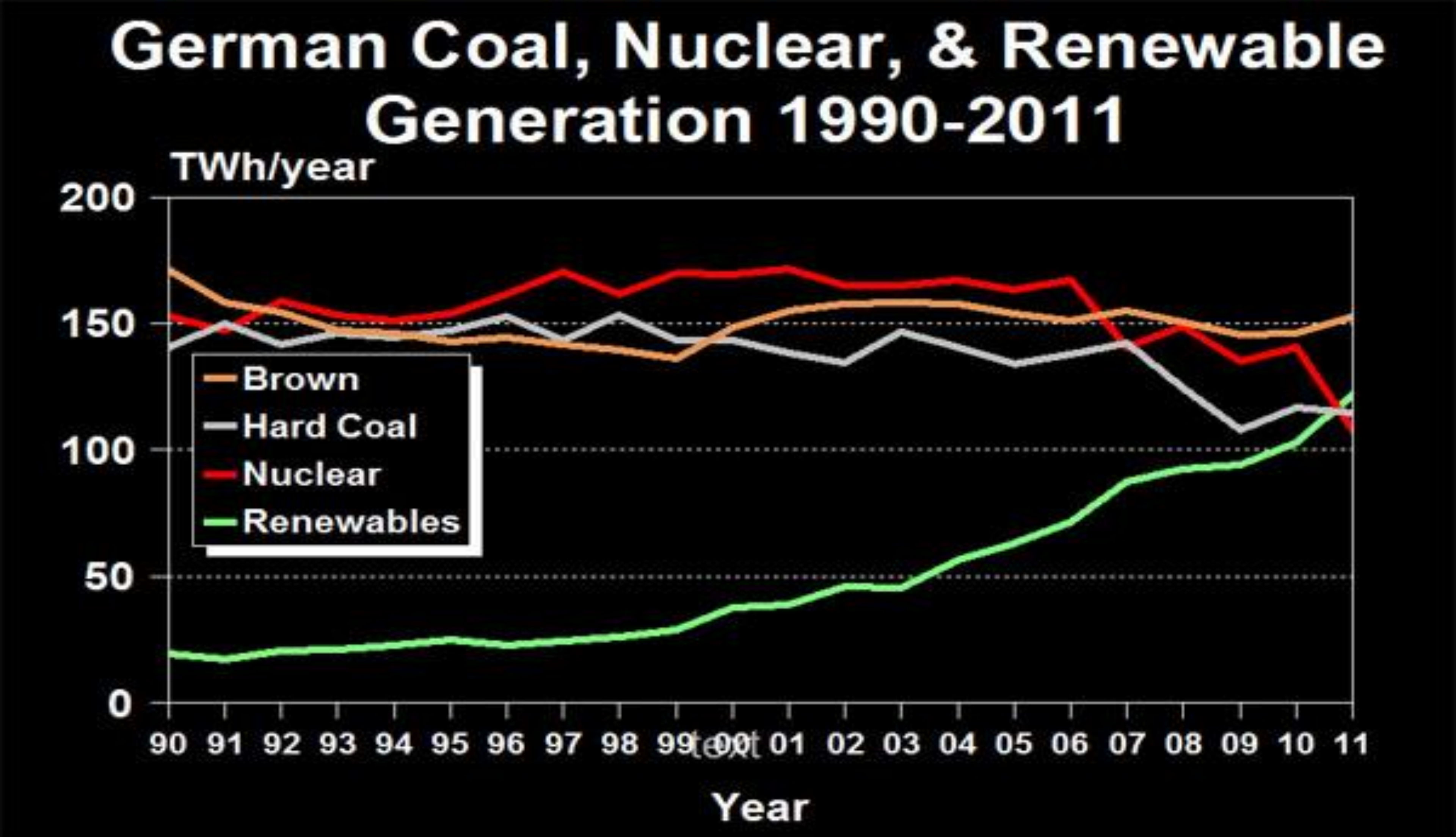
A. Solar Photovoltaics

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)

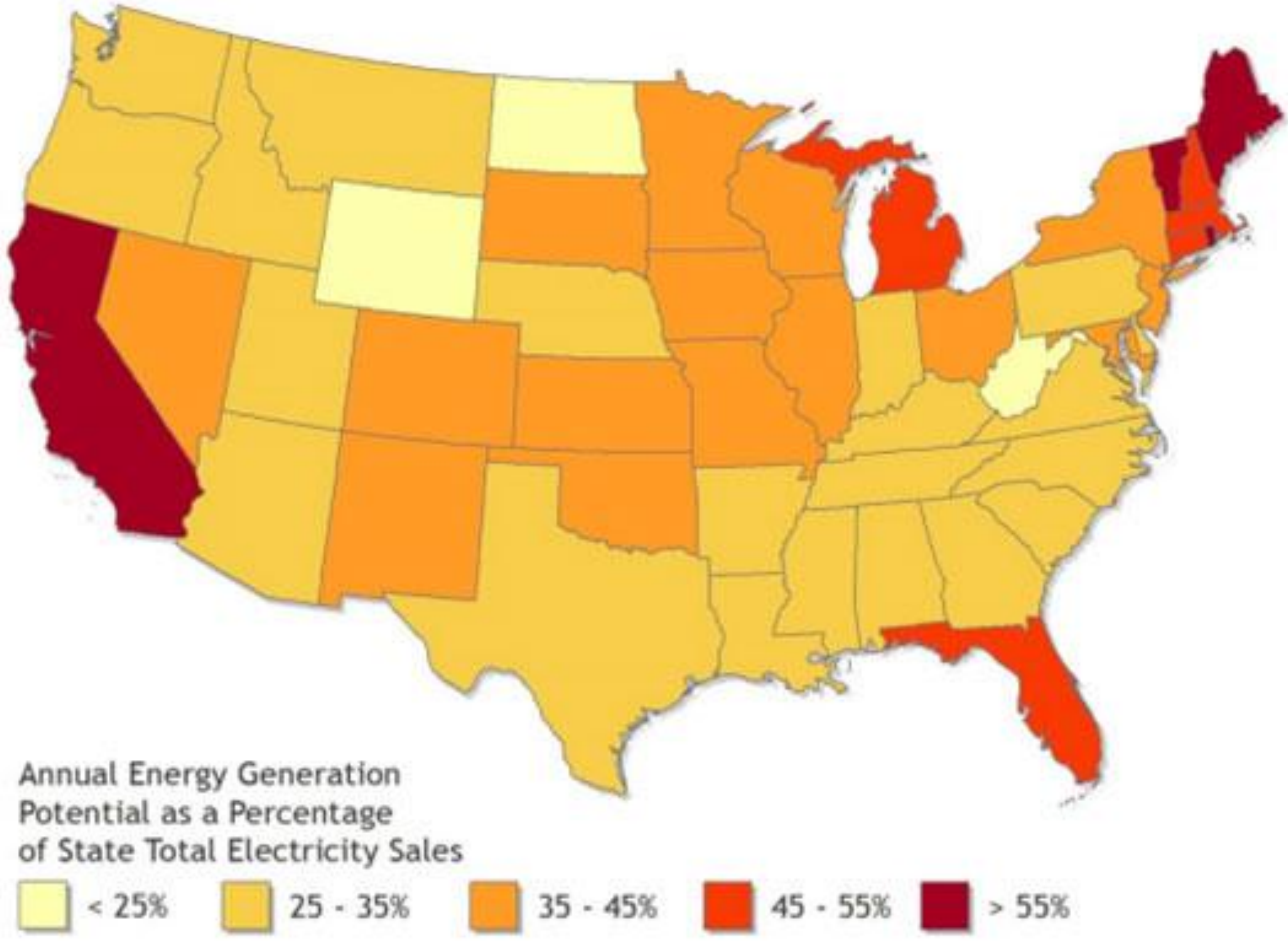


Figure ES-2. Potential rooftop PV annual generation from all buildings as a percentage of each state's total electricity sales in 2013

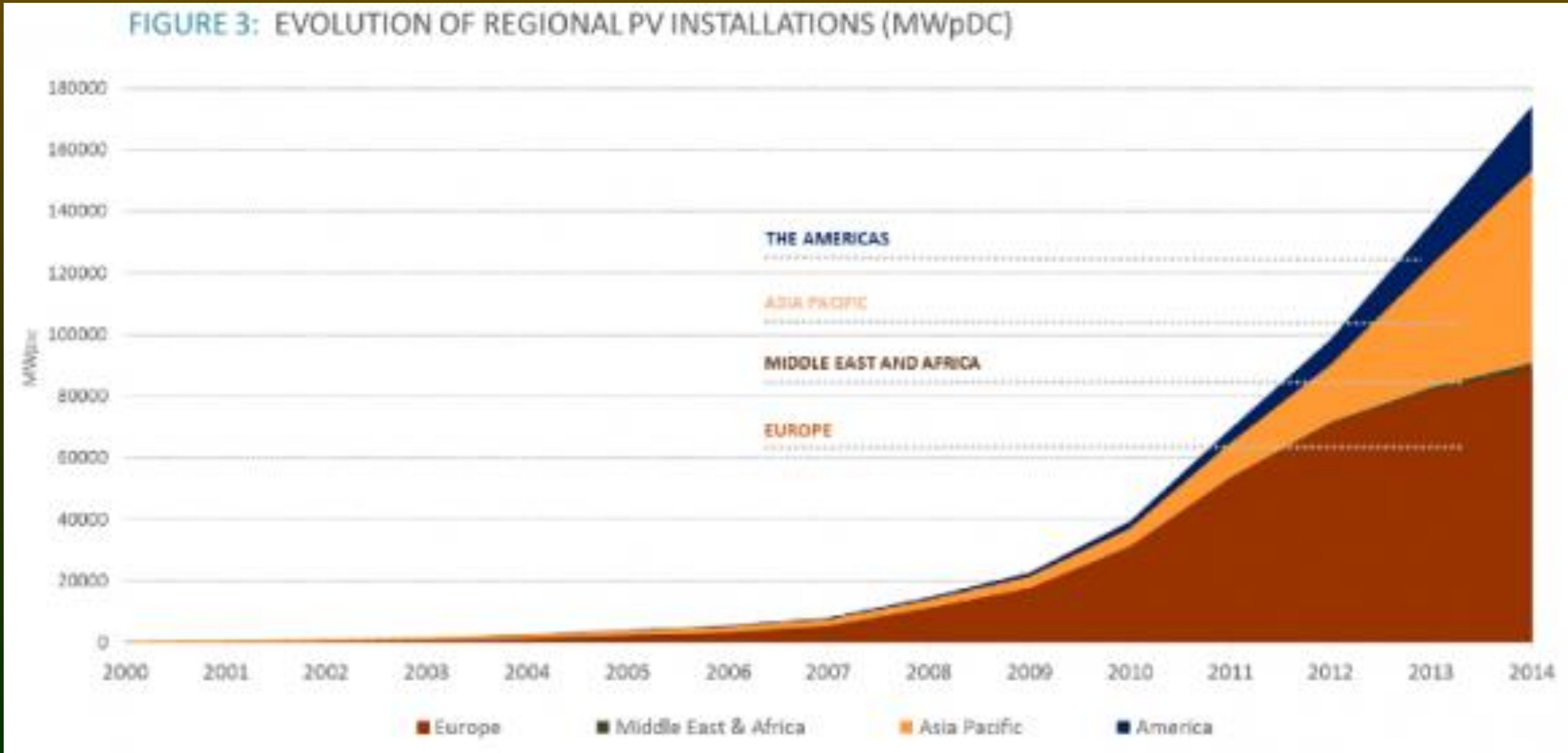
In Europe, while there's room for adding to rooftop Solar…

- …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).

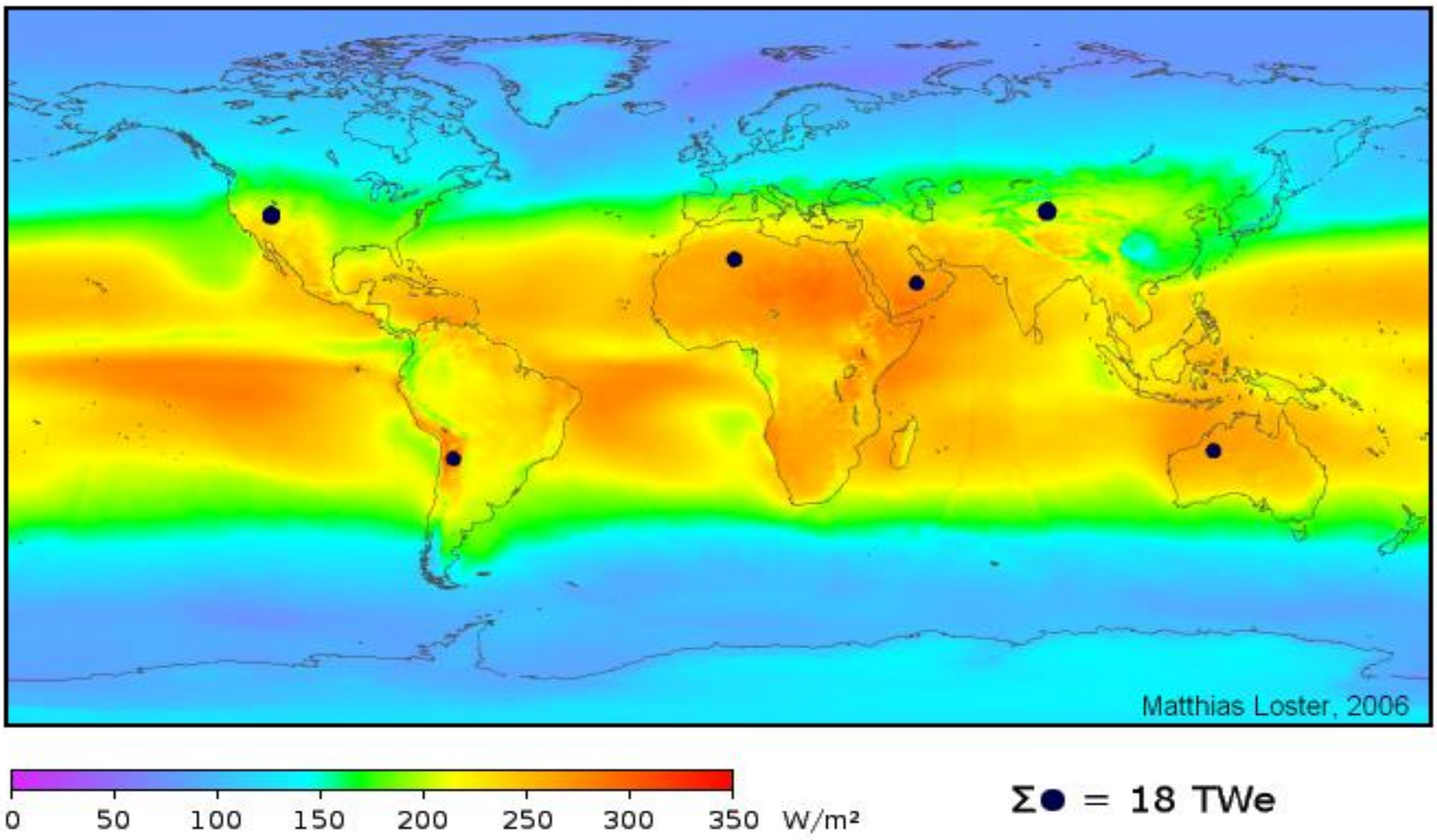
Rooftop Solar is Appealing

- 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)

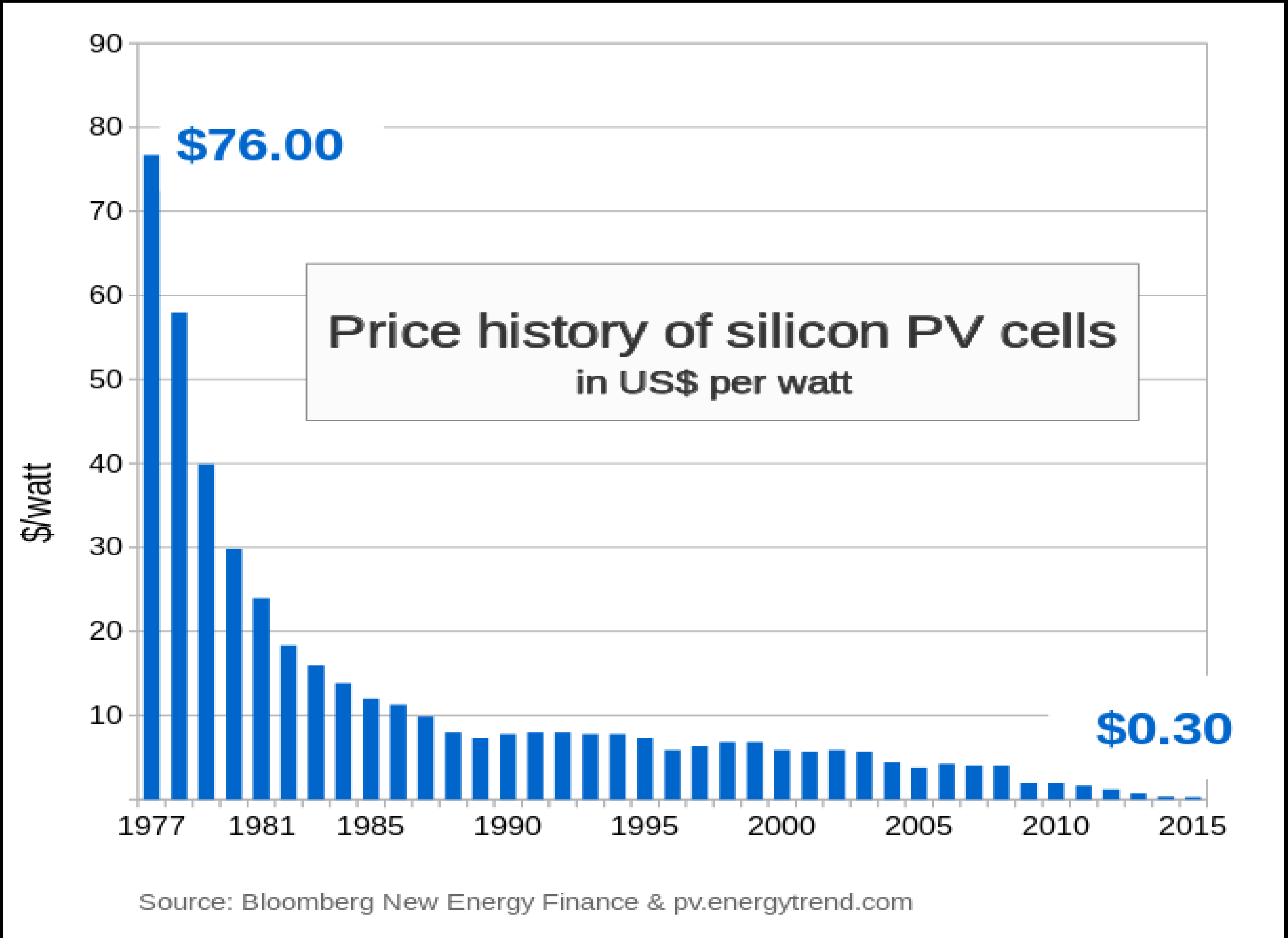
Initially growing exponentially, after the end of the 'Great Recession' in 2010, global solar PV deployment has dropped back to a constant annual deployment rate



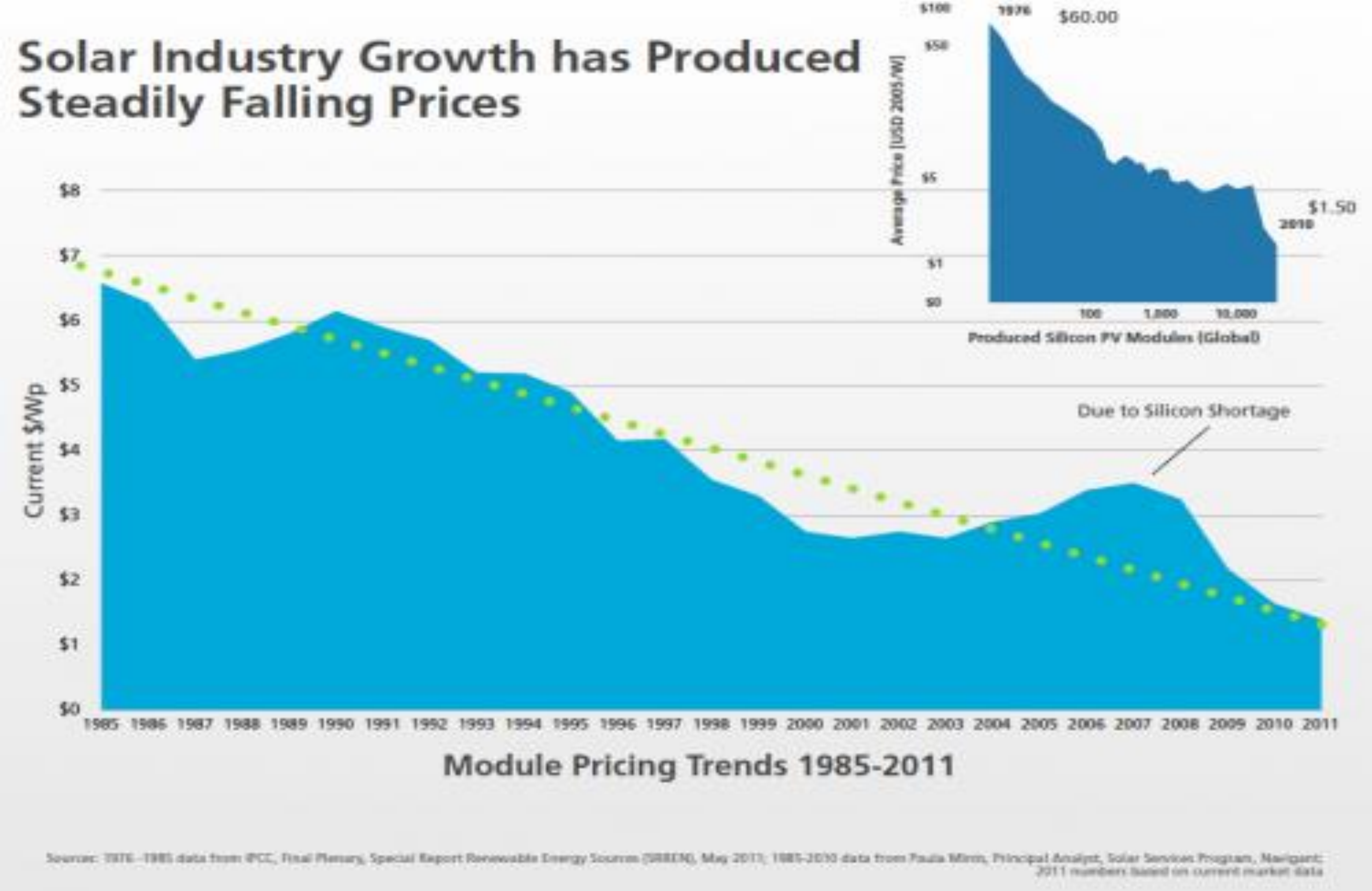
Solar PV Accessible Power Potential, Including Cloud Cover. Sum of black dot areas = total global power needs



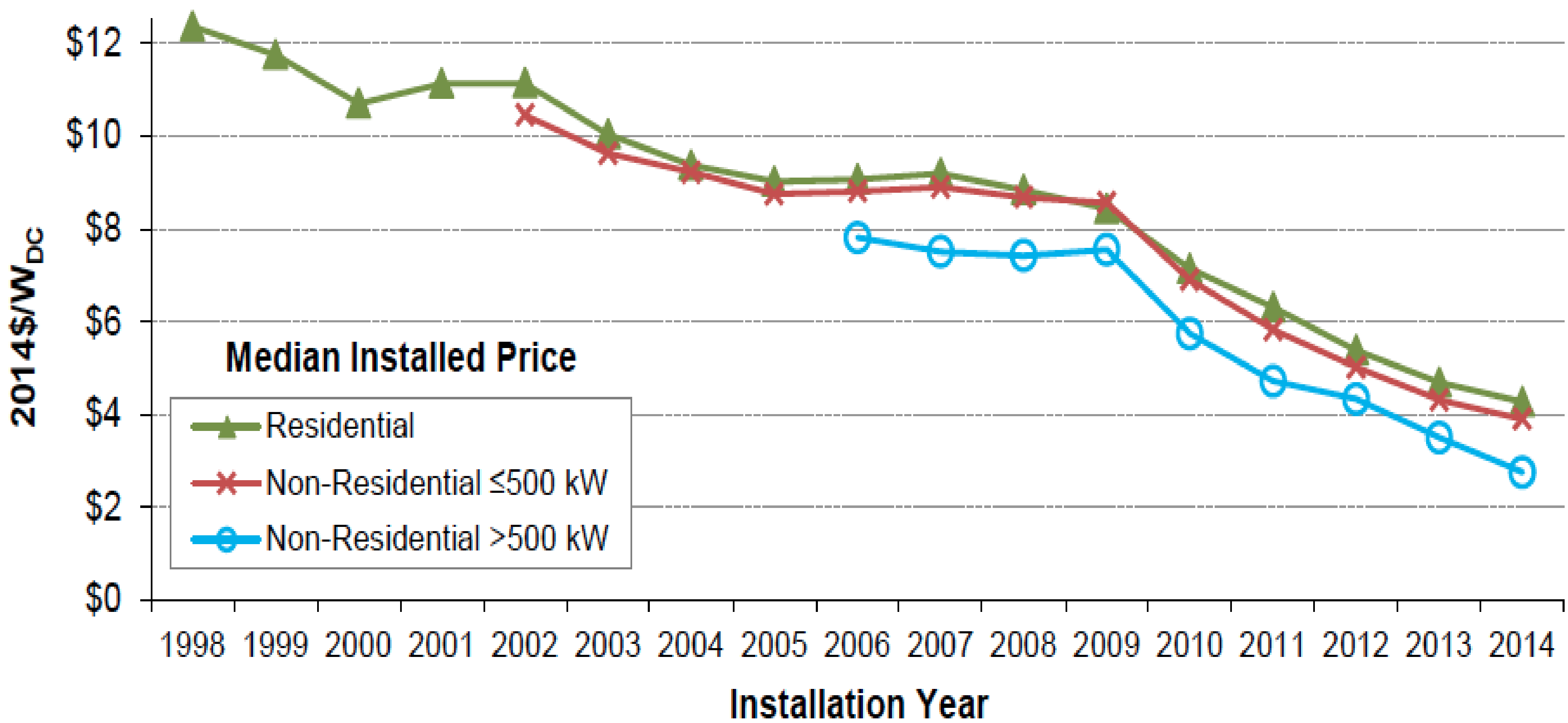
Silicon PV Cells costs continue to fall (not the same as entire PV Panels + Installation)



Solar PV module costs: 1985-2011



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

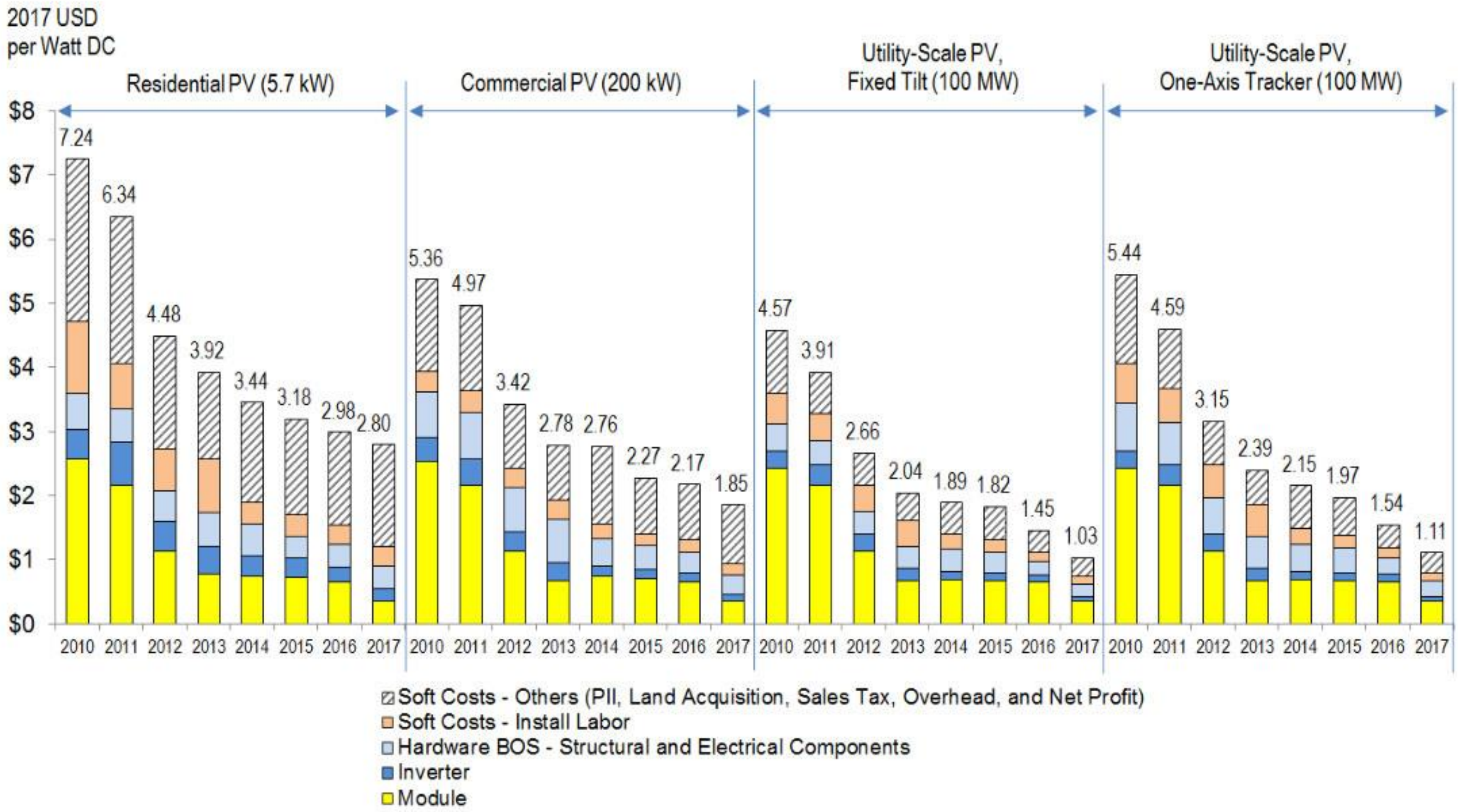
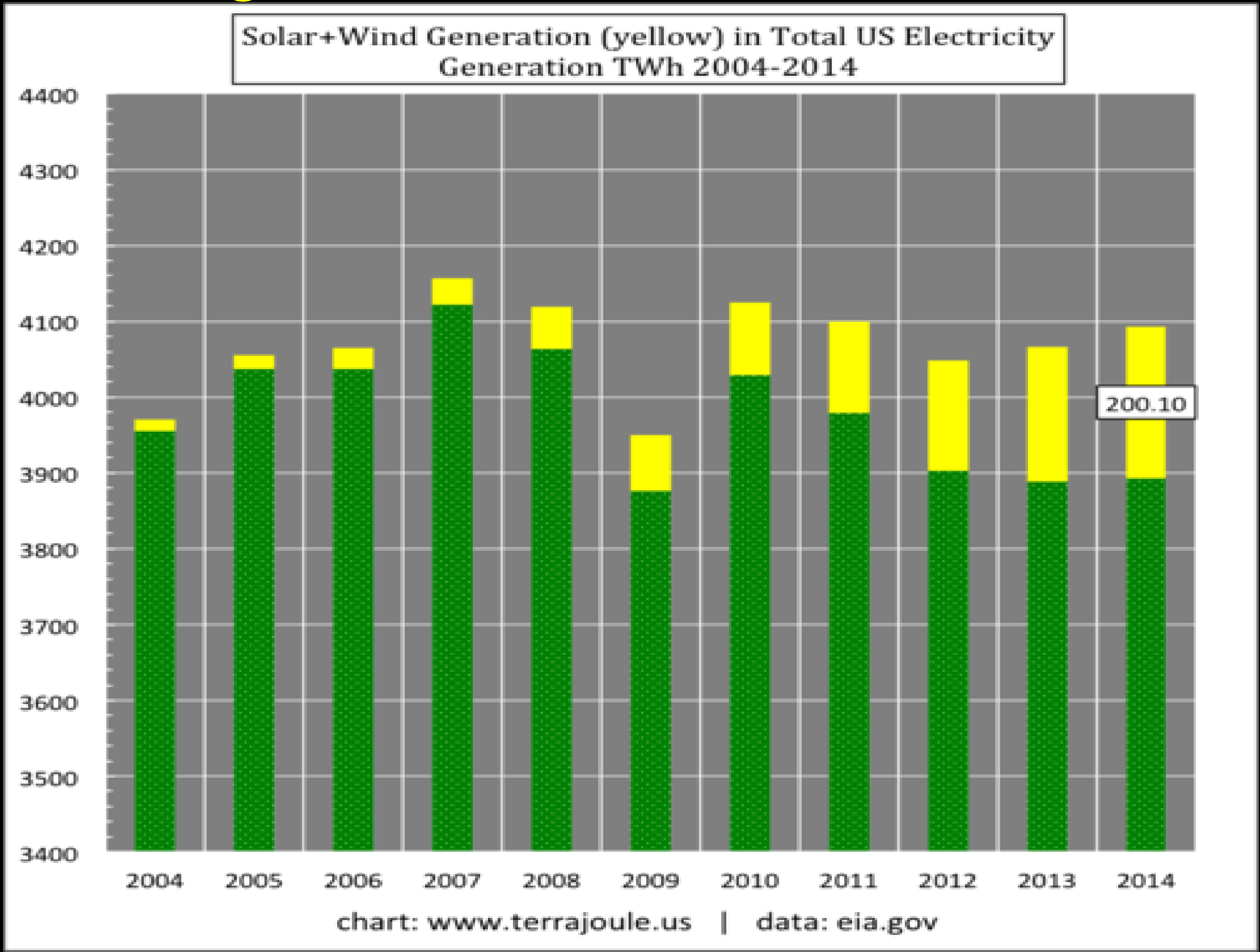


Figure ES-1. NREL PV system cost benchmark summary (inflation adjusted), 2010–2017

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

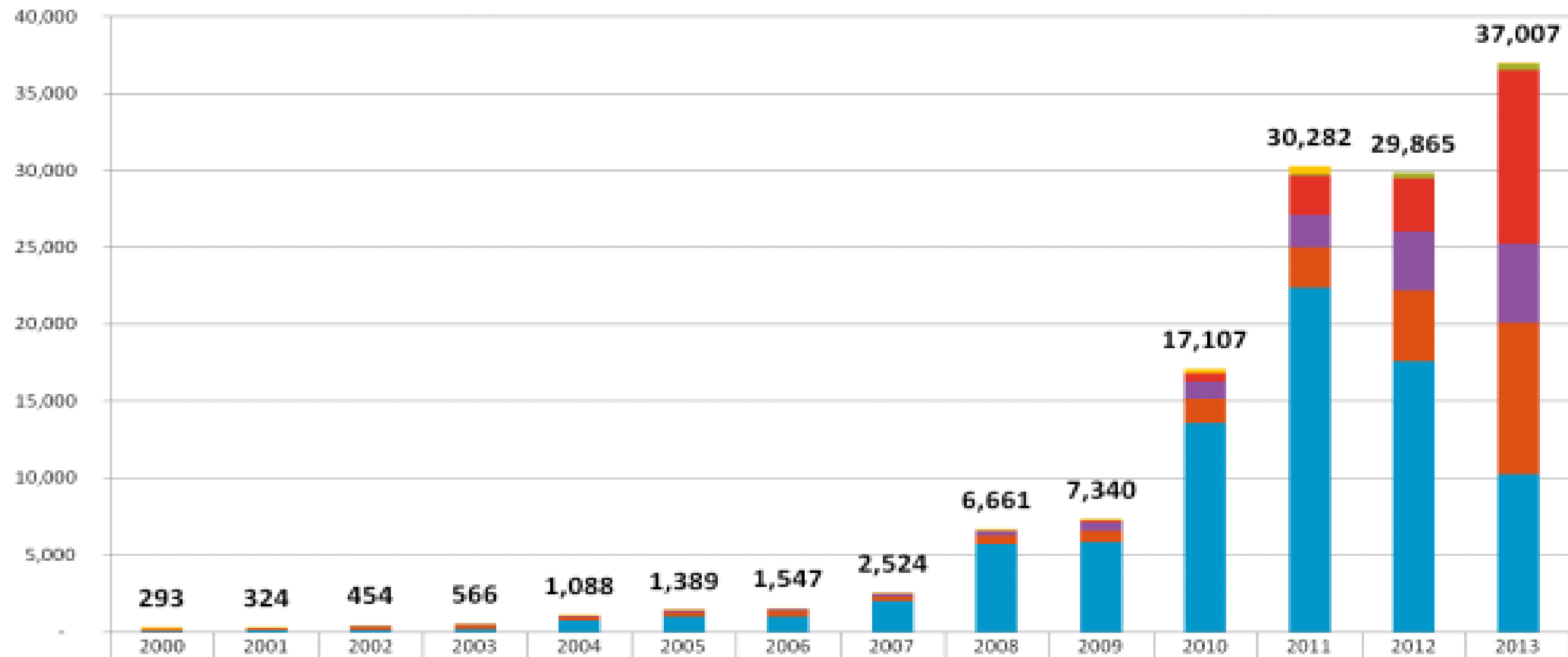


But Govt. Subsidies Have Given a Strong Boost to the Spread of Solar Energy

- 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)

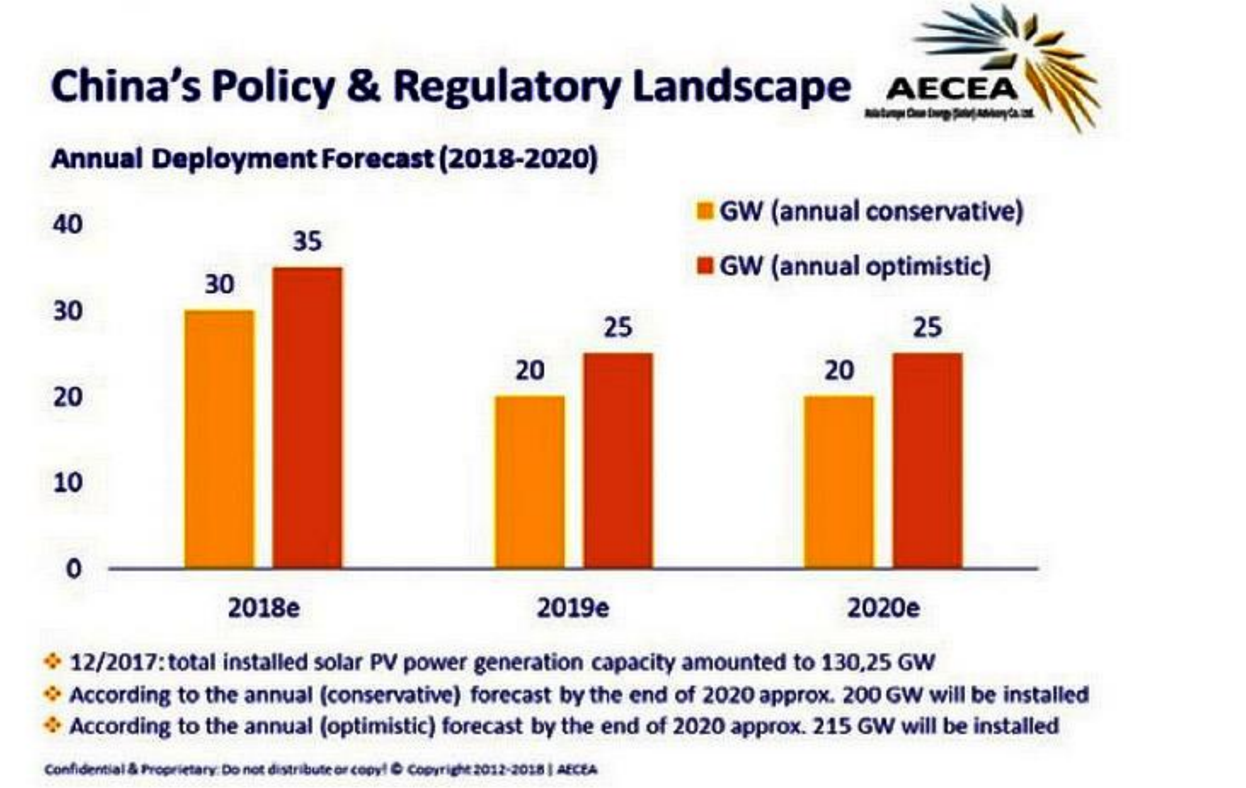


	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
ROW	88	56	80	77	29	10	105	42	76	80	284	508	-	85
MEA	-	-	-	-	1	0	0	1	1	22	46	125	365	383
China	19	5	19	10	10	8	10	20	40	160	500	2,500	3,500	11,300
AMERICA	2	3	30	48	61	82	110	166	306	500	1,082	2,181	3,774	5,153
APAC	126	128	190	230	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 expected to be 30% lower in '19 and '20 vs '18.



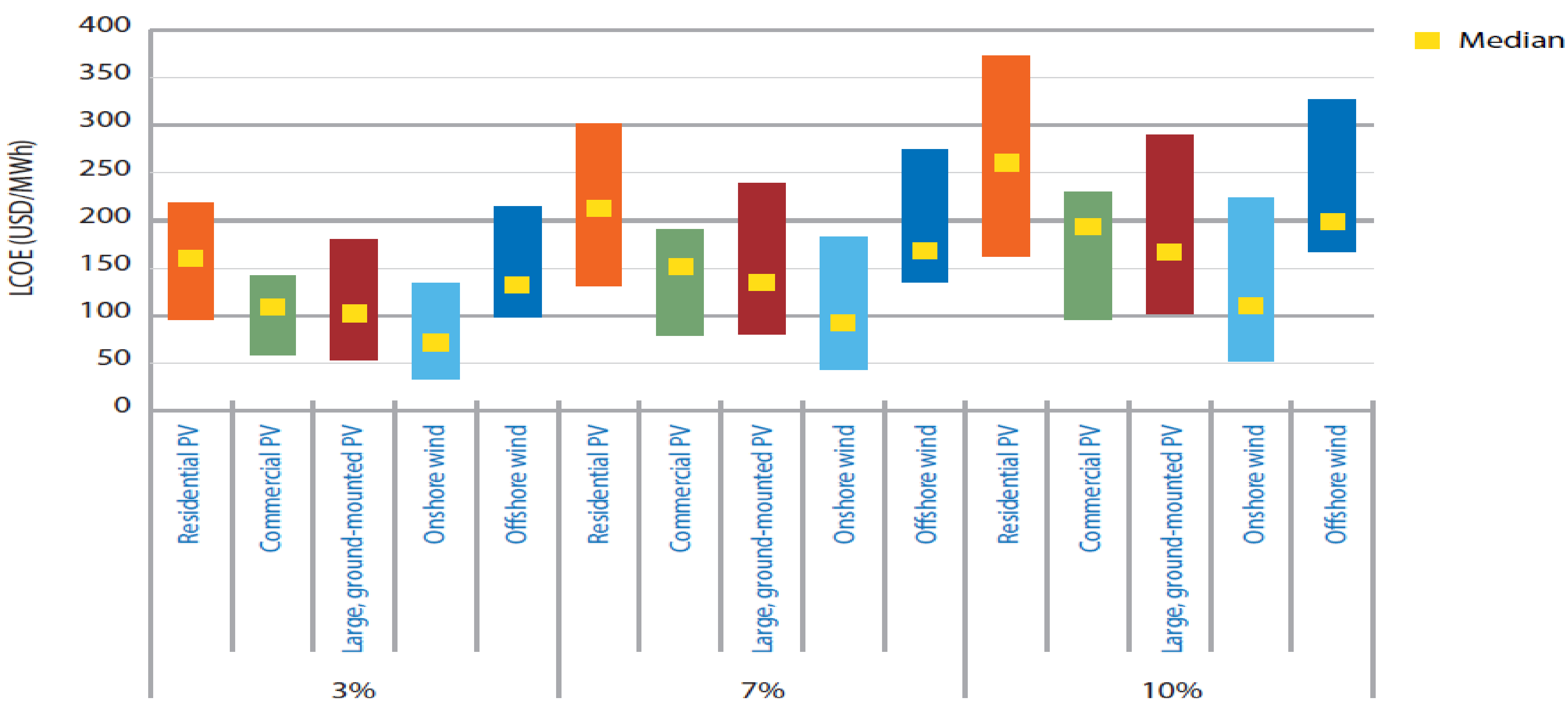
AECEA noted that total cumulative deployments could reach between 200GW to 215GW, targeting only annual deployments in a range 20GW to 25GW over the next two years. Image: AECEA

Levelized Cost of Electricity: LCOE

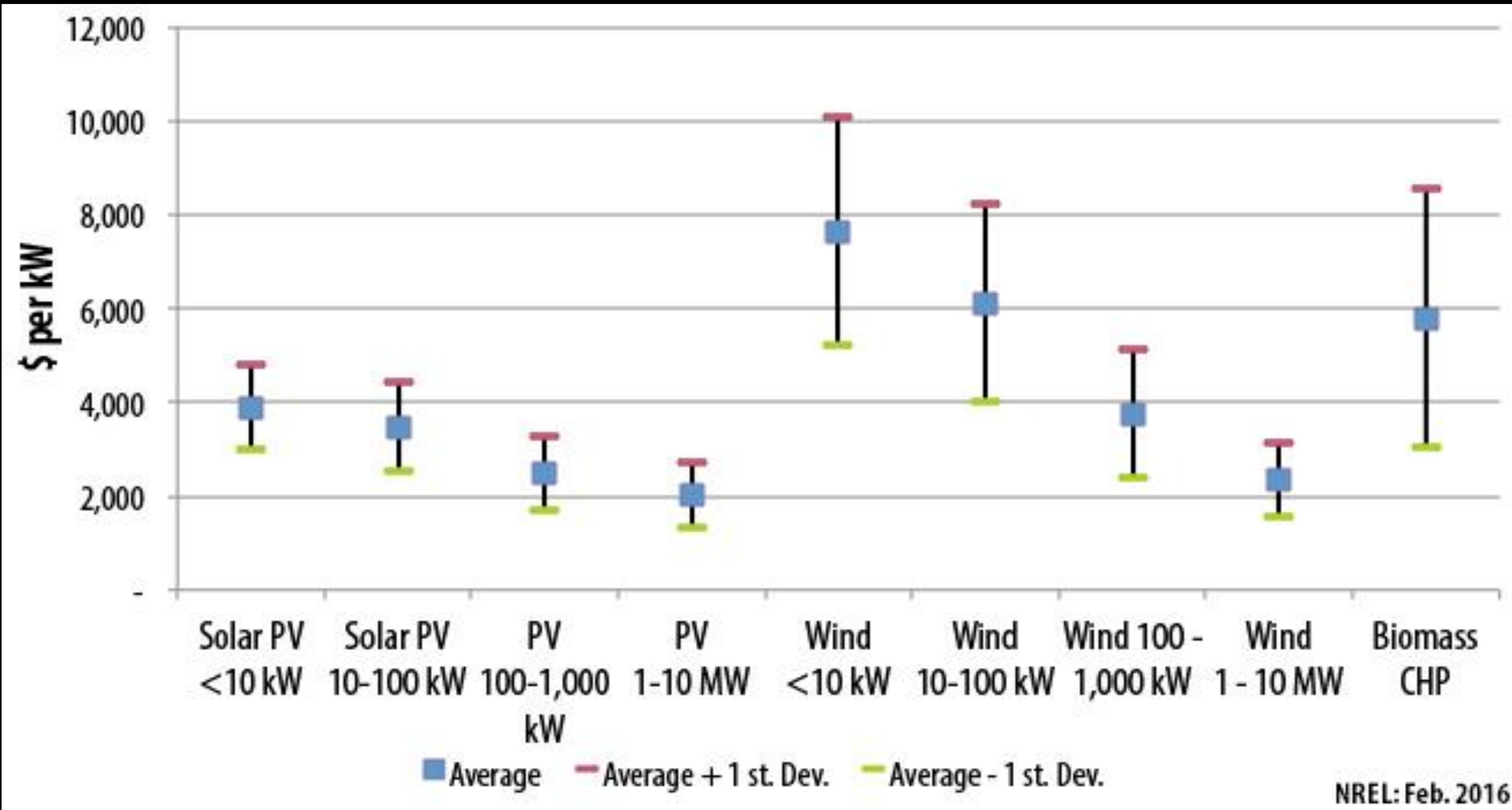
- "**Levelized cost"=LCOE =** The average total cost to build and operate a power-generating asset over its lifetime, divided by the total energy output over that lifetime.
- The LCOE can also be regarded as the minimum cost at which electricity must be sold in order to break-even over the lifetime of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

2015 Renewables LCOE's for range of countries, from EnergySolutions. Roughly comparable to Fossils. Utility solar still beats rooftop costs, (onshore) wind even cheaper. Range of forward discount rates don't change relative positionings. **Residential PV most expensive**

Figure ES.2: LCOE ranges for solar PV and wind technologies (at each discount rate)



2016 LCOE per unit of power output. Utility-scale is ~half the cost of small scale, for both solar PV and for wind

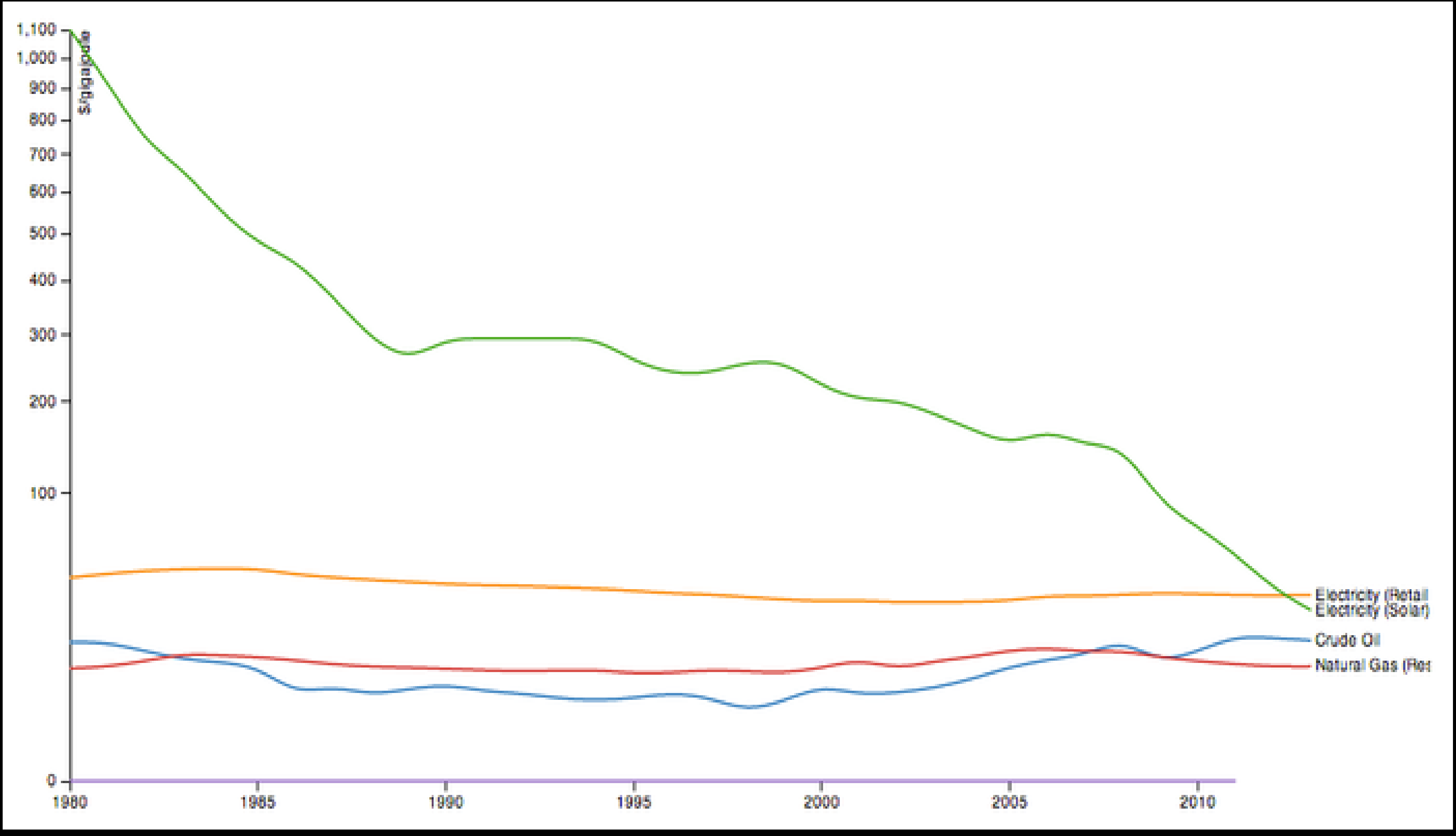


Projected levelized costs ($/MWh) for power plants entering service in 2020?

- $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**

Cost For Solar *vs.* Fossil Fuels: Improving Every Year to 2014. ($ per GigaJoule).

(In 2015+, strong price decline in fossil fuels, however)



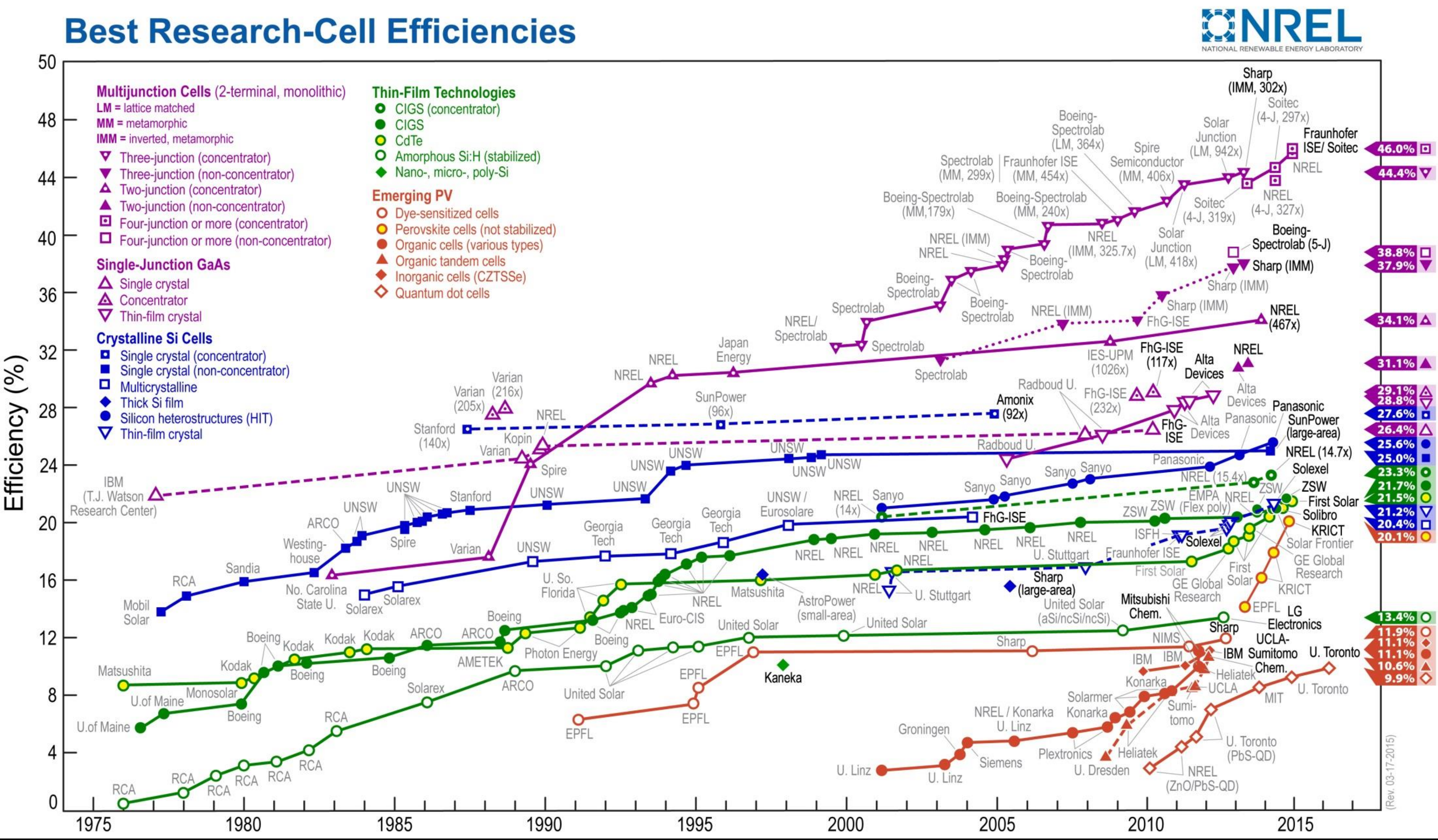
Solar PV costs likely to fall going forward, but not as fast…

- 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 close 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.
- Manor *et al.* 2016 described here
- Still…

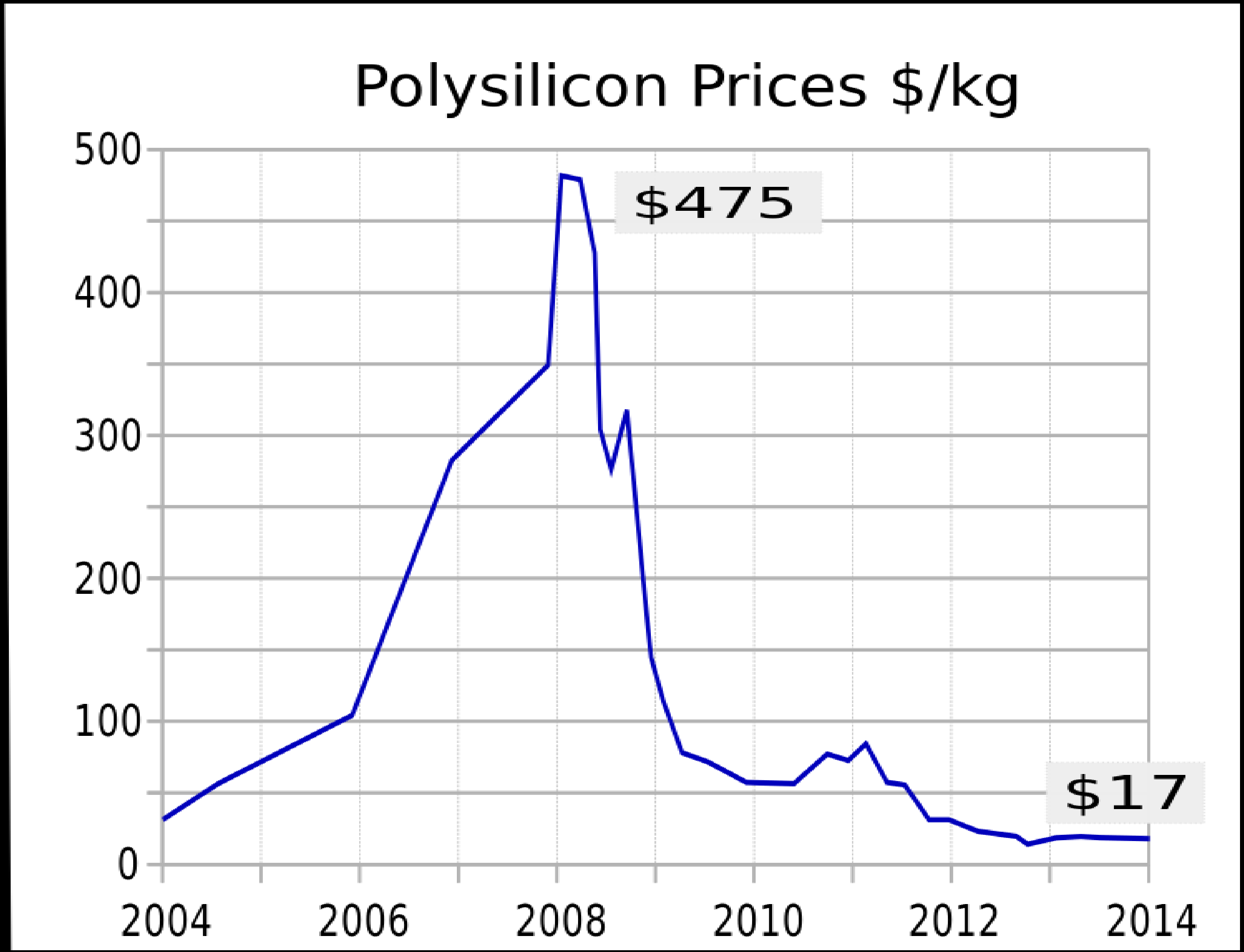
…Unlike computer power and Moore's Law, Solar's future efficiency gains will be slower. The dilute nature of incoming sunlight will always limit the energy density available



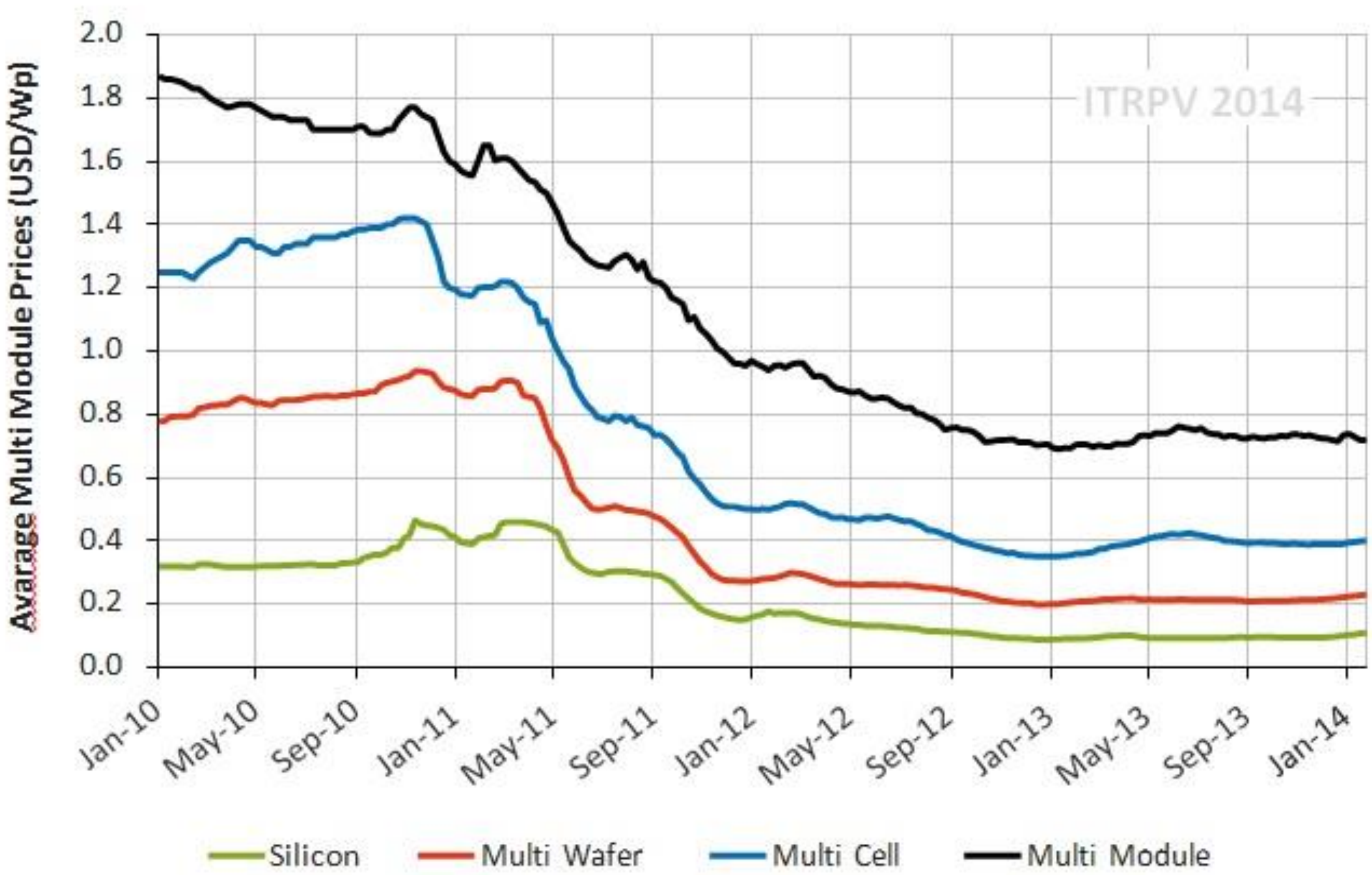
More important for cost…

- 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).

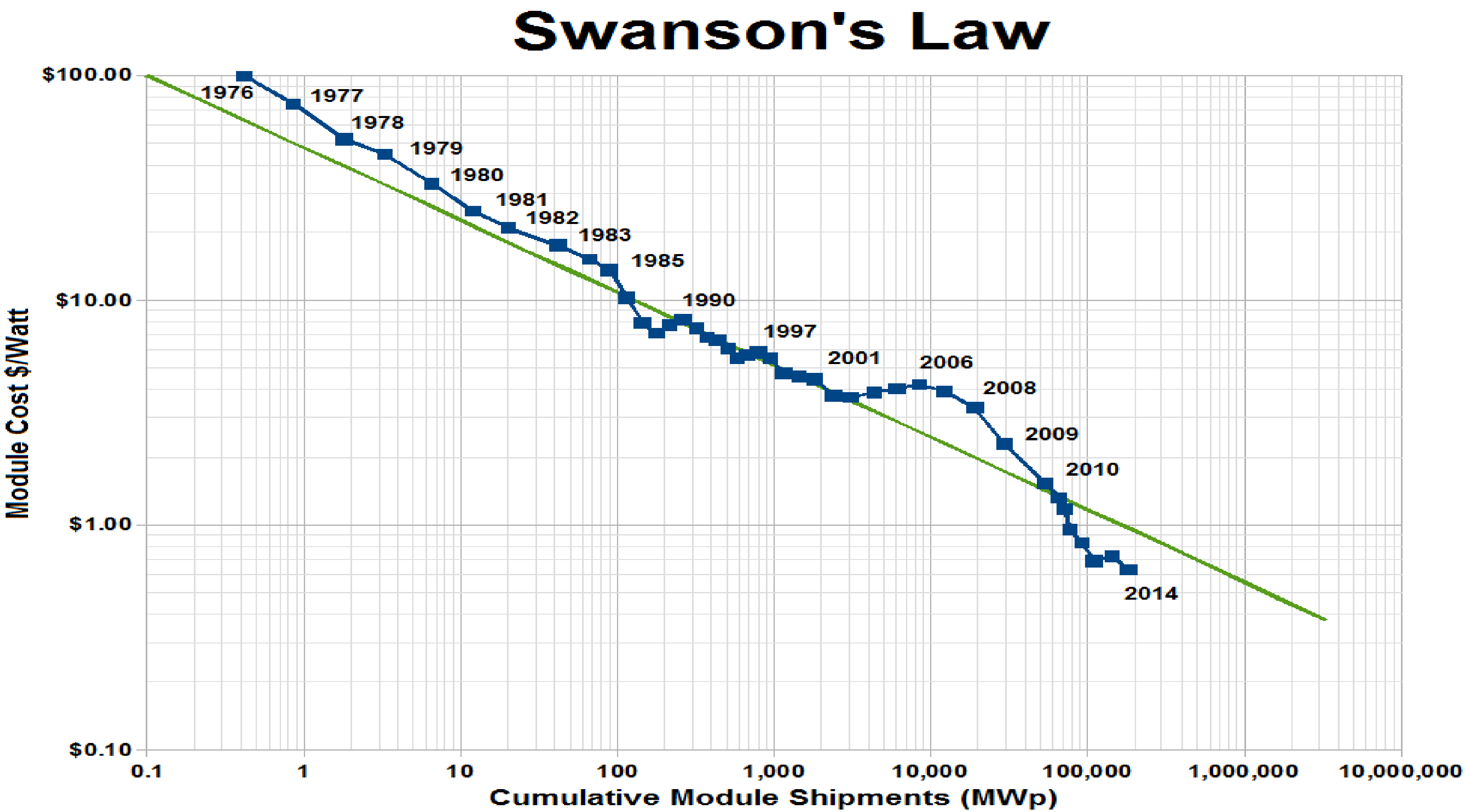
Polysilicon Prices – Past Decade. Price spike due to shortage, then a glut, and then stable cost past several years



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.

As of 2014: (source)

- Hardware: $1.76 per watt (44% of total cost)
- Install Labor and Electrician: $0.68 per watt (17% of total cost)
- Permits: $0.08 per watt (2% of total cost)
- Marketing/Outreach: $0.82/watt (20% of total cost)
- Overhead/Profit: $0.66 per watt (17% of total cost)
- Total system cost: $4 per watt ($16,000 for typical home)

- Hardware is already less than half the total cost
- Unless all these costs can come down at high rates, simple extrapolation of past trends is too rosy a projection. Beware agendas from the "economic growth is not to be questioned" policy people (see K43 Thermodynamics of Civilization PowerPoint)

We see that the 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
- <u>These facts argue that the large drops in solar costs have already largely occurred, and future drops will be more incremental</u>

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

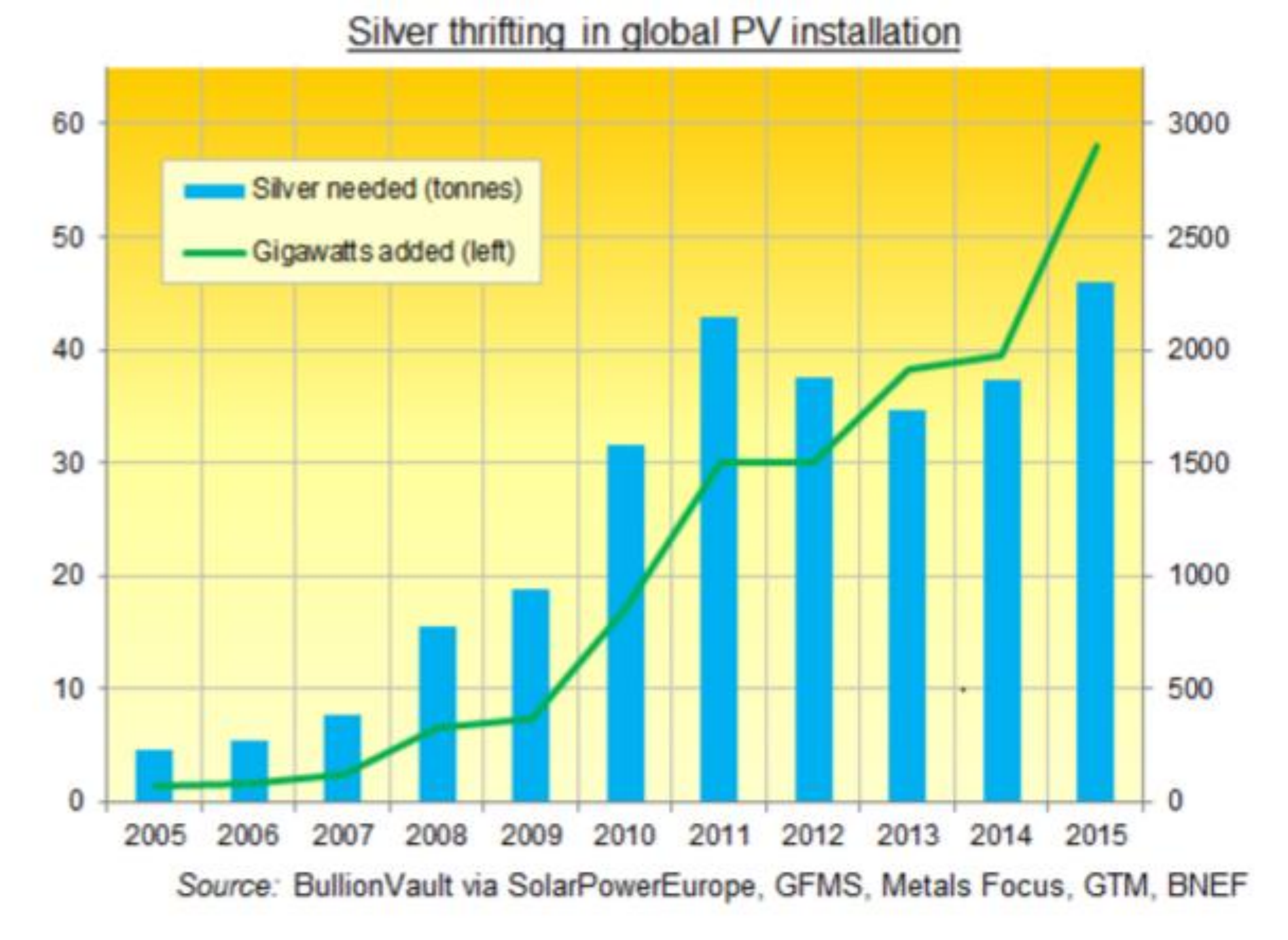
But Even the Very Optimistic SolarCellCentral.com Acknowledges

- *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. <u>If, by 2040, 20% of our electricity comes from solar and wind, almost everyone will be happy with the situation."</u>*
- **Everyone - except Planet Earth and Future Generations. It's just not fast enough.**

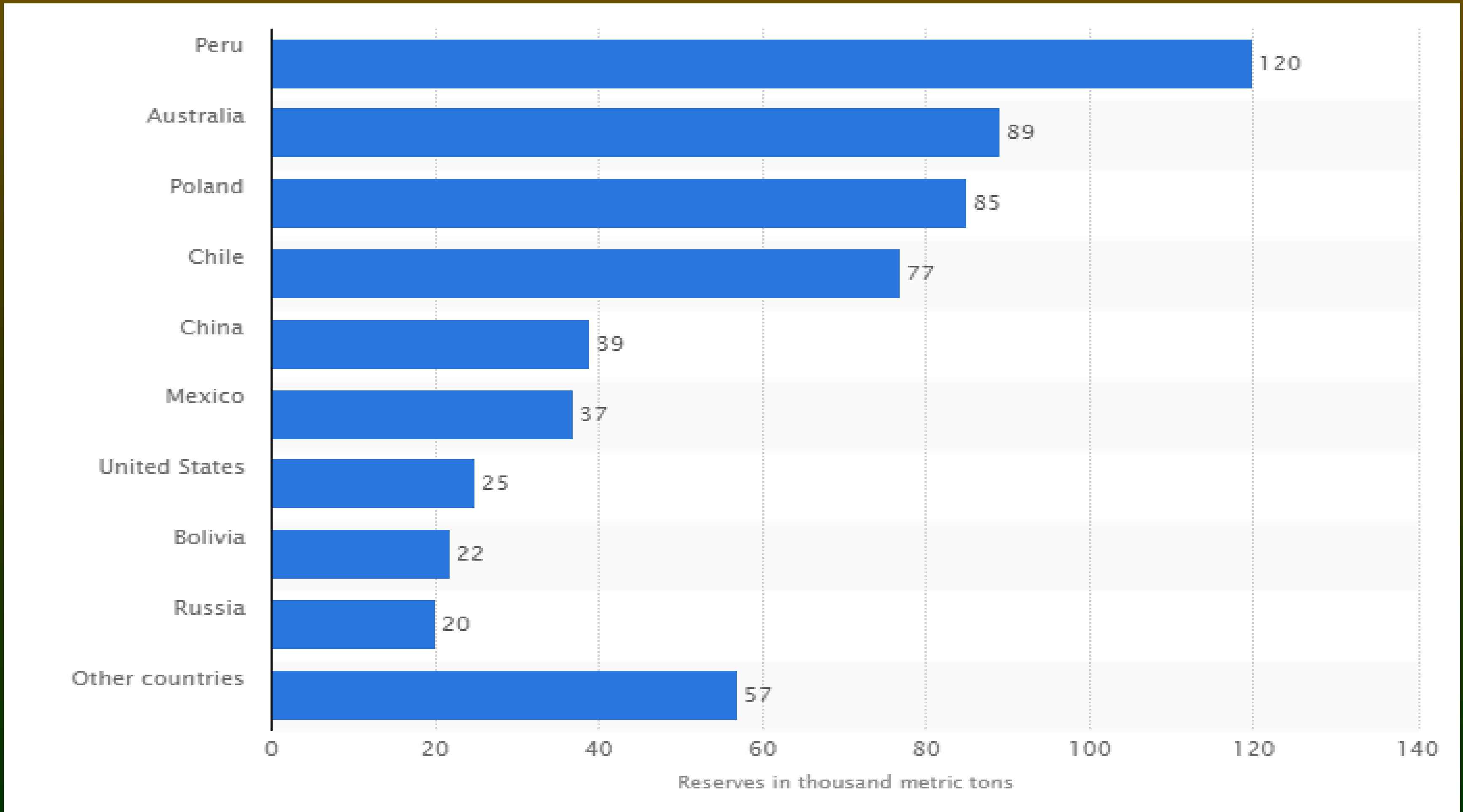
There's Potentially Another Problem: <u>Available Silver</u>

- Current solar panels (1.8 square meters) require 20g of silver.
- That's 11.1 <u>tons</u> 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 <u>tons</u> 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 – it's been an issue for years and the easy solutions are already done

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



The problem is, what's required is more than twice 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, yet this is after consuming the more than double all known reserves to reach solar PV powering the world.
- I’ve seen a lot of pro-solar rosy projections and promotions… but this issue never seems to be highlighted, hardly ever even mentioned.

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

- Some makers are already starting to use copper, but copper prices are rising too.
- However, 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 do the same job, accelerating the amount of required silver which is still used. Substitution is not necessarily a killer, but an inconvenient problem almost never mentioned.

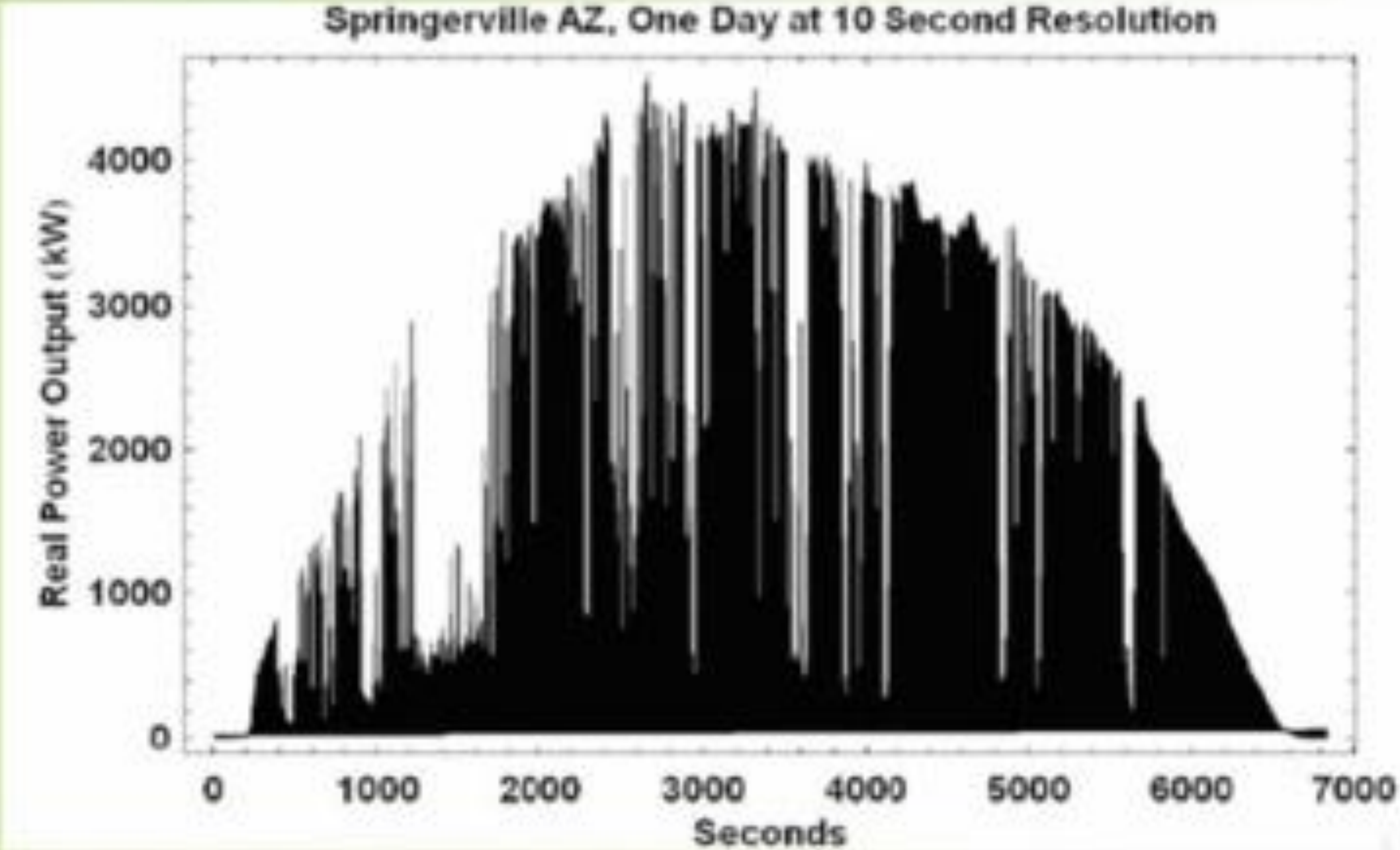
The Political/National Boundary Problem with Solar…

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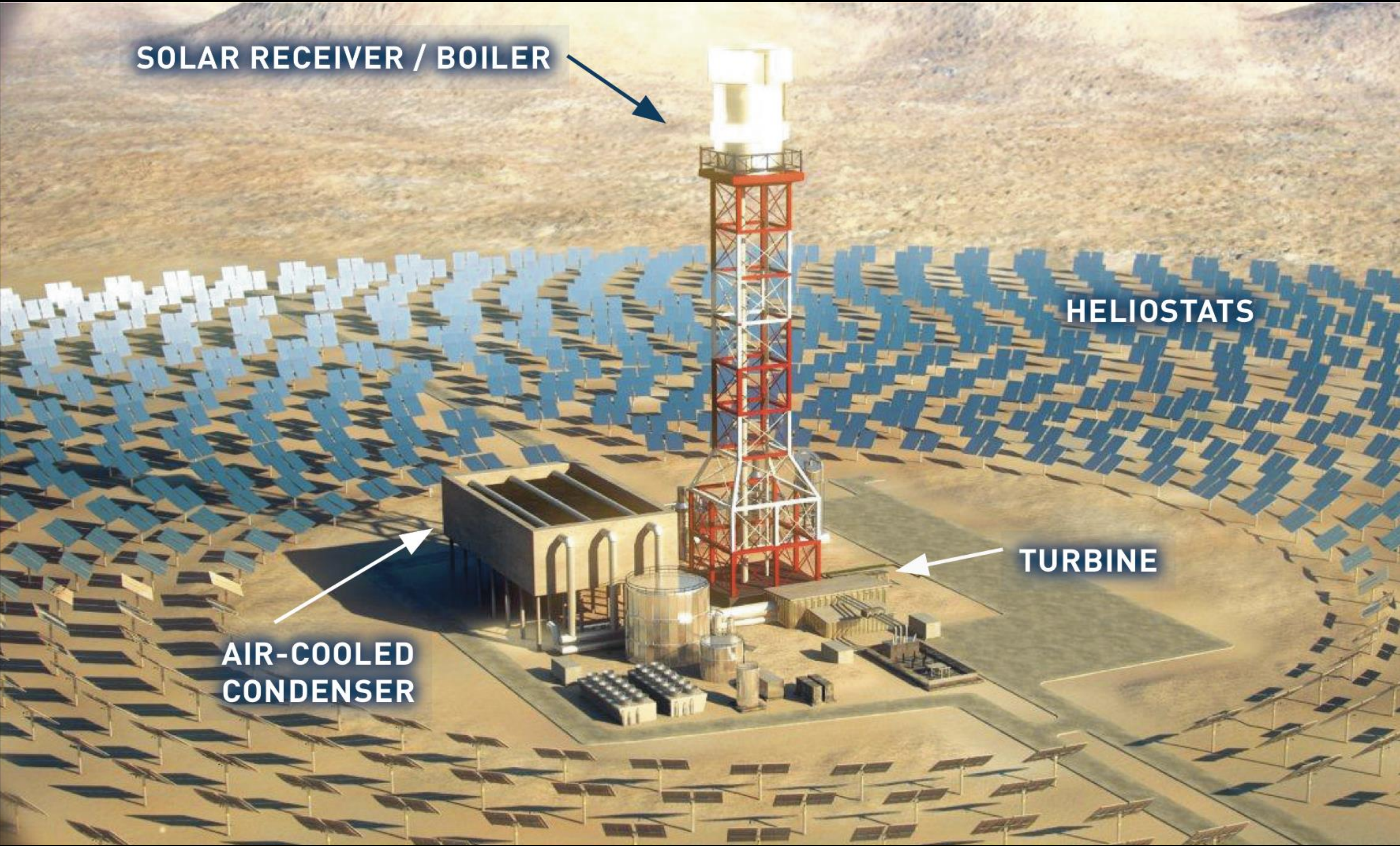
Requires better storage technology to be feasible. But progress is happening

- **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.

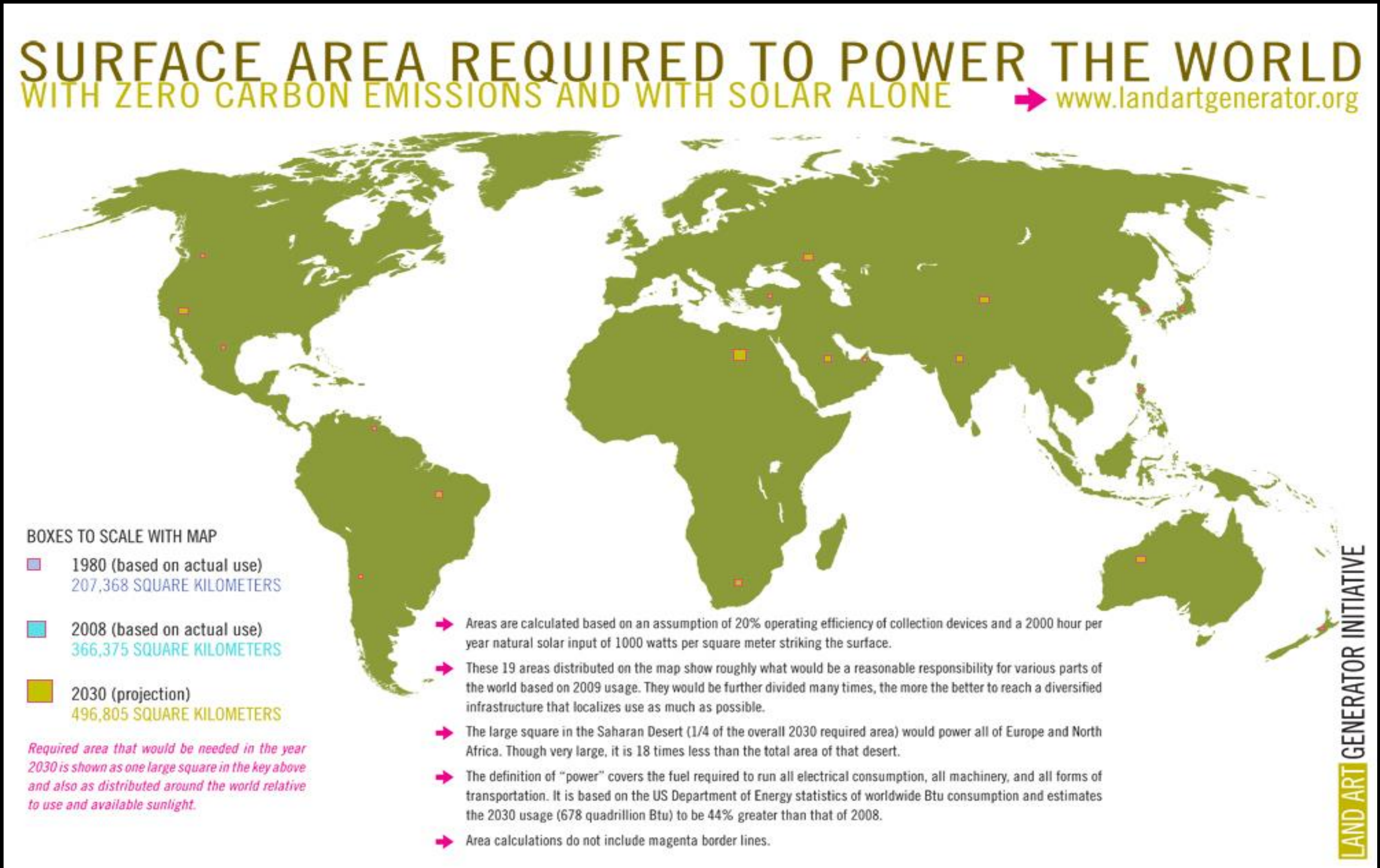
One Way Solar Can Address This is…

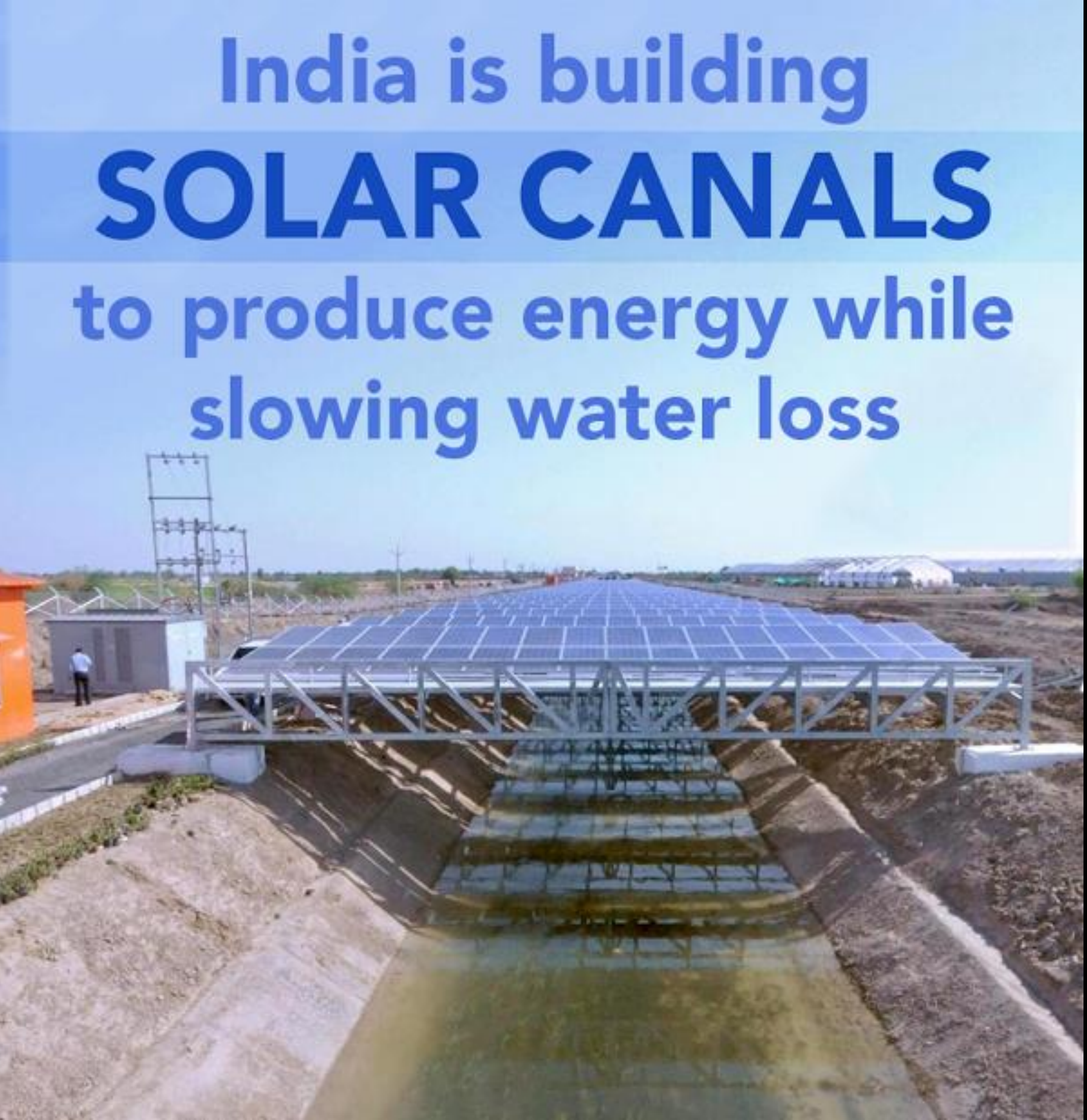
- **Solar Thermal**: Using solar power to heat a molten salt solution to far above the boiling point of water, store it in a well-insulated lining, and use it to boil water to drive power turbines after the sun has set
- It's not cheap, but still, it's getting cheaper. There are research projects on this in the Mojave Desert…

A Solar Thermal Power Plant on the Nevada Border



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

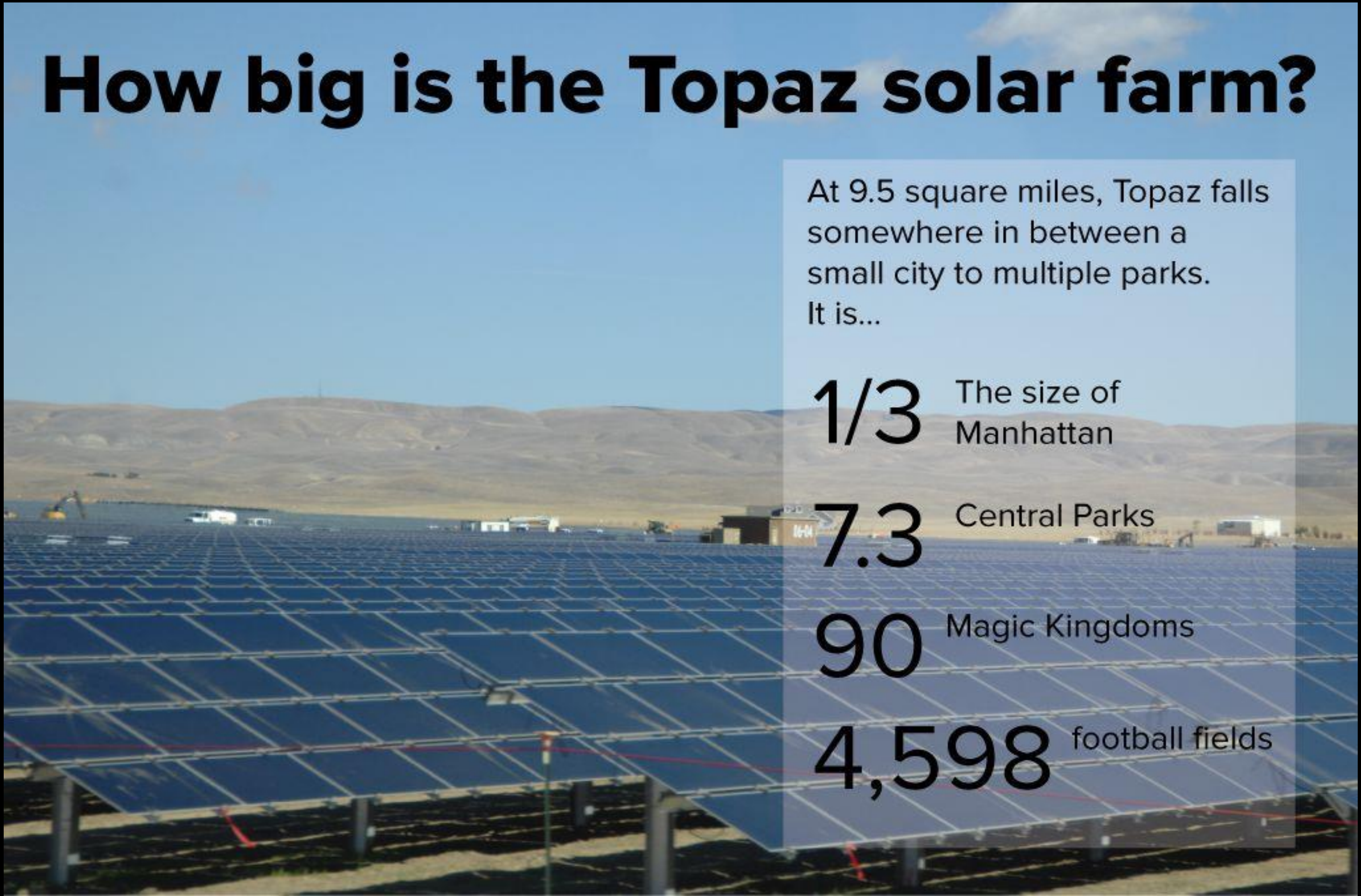
Is Utility-Scale the Way to Go?

- 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.



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 is having some success in their testing of a solar bikeway, producing good solar power, expected to produce 70 kwh/year per square meter when finished. An effort and testing in France also is worth following here , and in China here
- The road/bike way has solar panels protected by thick shatter-proof glass.
- Will it work? Is it cost-effective? Tempting; It's a lot of ground area otherwise wasted, but it's a tough environment and robust performance still unproven, and how expensive will it be to route resulting power from such expansive distributed sources? Totally unlike power plant distribution.

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)

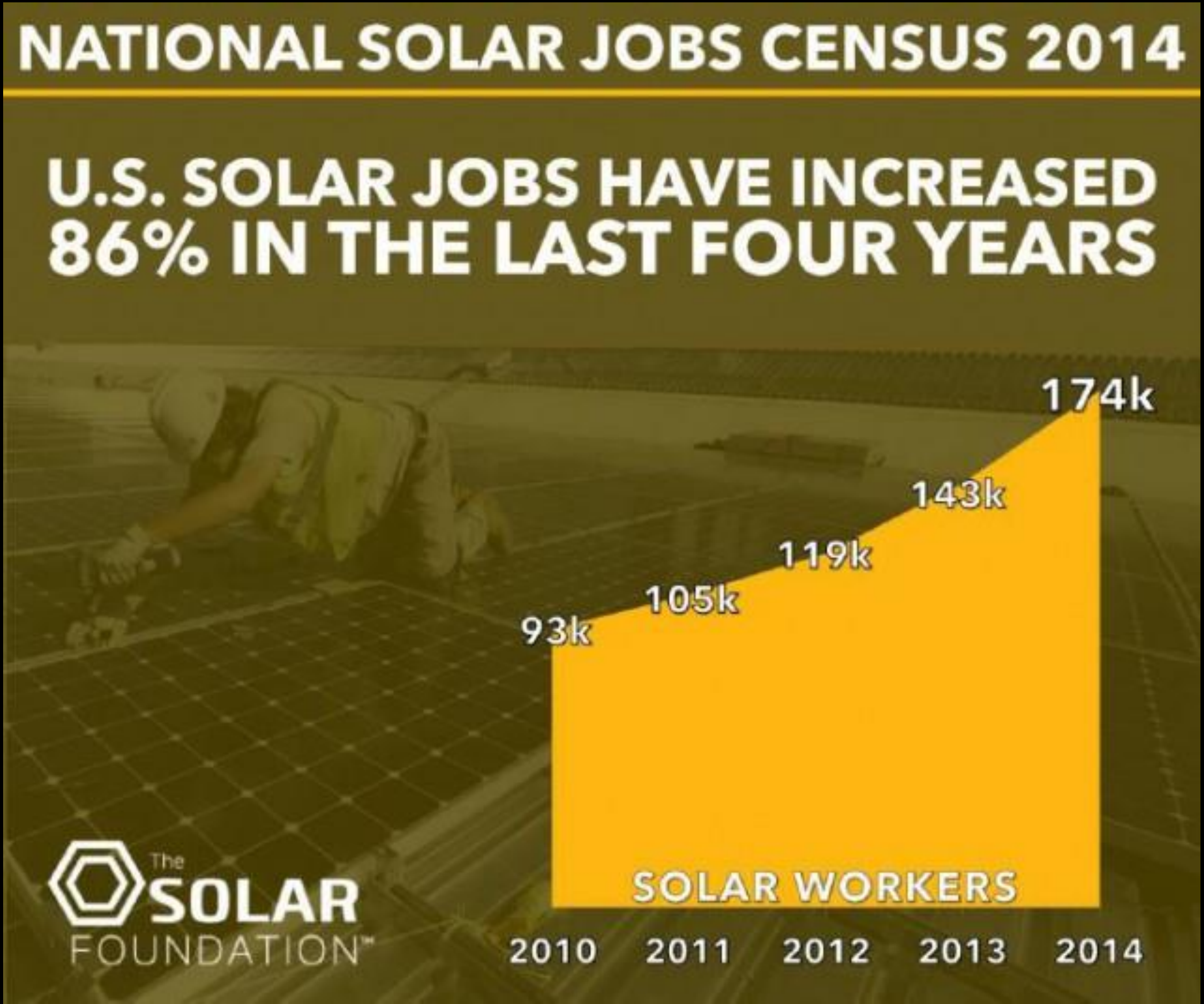
Solar Manufacture: Carbon Cost

- 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 CO2

- So that's 2.2 x 2.2 x 10^{14} lb of CO2 to make enough solar panels to power the Earth
- That's 2.4 x 10^{11} tons of CO2
- That's 240 gigatons of CO2 , or about 7 years of total current global emissions of CO2 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

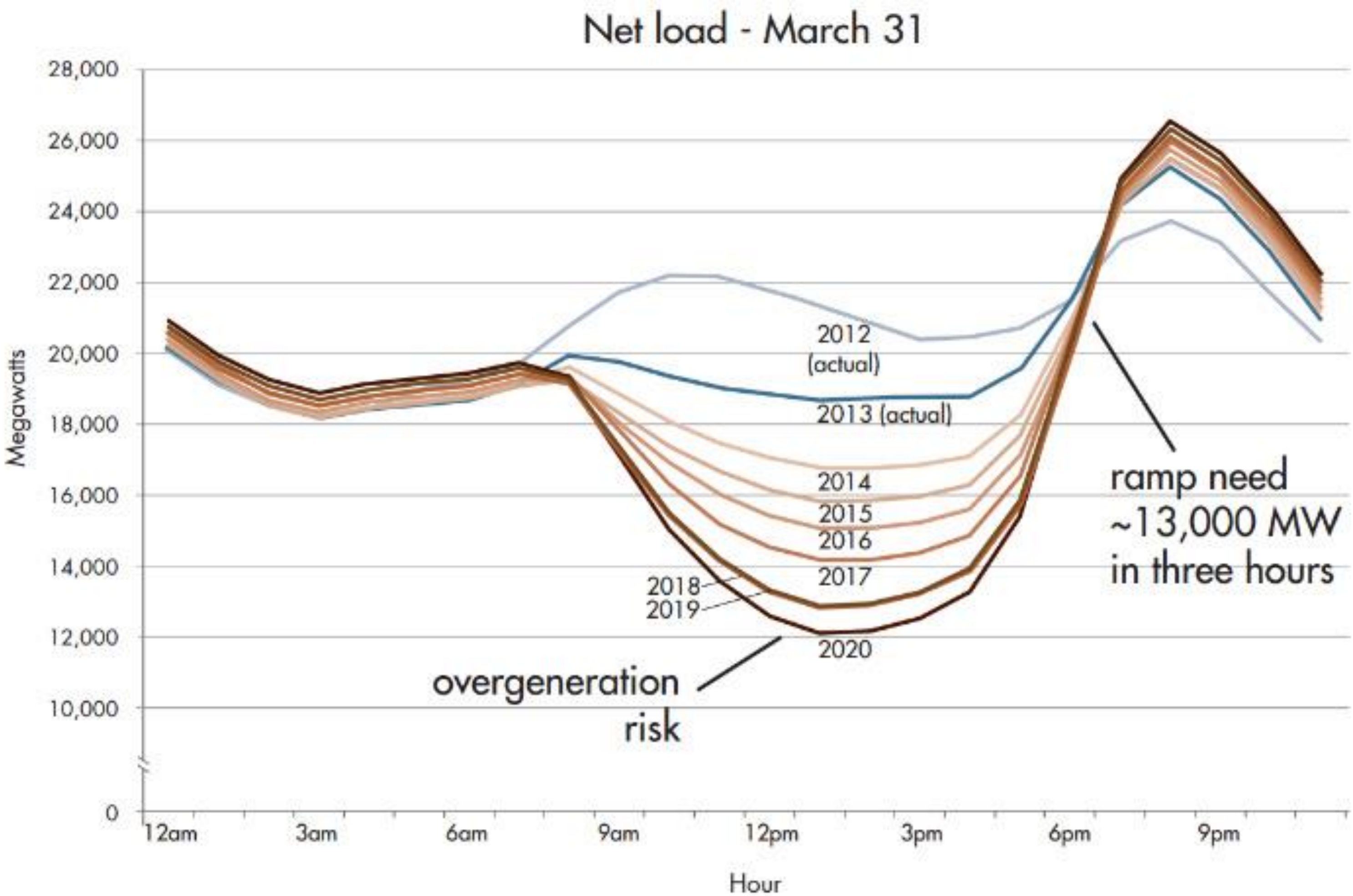


Figure 1. The CAISO duck chart

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

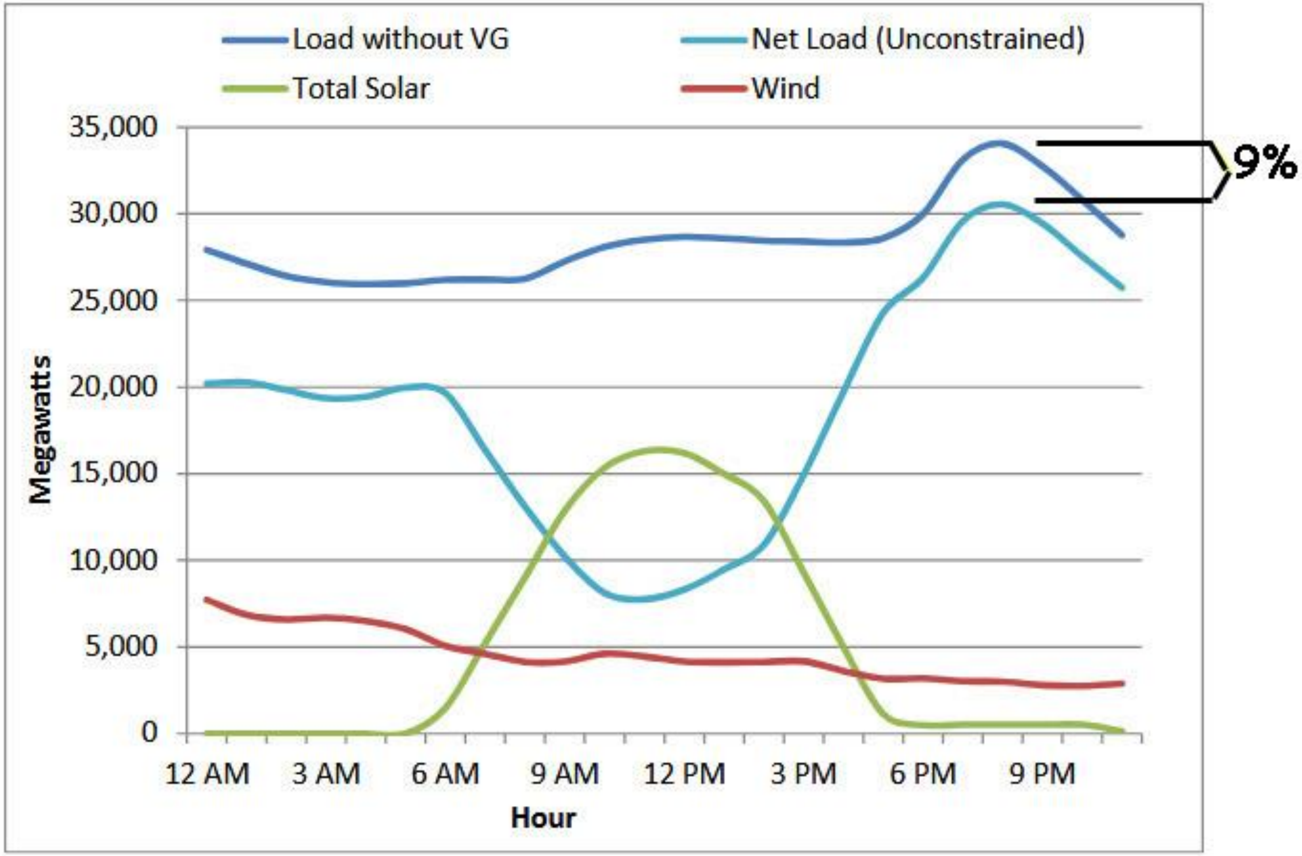


Figure 7. Load, solar, and wind profiles for California on March 29 in a scenario with 11% annual wind and 11% annual solar assuming no curtailment

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)

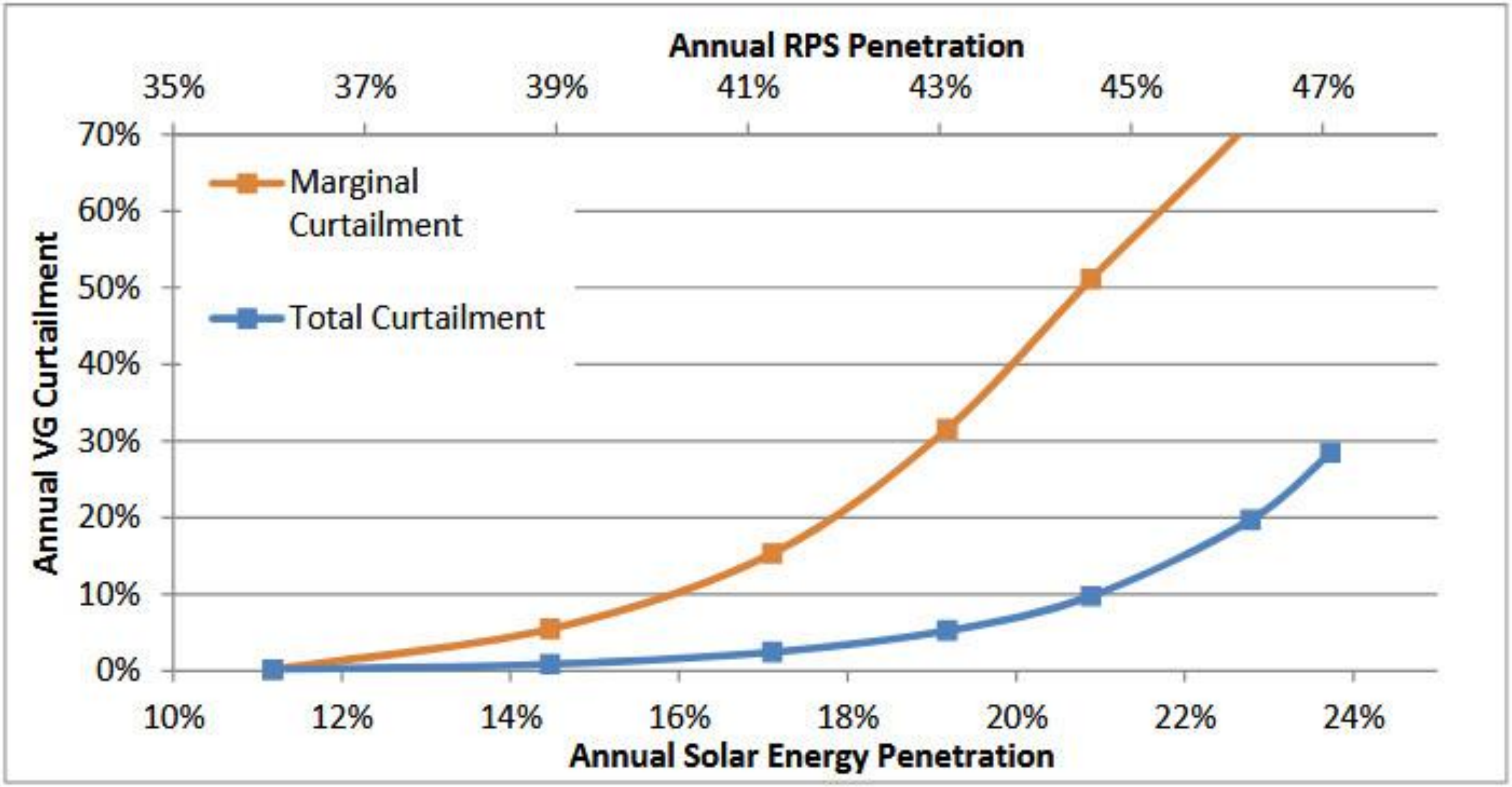


Figure 17. Marginal and average curtailment due to overgeneration under increasing penetration of PV in California with a 60% instantaneous penetration limit

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

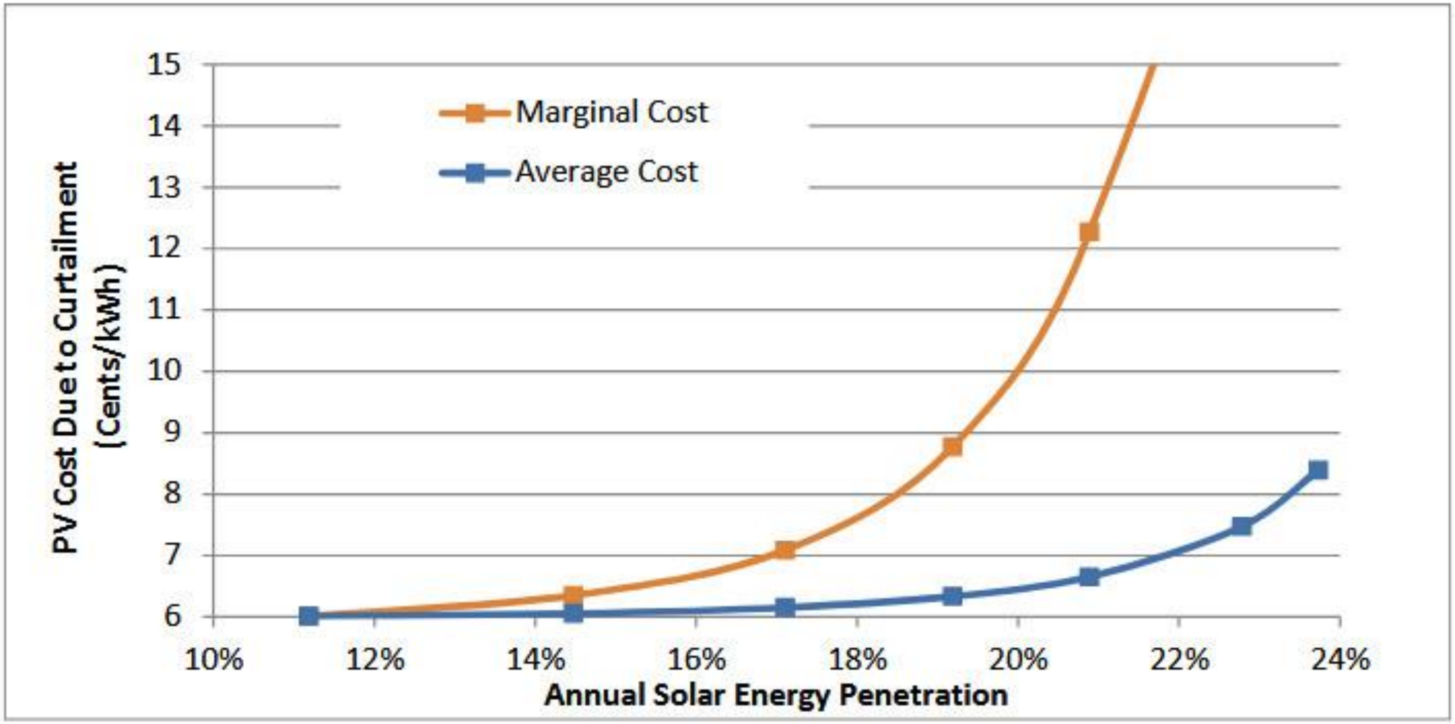


Figure 18. Marginal and average PV LCOE (based on SunShot goals) due to overgeneration under increasing penetration of PV in California with a 60% instantaneous penetration limit

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.

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 Good Features of Wind Power

- Blades need to be high above ground to access better wind speeds, and this also 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 another form, from pressure differences caused by differential heating of land

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).

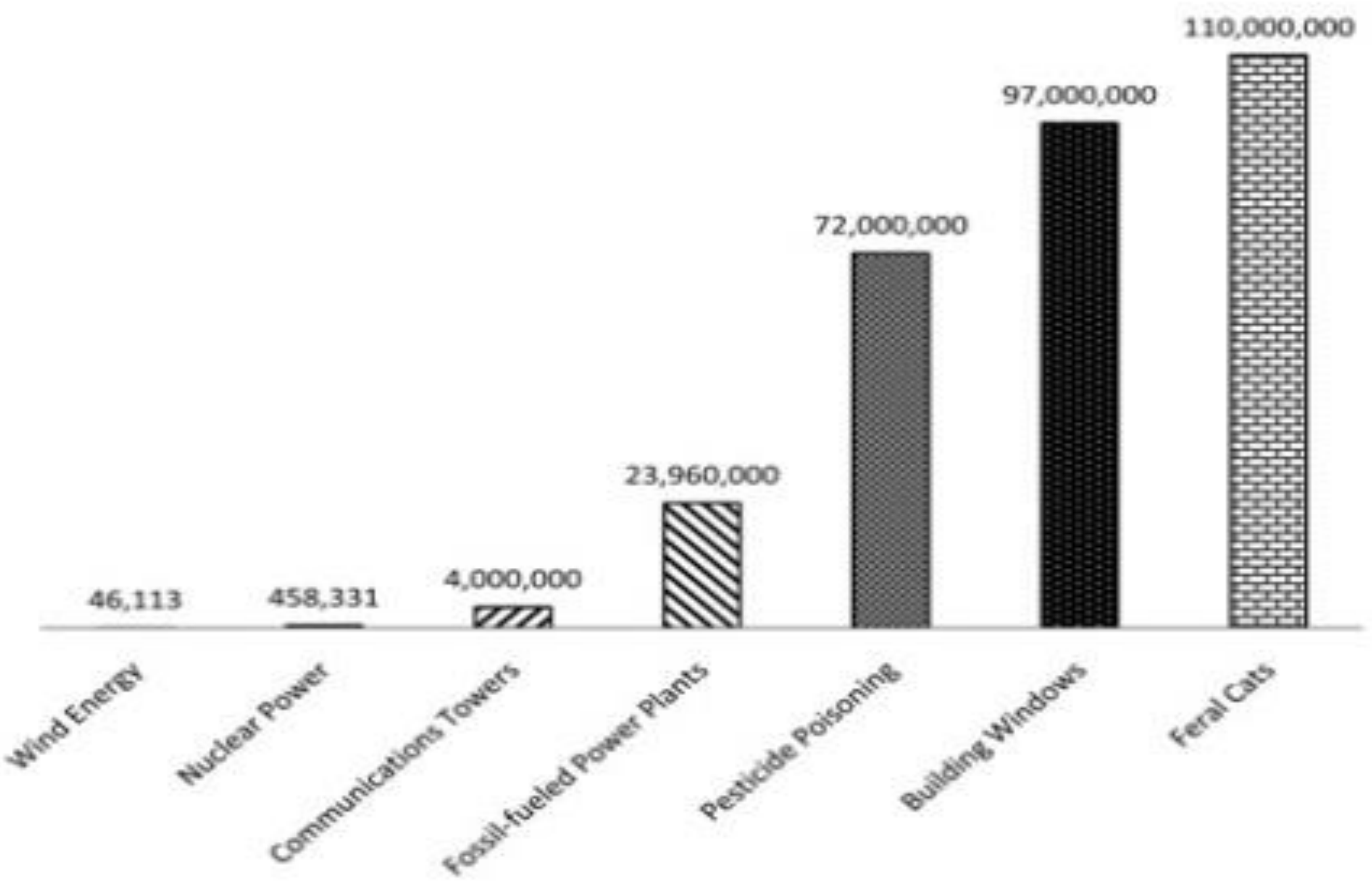
Eagles and Wind Turbines

- 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

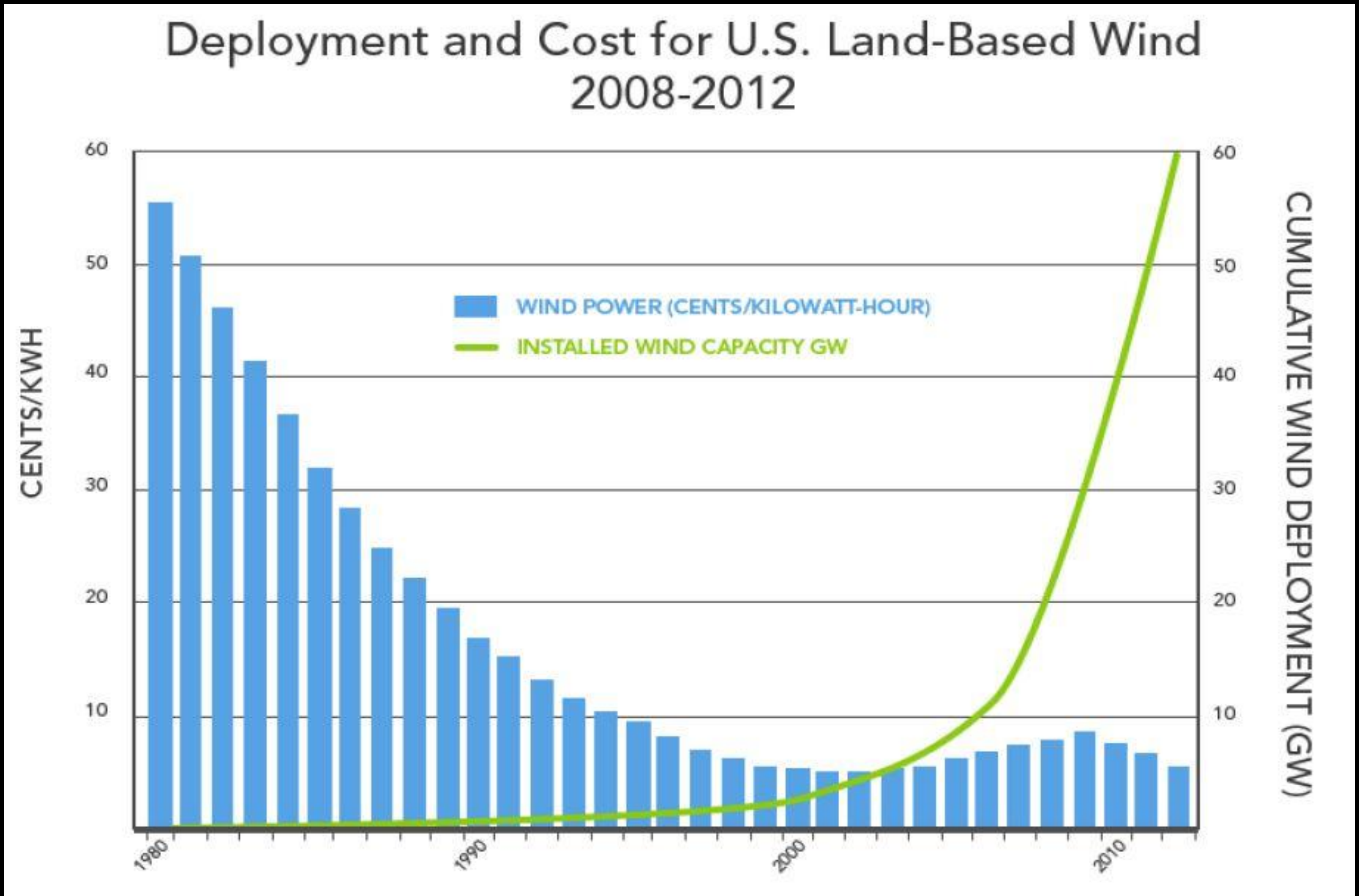
And For Birds, Wind Farms are the Least of their Worries



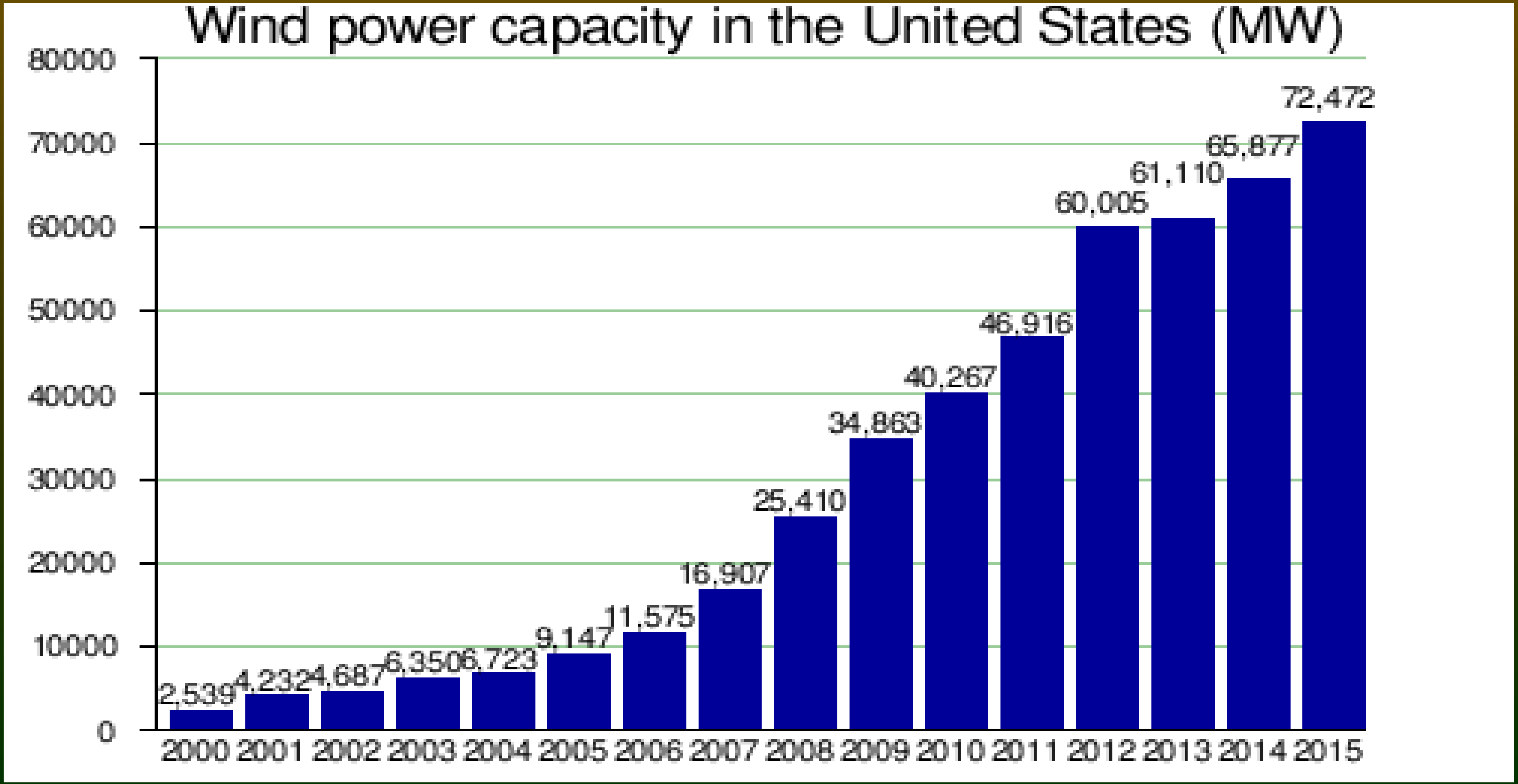
A Few Claim Nearby Wind Turbines Make them Sick

- 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

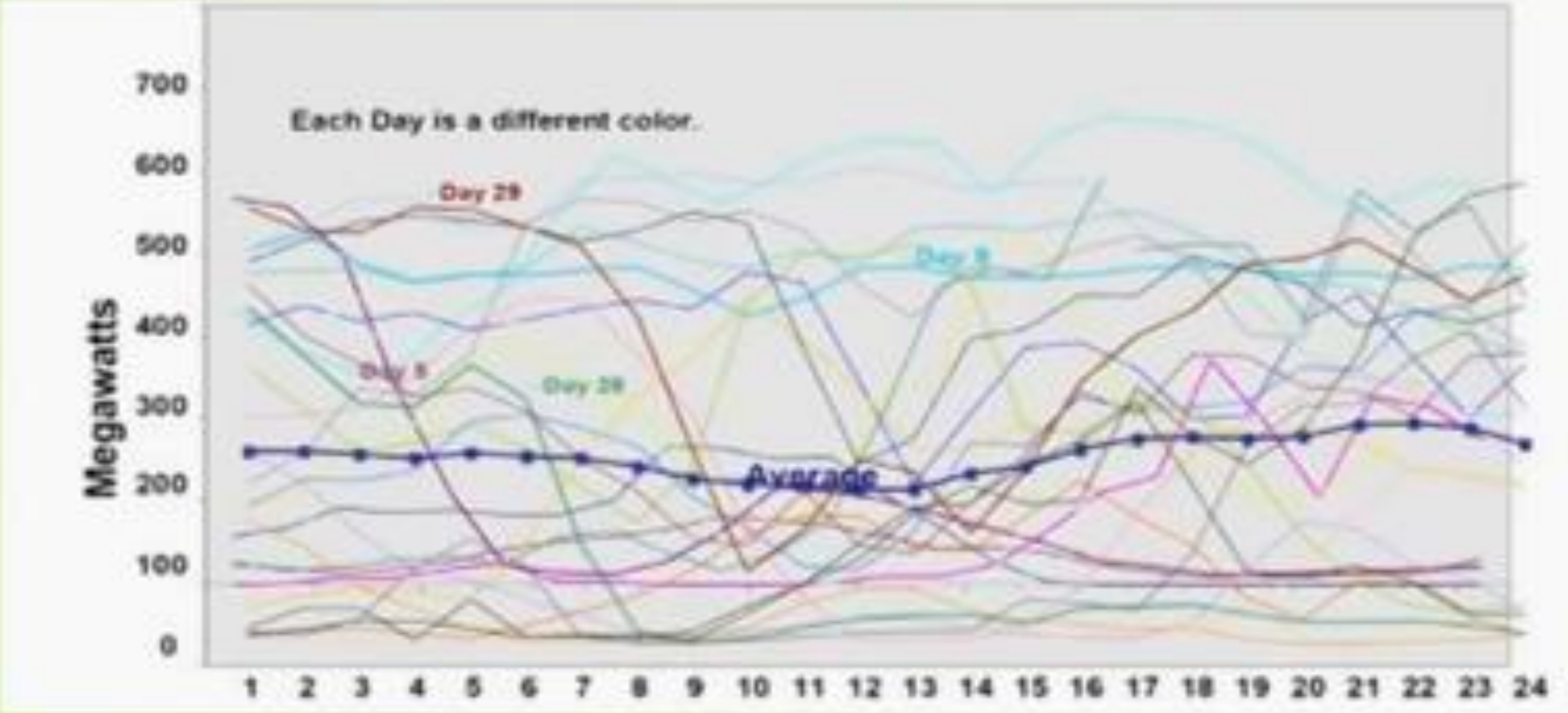


Updated through '15. In the past ~9 years, wind power deployment has decelerated. Growth rates accelerated strongly in the Bush years. Now, capacity is still growing but at declining rate. It's the economics, not the politics - prime spots mostly built early, leaving less economically favorable sites, and declining rate of cost decreases



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 big 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

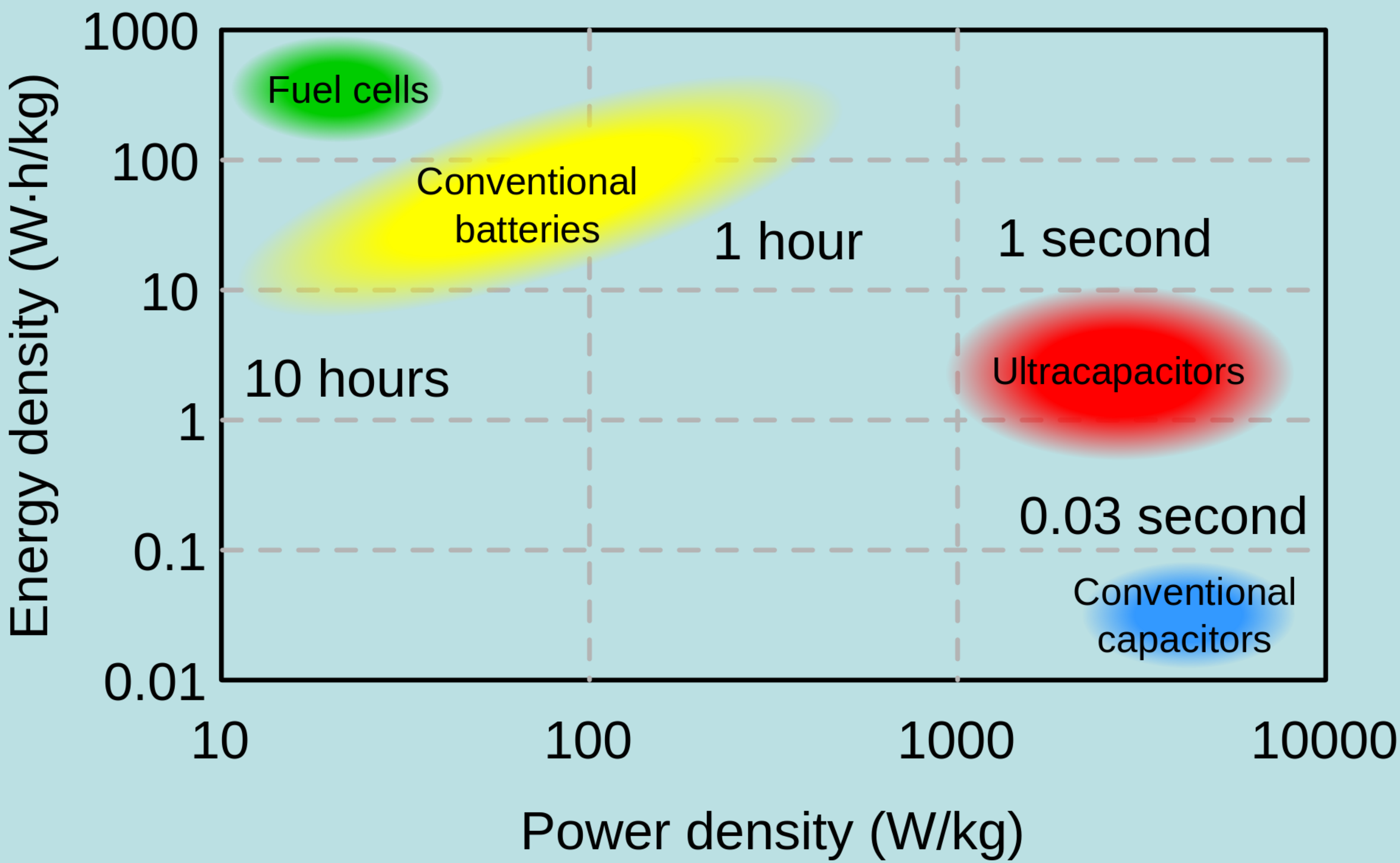
But Wind Turbines Cause a WARMING at Earth's Surface

- 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

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:

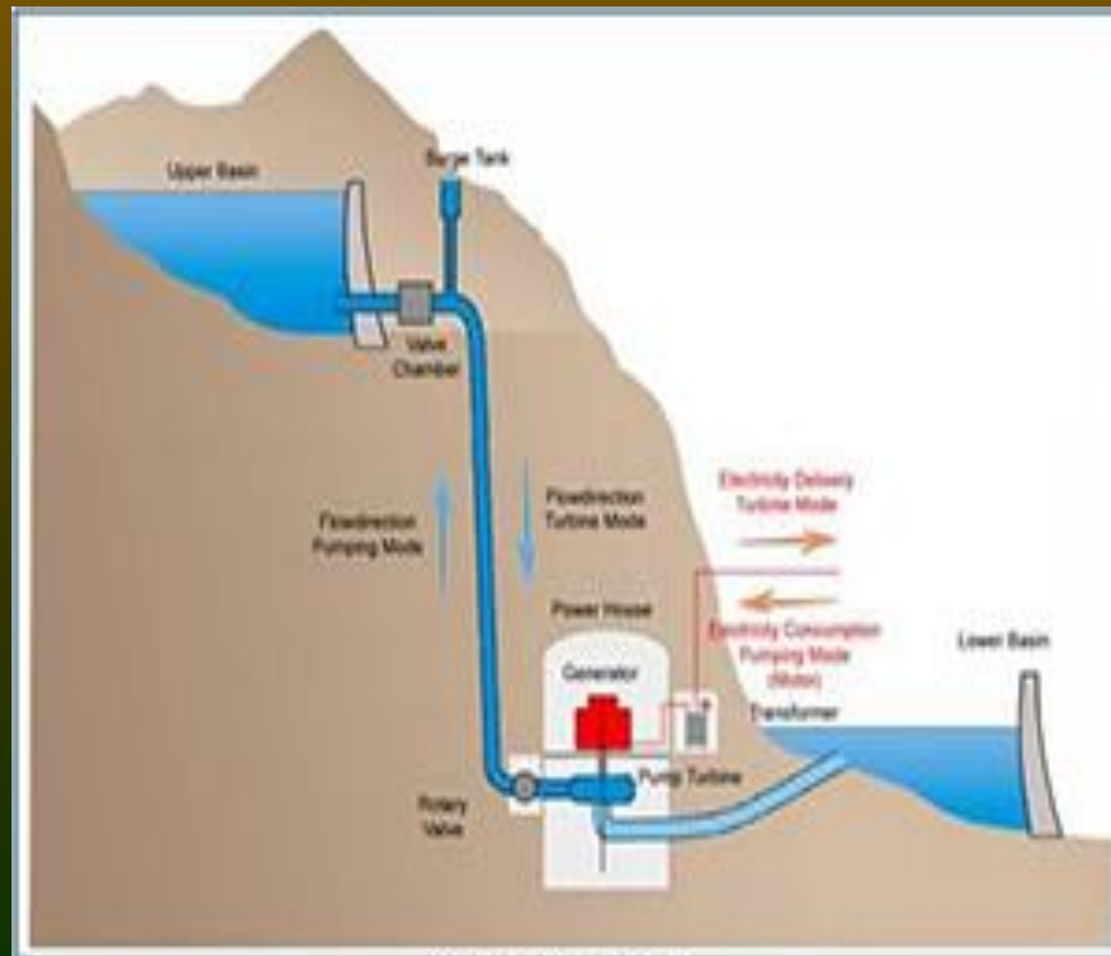
- Michigan start-up Sakti3 made big claims of the invention of a battery with 2x the energy density of Li-Ion and all solid-state, and that it was very close to achieving the Holy Grail: a battery which could provide a 300 mi driving range and cost $100/Kwh or less.
- High-profile photo-ops with President 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.

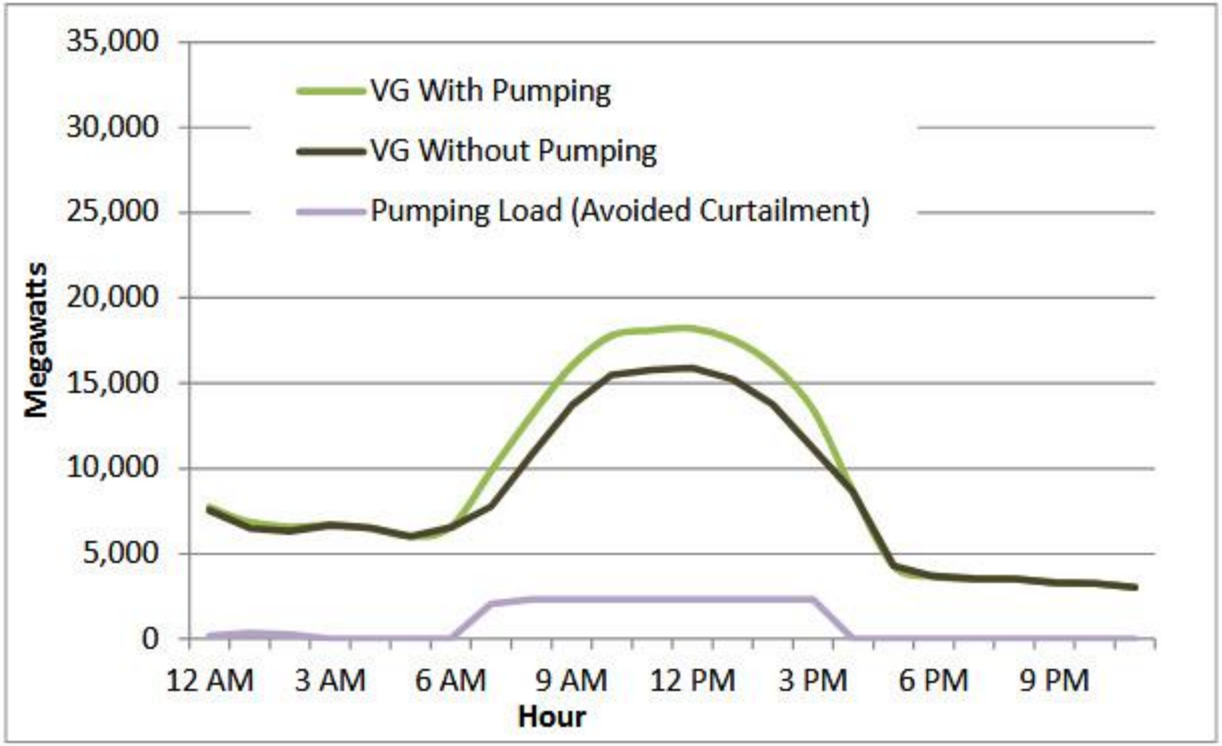
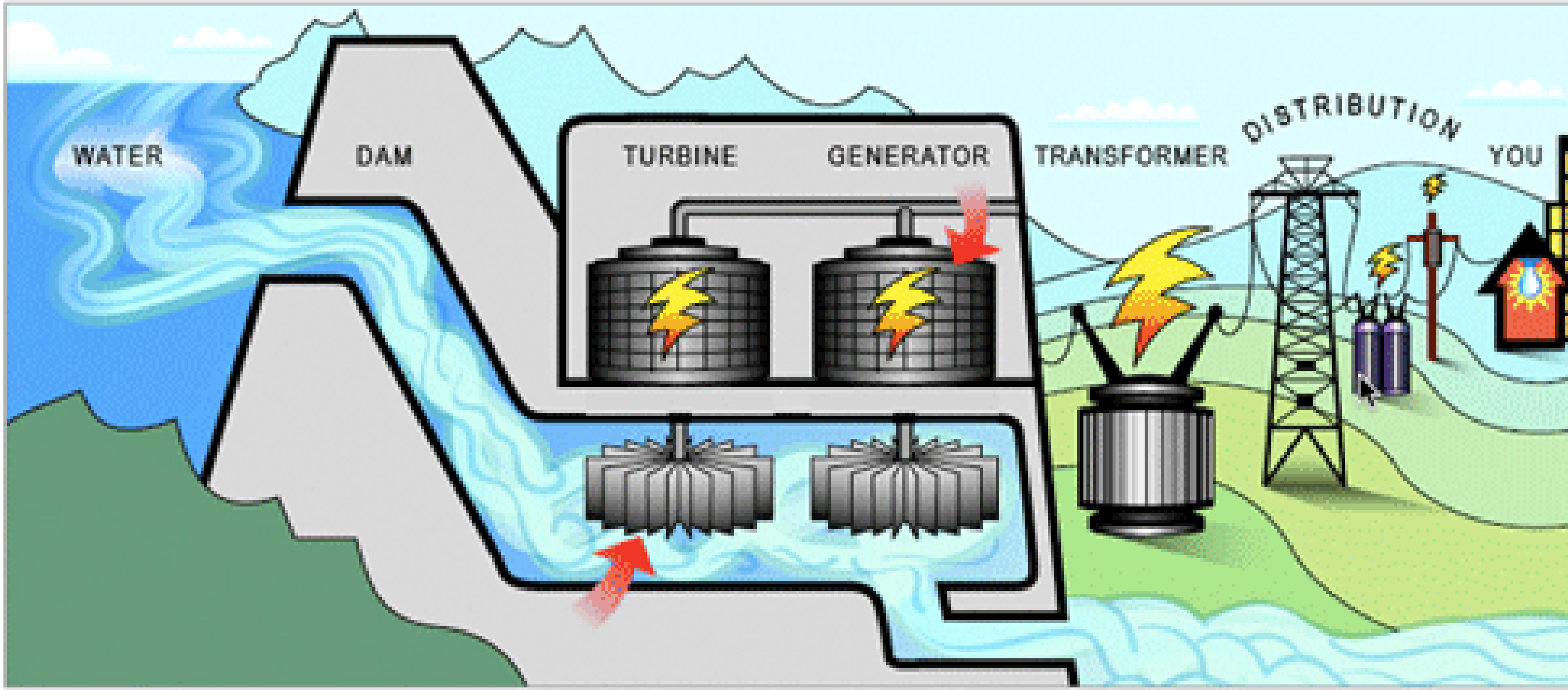


Figure 11. Increase in VG use resulting from schedulable pumped storage in a scenario with 11% annual wind and 11% annual solar

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

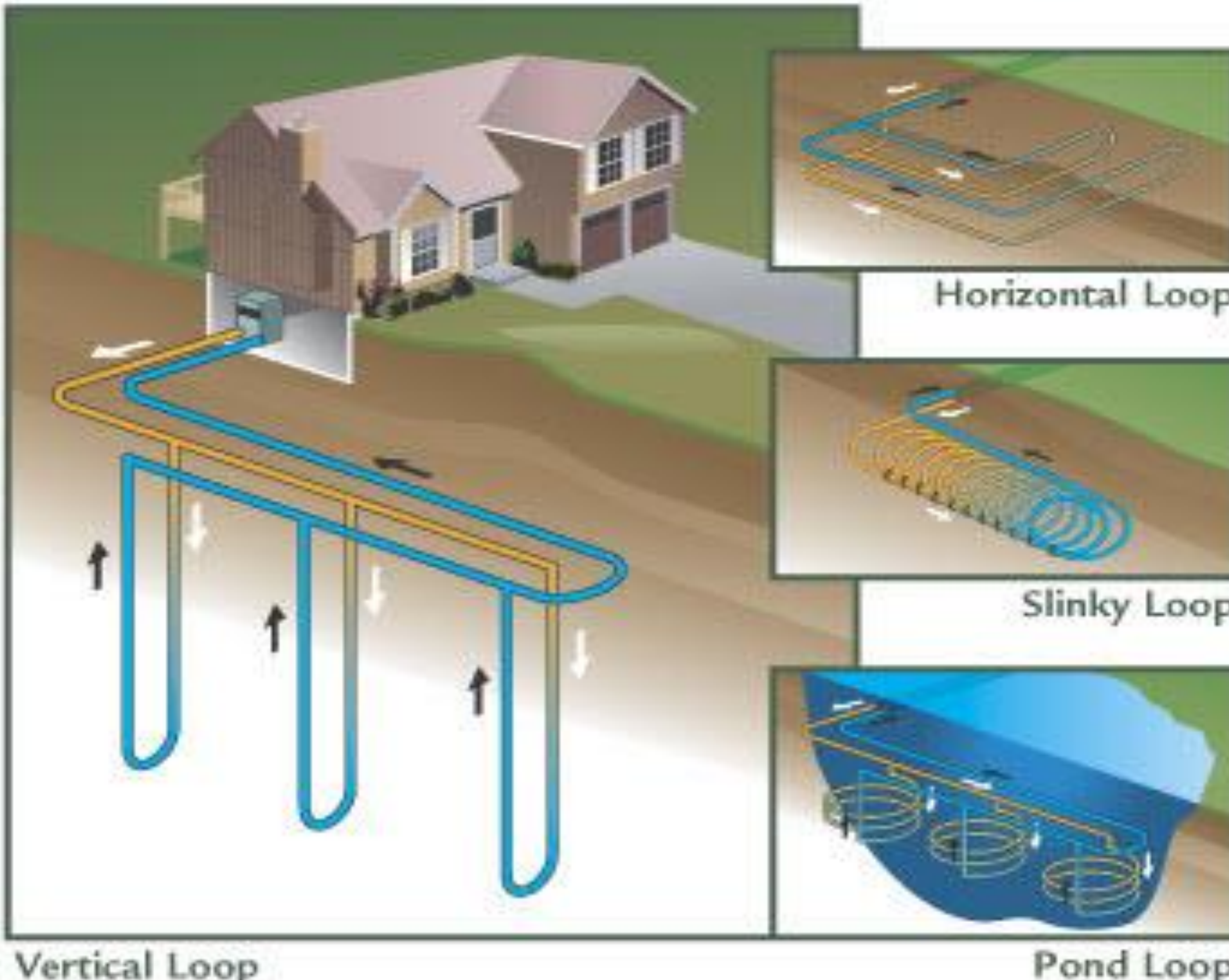
The Downside of Hydro-Electric

- 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 flooded lands 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.
- No good for high-grade needs like fuel, transportation, etc.

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.