Power Plant Land & Water Requirements

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Outline

How much power does a "typical" plant generate? How many plants does the U.S. need?

Calculation of power plant **land** use for all of the different technologies

- With design goals based on current U.S. power consumption:
  - 1000 power plants of 1 GW power production capacity
- Leading to table of net land use if each technology produced ALL of U.S. power

Calculation of power plant **water** use for all of the different technologies

- Water for 100% use of biofuel power is likely ~ ALL available fresh water
  - With portion returned to rivers often polluted by agricultural chemicals
- Water for 100% steam-driven power plants ~ 2X Mississippi River
  - But almost all of that water is returned to rivers "polluted" only by warming
- Minimal water consumption for solar PV, some solar thermal, wind and OCGT natural gas

(Written / Revised: August 2020)

Power Plant Land & Water Requirements

Power plants are all really power **conversion** plants

- Converting energy from one form into another

Meaning that they all require **fuel** of some sort

- Even if it is something as simple as wind or sunshine

But beyond fuels, a large fraction of power plants also depend upon **water**

- Not just those based on water, such as hydroelectric, tidal, or tidal flow plants
- But **any** plant producing electricity via steam turbines, which includes:
    - Coal, CC natural gas, nuclear, geothermal & many solar thermal plants

And while every power plant obviously requires some land/space,

- renewable power plants often require **HUGE tracts of land** (or ocean)

Today we'll **calculate** the latter often surprisingly large land & water requirements

How big should an ideal power plant be?

In planning a **manufacturing plant,** you'd normally focus upon averages:

"I need **average** production X to meet (hoped for) **average** demand"

But what if you made a gift item sold mostly at Christmas?

You'd then stockpile your product, saving it for those Xmas sales

Because, rather than enlarge your factory to cope with Xmas demand

It would **almost certainly be cheaper to add a warehouse**

But what if your product was a foodstuff with a **finite shelf-life**?

First, you'd probably do everything possible to extend its shelf life

Then you'd do an economic analysis of of possible factory expansion

Perhaps deciding to just forgo some holiday sales

Accepting the resulting customer disappointment

But as I've noted before: Electricity's shelf-life is milli-seconds!

That miniscule shelf-life stems from the fact that:

Electricity is not a THING, it's a process (of charge flow)

And you can't just stop and store a flow (because it's then not a flow!)

You MIGHT store a little excess **plus** charge here, and excess **minus** charge there

Which could later re-arrange themselves into a flow

But, electric forces make this difficult to do on a large scale

You MIGHT use any excess electricity to now do some work

For instance, pumping water up a hill into a "pumped hydro" reservoir

Recovering most of that energy later

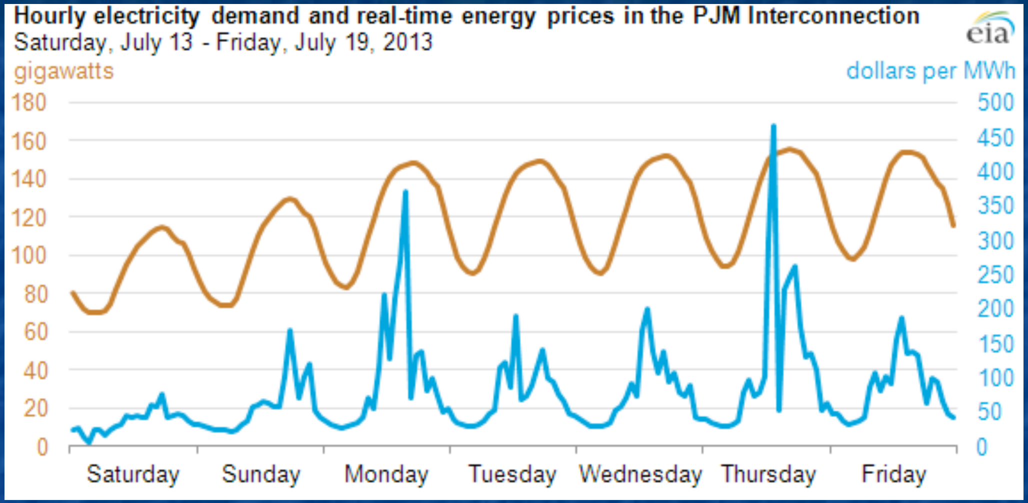
But these, and other storage alternatives, are still difficult and expensive

And electricity's Christmas sales **and** *January slump come once a day!*

EIA data on hour-by-hour power consumption at one Grid "node" (location)

Demand Cycles:

Cost Cycles:



www.eia.gov/todayinenergy/detail.cfm?id=12711

Customers are going to be awfully unhappy if you don't meet "Christmas demand"

Further, in many areas, those customers may be co-owners of your company

Elsewhere, via "public utility commissions," they regulate your profit margins

Besides, with the grid, "fall short" and your **entire production** probably crashes

So your plant **MUST** be large enough to cope with daily "Christmas Season"

How big are today's power plants, and how many are there?

The EIA says that the US now has 6997 power plants of at least 1 MW capacity [(1)]

And that the total US energy production in 2012 was 4,047,765 GW-h [(2)]

Which divided by 8760 hours/year => **US average power = 462 GW**

Leading to my easier to remember: **US average power ~ ½ Tera-Watt**

If you divide THAT by the 6997 power plants, average power/plant/time = 66 MW

But that is power **production** (= average) and NOT power **capacity** (= peak)

Further, that number is distorted by inclusion of many older smaller power plants

REALITY = A much smaller number of LARGER plants produce MOST of our energy

1) www.eia.gov/tools/faqs/faq.cfm?id=65&t=2   *2) www.eia.gov/electricity/annual/html/epa_03_01_a.html*

Capacities of TYPICAL U.S. power plants:

Per the Congressional Research Service study of REAL operating plants (2008)[1]:

FOSSIL FUEL POWER PLANTS:	~ 500 MW per plant
NUCLEAR PLANTS:	~ 1500-3000 MW per plant
SOLAR THERMAL:	≤ 250 MW per plant
WIND:	≤ 200 MW per plant
GEOTHERMAL:	≤ 150 MW per plant
SOLAR PHOTOVOLTAIC:	≤ 75 MW per plant

NOTE (!): Not only are most renewable power plants MUCH, MUCH smaller

But, data above cites the then **largest example** of each new technology

With MOST plants of that type being much smaller (hence "≤" signs!)

1) http://fas.org/sgp/crs/misc/RL34746.pdf

But the 1st two types produce the vast majority of our power:

TYPE:	TYPICAL SIZE	SHARE OF U.S. POWER (1)
Fossil Fuel Power Plants	~ 500 MW per plant	67%
Nuclear Plants:	~ 1500-3000 MW per plant	19%

It is from this and the preceding slide that I derived my oft repeated:

"Typical U.S. power plant capacities: 200-2000 MW"

"Average US Power Plant ~ 600 MW"

Comparing those numbers with data on preceding slide, one would conclude:

1) http://www.eia.gov/tools/faqs/faq.cfm?id=427&t=3

For more detailed information see my ***U.S. Power Production & Consumption*** *(pptx / pdf / key) note set*

To be major contributors, renewable plants must grow > 3-10 X

In fact, a good design goal for **all** power plants would be a capacity of ~ 1 GW

You COULD build smaller plants, but you'd need a LOT more of them

And then interconnection and operational costs might bite you

So let's use that as our 1st design goal:

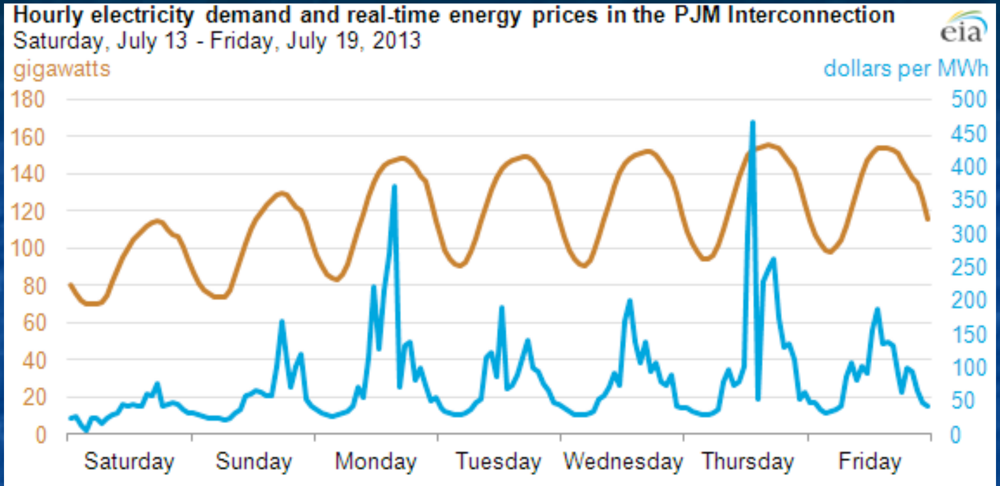
Capacity of a typical power plant ~ 1 GW

But I also want figure out TOTAL U.S. requirements

From above, time averaged U.S. power generation was 462 GW (~ ½ TW)

But this averages high evening loads with much lower overnight loads

Returning to those daily / weekly power cycles:



www.eia.gov/todayinenergy/detail.cfm?id=12711

Peak power consumption looks to be about 1.5 X the **average** consumption

Remember that our power plants must be designed for the peak not average

Then add in power plant downtimes for repair and/or refueling

=> Capacity had better be ~ 2 X times the average consumption

Which provides our 2nd design goal:

U.S. Power Capacity ~ 1 Tera-Watt => One thousand 1 GW plants

Part I: Power Plant Land Requirements:

Conventional (coal, gas, oil) plants are not that large – say 2-5 hectares

"hectare" = (100 m)(100 m) = 0.01 km^2 ~ 2.5 acres

Current capacity ~ 500 MW = ½ our design goal, so rounding upward:

1 GW fossil fuel plant ~ 0.1 km^2

Nuclear plants tend to be larger based on security and used fuel storage needs

Our local "Lake Anna" nuclear plant is probably a worst case on space

It includes a ~ 1400 hectare "waste heat treatment" plant

Which makes use of a ~ 3800 hectare manmade lake

Not counting the lake's area, its two reactors occupy 4.35 km^2

Those reactors have a power capacity of 1.89 GW, yielding:

1 GW nuclear plant ~ 2 km^2

What about renewable energy power plants?

Most of these are ultimately driven by solar energy:

Directly as in solar photovoltaic and solar thermal

Or quasi directly as in plant or algae photosynthesis

Or by solar heat producing convection-driven winds (or waves)

Or by solar evaporation of sea water collecting as rain in reservoirs

But the sun delivers, at the **very** best, only 1 kW / m^2 to the earth's surface

Tidal power is also very dilute, and geothermal even weaker

So plants tapping into dilute renewable energy sources must be **much larger**

Further, they'd better be **optimally located**

And/OR **optimally directed**

*Starting with **solar photovoltaic plants**:*

For max power, solar cells SHOULD always be aimed DIRECTLY at the sun

Requiring East to West daily tilting AND North to South seasonal tilting

Necessary motors and drives for tilting (one or two axes) add cost

Yielding options (in Northern hemisphere) of:

1) Fixed cells (tilted slightly South to best catch average noon sun) - OK

2) Motorized East-West daily tilt (with fixed Southern tilt) - BETTER

3) Motorized East-West daily AND North-South seasonal tilts - BEST

Option 1 is the most popular, but let's goose solar upward by using option 2:

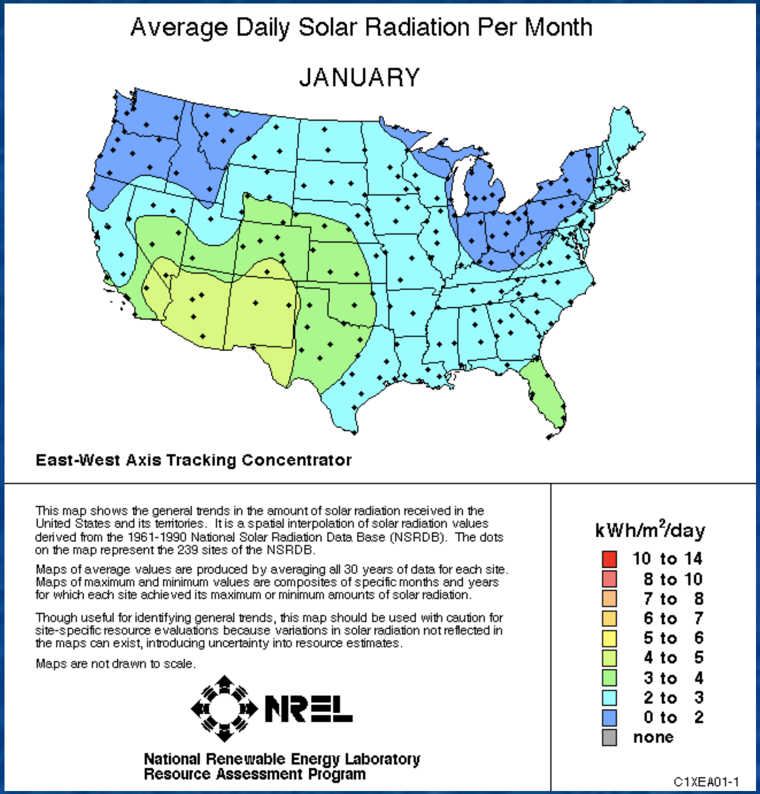
Go to NREL (National Renewable Energy Lab) webpage on U.S. insolation

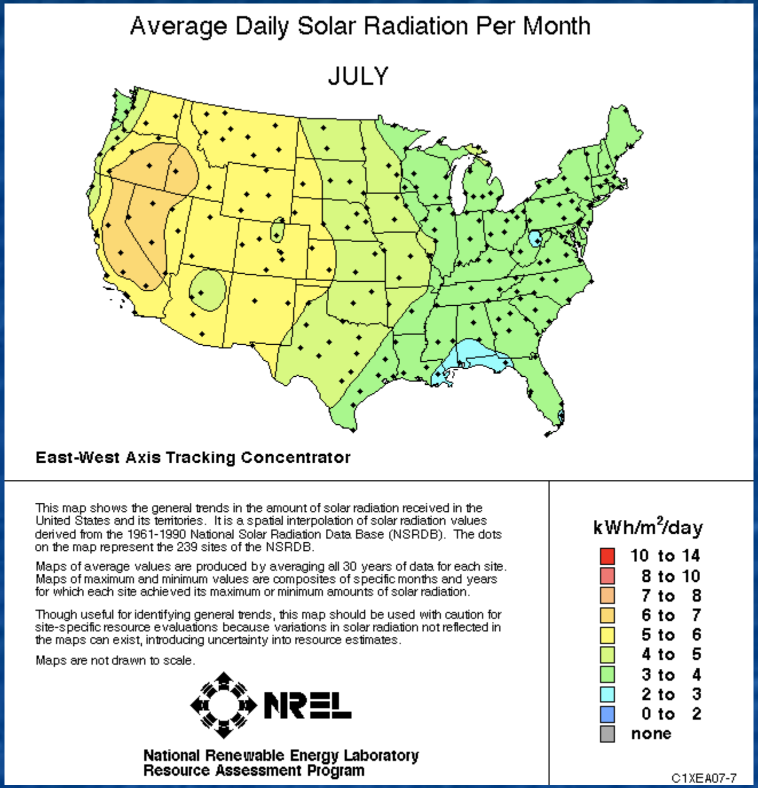
Select options of: - Average annual insolation

- East to west tracking (tilting) solar cells

Which then pops up these maps (for different months)

U.S. National Renewable Energy Lab map (by year, month, min, max or average):





http://rredc.nrel.gov/solar/old_data/nsrdb/1961-1990/redbook/atlas/

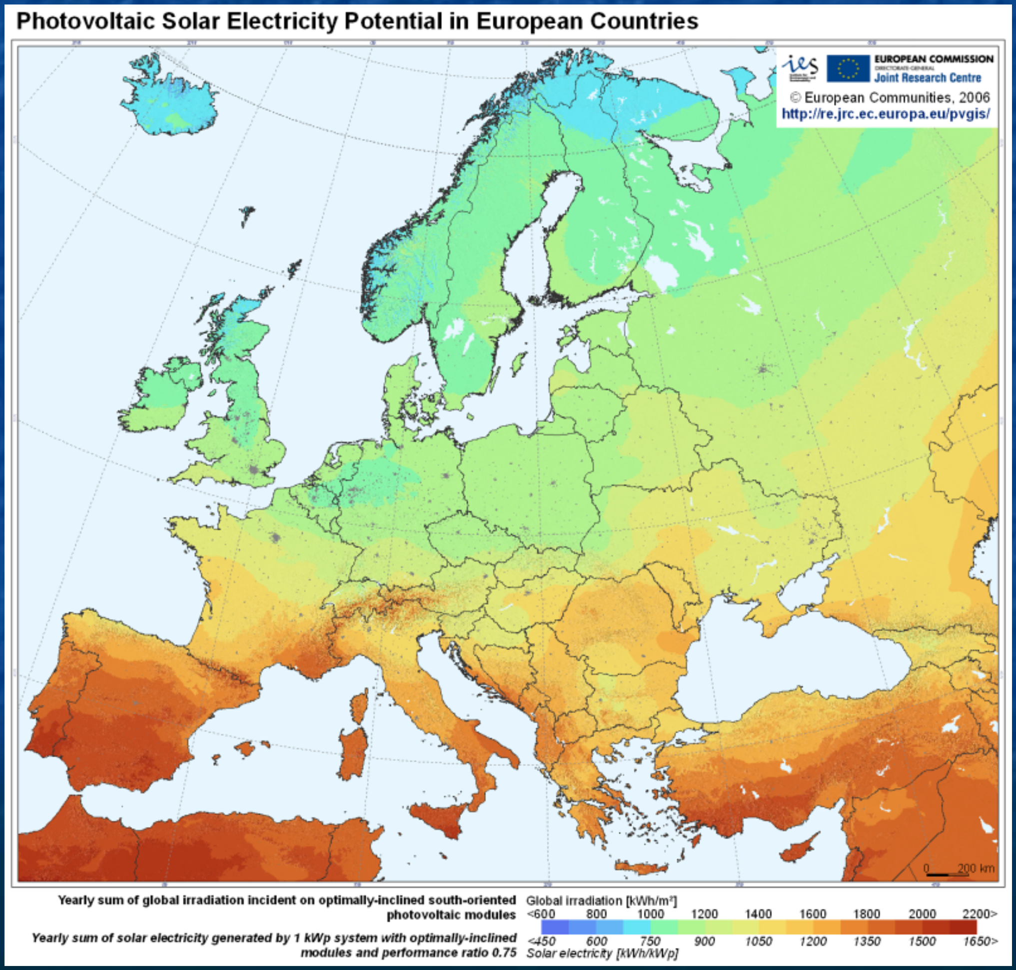
Conclusion? Build solar plants in the high deserts of the Southwest

(and we'll come back to the exact numbers in just a second)

What about Europe?

I did not spot maps with comparable (important!) tilt selection options

From European Joint Research Centre (http://re.jrc.ec.europa.eu/pvgis/countries/countries-europe.htm):

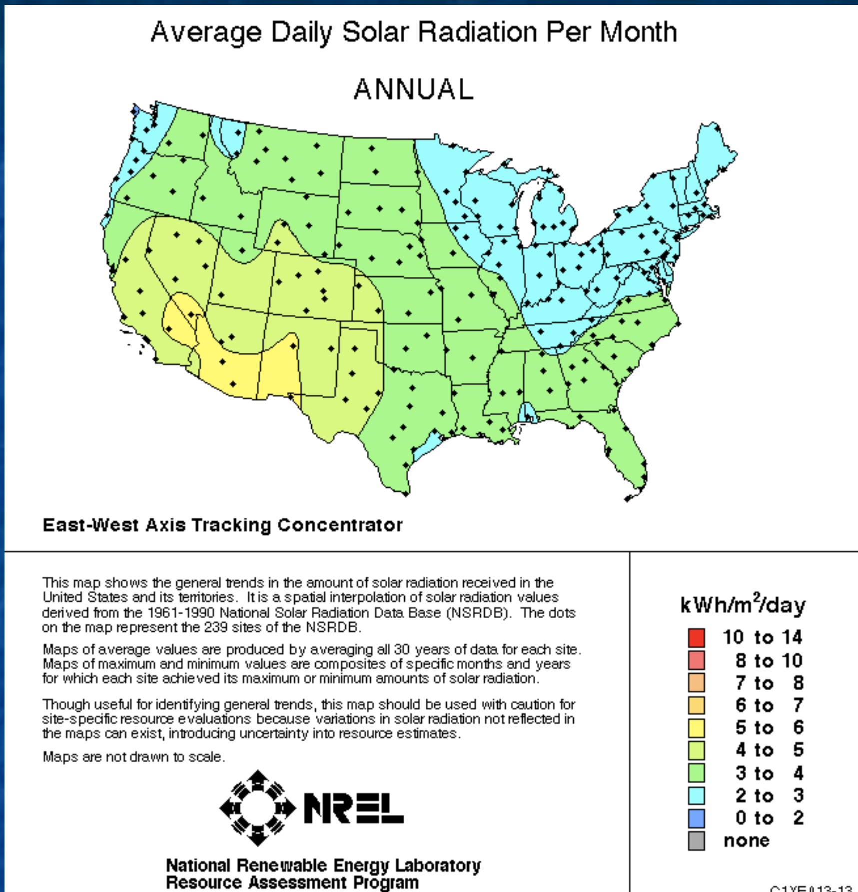


Conclusion?

Look to the Mediterranean

Or to North Africa?

Back to an ANNUALY AVERAGED NREL U.S. insolation map



http://rredc.nrel.gov/solar/old_data/nsrdb/1961-1990/redbook/atlas/

Let's build our solar plant right here!

Map gives, for Central Virginia:

3 kW-h/m^2/day average solar "insolation"

= 3 kW/m^2 x (h/day)

= 3 kW/m^2 x (1/24)

= 125 W / m^2

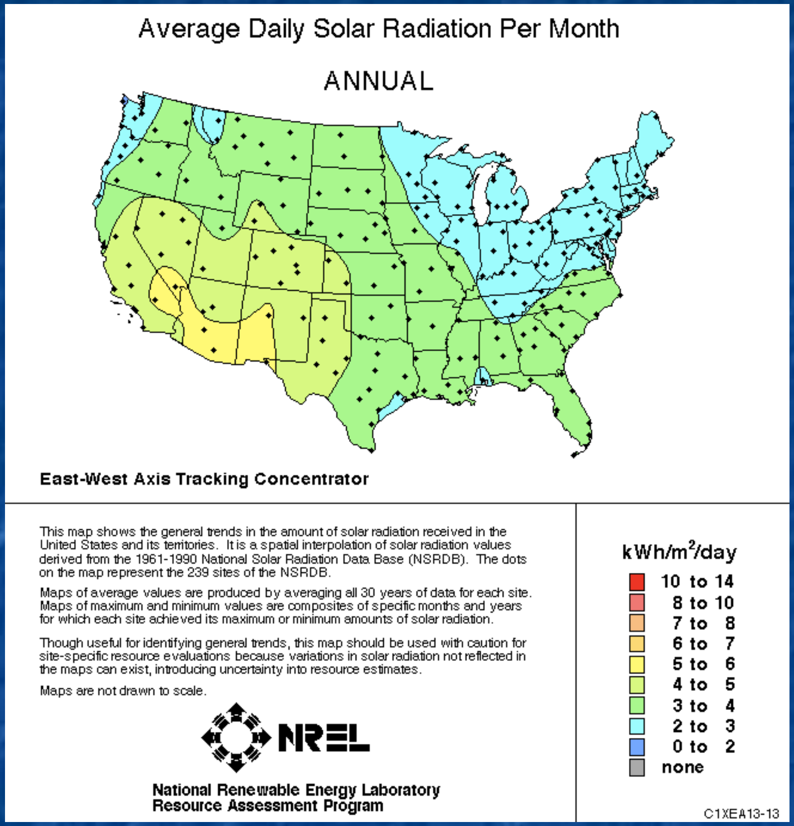
Earlier in class we learned that common Si crystalline solar cells are ~20% efficient:

If they occupied 100% of ground area:

Average energy harvested in central Virginia = 25 W / m^2

Working toward our goal for a competitive renewable plant:

That design goal specified a power production capacity of = 1 GW



Dividing that target by solar power per area:

Land = 1 GW /(25 W / m^2) = 40 million m^2

= **40 km^2** (in VA) ~ 4 mi x 4 mi !!

And we **still** have to figure out how to store daytime energy for evening use!

To heck with Virginia, let's build in Arizona!

Where we'd need half the land = **20 km^2** (AZ)

1 GW crystalline Si solar photovoltaic plant ~ 20 – 40 km^2

What about using alternative solar PV technologies?

PV plants using cheaper materials? From **Today's Solar PV** (pptx / pdf / key) notes:

Polycrystal Si cells are ~ 4/5 as efficient => 5/4 the land (**25-50 km^2**)

Amorphous Si cells are ~ ½ as efficient => twice the land (**40-80 km^2**)

Organic cells are ~ ¼ as efficient => four times the land (**80-160 km^2**)

And what about concentrated **Solar thermal?** (tower + heliostat mirrors)

Might that be much more efficient than PV's paltry 20% ?

From a textbook I've come to respect ("Energy and the Environment" – Fay & Golomb)

Average solar thermal power production (p. 186): "11.6-49 W/m^2" =>

1 GW solar thermal plant ~ 20 – 86 km^2

But for what type of solar thermal plant, and at what quality of location?

Trying to further pin down numbers for solar thermal:

Solar Thermal is another "Carnot Engine" (as explained in Exotics lecture):

=> Max energy conversion efficiency (%) = $(1 - T_{low} / T_{high}) \times 100$

Assume it uses oil, boiled in tower at 400°C, then air-cooled to 100°C

Maximum efficiency (%) ~ (1-373 °K/673 °K) ~ 45%

=> ~ 40% in real life

http://blog.zintro.com/clean-tech-alt-energy/page/2/

It receives same sunlight per area as solar photovoltaics

But moving mirrors seem to occupy only ~ ¼ of area:

Thus efficiency drops to 10% = ½ that of Xtal Si PV

So 1 GW Solar Thermal plant might be 2X size of Xtal Si solar or ~ **40-80 km**

Can we find any confirming data? What about California's big new plant?

From earlier Solar Energy lecture:

California's recently completed "Ivanpah" Mojave Desert farm:

"Tower of Power" Time Magazine June 24, 3013

NREL[(1)]: "Annual Generation (planned) = 1,079,232 MW-h / 3500 acres"

3500 Acres => 1400 hectares => 14 km^2

$P_{average\_out}$ / km^2 = (1079232 MW-h/ 8760 h) / 14 km^2 = 8.8 MW / km^2

So to produce 1 GW in this Arizona-like insolation, would need area of:

Area (in dessert CA or AZ) for 1 GW = 1 GW / (8.8 MW / km^2) = **113 km^2**

Poorer number could because Ivanpah uses water and not oil as working fluid!

1) http://www.nrel.gov/csp/solarpaces/project_detail.cfm/projectID=62

Summary of numbers for 1 GW Solar Thermal plant area:

1) From Fay & Golomb's Energy and the Environment textbook:

1 GW solar thermal plant = 20 to 86 km^2

2) From Carnot Cycle using oil as working fluid + photo of mirror ground coverage:

1 GW solar thermal plant = 40 - 80 km^2

3) From that NREL information on Ivanpah plant using water as working fluid:

1 GW solar thermal plant = 113 km^2 in CA

Which would then translate into 226 km^2 in VA

In calculations to follow, let's use Ivanpah-like numbers, good site vs. any old site:

1 GW solar thermal plant = 100 – 200 km^2

ADDED SUMMER OF 2020:

*There are **finally** significant numbers of large Solar PV & Solar Thermal Plants*

And for my note set on **Utility Scale Solar Power Plants** (pptx, pdf, key)

I gathered all the information I could find about them

compiling these long spreadsheet tables:

Utility Scale Solar PV Plants:

POWER PLANT CAPACITY in MW	COMPLETED	PV	ST (CSP)	PLANT AREA in km2	PLANT NAME	COUNTRY	PV TECHNOLOGY	REFERENCES
1547	2016	X		43	Tengger Desert	China	(c-Si ?)	1
1515	2019	X		40	Bhadla Solar	India	(c-Si ?)	1
1400	2019	X		53	Pavagada	India	(c-Si ?)	1
1177	2019	X			Noor Abu Dhabi	UAE	(c-Si ?)	1
1000	2017	X		24	Kurnool Ultra Mega	India	(c-Si ?)	1
1000	2016	X			Dataong Solar Power Top	China	(c-Si ?)	1
850	2015	X		23	Longyangxia	China	(c-Si ?)	1
828	2018	X		24	Villanueva	Mexico	(c-Si ?)	1
750	2018	X			Rewa Ultra Mega	India	(c-Si ?)	1
690	2012	X		20	Charanka	India	(c-Si ?)	1
648	2016	X		10.1	Kamuthi	India	(c-Si ?)	1
613	2019	X			Mohammed bin Rashid	UAE	(c-Si ?)	1
579	2015	X		13	Solar Star	US	(c-Si ?)	1
552	2016	X		16.2	Copper Mountain	US	(c-Si ?)	1
550	2015	X		16	Desert Sunlight	US	(c-Si ?)	1
550	2014	X		19	Topaz	US	CdTe Thin Film	1, 3
500	2014	X		23	Huanghe	China	(c-Si ?)	1
500	2018	X			NP Kunta	India	(c-Si ?)	1
500	2018	X			Three Gorges Golmud	China	(c-Si ?)	1
500	2018	X			Three Gorges Delingha	China	(c-Si ?)	1
460	2018	X		15.9	Mount Signal	US	(c-Si ?)	1
400	2016	X		9.3	Mesquite	US	(c-Si ?)	1
400	2018	X			Pirapora	Brazil	(c-Si ?)	1
400	2019	X		17	Ananthapurama	India	(c-Si ?)	1
380	2016	X			Yanchi	China	(c-Si ?)	1
350	2019	X		5.7	Springbok	US	(c-Si ?)	1
300	2015	X		2.5	Cestas	France	(c-Si ?)	1
300	2019	X		9.3	Techren	US	(c-Si ?)	1
292	2017	X			Nova Olinda	Brazil	(c-Si ?)	1
290	2014	X		9.7	Aqua Caliente	US	CdTe Thin Film	1, 3
280	2017	X		11.7	California Flats	US	(c-Si ?)	1
260	2018	X			Don Jose	Mexico	(c-Si ?)	1
254	2017	X			Ituverava	Barzil	(c-Si ?)	1
250	2017	X			Mandsaur	India	(c-Si ?)	1
250	2016	X		9.3	McCoy	US	(c-Si ?)	1
250	2016	X		11.7	Silver State	US	(c-Si ?)	1
250	2013	X		7.96	California Valley	US	(c-Si ?)	1
250	2016	X		6.82	Stateline	US	(c-Si ?)	1
250	2016	X		8.1	Moapa Southern Paiute	US	(c-Si ?)	1
246	2016	X			El Romero	US	(c-Si ?)	1
246	2019	X			Nikpol	Ukraine	(c-Si ?)	1
240	2019	X			Pokrovske	Ukraine	(c-Si ?)	1
240	2016	X		7.7	Escalante	US	(c-Si ?)	1
236	2019	X		6.1	Midway	US	(c-Si ?)	1
235	2016	X		8.1	Blythe	US	(c-Si ?)	1
235	2018	X		2.6	Setouchi Kirei	Japan	(c-Si ?)	1
235	2017	X		7.7	Upton Solar 2	US	(c-Si ?)	1
230	2015	X		8.5	Antelope Valley	US	CdTe Thin Film	1, 4
212	2016	X		5.3	Roserock	US	(c-Si ?)	1
202	2018	X		5.1	Buckthorn	US	(c-Si ?)	1
200	2017	X		3	Cixi	China	(c-Si ?)	1
200	2019	X		8.1	GA Solar 4	US	(c-Si ?)	1
200	2013	X			Gansu Jintai	China	(c-Si ?)	1
200	2016	X		8.1	Garland	US	(c-Si ?)	1
200	2013	X			Gonghe I	China	(c-Si ?)	1
200	2018	X		6.5	Great Valley	US	(c-Si ?)	1
200	2016	X		7.7	Tranquility	US	(c-Si ?)	1

Utility Scale Solar Thermal Plants:

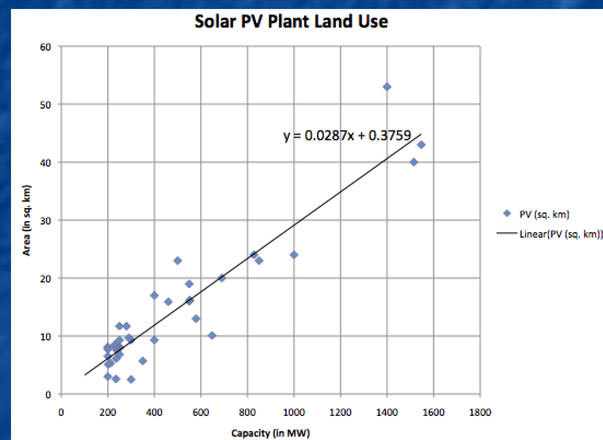
POWER PLANT CAPACITY in MW	COMPLETED	PV	ST (CSP)	PLANT AREA in km2	PLANT NAME	COUNTRY	PV TECHNOLOGY	ST TECHNOLOGY	HEAT STORAGE in hours	REFERENCES
510 Thermal + 72 PV	2013-18	X	X	4.5 Trough + 6.8 Trough + 5.5 Tower	Noor Quarzazate	Morocco	(c-Si ?)	Tower + Trough + Tower	3 / 7 / 7.5	2, 5
392	2014		X	14.2	Ivanpah	US		Tower		2, 6
354	1984-90		X		SEGS	US		Trough		2,7
280	2014		X	7.14	Mojave	US		Trough		2, 8
280	2013		X	7.8	Solana	US		Trough	6	2, 9
250	2014		X	7.8	Genesis	US		Trough		2, 10
200	2012-13		X		Solaben	Spain		Trough		2
150	2010		X	3.45	Solnova	Spain		Trough		2, 11
150	2008-11		X	6	Andasol	Spain		Trough	7.5	2,12
150	2010-12		X	6	Extresol	Spain		Trough	7.5	2, 13
125	2014		X		Dhursar	India		Fresnel		2
121	2019		X	3.15	Ashalim	Israel		Trough	4.5	2, 15
121	2019		X		Megalim	Israel		Tower		2
110	2015		X	6.7	Crescent Dunes	US		Tower	10	2, 14
100	2018		X	0.8	Kathu	S. Africa		Trough	4.5	2, 16
100	2015		X	11	KaXu Solar One	S. Africa		Trough	2.5	2, 17
100	2017		X		Xina Solar One	S. Africa		Trough	5.5	2
100	2011		X		Manchasol	Spain		Trough	7.5	2
100	2011		X	1.02	Valle	Spain		Trough	7.5	2, 18
100	2011-12		X		Helioenergy	Spain		Trough		2
100	2012		X		Aste	Spain		Trough	8	2
100	2012		X		Solacor	Spain		Trough		2
100	2012		X		Helios	Spain		Trough		2
100	2013		X	2.5	Shams	UAE		Trough		2, 19
100	2013		X		Termosol	Spain		Trough		2
100	2010		X		Palma del Rio	Spain		Trough		2
100	2018		X		Llanga 1	S. Africa		Trough	5	2, 20
100	2018		X		Shouhang Dunhuang	China		Tower	7.5	2

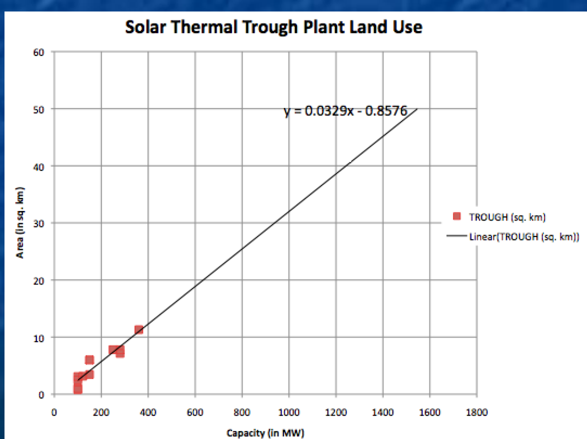
NOTE: For almost **all** of the Solar PV plants in the table on the left, the PV cells used were **single crystal silicon PV cells**

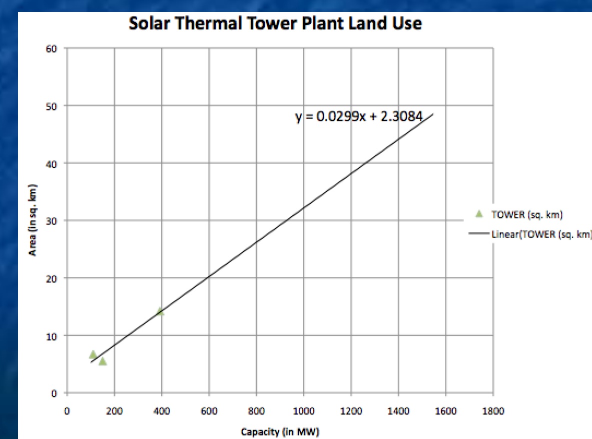
But most sources still omitted information about solar plant area

And instead gave the cumulative areas of the solar cells or solar collectors alone

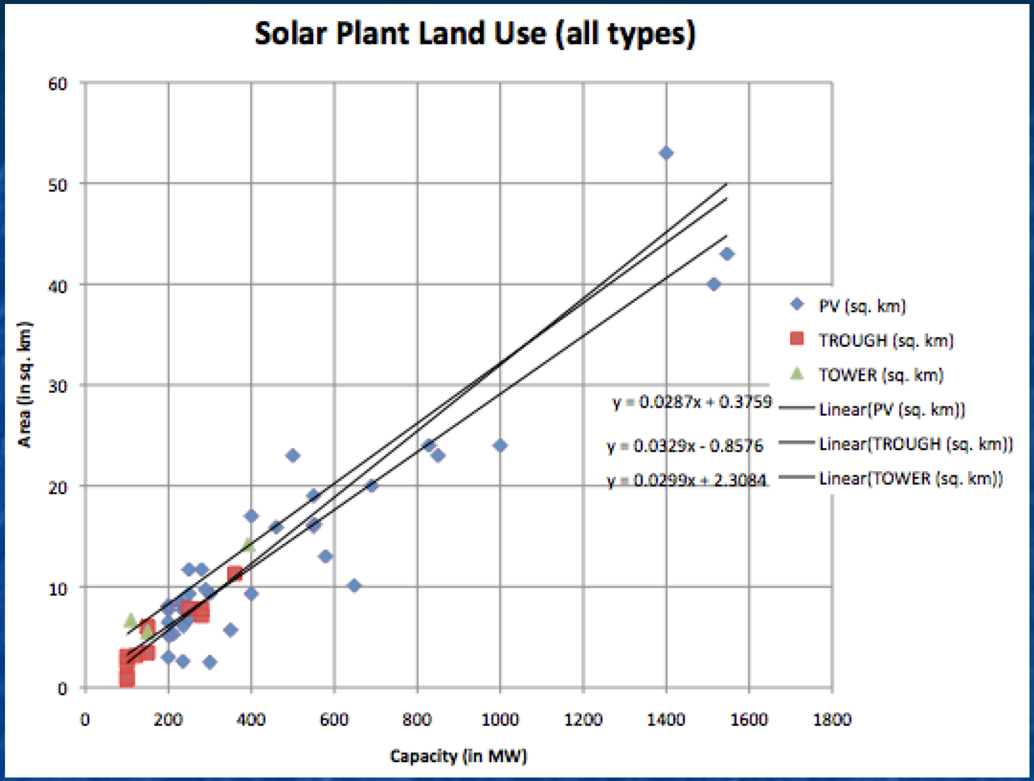
But in the end, I was able to find enough reliable information to make these statistically significant **Plant Power Output vs. Plant Area** correlations:







The Solar PV and Solar Thermal correlations were surprisingly similar:



Silicon Solar PV:
0.029 km² / MW => 34 W / m²

Thermal Troughs:
0.033 km² / MW => 30 W / m²

Thermal Towers:
0.030 km² / MW => 33 W / m²

And thus for all 2020 commercial Solar Plants: Land use ~ 0.03 km² / MW

meaning that for our targeted goal of a 1 GW plant:

1 GW Commercial Solar Plant Area = ~ 30 km²

*Which **supplants** my earlier predictions about 1 GW Solar Plant Sizes:*

Based on textbook / single plant data:	Based on existing 2020 plant data:
Crystalline Silicon Solar PV ~ 20-40 km^2	Crystalline Silicon Solar PV ~ 30 km^2
Poly Si PV (5/4 of Xtal Si) ~ 25-50 km^2	Poly Si PV (5/4 of Xtal Si) ~ 37.5 km^2
Amorphous Si PV (2X Xtal Si) ~ 40-80 km^2	Amorphous Si PV (2X Xtal Si) ~ 60 km^2
Organic PV (4X Xtal Si) ~ 80-160 km^2	Organic PV (4X Xtal Si) ~ 120 km^2
Solar Thermal Tower ~ 100-200 km^2	Solar Thermal Trough or Tower ~ 30 km^2

*What about **biofuels**?*

Biofuels are a form of Solar Energy [1]

Because their ultimate source of energy **IS** the sun

But while photovoltaic solar cells have conversion efficiencies of:

20-25% for widely commercialized cells

50% for complex research "tandem" solar cells

Or 1-10% for (potentially) much cheaper emerging types

Plant photosynthesis has a solar energy conversion efficiency of ~ 1% [2]

Algae (including saltwater tolerant species) can achieve ~ 10%

These are the fundamental (unbeatable) chemical conversion efficiencies

And thus not something that better / more mature engineering will improve

*1) For a general discussion see my **Biomass & Biofuels** (pptx / pdf / key) note set*

2) From Vanek et al.: Energy Systems Engineering – Evaluation and Implementation (p. 453)

Which allows for a technology-independent land use estimate:

Crystal PV solar cells with ~ 20% conversion efficiencies:

To produce 1 GW require 20-40 km2

Scaling from this, based on an intrinsic 10% photosynthetic conversion efficiency,

To produce 1 GW **algae based biofuels** should require at least **40-80 km^2**

Based on an intrinsic 1% photosynthetic conversion efficiency,

To produce 1 GW **plant based biofuels** should require at least **400-800 km^2**

Comparing to actual data from Fay & Golomb's Energy and the Environment (p. 168):

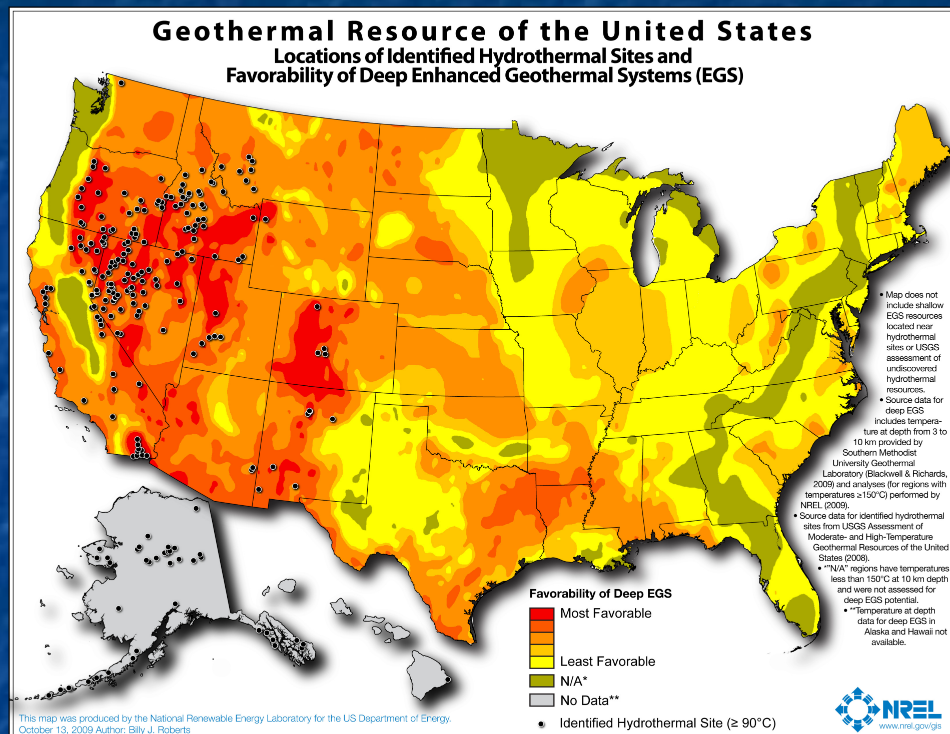
Time averaged P_{output} ~ "0.42 W/m^2" (discussing agricultural crops)

To get 1 GW => 2.4 x 10^9 m^2 => **2400 km^2**

Yielding a fair consensus on biofuels: Theoretical limit vs. measured values ~ 3:1

What about technologies that CAN SHARE the land?

Geothermal - NREL Geothermal map from **Exotic Power Sources** lecture:



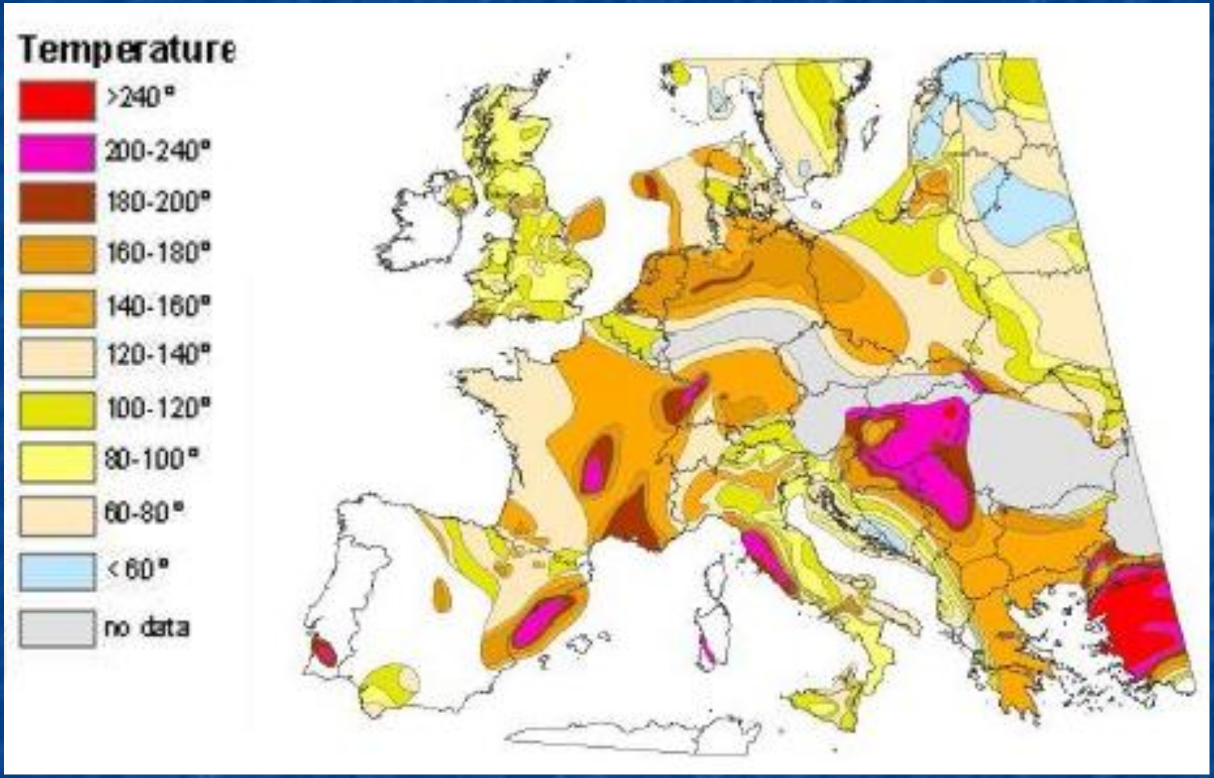
http://www.nrel.gov/gis/images/geothermal_resource2009-final.jpg

Which steers us toward West/Northwest and suggests other "favorable" locations

But does NOT give any hard heat flux numbers!

Comparable incomplete geothermal data for Europe:

European Commission:



http://ec.europa.eu/research/energy/eu/research/geothermal/background/index_en.htm

So to estimate Geothermal requirements: Back to single numbers:

From my earlier **Exotic Power Technologies** (pptx / pdf / key) note set:

Thermodynamics' Carnot cycle gives maximum "heat engine" efficiency of

$$\text{Max efficiency (\%)} = (1 - T_{low} / T_{high}) \times 100$$

For geothermal heat engines, T_{low} ~ earth surface temperature ~ 300°K

And T_{high} might be 200°C higher, e.g. 500°K giving theoretical limit of

$$\text{Max geothermal efficiency} \sim (1 - 300 / 500) \times 100 \sim 40\%$$

Wikipedia specs average thermal flux as 65 mW / m^2 land (vs. 110 ocean bottom)

USGS gives about the same at ~ 50 mW / m^2

From those numbers:

1) With 40% capture of 50-65 mW / m^2:

$P_{geothermal}$ = 20-26 mW / m^2 = 20-26 x 10^6 mW / km^2 = 20-26 kW / km^2

Area of 1 GW plant => 1 GW / (20-26 kW / km2) = 38500-50000 km^2

1 GW geothermal plant ~ 38,000-50,000 km^2

2) But "Sustainable Energy – Without the Hot Air" (p. 99)[1] gives: 25 – 150 mW / m^2

Which would expand range to:

1 GW geothermal plant ~ 6,666-40,000 km^2

Low 6,666 km^2 area number suggests McKay included enhanced locations

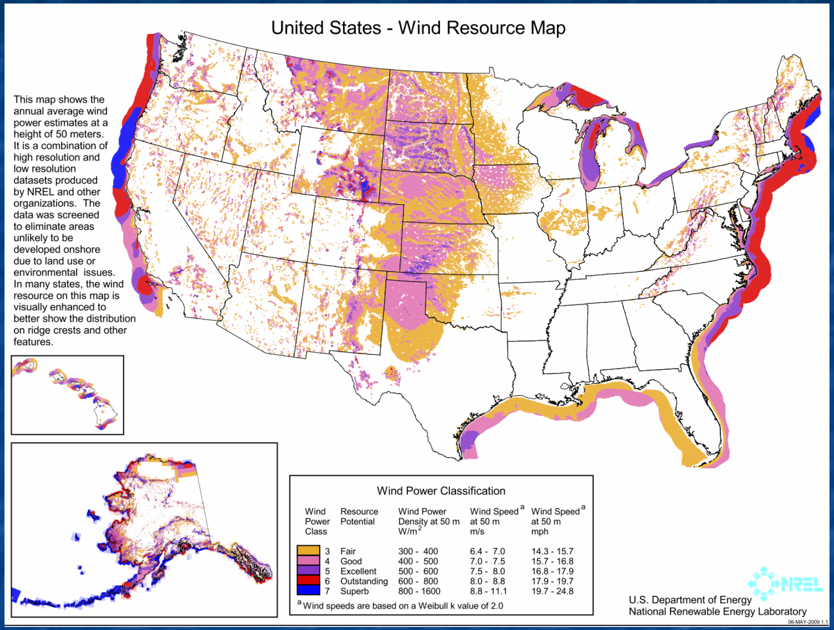
E.G., Yellowstone which has ~ 50X higher heat (peaking ~ 2000X higher!)

So assuming enhanced (but not extraordinary) locations, I'll use McKay's:

1 GW geothermal plant ~ 6,666-40,000 km^2

Moving on to second land-sharing power source: **Wind**

Back to maps – here a much more useful NREL map (with hard numbers!):



www.nrel.gov/gis/wind.html

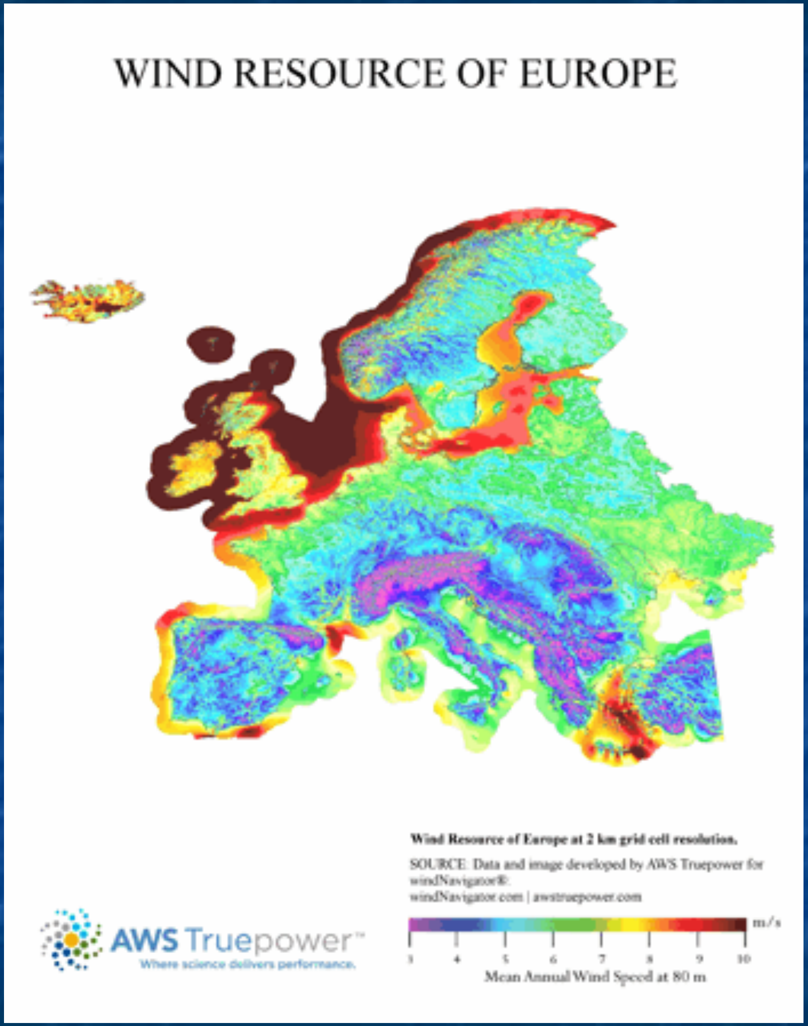
Conclusions: Northern coast = Best Abundant HIGH plains = Very good

Low hills = Fair Tall Mountains / Low plains = Poor

TALL mountains block, or divert winds upward beyond turbine's easy reach!

Offshore is great but costs escalate on more quickly deepening western coasts

Or comparable data for Europe:



Conclusions are very similar:

High mountains = Bad (block/lift wind)

Low hills = Fair

Low altitude plains = Poor (e.g. Veneto Italy)

Offshore = Best

Especially at northern latitudes

But water cannot be too deep!

~ Excluding mountainous coasts

But conversion of average wind speed to power extracted / area requires:

Answering wind farm design questions of:

- How far should turbines be spaced from one another?

- How big should individual turbines be?

Recalling results from my earlier **Wind Power** (pptx / pdf / key) note set:

1) As turbine slows wind, back-pressure causes air to divert around it

2) Wind speed increases sharply as you rise above ground level

Because the ground, its grass, bushes and trees retard air movement

3) Wind power passing by a turbine increases as wind speed **cubed** (v_{wind}^3)

Because the air's kinetic energy (per volume) goes as v_{wind}^2

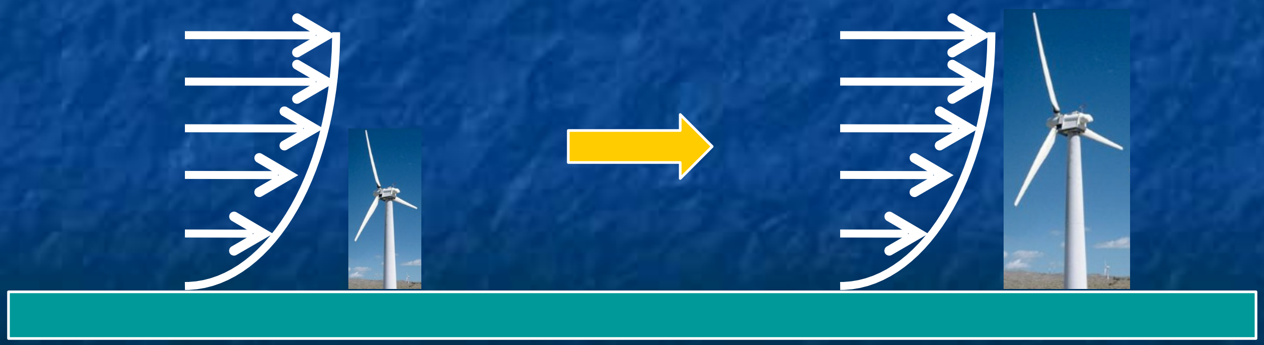
And the volume of air passing by the turbine goes as v_{wind}

Which led to our rules about turbine spacing and size:

Turbines should be separated by ~ 5 times their blade diameter [1]

Implying, turbines per plant area = 1 / (5 x turbine-blade-diameter)^2

With turbines should be as tall/big as possible to capture higher speed upper winds:



1) "Sustainable Energy – Without the Hot Air" – McKay, page 265

Conversion of map's wind speed => Wind farm power output

As derived in my earlier lecture (and "Sustainable Energy without the Hot Air"):

P_{wind} (thru area A) = ½ (air density) x (air velocity)^3 A = ½ rho v^3 A

where air density rho (ρ) will be taken as 1.2 kg / m^3

Solving this, for instance, with a wind speed of 8 m / s:

P_{wind} (at 8 m/s wind passing thru area A) = 307 (W / m^2) x Area

However, as I discovered by analyzing NREL data (but the book "Hot Air" did not!):

The v_{wind}^3 dependence of power upon wind speed

means that you shouldn't use **average** wind speeds

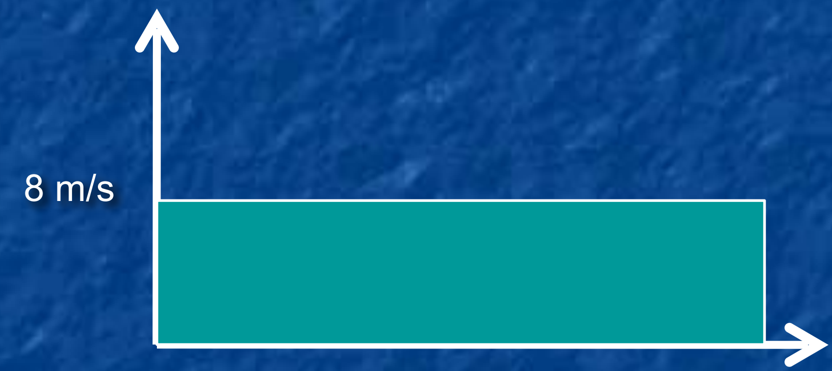
Because, for same average speed, variable winds give more energy!

Which I demonstrated via this case comparison:

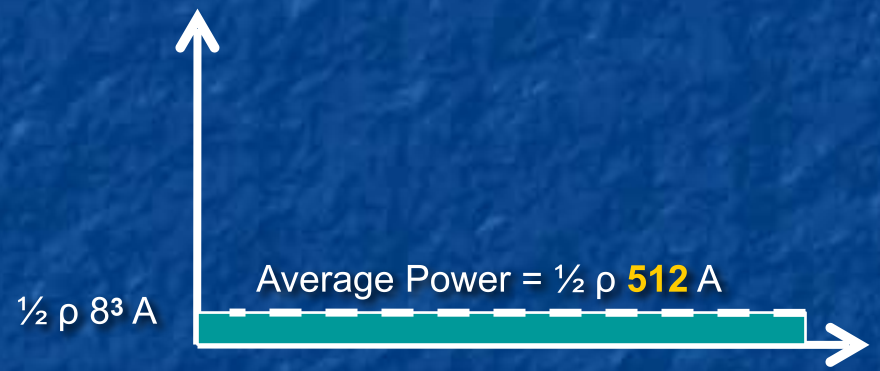
Using formula from above, for two cases with SAME average wind speed of 8 m/s:

CASE 1: Constant daily wind speed of 8 m/s:

Wind speed over day:

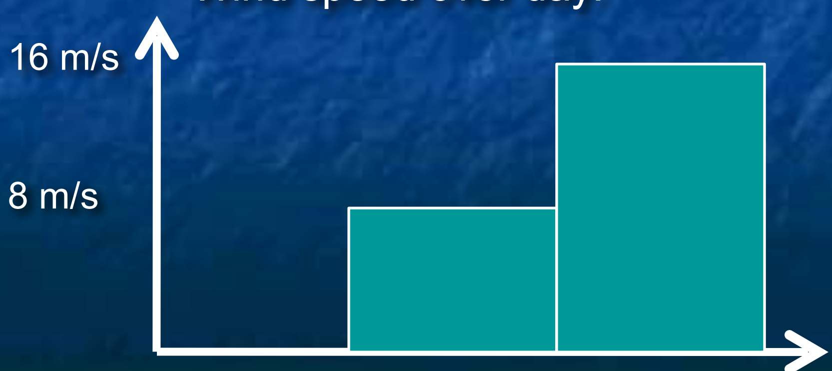


Wind power over day:

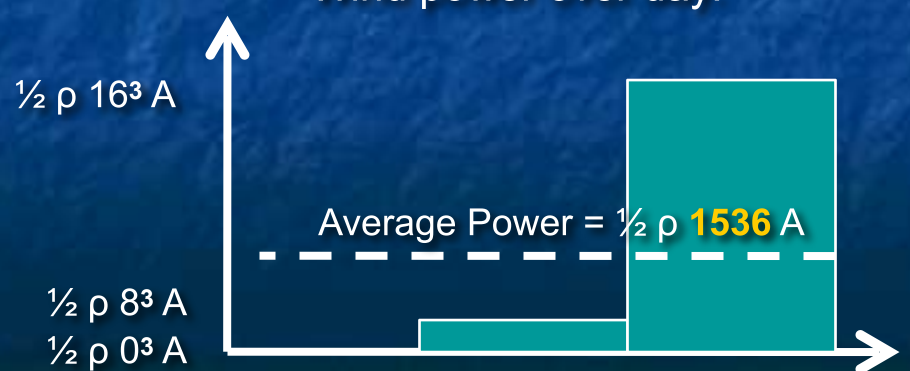


CASE 2 : Variable wind speed averaging (over day) 8 m/s:

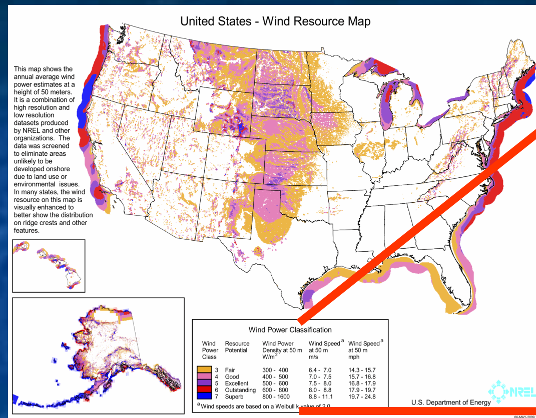
Wind speed over day:



Wind power over day:



Comparison with NREL map suggested real life enhancement of 2X:



Wind Power Density at 50 m W/m^2	Wind Speed at 50 m m/s
300 - 400	6.4 - 7.0
400 - 500	7.0 - 7.5
500 - 600	7.5 - 8.0
600 - 800	8.0 - 8.8
800 - 1600	8.8 - 11.1

Formula: Constant wind speed of 8 m/s => P_{wind} = **307 W/m² x A**

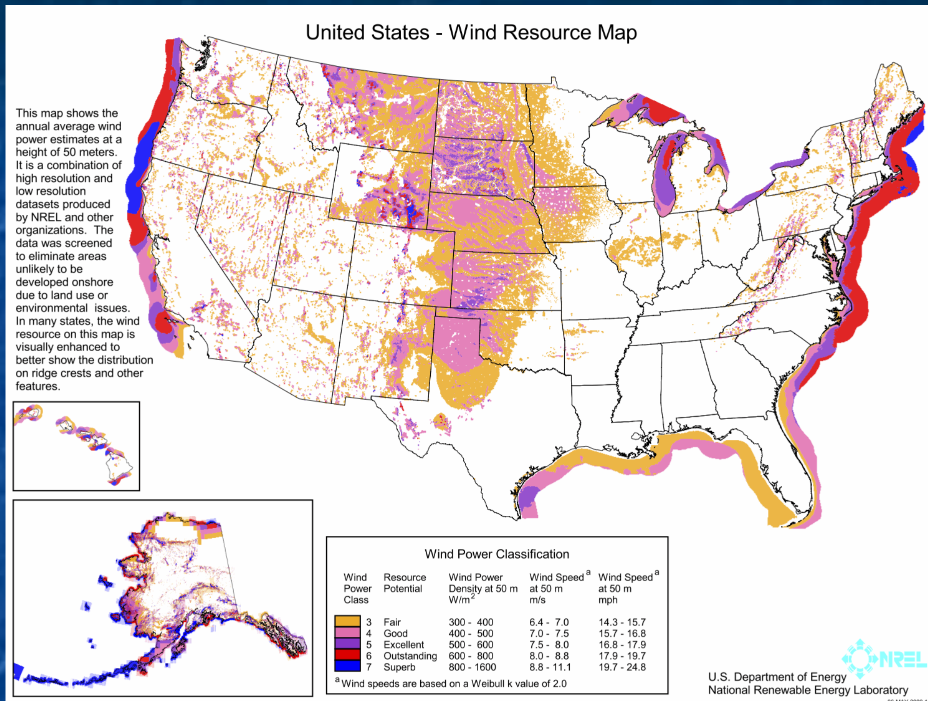
My model: Variable wind with 8 m/s average => P_{wind} = **921 W/m² x A**

NREL data: With real life wind, 8 m/s average => P_{wind} = **600 W/m² x A**

So we can use P_{wind} formula (~ doubling its results to account for variable winds)

OR, where sources like NREL give variable wind power densities, just use that data!

Enlarging the NREL U.S. map so that we can read off numbers:



Wind Power Classification

Wind Power Class	Resource Potential	Wind Power Density at 50 m W/m^2	Wind Speed[a] at 50 m m/s	Wind Speed[a] at 50 m mph
3	Fair	300 - 400	6.4 - 7.0	14.3 - 15.7
4	Good	400 - 500	7.0 - 7.5	15.7 - 16.8
5	Excellent	500 - 600	7.5 - 8.0	16.8 - 17.9
6	Outstanding	600 - 800	8.0 - 8.8	17.9 - 19.7
7	Superb	800 - 1600	8.8 - 11.1	19.7 - 24.8

[a] Wind speeds are based on a Weibull k value of 2.0

Location:	Ave. Wind @50m (m/s)	Ave. Wind Power Density @50m (W/m^2)
Onshore Central Virginia	<< 6	<< 300
Onshore Great Plains	~ 7	~ 400
Offshore Virginia	~ 8	~ 700
Offshore N. CA / S. OR	~ 10	~ 1200

Starting calculation with a single wind turbine:

"Betz Law" said theoretical max wind turbine power conversion efficiency = 59.3%

So let's assume that for our real world-turbines, $\varepsilon_{turbine}$ **= 50%**

For **50 m diameter wind turbine**, wind area intercepted = 1963 m^2

$P_{50m\ turbine}$ = (50% efficiency) (turbine blade area) (wind power per area)

= 982 m^2 x (wind power per area)

Filling in wind power per area from preceding slides, get $P_{50m\ turbine}$ =

Location:	**Using wind speed in formula:**	**Using wind power density data:**
Onshore Central Virginia	<< 127 kW	<< 295 kW
Onshore Great Plains	201 kW	392 kW
Offshore Virginia	301 kW	687 kW
Offshore N. CA / S. OR	587 kW	1178 kW

Then using spacing rule to build a full wind farm:

Power / plant area = Power per turbine / turbine footprint (with optimum spacings)

$$P_{\text{per plant land area}} = P_{\text{50m turbine}} / (5 \times \text{turbine-blade-diameter})^2$$

$$= P_{\text{50m turbine}} / (62{,}500\ m^2) = 16\ P_{\text{50m turbine}} / km^2$$

Plugging in $P_{\text{50m turbine}}$ data from preceding slide, get **$P_{\text{per plant land area}}$ =**

Location:	**Using wind speed in formula:**	**Using wind power density data:**
Onshore Central Virginia	<< 2 MW / km^2	<< 4.7 MW / km^2
Onshore Great Plains	3.2 MW / km^2	6.3 MW / km^2
Offshore Virginia	4.8 MW / km^2	10.9 MW / km^2
Offshore N. CA / S. OR	9.36 MW / km^2	18.7 MW / km^2

And dividing this into our 1 GW power capacity goal:

We get 1 GW wind farm land areas of:

Location:	**Using wind speed in formula:**	**Using wind power density data:**
Onshore Central Virginia	>> 500 km^2	**>> 213 km^2**
Onshore Great Plains	312 km^2	**159 km^2**
Offshore Virginia	208 km^2	**92 km^2**
Offshore N. CA / S. OR	106 km^2	**54 km^2**

Recalling that formula did not account for enhancement due to variable winds

And that power should thus be doubled (halving the land requirement)

Both methods give almost identical results = That of table's final column

Hence my **highlighting** of that column's data

Grand summary of estimated 1 GW power plant sizes:

Plant Technology:	Good / Best Site:	Random Site:
Fossil Fuel	**~ 0.1 km^2**	**0.1 km^2**
Nuclear	**~ 2 km^2**	**~ 2 km^2**
Crystal Si PV solar	**~ 30 km^2**	**~ 60 km^2**
Solar Thermal	**~ 30 km^2**	**~ 60 km^2**
Poly Si PV solar	**~ 37.5 km^2**	**~ 75 km^2**
Offshore Wind	**~ 55 km^2**	**~ 90 km^2**
Amorphous Si PV solar	**~ 60 km^2**	**~ 120 km^2**
Organic PV solar	**~ 120 km^2**	**~ 240 km^2**
Onshore Wind	**~ 160 km^2**	**>> 200 km^2**
Biofuel (algae)	**~ 200 km^2**	**~ 200 km^2**
Biofuel (plants)	**~ 2000 km^2**	**~ 2000 km^2**
Geothermal	**~ 6000 km^2**	**~ 40,000 km^2**

For full U.S. power (1000 such plants on "good/best" sites):

Technology:	Good Sites:	Equivalent to area of:	% of US:
Fossil Fuel	**100 km^2**	½ of Washington DC	0.001%
Nuclear	**2,000 km^2**	½ of Rhode Island	0.02%
Crystal Si PV solar	**30,000 km^2**	Maine	0.3%
Solar Thermal	**30,000 km^2**		0.3%
Poly Si PV solar	**37,000 km^2**		0.37%
Offshore Wind	**55,000 km**		0.55%
Amorphous Si PV solar	**60,000 km^2**	Georgia	0.6%
Organic PV solar	**120,000 km^2**		1.2%
Onshore Wind	**160,000 km**		1.7%
Biofuel (algae)	**200,000 km^2**		2%
Biofuel (plants)	**2,000,000 km^2**	TX+CA+MT+NM+AZ	20%
Geothermal	**6,000,000 km^2**	AL+TX+CA+MT+NM+ AZ+NV+CO+OR+WY+ MI+MN+UT+ID+KS	61%

Power Plant Land Requirement Bottom Lines:

Because renewable energy **sources** are very dilute (i.e., average power / area),

in order to deliver a good fractions of US power requirements,

their cumulative land areas range from smaller state to most states

And this was for "good to best locations" for each type of plant

I suspect practical limit will not exceed onshore wind's cumulative 100,000 km^2

And only then because wind can SHARE land with other uses

From an aggressive land use perspective, **viable renewables** appear to be:

Wind or **Solar Photovoltaics**

From a less aggressive land use perspective, **viable renewables** appear to be:

Offshore Wind or **Crystal/Polycrystal Silicon Solar Photovoltaics**

Both of which are more plausible when supported (at least for now) by:

Quasi-renewable **Nuclear**

Part II: Power Plant Water Requirements:

Biofuel water consumption: Much of the above crop area would be irrigated

Actual water use would depend upon crop, soil and weather conditions

Making crop by crop calculations very complicated

But from **Biomass and Biofuel** (pptx / pdf / key) notes, water use would be **huge**

A Georgia Tech study even concluded (to the researchers' surprise) that:

1st world dependence on biofuels would require ALL of world's fresh water [1, 2]

Further, water released from corn biofuel farms is polluted by agricultural chemicals

And then there is the preceding damning computation of biofuel **land** requirements

Which all combine to make exact water use computations effectively moot

(But links to the above articles are given on this note set's Resources Webpage)

1) Biofuel's Water Problem, IEEE Spectrum, June 2010 2) Organic But Not Green IEEE Spectrum, November 2009

Water consumption of more conventional power plants?

Hydropower water consumption: I've already mentioned the GREAT DROUGHT

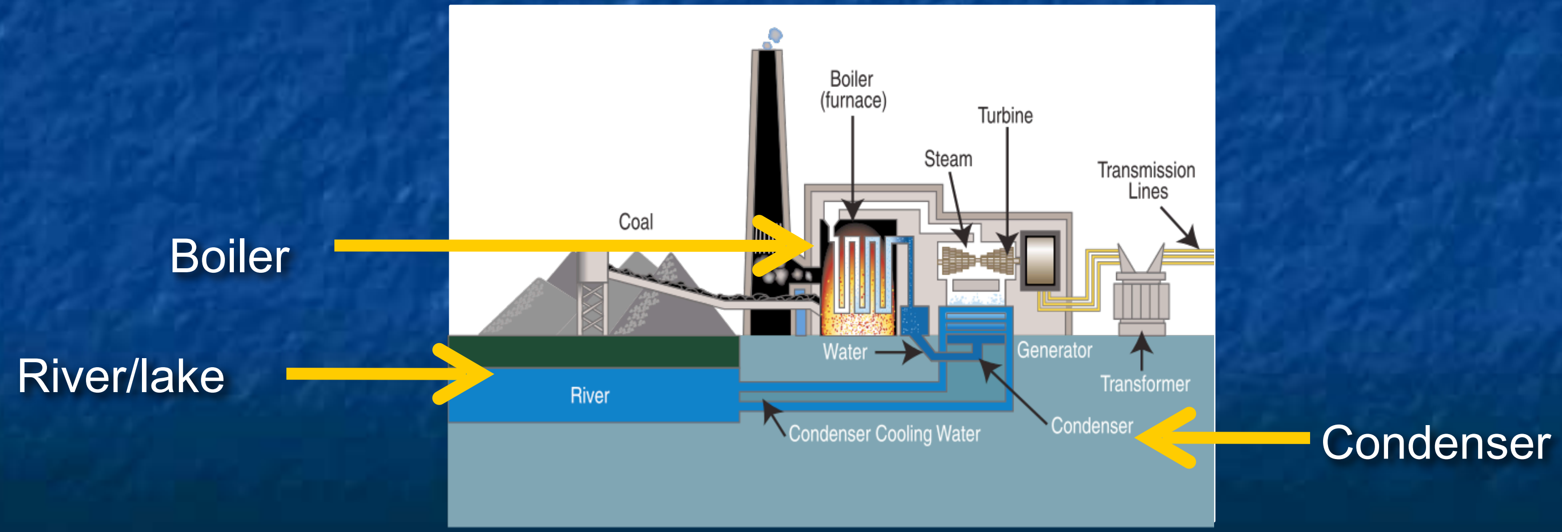
Which is jeopardizing hydropower in the Southwest

Possibly even crippling hydroelectric plants such as the Hoover Dam

Steam driven power plant water consumption:

= All fossil fuel plants (except OCGT natural gas), nuclear, some solar thermal

The issue here is the water used to cool and recondense that steam:



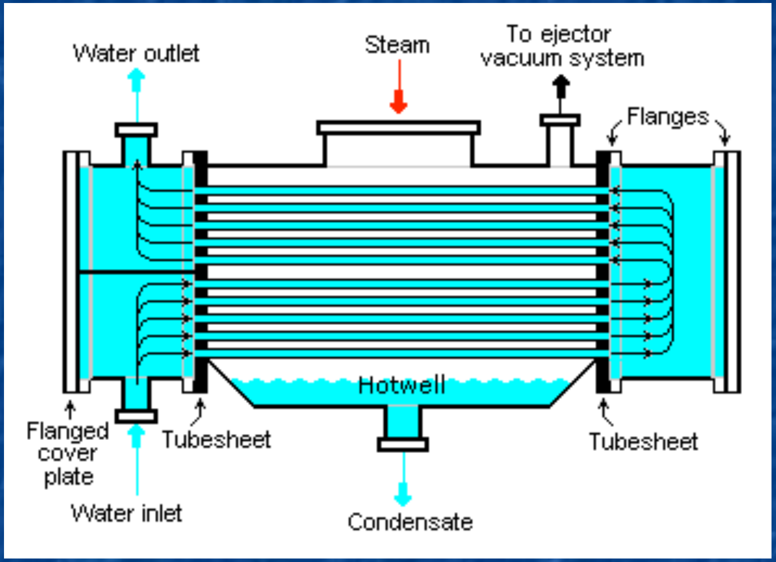
http://en.wikipedia.org/wiki/Fossil-fuel_power_station

Steam condensation occurs in water-cooled "condensers"

Which allow two loops (or volumes) of water to come into close contact

One carrying steam that has just exited the turbine generator

One with "cooling water" (from river / lake. . . then returning to same)



http://en.wikipedia.org/wiki/Surface_condenser

Heat from the much hotter steam migrates to the much cooler cooling water

The steam condenses, the cooling water gets warmer

Warming of that cooling water has consequences:

For smaller lakes and rivers, water temperature rise can be very important:

Harming wildlife, or perturbing the ecosystem

For example by fostering alga growth => Oxygen depletion => Fish die offs

How might one calculate the cooling water's temperature change?

$\text{Power}_{\text{Steam => Cooling Water}}$ = (Steam mass / time) (H_2O heat of vaporization)

Which should cause that cooling water's temperature to rise by:

$\Delta T = \text{Power}_{\text{Steam => Cooling Water}}$ / [(Cooling H_2O mass per time) (H_2O specific heat)]

Combining those equations:

$$\Delta T = \frac{(\text{Steam mass per time})\ (H_2O\ \text{heat of vaporization})}{(\text{Cooling } H_2O \text{ mass per time})\ (H_2O\ \text{specific heat})}$$

Looking up relevant physical constants for water:

Water's heat (or "enthalpy") of vaporization = 2260 k Joules / kg

Water's specific heat (or heat capacity") = 4.179 Joules / g / °C

Inserting those values into equation above:

ΔT = 540 °C x (Steam mass per time)/(Cooling water mass per time) (1)

Use **more** cooling water => Get **smaller ΔT rise**

But steam mass per time DRIVES the turbine generator, thus I'd expect:

Electrical power generated should be proportional to steam flow

And I could indeed dig that proportionality out of a textbook:

Incorporating steam to electrical conversion efficiency:

From Rubin's Introduction to Engineering & the Environment (p. 190-191):

(Electrical energy output of turbine) / (Heat energy added to steam) ~ 42%

But heat added to steam = heat of vaporization = 2260 k Joules / kg   Thus:

0.42 = (Electrical Output of turbine) / (2260 k W-s / kg steam)

Rearranging that:

(kgs of steam / sec) = 0.42 (Electrical Output of turbine) / (2260 kW)

= (1.86×10^{-4} / kW) (Electrical Output of turbine) (2)

Combining equations (1) & (2) to get warming of cooling water per power output

ΔT (Cooling water kg / s) / (540 °C) = (1.86×10^{-4} / kW) (Electrical Output) =>

ΔT = (0.1 °C / kW) (Electrical Power Output) / (Cooling water kg / s)

Cooling water load for our target 1 GW power plant:

Inserting 1 GW (= 10^6 kW) for "Electrical Output" in the above equation:

$\Delta T = 10^5$ °C / (Cooling water kg / s)

If we could accept a 3°C (~ 5°F) cooling water temperature increase then:

Cooling water (kg / s) = 33,000 => 33 kilo-liter / sec

Converting this to an annual water use number, 1 GW plant needs:

~ 120 mega liters / hr => 10^{12} liters / yr = 250 billion gallons / yr

With that volume **inversely** proportional to allowed temperature rise

If one such water-cooled technology provided **total US power** (~1000 x 1 GW):

Cooling water (for total U.S. power) ~ 10^{15} liters / yr = 250 trillion gal / yr

~ Twice the Mississippi River's total flow (if water not reused)

Confirmation of that seemingly huge steam plant water consumption?

From one analysis published in journal Environmental Research Letters:[1]

Hourly water consumption per power produced ~ 50,000 gal/hr/MW

=> 50 M-gal/hr/GW => 200 mega-liters/hr/GW = 1.6 X my 3°C number!

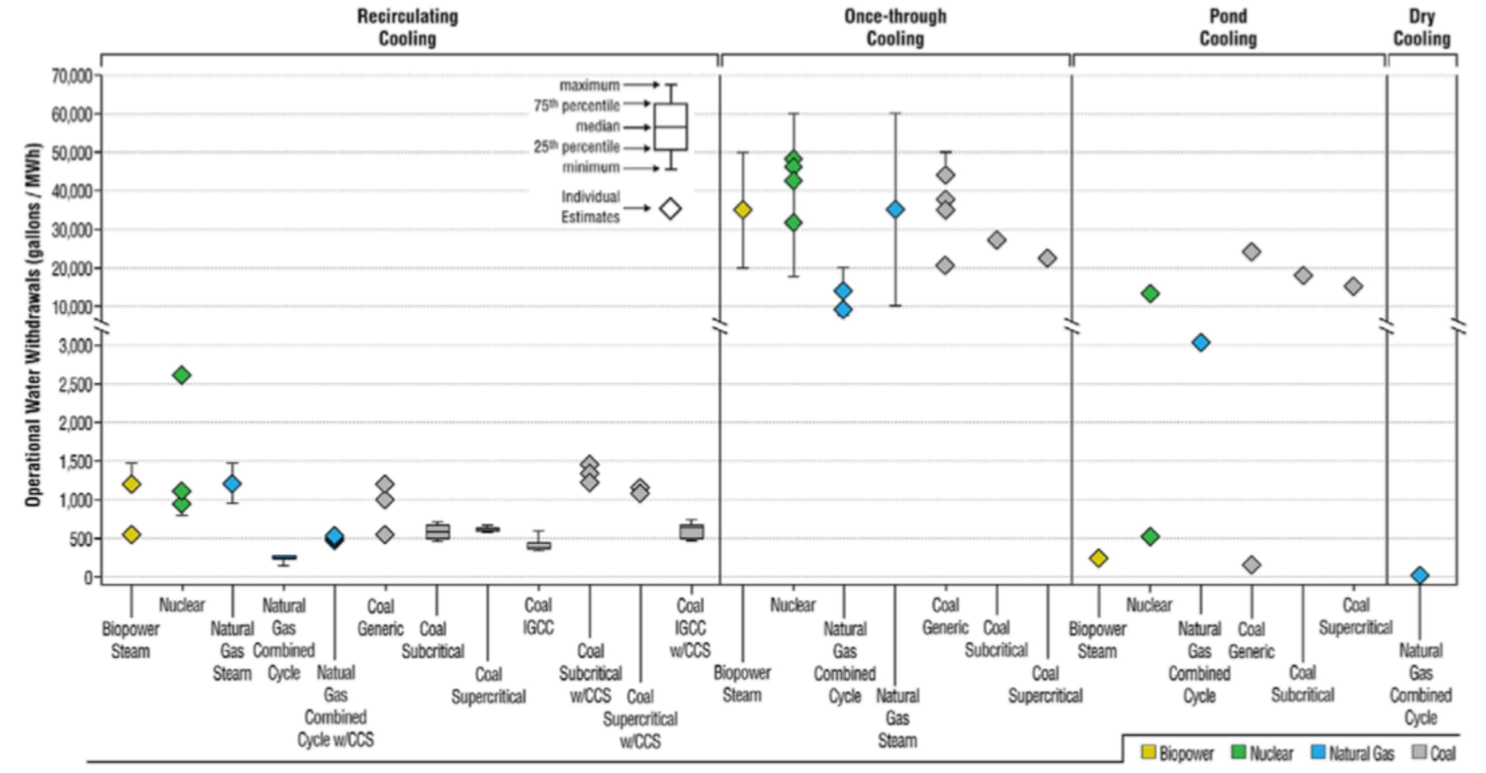


Figure 2. Operational water withdrawals for fuel-based electricity generating technologies. IGCC: integrated gasification combined cycle. CCS: carbon capture and storage.

1) J. Macknick et al.: http://iopscience.iop.org/1748-9326/7/4/045802/pdf/1748-9326_7_4_045802.pdf

Finally, likely water requirements for solar and wind:

Wind power: No operating water requirement

Solar PV: No operating water requirement

However, for both of the above. lifecycle analysis **would** include some water use:

As used in mining and refining building materials such as Al and Si

But likely still small compared to steam power plant water use numbers

Solar Thermal:

If water is boiled into must-be-condensed-steam => steam plant water numbers!

But if boiling oils are instead used, one might **eliminate** water use

Because hotter oil vapor can be effectively cooled/condensed by ambient air

Power Plant Water Requirement Bottom Lines:

FOR STATUS QUO: Use power from H_2O steam generation & condensation:

Coal, natural gas combined cycle, nuclear, biomass, much solar thermal

=> Mississippi-scale water consumption

But remember: Most of that cooling water is reusable

At least after environment has cooled it down (e.g. down river)

FOR REDUCED WATER CONSUMPTION: Use ~ water-free technologies

= Gas turbines, wind, solar photovoltaics, some solar thermal (those using oils)

FOR RADICAL INCREASE IN WATER CONSUMPTION: Use water as prime input

= Biofuels

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This set of notes was authored by John C. Bean who also created all figures not explicitly credited above.