Broader Impact and Requirements of Power Plants

John C. Bean

Outline

Some of which are cited in social media (and even respected newsfeeds)

as reasons to abandon certain established or emerging energy technologies

But those criticisms may or may not be supported by actual data and facts

And I've found more damning ones that are overlooked - Calling for a closer examination of:

Raw Materials required by Power Plants

Their natural abundance, where the are found, how they are extracted

Necessary refining of those Materials

Transportation of those Materials

From Mines & Wells to Refineries, to Power Plants

The Energy they Produce vs. Energy Invested in their Extraction, Refining and Transportation

Sometimes misleadingly quantified in "Energy Payback Time" (EPBT)

But more appropriately described by "Energy Return on Invested Energy" (EROI)

Which ranges over more than a factor of ten for today's energy technologies

Unintended Consequences of some of the above, including (possibly):

Leaks, fires, ground water & aquifer contamination, desecrated landscapes . . . earthquakes

(Revised September 2024)

Broader Impact and Requirements of Power Plants

I've compared power plant land & water requirements

And later I'll compare power plant atmospheric / global warming impacts

But **other** impacts & requirements are difficult to compare. A prime example:

The impact of raw material mining, refining and transportation

Why? Because different power technologies depend on very different materials

The impact of each must be **separately** studied

Often resulting in apple to orange to pear comparisons

This can produce a large gray information void

Filled by lavishly funded marketing campaigns for entrenched energy technologies

Or (sadly) by scientists denigrating one technology to promote their own

This note set will venture into this "gray information void"

In a **few** cases, I've actually found data that support or refute a specific claim

But for the much larger number of **ambiguous cases**,

I can at least dig deeper into the issues and facts,

getting well beyond blogger and advertising hype

With luck, this may transform scattered **orange vs. apple vs. pear** claims

Into more meaningful **orange to lemon to lime to grapefruit** comparisons

To begin: Energy production nearly always involves

Raw materials to build power plants and/or fuel those power plants:

What are their natural abundances?

Where, and in what form, do they naturally occur?

How are they extracted from these locations?

Refining to convert these raw materials into useful forms

Transportation from mines/wells to refineries, and then to the power plant itself

Energy investment to accomplish all of the above

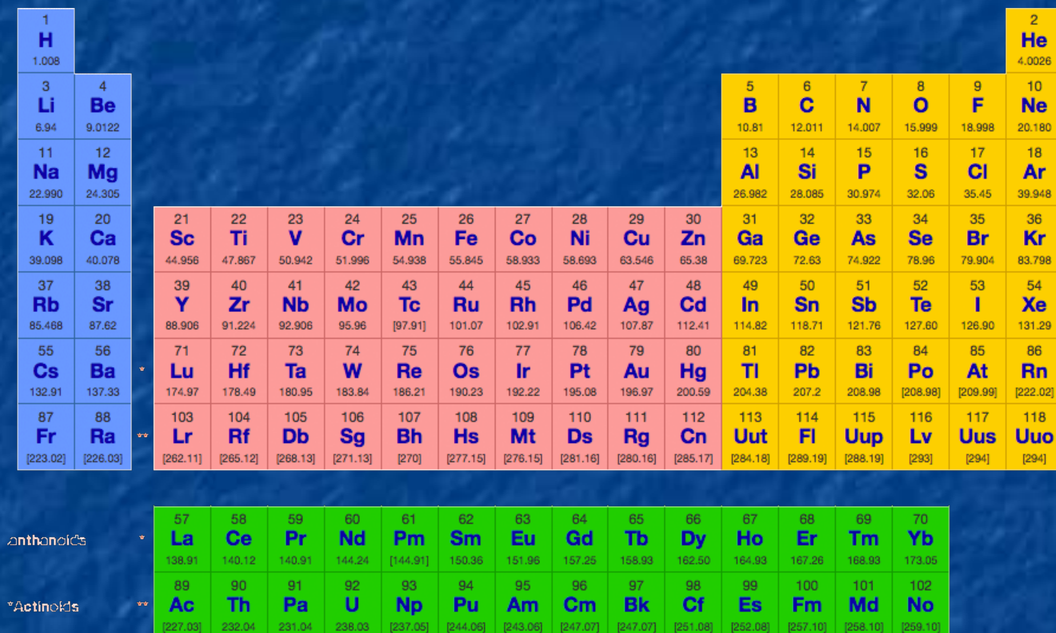
Unintended consequences / side-effects

Upon aquifers, rivers, the air we breathe . . .

Starting with issues relating to ***raw material*** *sources:*

Which atomic elements will we need for energy production?

Probably these (that is, almost all of them):



Where must they be found? In the **accessible** top 1-2 miles of the earth's crust

OK, then what's in the crust, particularly the near-surface crust?

Source: http://www.webelements.com/

The earth started out as, and pretty much still is, a molten ball

Gravity drives denser things to the center

With progressively less dense things forming shells around the denser things

Which would leave the least dense things at the surface

- Where they, alone, can radiate heat into space, causing them to cool
  - Forming a thin solid **surface scum** that we call the earth's **crust**

Now, add in the fact that the earth is 4.5 billion years old

- Giving all of those liquids a lot of time to cool and sort themselves out

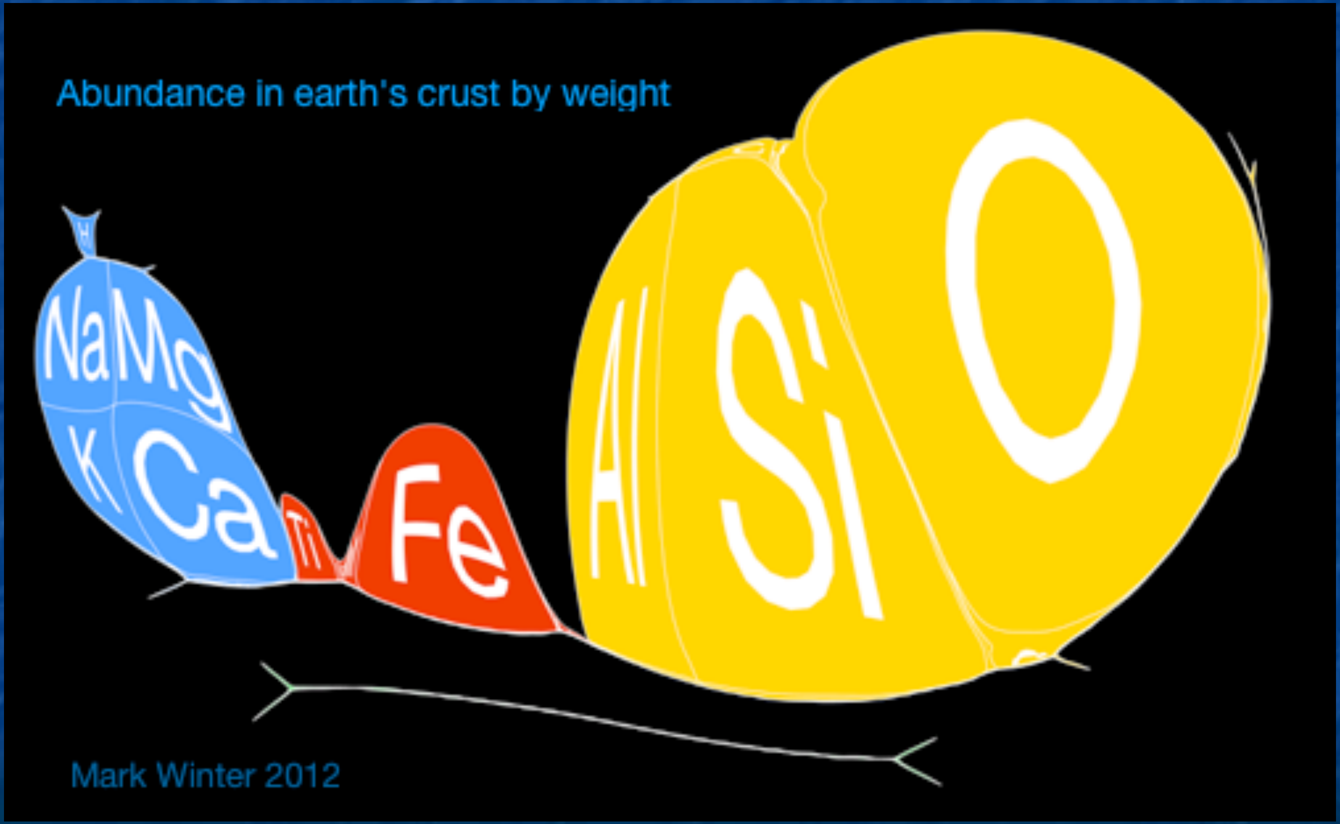
From which you'd then expect the earth to be layered like an onion:

- With spherical shells of pretty uniform material
  - Layered on top of other shells of denser material

We thus expect the outermost crust layer to be rich in light elements

=> This wonderfully reworked version of the Periodic Table

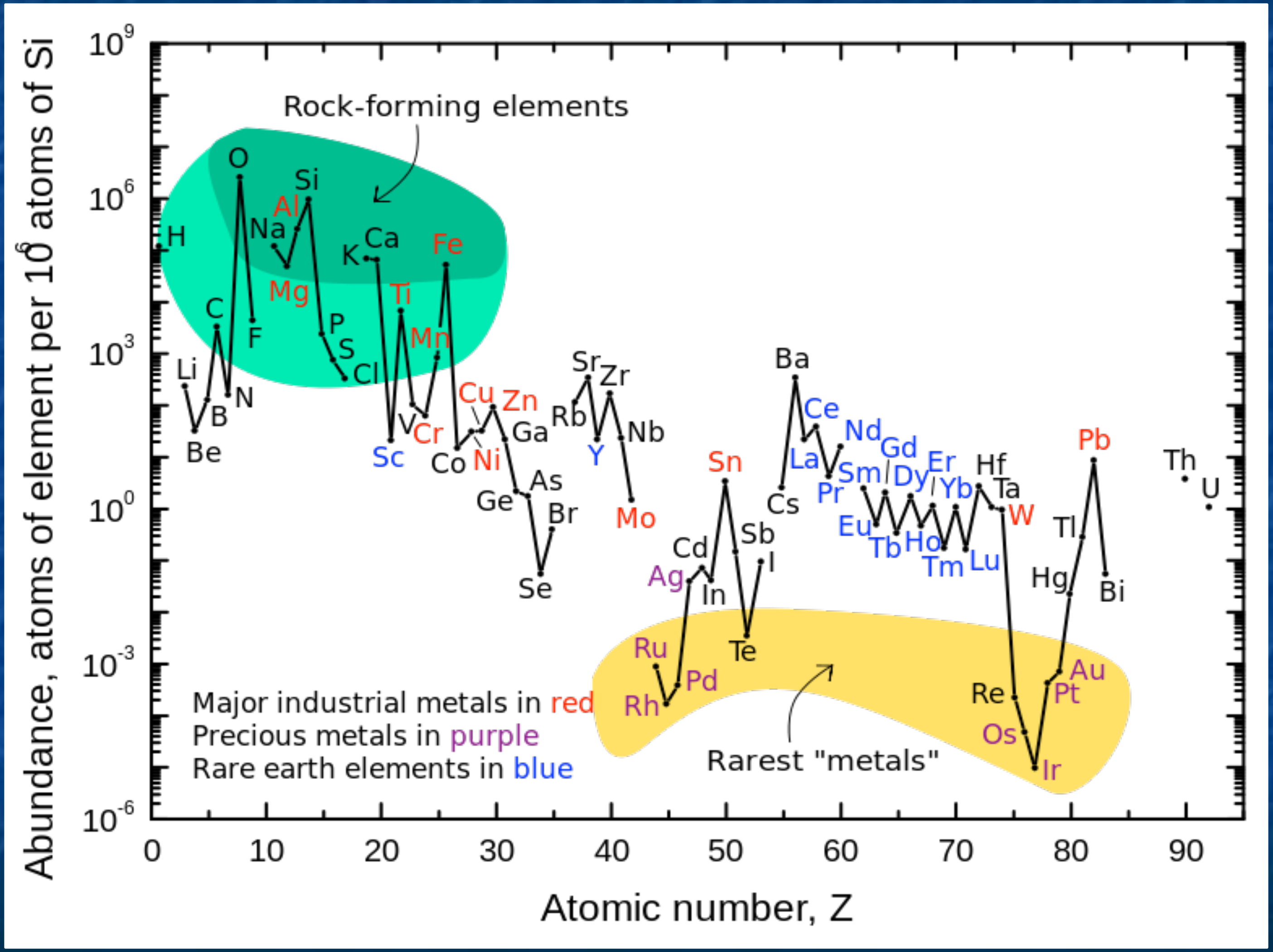
With cell size proportional to element's crustal abundance:



Source: http://www.webelements.com/

IN FACT: Si, O, Al, Fe, Ti, Ca, Mg, Na and K are **so common**

That we need a **12 decade semilog plot** (!) to even list other crustal elements:



http://en.wikipedia.org/wiki/Abundance_of_elements_in_Earth%27s_crust

But my Onion Earth Model omits something very important:

Convection

Exposed outer layers of lighter materials are cooling, and thus becoming denser

Trapped inner core layers cannot radiate, and thus cannot similarly cool

In fact, the **core may not cool at all** because it has sucked in heavy atoms

Which include a higher proportion **radioactive atoms** (which tend to be heavy)

These eventually undergo "radioactive decay," meaning that they fall apart

1) Creating lighter atomic elements AND

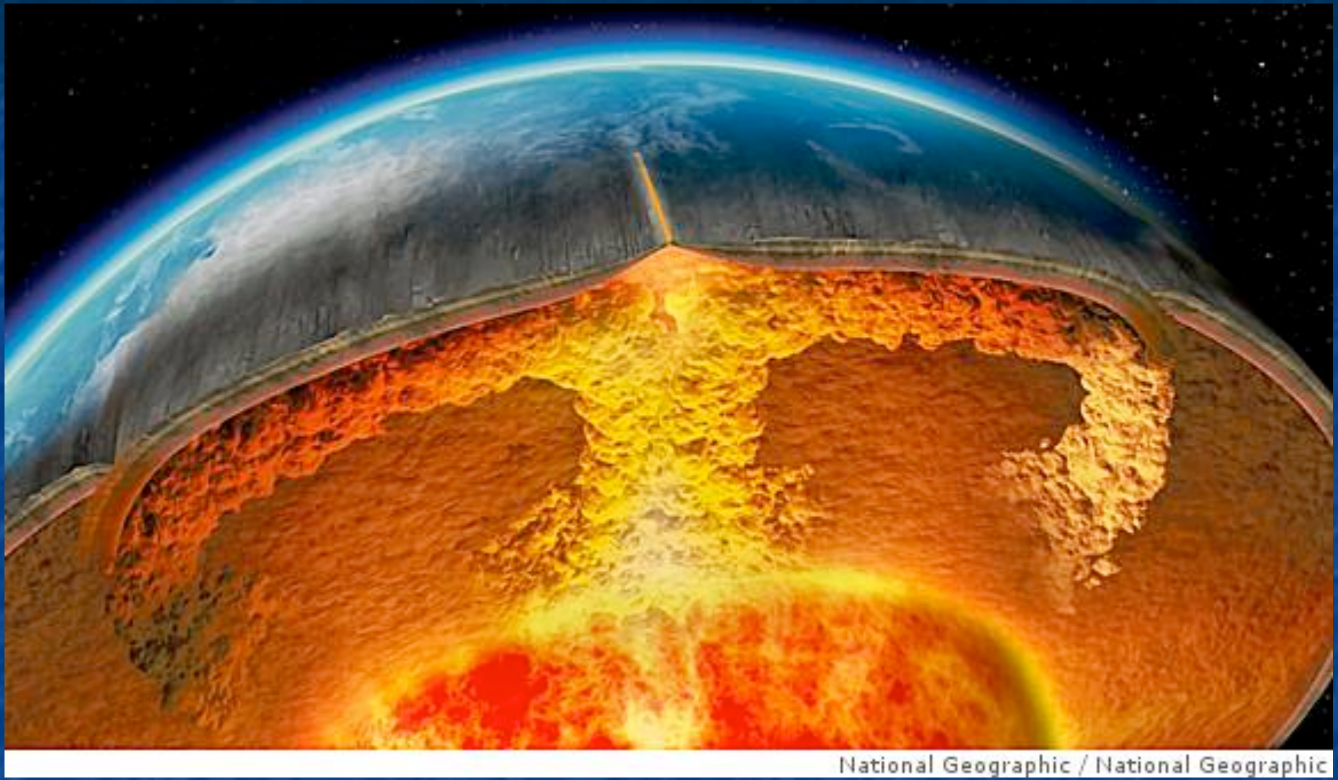
2) Liberating massive amounts of heat

Which causes materials around them to expand

Both => Formation of less dense material in the earth's core

Gravity then drives that less dense material upward:

Setting up mega ***convection currents****:*



These mega convection currents **drag along some of the heavy elements**

Disrupting the otherwise uniform layering of my Onion Earth Model

Surface flows then push chunks of crust to their sides => **Plate Tectonics**

Plate tectonics drives **subduction***:*

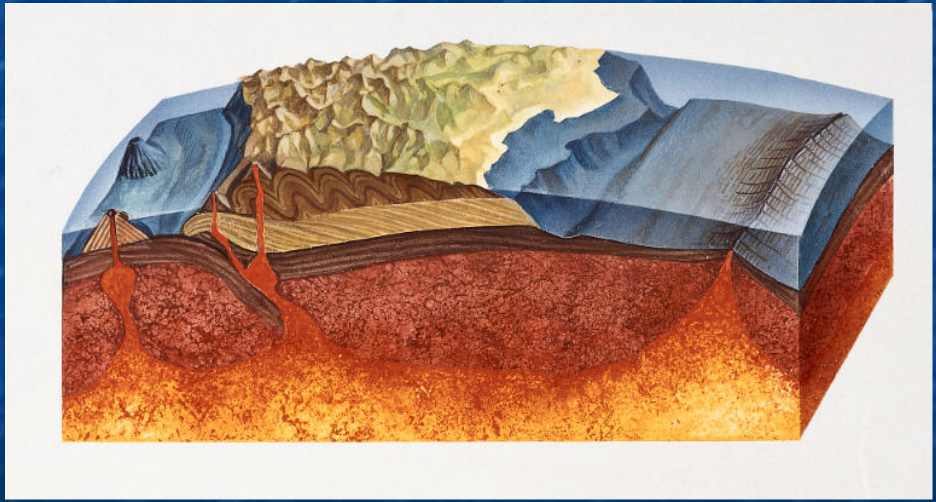
If convective upwelling is pushing plates **apart somewhere**

It must be driving them **together elsewhere** (e.g. where convective flows dive)

Where plates are driven together, there are only two possibilities:

1) Plate edges crumple => Mountain formation (**"upthrust"**)

2) One plate edge burrows under the edge of the other (**"subduction"**)



Lighter material is thus driven below heavier material

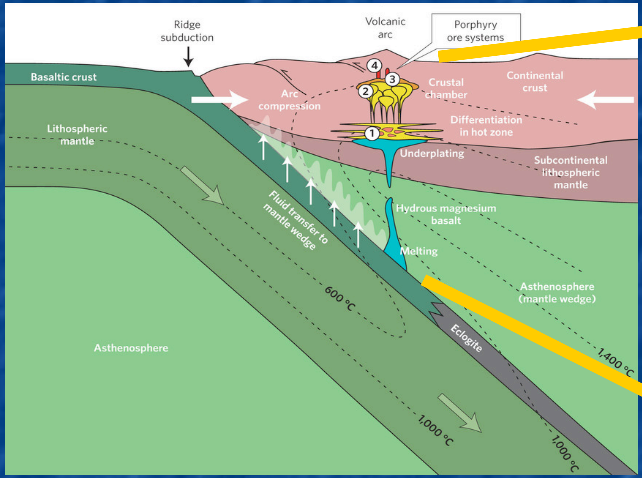
Attributed by Google Images to www.geodesy.cwu.edu – but no longer found at that URL

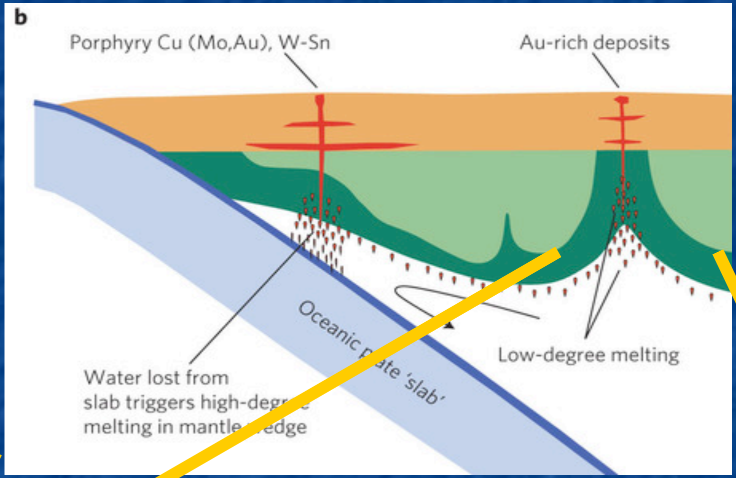
As subducting lighter material heats up and melts:

Its now liquid lighter components can bubble upwards => **Volcanoes**

As water (w/ minerals) can percolate up through cracks => **Hot springs & Geysers**

Both of which can create localized surface / near-surface **ORE DEPOSITS**





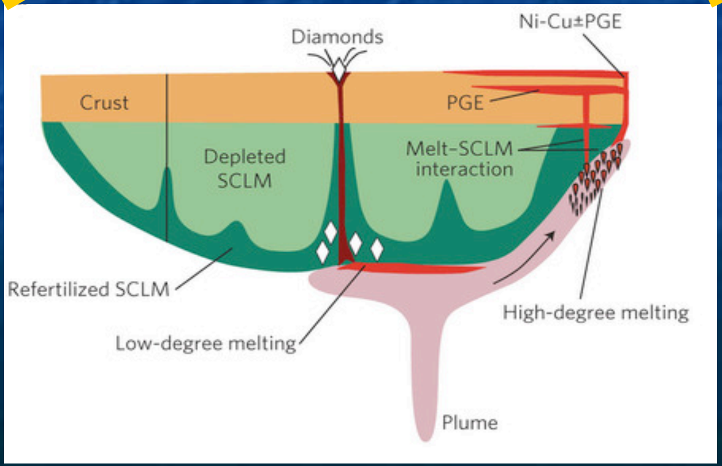


Fig. 1: Triggers for the Formation of Porphyry Ore Deposits in Magmatic Arcs, J.J. Wilkinsen, Nature Geosciense 6, pp. 917-25 (2013) http://www.nature.com/ngeo/journal/v6/n11/full/ngeo1940.html

Figs. 2 & 3: Continental-root Control on the Genesis of Magmatic Ore Deposits, W.L. Griffin et al., Nature Geoscience 6, pp. 905-10 (2013) http://www.nature.com/ngeo/journal/v6/n11/fig_tab/ngeo1954_F4.html

ADD TO THIS: Thin sedimentary layers produced by water & plants

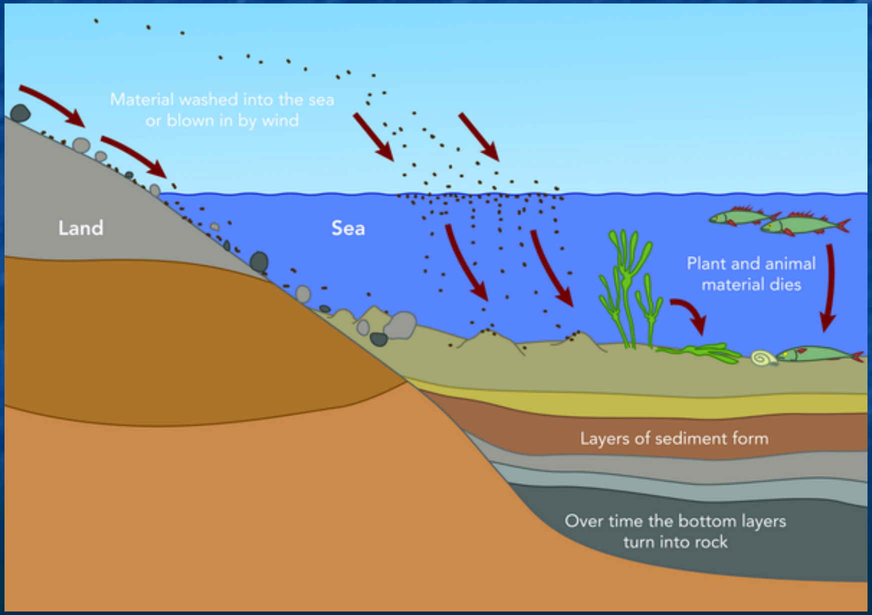
Water erodes away high points, washing materials into a sea or lake

Material then settles out into thin layers at their bottom

OR: Shallow sea/lake itself **dissolves** specific materials **from** the surrounding **crust**

Sea/lake dries out, dissolved materials => New thin layers (e.g. salt flats)

OR: The above sedimentation process buries layers of plants previously on surface

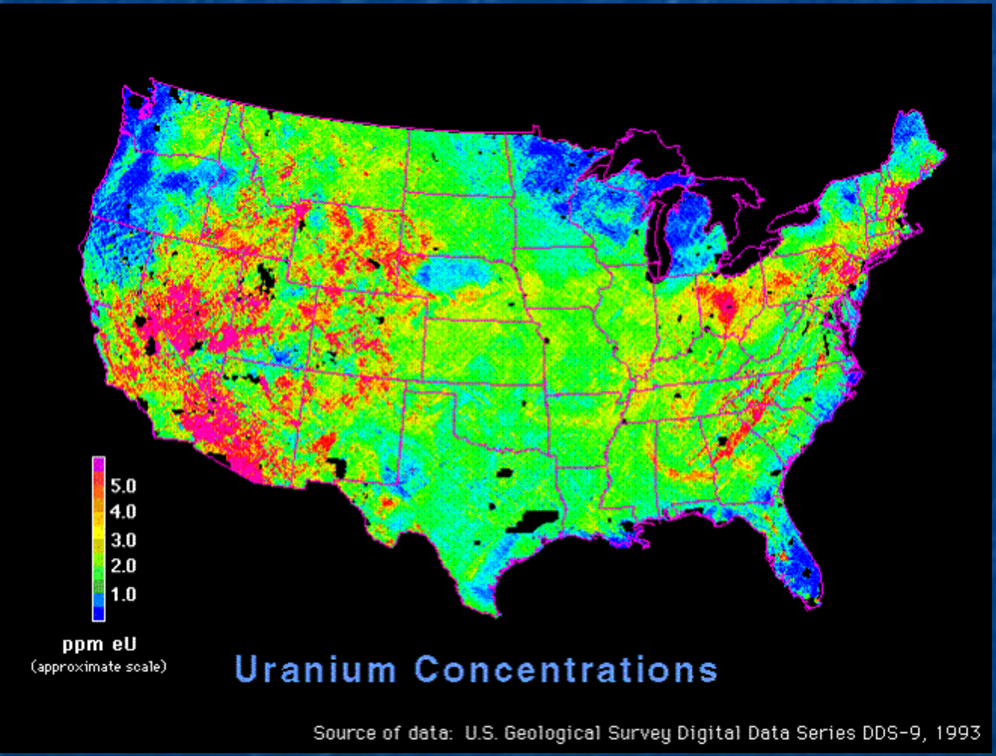


http://www.thunderboltkids.co.za/Grade5/04-earth-and-beyond/chapter3.html

Ultimately leading to crustal raw material maps such as these:

Uranium:

Overall U.S. abundance:



http://energy.usgs.gov/portals/0/Rooms/uranium/images/uranium_concentrations.gif

U.S. mining regions:

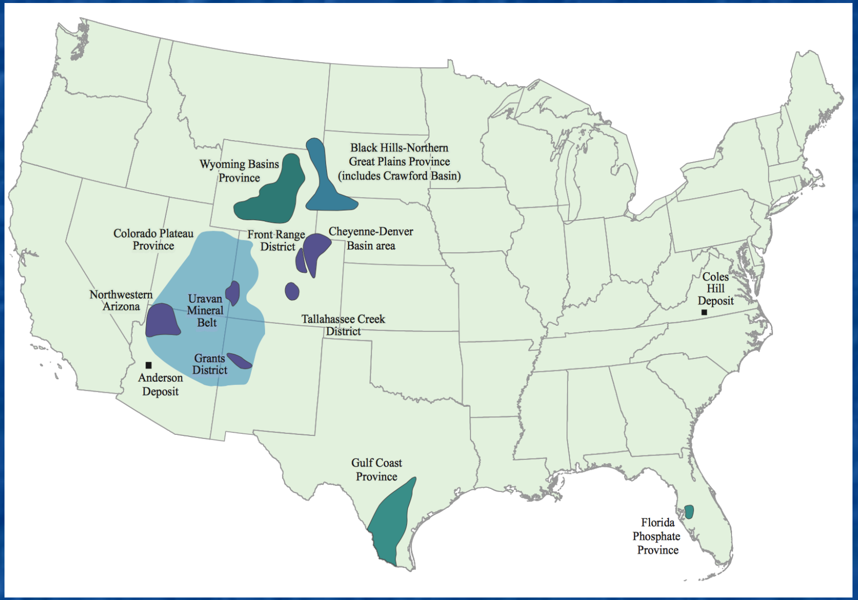
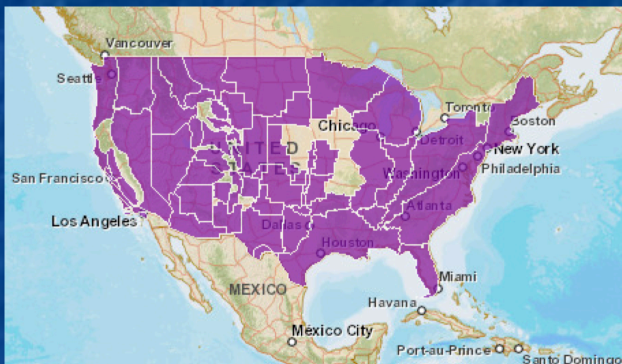
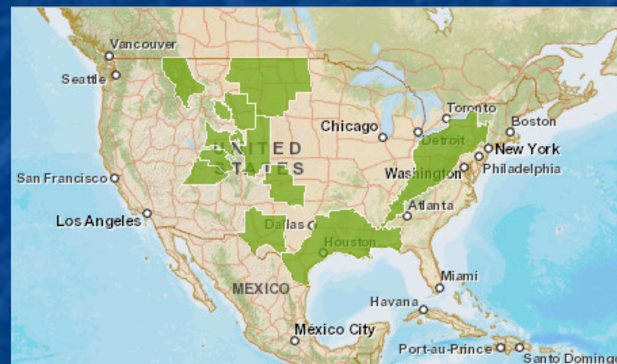


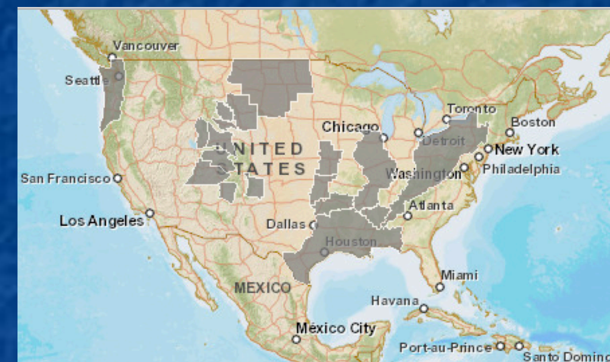
Fig. 1-23 in:
Critical Analysis of World Uranium Sources – USGS (2012)
http://pubs.usgs.gov/sir/2012/5239/

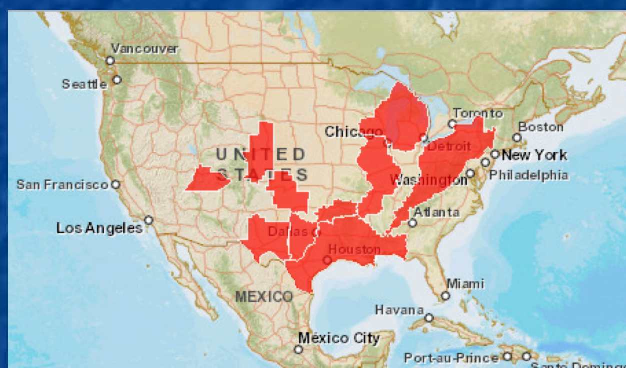
Oil and Natural Gases:

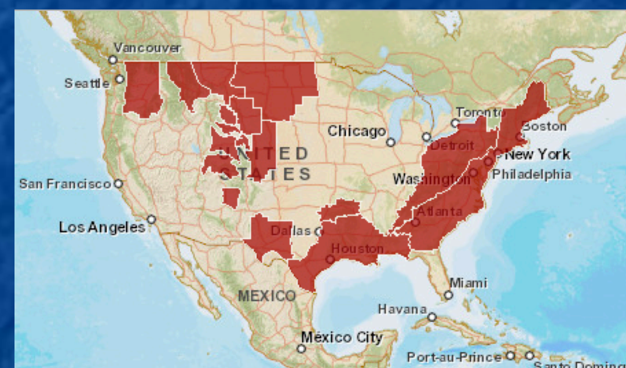
From a United States Geological Survey (USGS) interactive map:







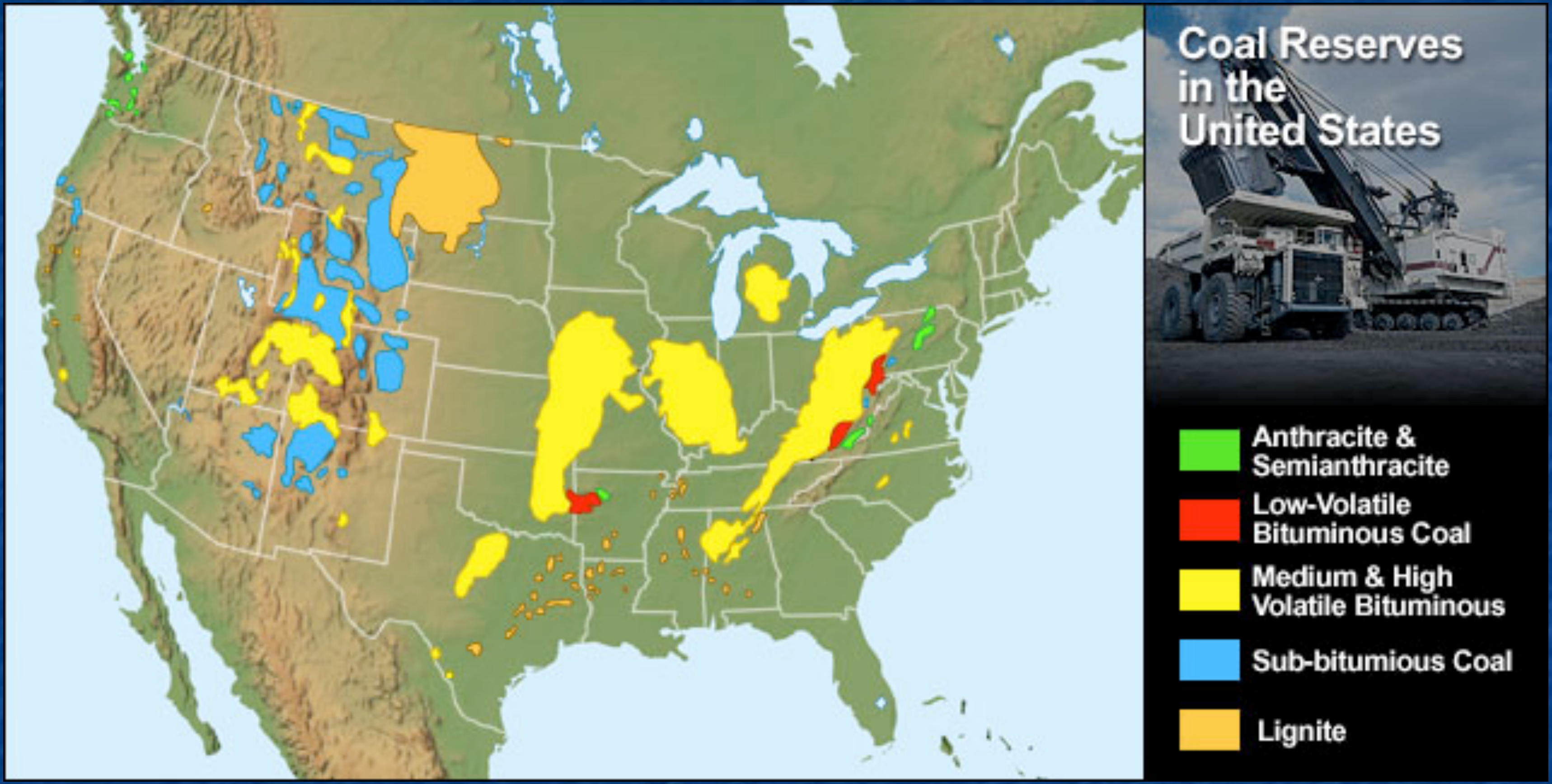




- ○ Conventional (Oil & Gas)
- ○ Continuous Oil
- ○ Coalbed Gas
- ○ Shale Gas
- ◉ Tight Gas

http://certmapper.cr.usgs.gov/data/website2011_iframes/statusmapdnn.html?state=

Coal:



http://www.earthlyissues.com/coal.htm

Copper:

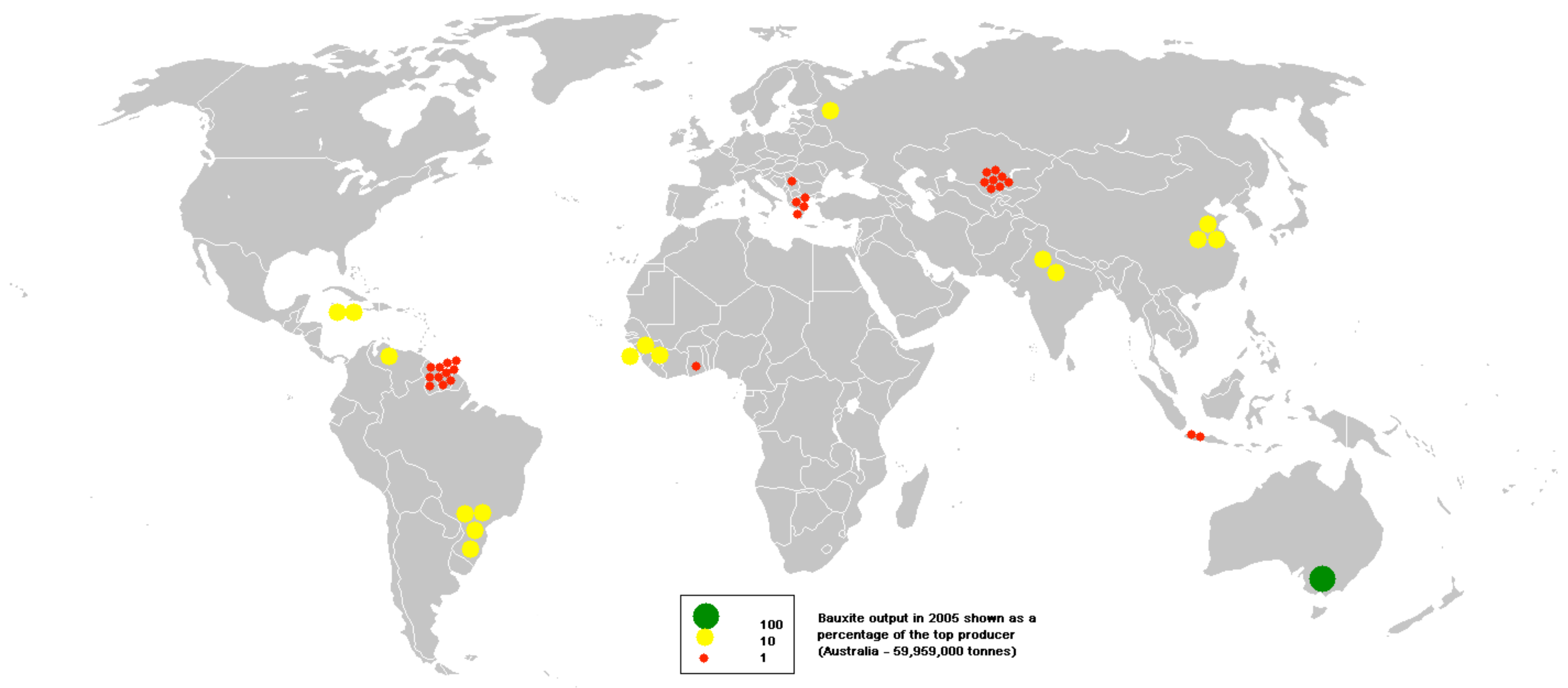
Location of major U.S. copper mines:

https://en.wikipedia.org/wiki/Copper_mining_in_the_United_States

Aluminum:

As embedded in **bauxite** ore, which consists of:

"the minerals gibbsite $Al(OH)_3$, boehmite y-AlO(OH) and diaspore α-AlO(OH), mixed with two iron oxides goethite and haematite, the clay kaolinite and small amounts of anatase TiO_2"



Quotation and figure from: https://en.wikipedia.org/wiki/Bauxite

Power plants use many **other** *materials*

For instance, they certainly use a lot of **iron**

And plants like hydro & nuclear use a lot of **concrete**

But they account for only a small part of our TOTAL iron & concrete consumption

Even if we converted to 100% hydroelectric (as I'll prove in a later lecture)!

So while energy **contributes** to iron, concrete, and other raw materials use

Energy choices will not strongly affect their overall consumption

And because my goal here is to assess the impact of **energy choices**

I believe it's fair to limit ourselves to the raw materials listed earlier

Thus having addressed: Natural abundance? & Location?

Let's move on to: How are they extracted from these locations?

If we want to minimize extraction cost AND environmental upheaval:

Our **first choice** would be for raw materials to occur right on the earth's surface!

Where we could just cut them down or scoop them up

Disturbing nothing else / Liberating nothing else

Do some of our energy raw materials occur right on the earth's surface, Yes:

Biofuels and Biomass:

Farms and forests

Lithium:

Altacama Chile salt flats

Silicon:

White sand (= quartz = SiO_2)

Left: http://auslaogroup.com/biomass/auslao-biomass/
Center: http://en.wikipedia.org/wiki/Salar_de_Atacama
Right: http://boraboraphotos.com/beautiful-white-sand-beach-in-bora-bora/

Second choice for raw material location (and form)?

Highly concentrated liquid or gas pockets

Minimizing both extraction cost and environmental disruption because:

Extraction requires only a limited number of small-footprint wells

With which we, and nature, can co-exist pretty well

At least in the short term . . . At least if no one screws up

Left: https://www.hcn.org/blogs/goat/los-angeles-city-council-votes-for-a-fracking-moratorium-and-hopes-california-follows-suit
Right: http://www.annarbor.com/news/saline/crude-oil-drilling-in-saline-township-paxton-resources/

That is the classic oil / petroleum scenario

But these fossil fuels **start as thin layers** of surface organic material

Which are buried by sediments

Which produces elevated pressure + heat => transformation

Sometimes (but not always) producing liquids and gases

If they REMAIN in thin layers, there's very little of them per land-area

And we'd need a **huge number of wells** to gather significant quantities

http://archive.fortune.com/galleries/2007/fortune/0704/gallery.f500_photos.fortune/4.html

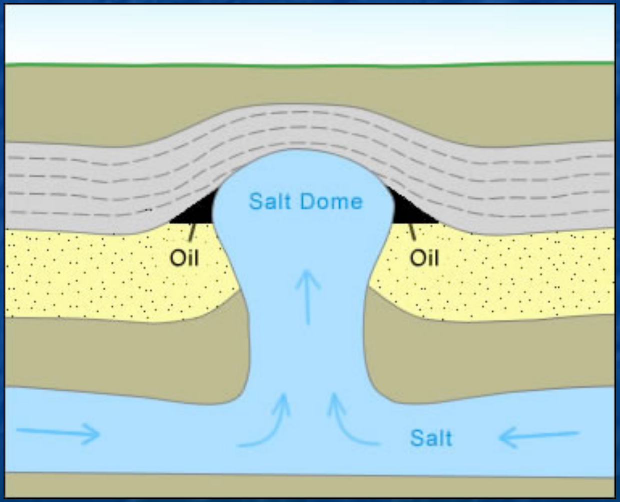
So we want **liquid/gas pockets**, *requiring two more things:*

1) **Porous layers in the crust** through which liquids and gases can move

2) **Geological transformation** of these originally flat layers into bulges

=> Lower density hydrocarbons then accumulate near tops of bulges

Classic location/mechanism = **Salt Domes** associated with oil reservoirs:



http://geology.com/stories/13/salt-domes/

Salt & Oil start as thin flat sedimentary layers

Sediments above try to compact both

But crystal structure of salt resists compaction

Leaving it less dense than surroundings

Causing it to eventually float/bulge upward

With less dense oil also "floating along"

Third choice: Big, rich, concentrated, **solid pockets**

Which could then be dug out creating only a few **really big holes**

Which, individually, are not very nice

But we need only a **small number** of them

(Sometimes: One or less per nation)

And while their local environmental disruption can be massive

It is localized, and thus easier to mitigate

(at least in principle . . . if governments require it)

Driven by radioactivity, convective plumes, and plate tectonics,

Nature **does** provide us with variation in crustal minerals

And, every once in awhile, produces the desired concentrated local solid pockets

Which we seek out, and then dig out, in **Quarries & Open Pit Mines**

From a listing of the worlds biggest open pit mines: [1]

Bingham Canyon, Utah (Copper Ore)

Chuquicamata, Chile (Copper Ore)

Escondida, Chile (Copper Ore)

Udachny, Russia (Diamonds)

Grasburg, Indonesia (Copper & Silver Ore)

Size of those dump trucks:

These (NOT Egyptian Pyramids!) are biggest man-made structures seen from space

1) www.mining-technology.com/features/feature-top-ten-deepest-open-pit-mines-world/

Shocked? Think we need to revert to pre 20/21st century technology?

Think again: Huge quarries are not just 20/21st century technology

On a warm June day I saw what appeared to be strangely snow-covered mountains:

They were actually the Carrera marble quarries started by the Romans

And what about Rome's civilization-supporting roads and aqueducts?

Where do you think they **got** all of that stone?

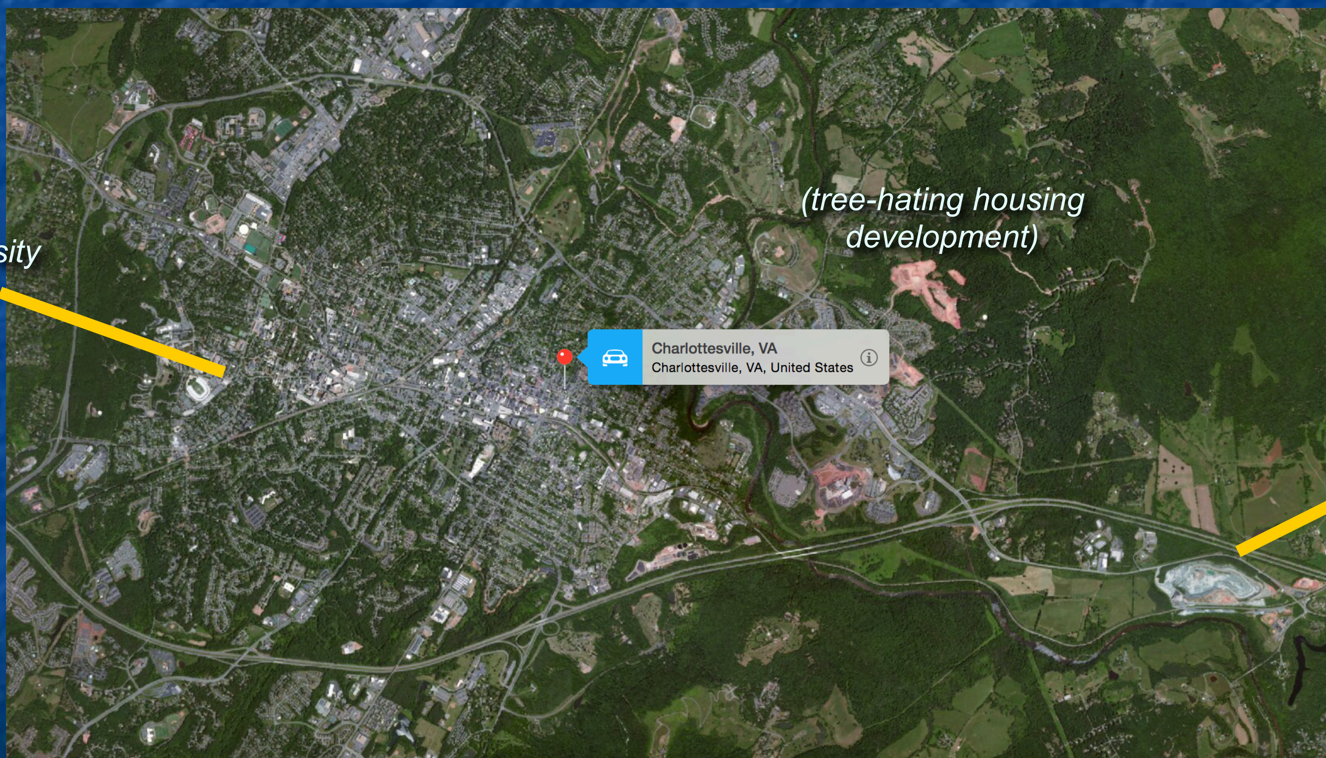
John C. Bean vacation photographs

Civilizations, ancient and modern, ***depend*** *upon quarries*

Even if we may not always be aware of them

For instance, see this Apple Maps satellite picture of my town of Charlottesville:

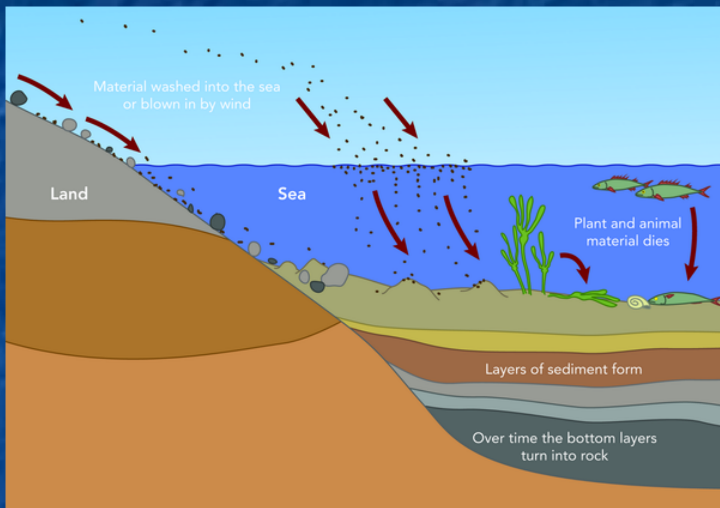
University

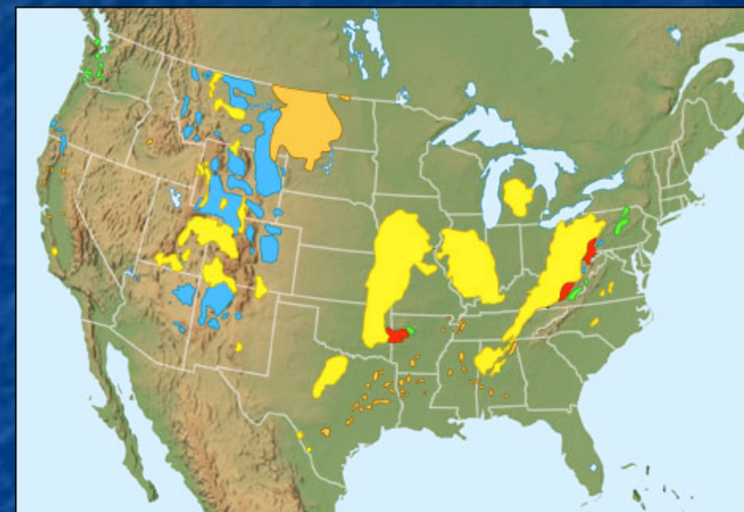


NEAREST QUARRY

Fourth & worst choice: Widely dispersed raw materials

Likely from mostly undisturbed and un-redistributed **sedimentary layers** (left)





Extending for **1000's of square miles,** as in U.S. coal deposits (right)

But with layers **only a few meters thick** (and often 100's of meters down)

So to get enough, we must (hugely) disturb 1000's of square miles!

The best alternatives (for this worst alternative)?

Environmental damage is lessened if layers are deeper and must be mined

Because, assuming **mines** (and mine tailings) are not too extensive,

Ecosystem (largely at surface) will be less affected

But based on economics alone, you'd probably want layers **near** the surface

Making them accessible via **strip-mining** or **mountaintop-removal**

Contemporary West Virginia examples of coal removal via:

Classic Mining

http://www.coalcampusa.com/sowv/logan/stirrat/stirrat.htm

Strip-Mining

http://vault.sierraclub.org/sierra/201209/mountaintop-removal-coal-mining-west-virginia-251.aspx

Mountaintop-Removal

http://www.sourcewatch.org/index.php/Mountaintop_removal

Exact differences between these three alternatives?

Raw material (in this case coal) is all in one, or a few, thin layers

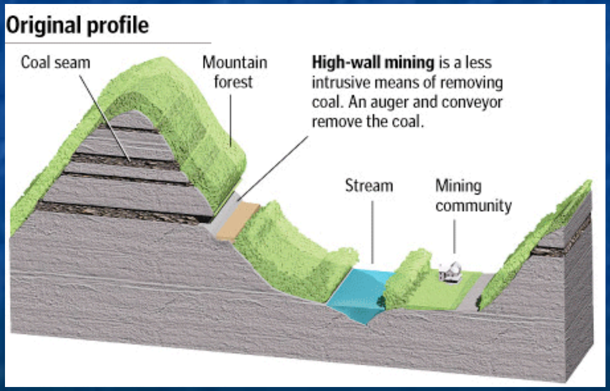
Covered by 10's or 100's of meters of other layers = "**overburden**"

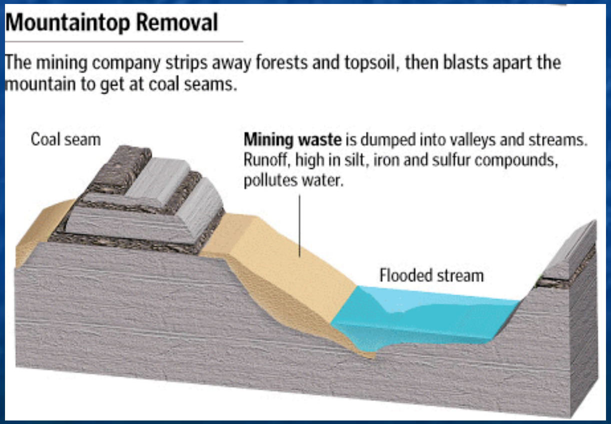
Classic mining: Overburden is left in place (as mines burrow beneath it)

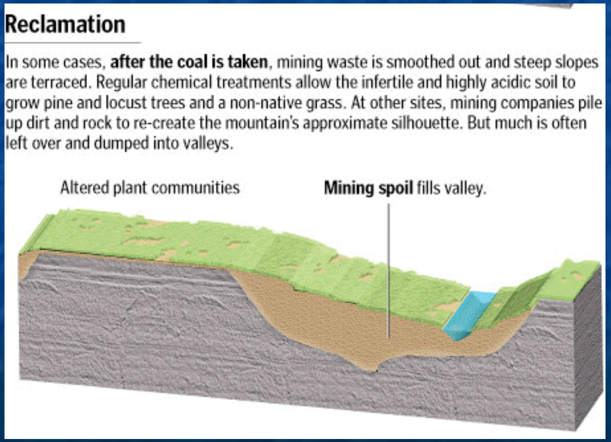
Strip-mining: Thinner overburden is instead pushed aside – into piles

Mountaintop-removal: Overburden **covering whole mountain tops**

is pushed aside to **fill adjacent valleys**







https://confluence.furman.edu:8443/display/GGY230F10/Surface+Mining2

Mountaintop removal can devastate entire landscapes because:

1) Final, full reclamation step may never occur

Due to bankruptcies AND long history of federally granted "variances" [1]

2) If reclamation does occur, use of artificial organic-poor soil is allowed

=> Diminished fertility => Diminished plant and animal diversity

Persisting on the time scale of centuries [1]

3) Rain flows into now crumbled valley-filling overburden

Leaching out (previously sealed in) heavy metals

Which can then massively pollute out-flowing streams [1]

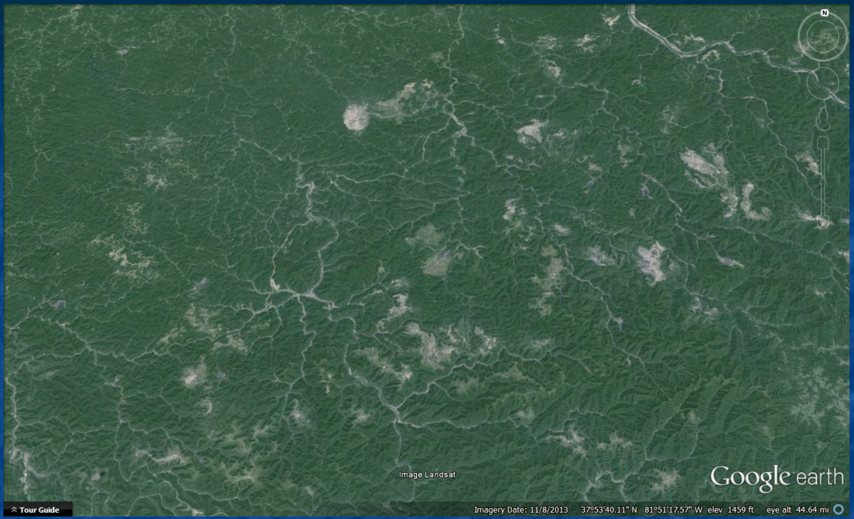
4) Scale and extent of mountaintop removal is huge:

"MTR will mine over 1.4 million acres (5700 square kilometers) by 2010, an amount of land area that exceeds that of the state of Delaware." [1]

1) https://en.wikipedia.org/wiki/Mountaintop_removal_mining and references therein cited

Satellite views of West Virginia:

1) http://gulahiyi.blogspot.com/2008_12_01_archive.html



2) http://appvoices.org/2014/08/15/its-still-happening/

3) http://wvhighlands.org/wv_voice/?category_name=mining-matters&paged=31

4) http://designandviolence.moma.org/mountaintop-removal-various-designers/

"Five hundred mountains and counting . . . " [2]

Similar: Tar sands (a.k.a. oil sands)

"A combination of clay, sand, water, and **bitumen**, a heavy black viscous oil" [1]

They are so viscous that they do not flow well enough to be sucked up by wells

So they've been strip mined. And once on the surface, super-heated:

By steam, from water (via burning of other oil & gas)

Until viscosity decreases to point that oil and sand can be separated [2]

But more recently: Steam + solvents have just been **injected into** the ground [3]

And hot, lower viscosity, oil/tar pumped out =>

Less land disruption / But more energy expended (plus, fate of solvents?)

Steam injection has ALSO long been used for overly viscous classic oil deposits

As for "Heavy California Oil" [4] (which shows up later in this note set)

1) http://ostseis.anl.gov/guide/tarsands/ *2) https://en.wikipedia.org/wiki/Oil_sands*

3) The Opposite of Mining – Tar Sand Steam Extraction, Scientific American, January 2013

4) The True Cost of Fossil Fuels, Scientific American, April 2013

And this brings us naturally to **hydraulic fracturing**

Known unpopularly as **FRACKING**

Natural gas is also produced by fossilization of organic sediments

Meaning that it is also formed in broad but thin (and thus dilute) layers

If adjacent rock layers are porous and/or fractured

Gas can migrate and accumulate => Extraction via wells (see above)

But if surrounding layers are solid, gas remains in myriad tiny separated pockets

But we can fracture that solid surrounding solid material

By pumping in fluids at **extremely high pressure**

Which shatters those surrounding rock layers

Complete process:

WATER is injected at extremely high pressure to crack surrounding stone

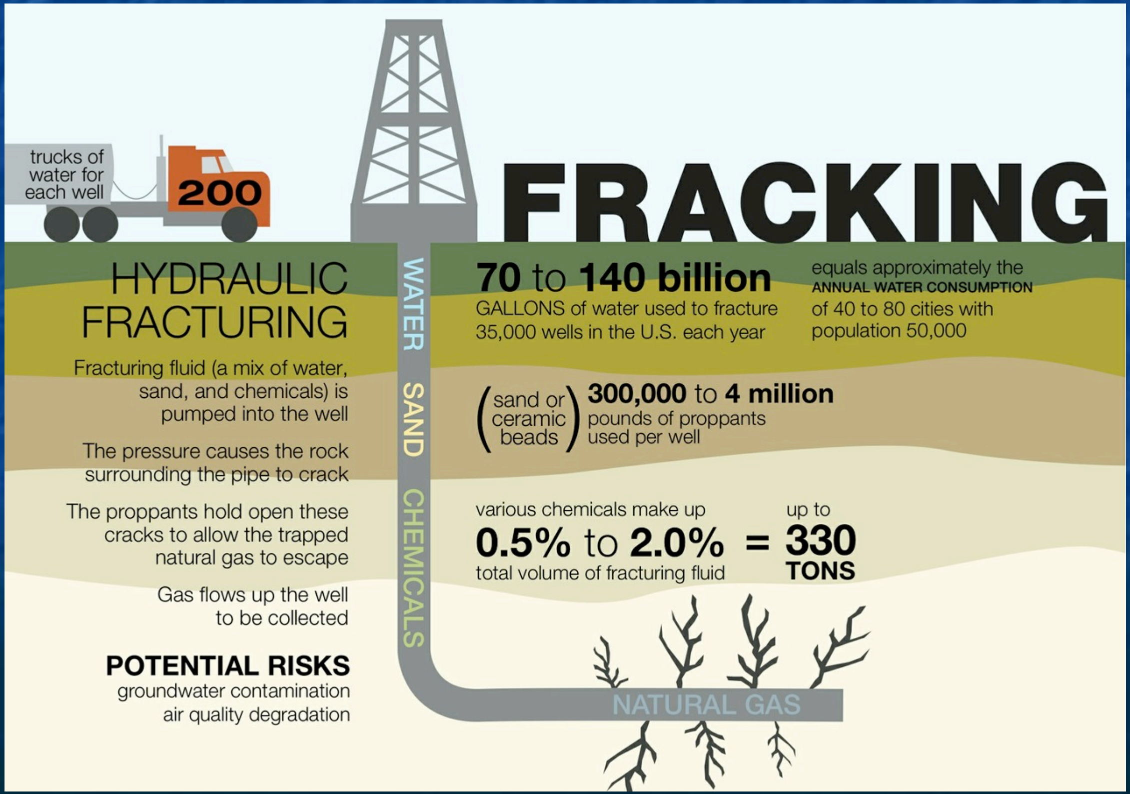
Sand / grit is added to hold cracks open after water pressure is released

Plus other additives, including possibly:

Acids to etch and roughen crack surfaces => Preventing their tight re-closure

Solvents / detergents to dissolve oilier materials

https://socinnovation.wordpress.com/2014/07/05/sia-fracking/



Objections to fracking?

1) **Water:** Previous figure claims 70-140 billions of gallons per year for the U.S.

But water is still abundant in some places

And it need not be pure: Even brackish (mildly salty) water would suffice

2) **Earthquakes:** Fractured rock layers can shift more easily

Triggering release of tectonic stresses (which are the real **cause**)

3) **Cracks:** Which allow not only gas to move, but anything else down there

Including, possibly, **toxic heavy metals dissolving in water**

4) **Chemical Additives:** Which can include a **witch's brew** of possibilities

Now chosen SECRETLY in petroleum company back rooms

Even on U.S. lands, government is <u>only beginning</u> to require disclosure

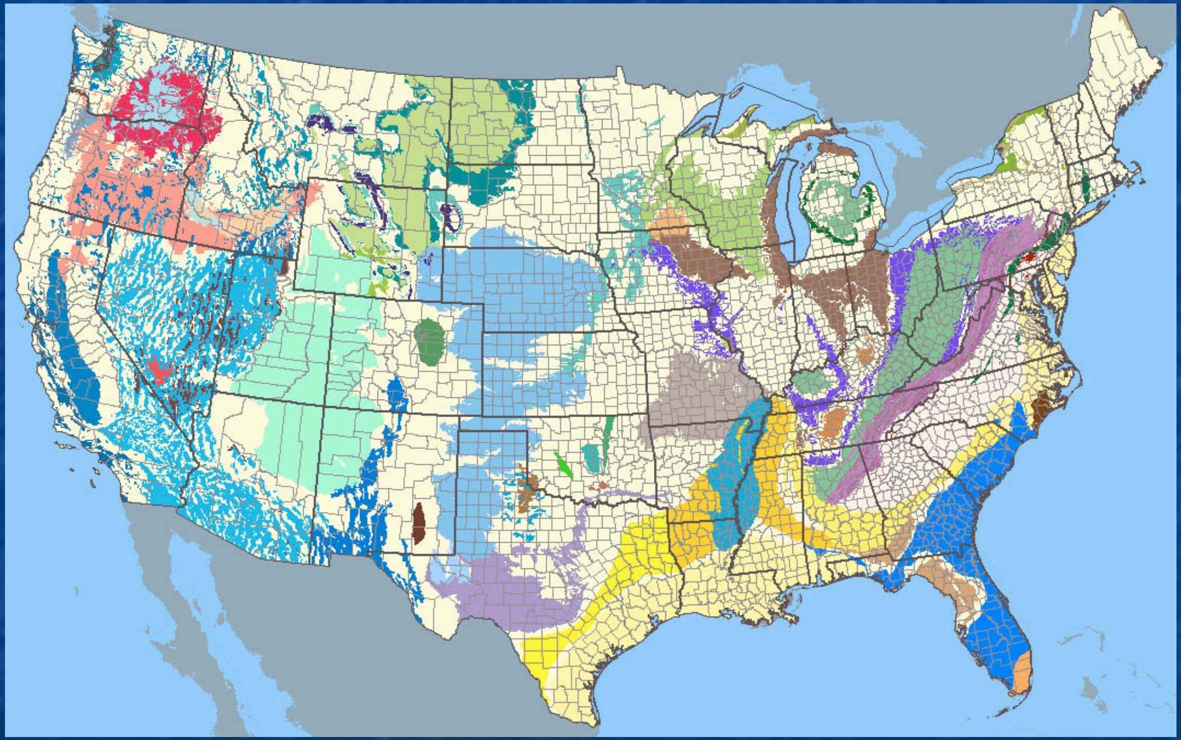
And is <u>still</u> giving companies a free hand on what they decide to add!

And now we bring in aquifers:

Which are huge broad swaths of buried, naturally fractured or porous rock layers

Into which, over many thousands of years, water has percolated

= Vast "underground lakes" **supplying our drinking & farm water wells**

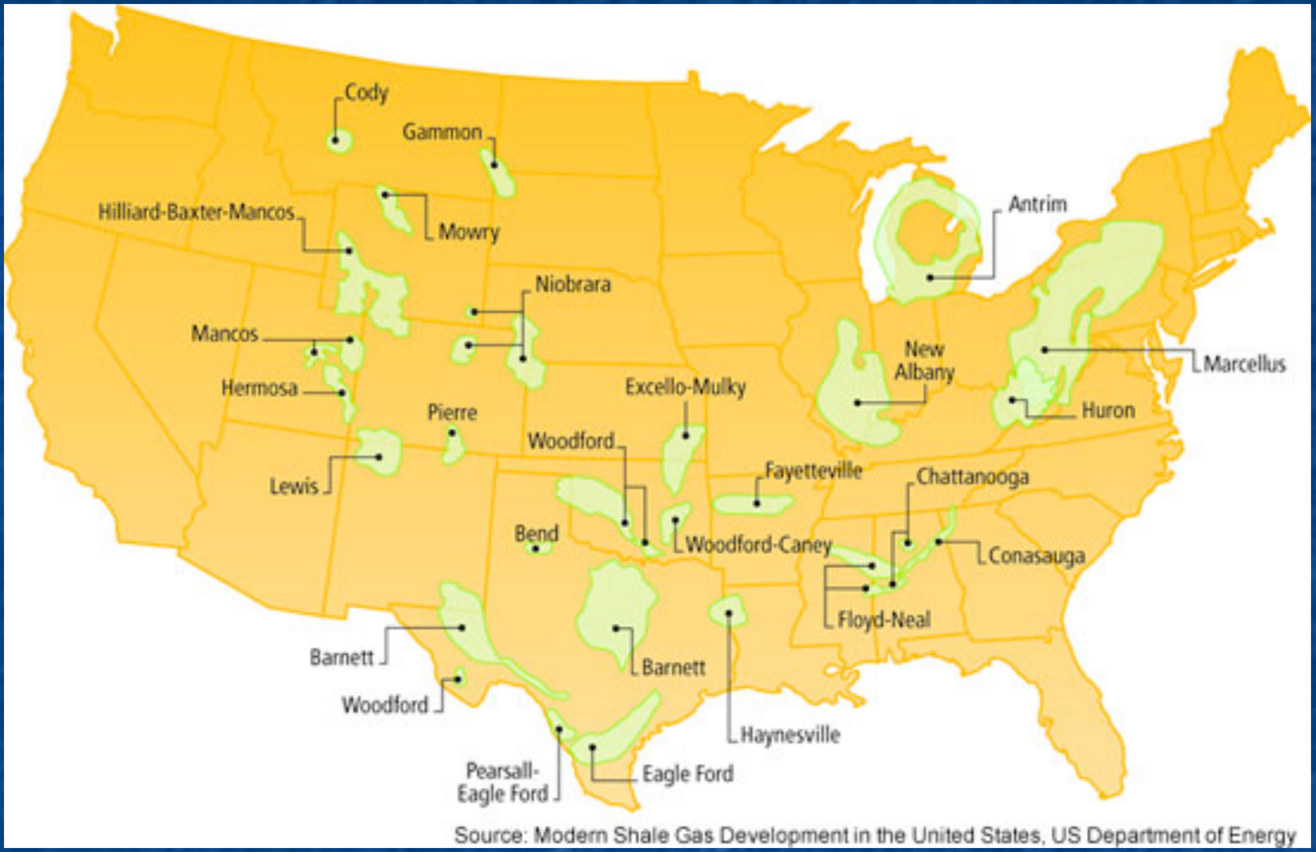


If fracked region connects, its chemicals could be dispersed into aquifer

http://modernsurvivalblog.com/retreat-living/united-states-aquifer-locations/

The potential for large-scale groundwater pollution?

Current U.S. fracking sites:



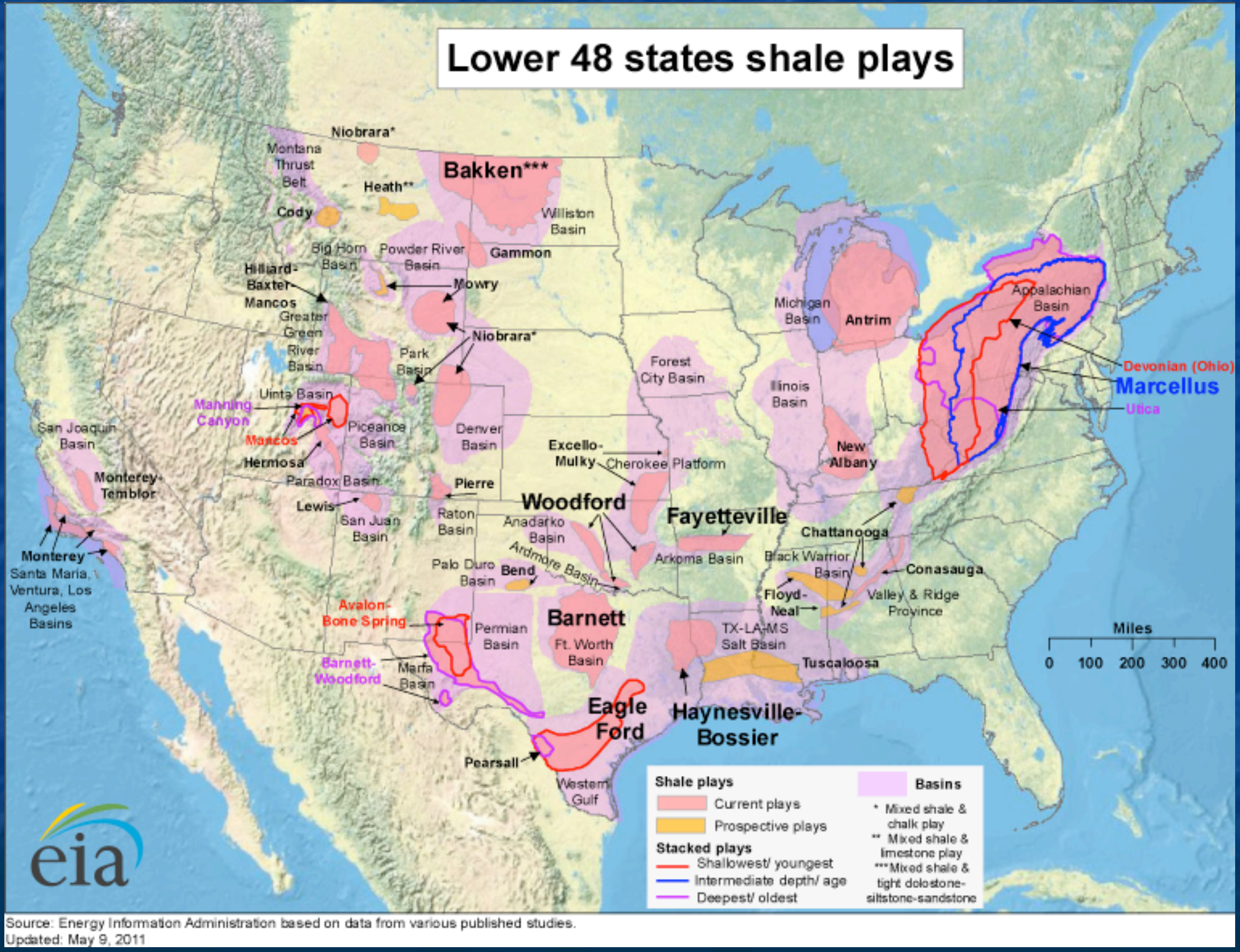
With groundwater pollution already identified in Montana and Pennsylvania

(and strongly suspected elsewhere)

https://fracfocus.org/hydraulic-fracturing-how-it-works/hydraulic-fracturing-process

Would-be fracking sites:

EIA map of shale gas occurrence:



http://www.eia.gov/analysis/studies/usshalegas/

Things that strike me about the fracking controversy:

We (the U.S. public) are at least a bit complicit:

Torrent of fracked natural gas is what has driven down our energy prices

And has given us our much beloved sub $3 per gallon gasoline

To get this we effectively "**sold our souls**" by allowing:

The petroleum industry, with their long record of environmental pollution,

To **secretly** choose which chemicals are injected into our ground

And it's now "**progress**" if they just tell us what they're injecting?

And the full witch's brew of chemicals may not even be necessary:

I've read interviews with reputable energy industry sources

Who say that with **water + sand/grit alone**, fracking would still work

Not quite as well, not extracting quite as much gas

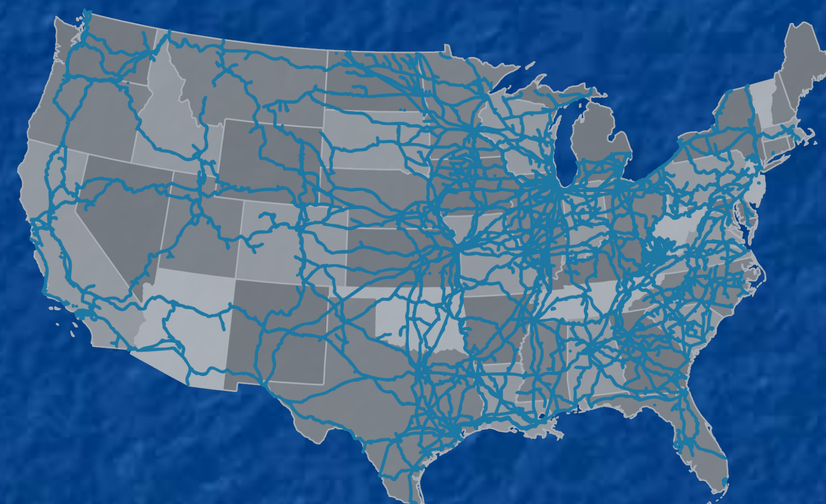
But still hugely productive and economically viable

On to **raw material transportation**

Where one thinks of:

Our highways

And our freight railways



But highways are increasingly congested (as indicated by thickened lines at left)

Besides, who wants to drive next to a fully-loaded gasoline tanker?

However, lately, our freight railways have gone seriously off track:

p. 36:
Freight Facts and Figures 2013, Federal Highway Administration, US Department of Transportation
http://ops.fhwa.dot.gov/Freight/freight_analysis/nat_freight_stats/docs/13factsfigures/pdfs/fff2013.pdf

http://archive.freightrailworks.org/network/class-i/

Lac-Megantic Canada (near the Maine border), 6 July 2013:

Crude oil tank cars derailed in the town center =>

1 km diameter fireball

47 people burned to death

30 buildings destroyed

http://globalnews.ca/news/2094045/two-years-later-rebuilding-after-the-lac-megantic-train-derailment/

http://www.theglobeandmail.com/news/national/lac-megantic-derailment-anatomy-of-a-disaster/article20129764/

Railways argue that solution is just newer tougher tank cars:

The tank cars involved were U.S. DOT-111 / Canadian CTC-111A

Which is the older, unpressurized, unreinforced "classic" tank car

Accounting for 80% of Canadian cars / 69% of U.S. cars [1]

Effective 1 October 2011, U.S. DOT **had** revised design standards

Requiring thicker steel as well as increased shielding for filling valve head

But new standard applied only to newly constructed cars

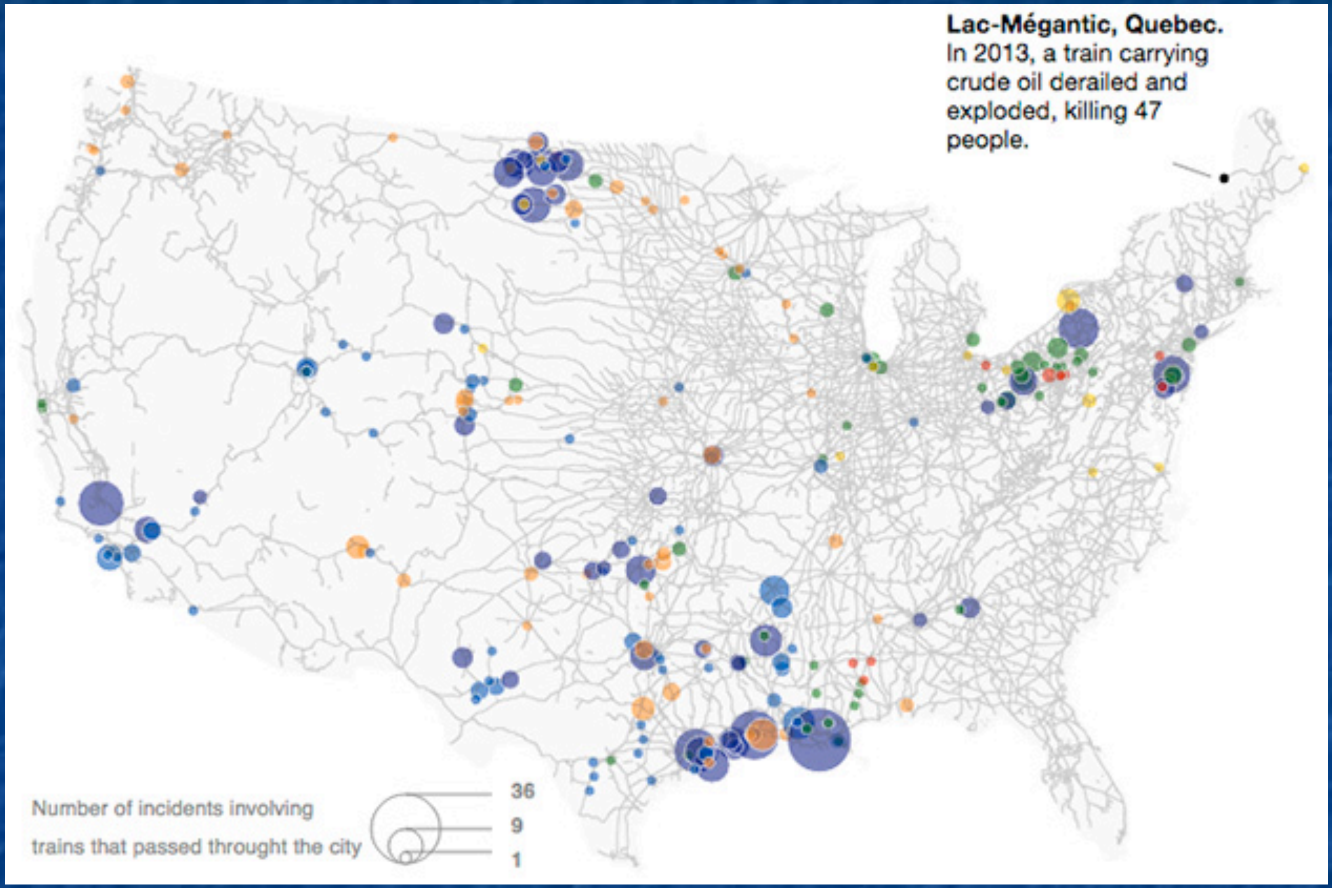
And there was no requirement to retrofit existing cars

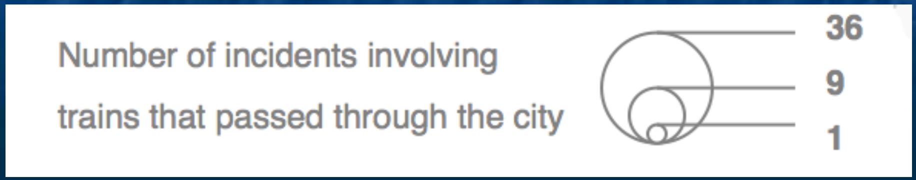
And no mandatory schedule for retiring older cars

1) https://en.wikipedia.org/wiki/DOT-111_tank_car

And rather than decreasing, derailment fires have become epidemic

Interactive map on recent railway accidents (along with enlarged keys to map): [1]





1) http://www.propublica.org/article/govt-data-sharpens-focus-on-crude-oil-train-routes

I caught a data-laden June 2015 CBS News story about this trend

Hoping for a neutral source, I Googled "CBS News tank car derailment and fire"

Giving me accident overload:

After further narrowing my search, I found:

"Newer '**safer**' tank cars were involved in Lynchburg VA oil train fire" [1]

"**Safer** tank cars on CSX train didn't prevent blast" [2]

"BNSF: Oil train derailment near Galena involved **safer** tank cars" [3]

"Oil train accidents prompt review of tank car safety" [4]

Culminating with this April 6, 2015 announcement:

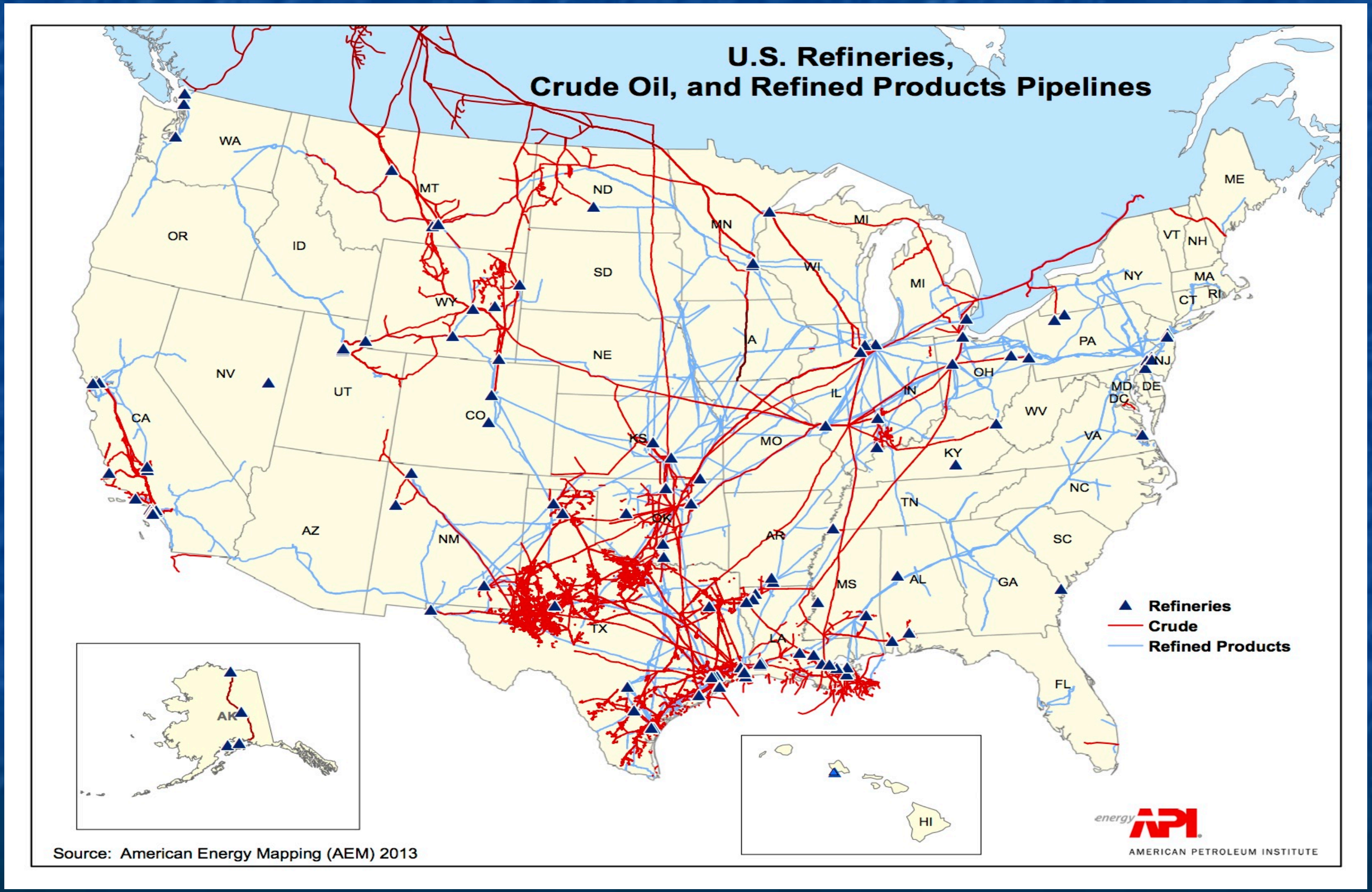
"NTSB Issues Urgent Recommendations Calling for Improved Rail Cars to Carry Flammable Liquids" [5]

1) *http://daily.sightline.org/2014/05/01/new-safer-tank-cars-were-involved-in-the-lynchburg-oil-train-fire/*
2) *http://www.lohud.com/story/news/transit/2015/02/17/oil-train-accident/23561871/*
3) *http://www.chicagotribune.com/news/local/breaking/chi-galena-train-derailment-20150305-story.html*
4) *http://www.startribune.com/jan-8-oil-train-accidents-prompt-review-of-tank-car-safety/239194271/*
5) *http://www.ntsb.gov/news/press-releases/Pages/pr20150406b.aspx*

But economics (and possibly safety) long ago stimulated an alternative

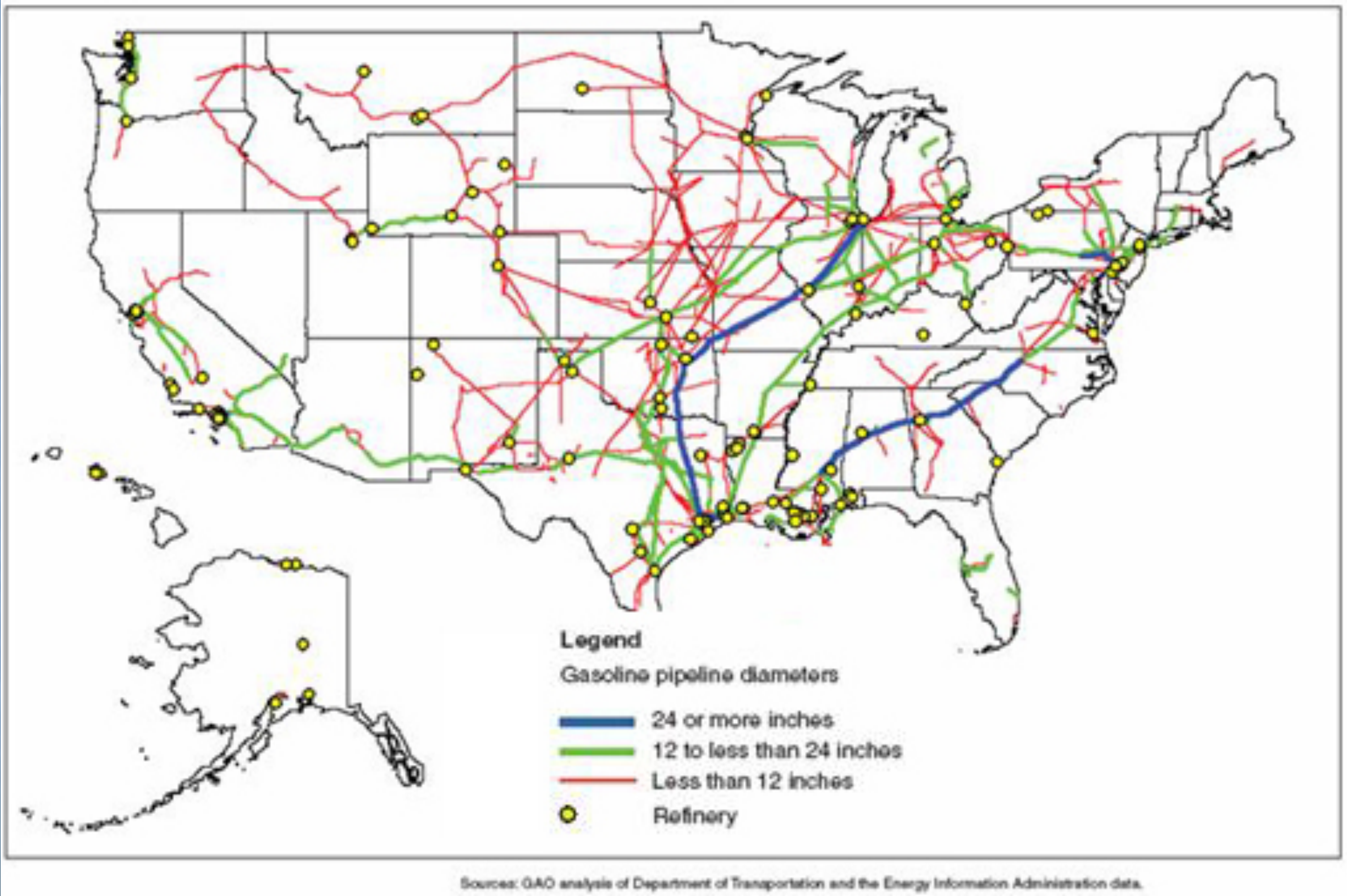
Of which you are probably not fully aware

Continent-spanning **oil pipelines**



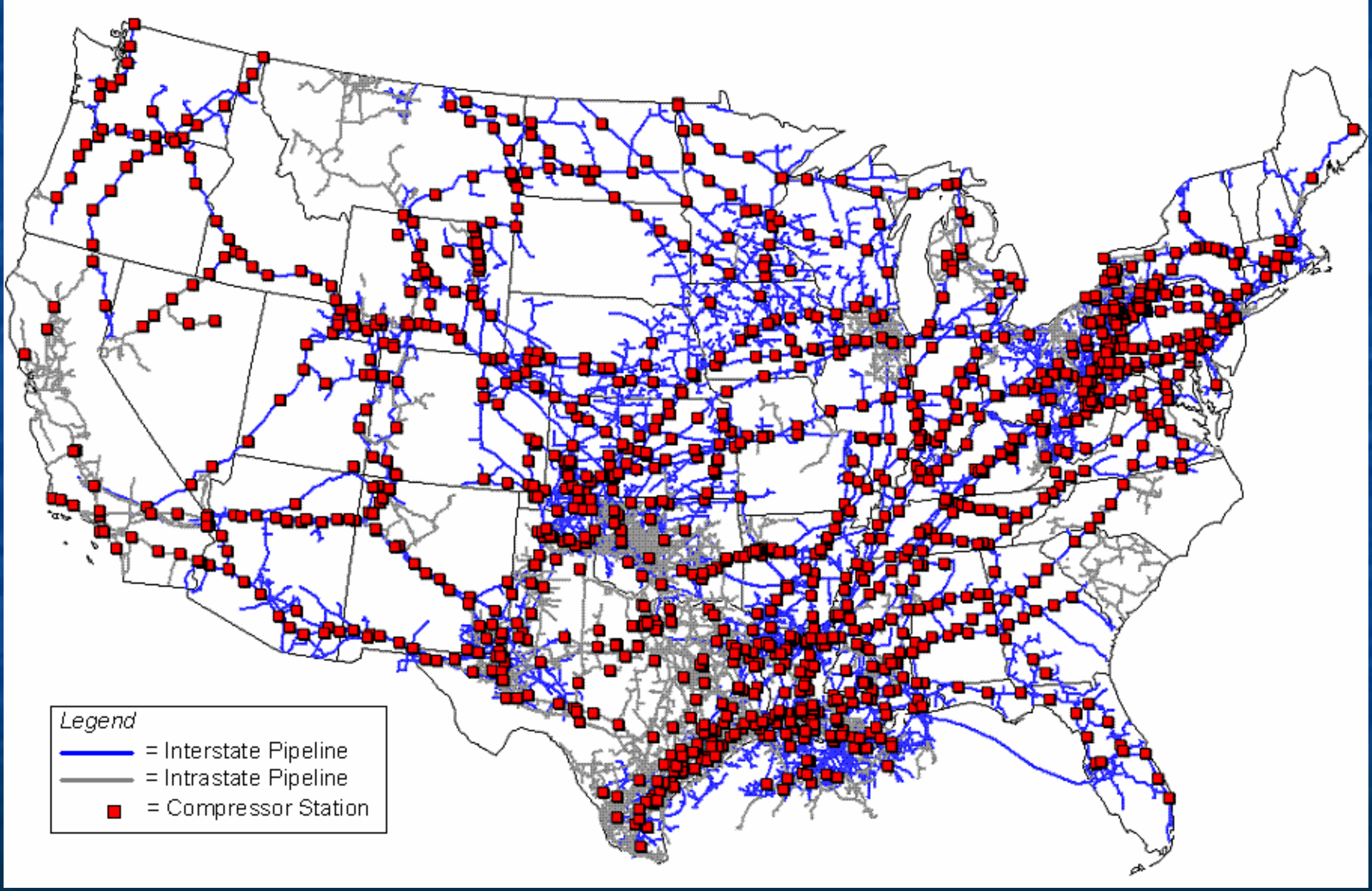
http://www.api.org/oil-and-natural-gas-overview/transporting-oil-and-natural-gas/pipeline/where-are-the-oil-pipelines

And **gasoline** *pipelines:*



https://www.azag.gov/consumer/gasoline

And **natural gas** *Pipelines:*



http://www.eia.gov/pub/oil_gas/natural_gas/analysis_publications/ngpipeline/images/compressorMap.gif

They are not absolutely accident free:

Buried steel pipe does eventually corrode

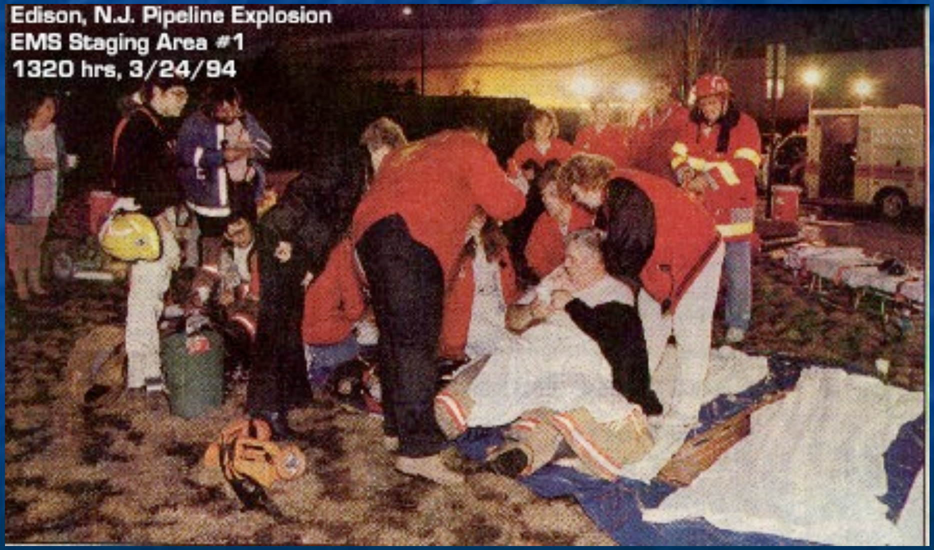
And underground, breaks and leaks may go undetected => Explosions / Fires

Producing, in recent years, these well known gas leaks & explosions:

2010 - San Bruno California
8 dead

http://crazifornia.com/category/the-blog/

1994 - Edison New Jersey:
1 dead (1500 evacuated, 100 homeless)



http://spectrabusters.org/2014/02/21/spectras-durham-woods-apartment-fire-edison-nj-1994/

I looked for safety cross-comparisons of these transportation modes

U.S. Department of Transportation[1] had highway and rail data (only):

"Hazardous Materials Fatalities, Injuries, Accidents & Property Damage" [2]

Their Table 2.6 was way to big[3] to insert here, so I've excerpted just parts of it:

	2000	2002	2004	2006	2008	2010	2012
Hazmat highway fatalities:	16	8	10	6	6	8	12
Hazmat rail fatalities: 0	1	3	0	0	0	0	
Hazmat highway injuries:	164	118	155	192	150	152	144
Hazmat rail injuries:	82	14	122	25	63	38	18
Hazmat highway incidents:	15.0k	15.5k	13k	17.2k	14.8k	12.7k	13.2k
Hazmat rail incidents:1.1k	0.9k	0..8k	0.7k	0.7k	0.7k	0.7k	

Table supports my expectation that rail safety is superior to highway safety

It is also my impression is that pipeline safety is superior to both of those

1) http://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/national_transportation_statistics/index.html
2) http://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/national_transportation_statistics/html/table_02_06.html
3) http://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/national_transportation_statistics/index.html#chapter_2

Bringing us to a final topic: **Energy Investment**

You most frequently hear about this in discussions (arguments) about solar cells

For PV, a key metric is called the cell's **Energy Payback Time (EPBT)**

= Time a solar cell would have to be operated

to **generate** energy equal to the total **energy invested** in it

This is NOT just the energy used to operate that solar cell or solar farm!

Instead, for **every** raw material and component used in that solar cell / solar farm

You must add in ALL of the energy used for:

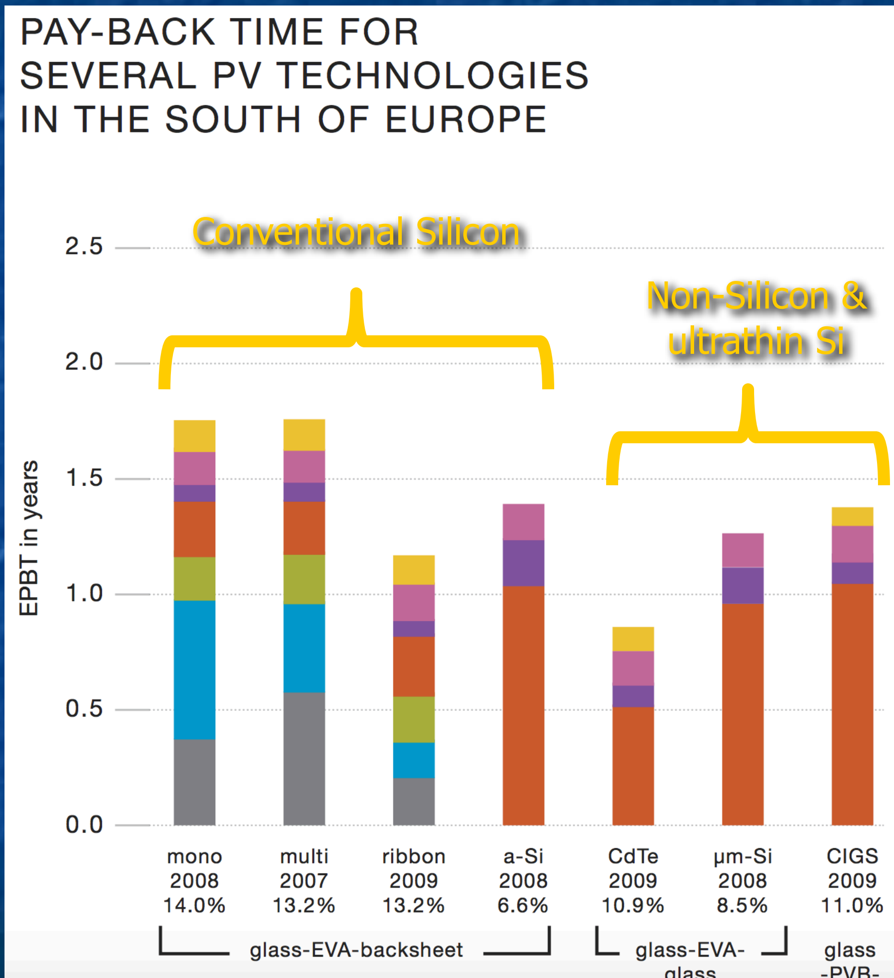
Mining + refining + transportation + manufacture + operation +

decomissioning + disposal + recycling + reclamation

Making this a LIFE CYCLE ASSESSMENT (or LCA)

Data on Energy Payback Time (EPBT) for Solar Cells:

From the European Photovoltaic Energy Association:



Contributing factors & steps:

Si PV **does** have longer EPBT:

1.75 years for mono Si PV

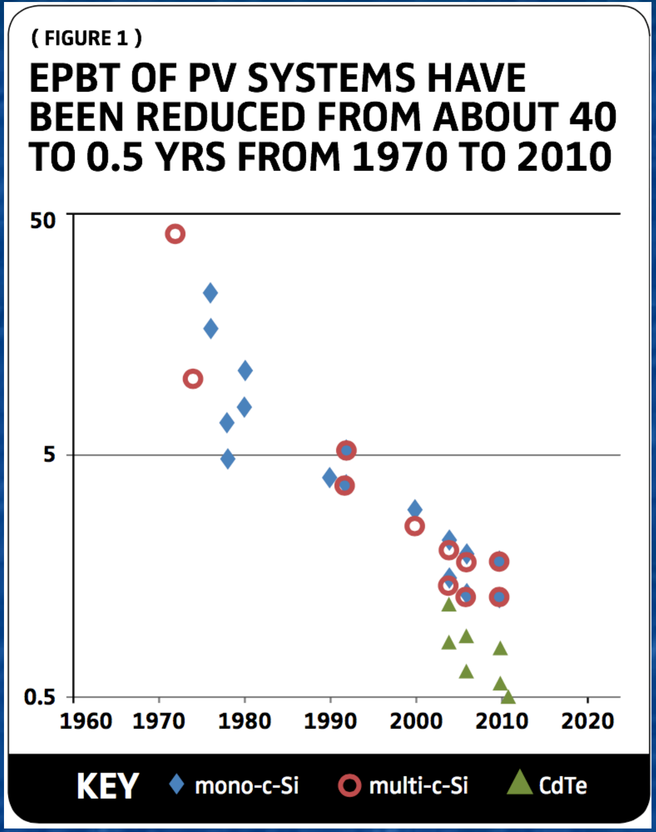
vs.

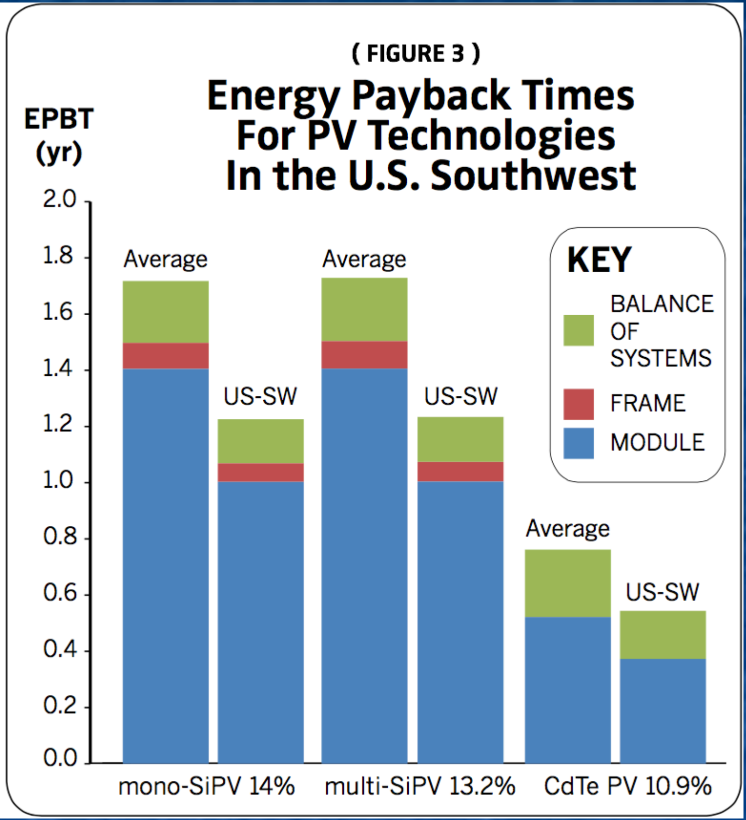
0.8 years for CdTe PV

Source: p. 84, Solar Generation 6 – European Photovoltaic Energy Association
http://www.greenpeace.org/international/Global/international/publications/climate/2011/Final%20SolarGeneration%20VI%20full%20report%20lr.pdf

From a less partisan source:

U.S. National Society of Professional Engineers:





This neutral source agrees well with preceding trade association data!

How Long Does it Take for Photovoltaics To Produce the Energy Used
PE Magazine, Society of Professional Engineers, February 2012
http://www.clca.columbia.edu/236_PE_Magazine_Fthenakis_2_10_12.pdf

But when you think about it, EPBT is a rather dumb metric:

Because, while two types of cell might have the same EPBT (= energy in),

One might **produce** energy for 2X as long (e.g., by using Xtal vs. poly Si)

Instead, what we clearly need (for **EVERY** energy technology!) is the **RATIO** of:

Lifetime Energy Produced / Lifetime Energy Invested

Where BOTH numerator and denominator must include ALL energies

For every single material & component used for/in that technology

from the absolute beginning of the process to the absolute end

This much more broadly applied figure of merit is called :

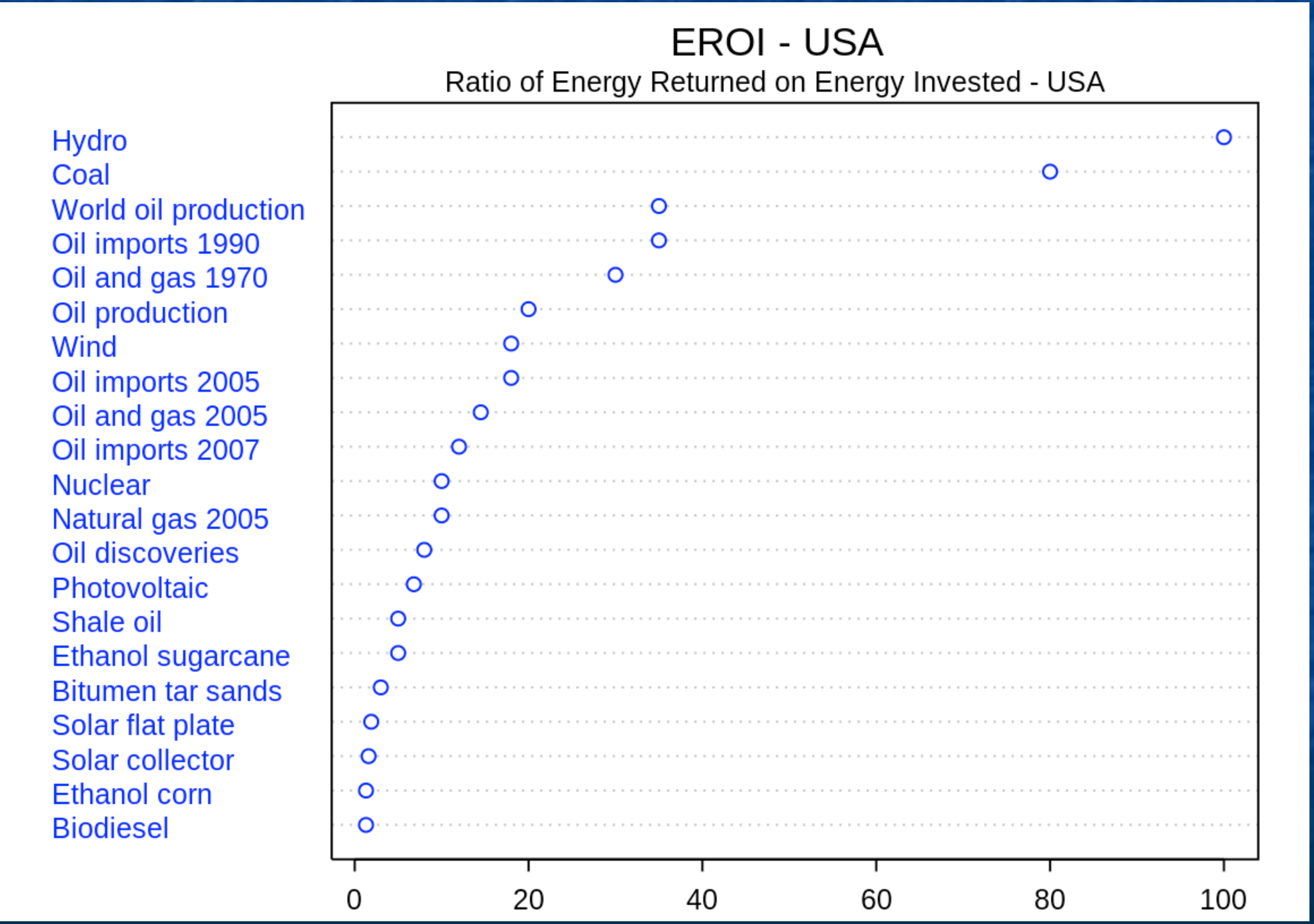
Energy Return on Investment (EROI)

Or, less ambiguously: **Energy Return on Invested Energy (EROIE)**

Energy Return on Investment (EROI) for energy technologies:

Here from the seminal (i.e., pioneering) publication on EROI's :[1]

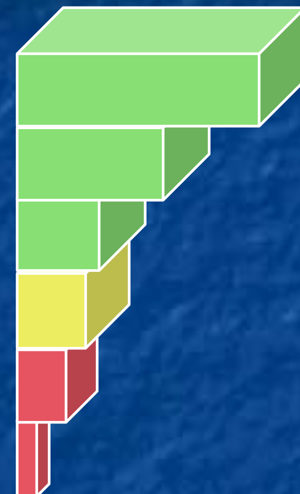
Which, rather surprisingly, did not come out until 2010!

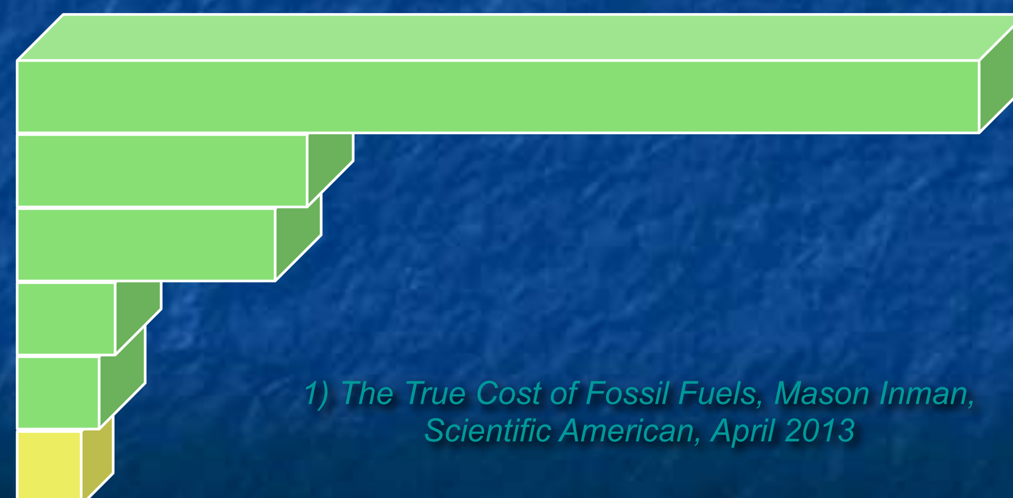


1) D.J. Murphy & C.A.S. Hall, "Year in review EROI or energy return on (energy) invested". Annals of the New York Academy of Sciences ***1185, pp.*** *102–118 (2010)*

Newer EROI data (from multiple original sources): [1]

Technology	EROI
Liquid Fuels:	
Conventional oil	16
Ethanol from sugarcane	9
Biodiesel from soy	5.5
Tar Sands	5
Heavy oil from California	4
Ethanol from corn	1.4
Electricity from:	
Hydroelectric Dams	40+
Wind	20
Coal	18
Natural Gas	7
Solar PV	6
Nuclear	5





1) The True Cost of Fossil Fuels, Mason Inman, Scientific American, April 2013

Color coded to reflect claim that economic viability requires EROI of at least 5

But it's very difficult to evaluate **full lifetime** *energies*

So **many** researchers have worked to further refine such calculations

Particular attention has been paid to calculation of photovoltaic number(s)

Including efficiency change over lifetime of **different** PV technologies

And differences between the lifetimes themselves

2015 "meta-data" analysis of **232 peer-reviewed studies** computed EROI's of:

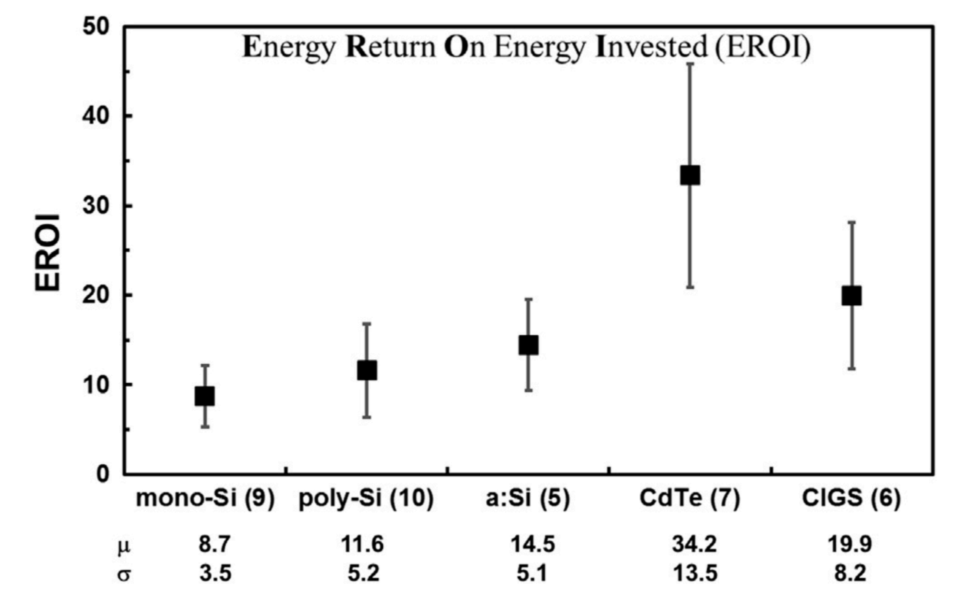


Fig. 7. Mean harmonized EROI with error bars representing one standard deviation. The number of values for each module type is included in parentheses. Mean (μ) and standard deviation (σ) are shown at the bottom of the graph.

Mono-crystalline Si PV = 8.7

Poly-crystalline Si PV = 11.6

Amorphous Si PV = 14.5

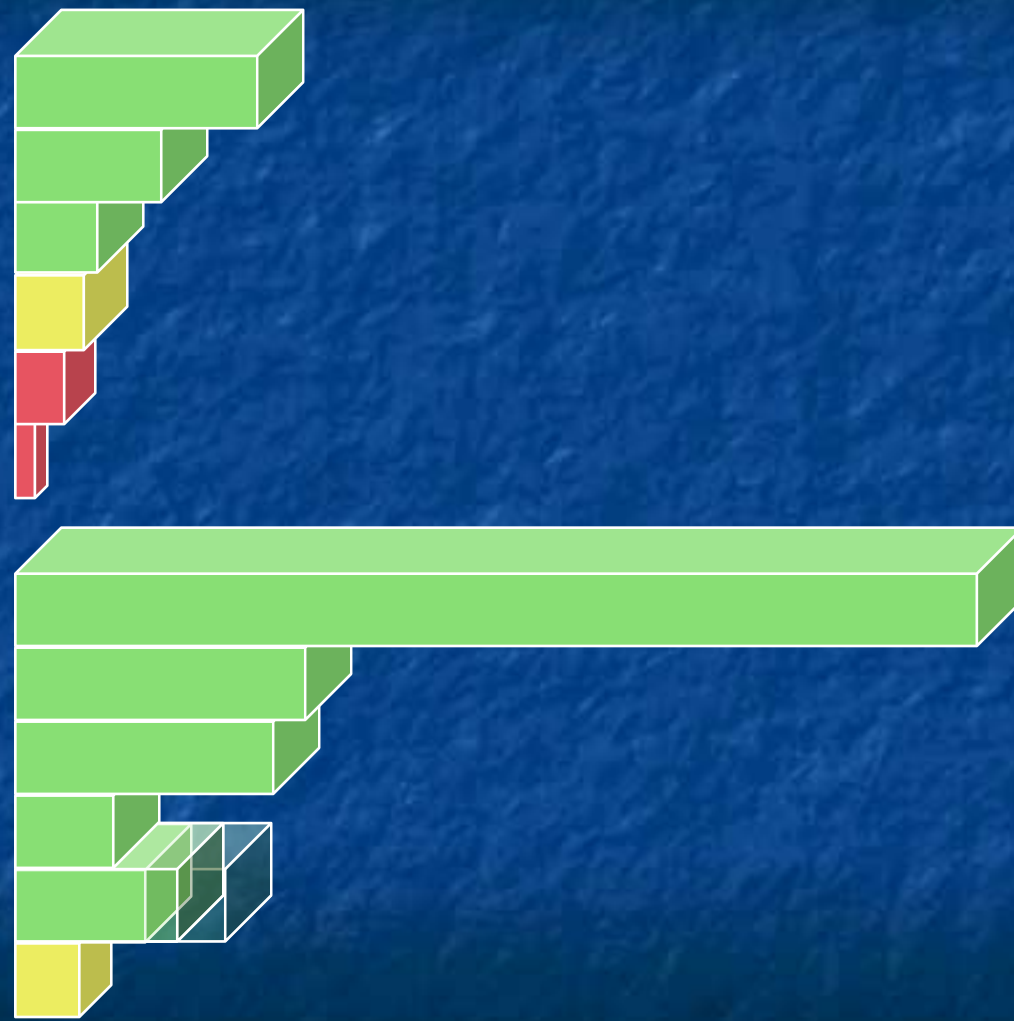
CdTe PV = 34.2

CIGS PV = 19.9

Energy payback time (EPBT) and energy return on investment (EROI) of solar photovoltaic systems: A systematic review and meta-analysis, Khagendra P. Bhandari et al., Renewable and Sustainable Energy Reviews 47, pp. 133-141 (2015)

Adding in more extensive Si PV data (single crystal vs. poly vs. amorphous):

Technology	EROI
Liquid Fuels:	
Conventional oil	16
Ethanol from sugarcane	9
Biodiesel from soy	5.5
Tar Sands	5
Heavy oil from California	4
Ethanol from corn	1.4
Electricity from:	
Hydroelectric Dams	40+
Wind	20
Coal	18
Natural Gas	7
Solar PV using Si	6-15
Nuclear	5



Color coded to reflect claim that economic viability requires EROI of at least 5

Take a moment to truly absorb these very important results:

Noting Scientific American's claim that economically viable EROI must be at least 5 [1]

Champions, in descending order:

Hydro (40+), CdTe PV (34.2), Wind (20), CIGS PV (19.9), Coal (18), Oil (16)

Weaker but still viable:

poly-Si PV (11.6), Sugarcane Ethanol (9), mono-Si PV (8.7), Natural Gas (7)

Marginal:

Soy Biodiesel (5.5), Tar Sands (5), Nuclear (5)

Apparently non-viable:

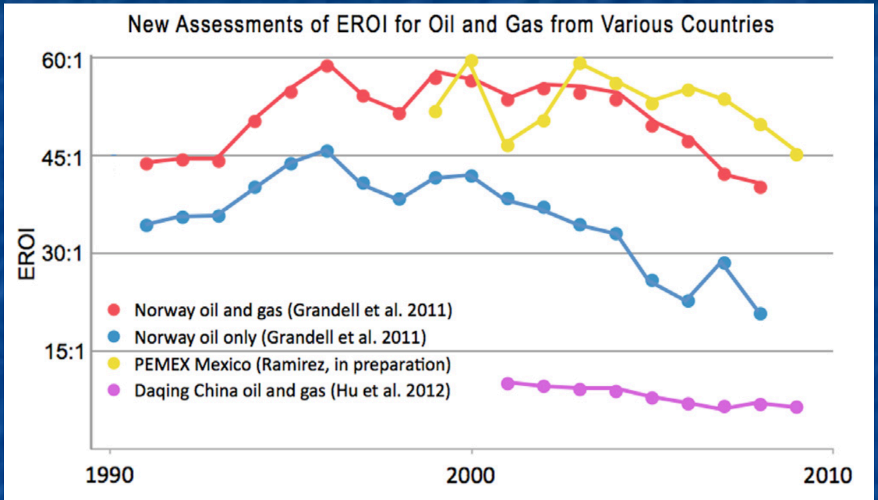
Heavy Calif Oil (4), Corn Ethanol (1.4)

But looking more closely at those orange highlighted fossil fuel cases:

1) The True Cost of Fossil Fuels, Mason Inman, Scientific American, April 2013

EROIs evolve with new raw material reserves & extraction technologies:

With harder-to-extract new reserves, classic fossil fuel EROI's are **falling**: [1, 2]



Steam injection (to liquefy "heavy" viscous oil) causes EROI to plummet

From previous page: EROI drops from 16 to a ~ non-viable value of 4

New non-strip mining extraction of tar sands adds same steam injection technique

It's thus likely that steam-extracted tar sand EROI will be ~ 1 (i.e., 5/4)

(and I've seen data supporting this contention)

1) The True Cost of Fossil Fuels, Mason Inman, Scientific American, April 2013
2) EROI of Different Fuels and Implications for Society, C.A.S. Hall et al., Energy Policy 64, pp. 141-52 (2014)

Conclusions: Notice a recurring pattern?

I opened this note set with some "common wisdoms" about energy technologies

But when I more carefully explored many such contentions, I found:

A germ of reality, but one which was undercut (or even overturned!)

by fuller facts and numbers

The "Gray Void" is FILLED
with such disconnects between sound bites and reality

FACTS are almost always more subtle, nuanced, and less straightforward

Credits / Acknowledgements

Some materials used in this class were developed under a National Science Foundation "Research Initiation Grant in Engineering Education" (RIGEE).

Other materials, including the "Virtual Lab" science education website, were developed under even earlier NSF "Course, Curriculum and Laboratory Improvement" (CCLI) and "Nanoscience Undergraduate Education" (NUE) awards.

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