GEOS 24705 / ENST 24705
Fossil fuels II, solar industry/buildings, wrap-up

Oil and gas: believed to come mostly from phytoplankton

Possibly diatoms: photosynthetic plankton w/ siliceous skeleton and high natural oil production (as in some modern algae)

Oil and gas are hydrocarbons (essentially only Cs and Hs), but fatty acids can become hydrocarbons via single elimination:

$$RCO_2H \text{ -> } RH + CO_2$$

C:H nat. gas 1:4
crude oil 1:1

Unclear T, P of formation: high or as low as 100 C? Depths < 20,000 feet?

Confusion still about exactly what precursor molecules are Lipids (fats) or also carbohydrates?

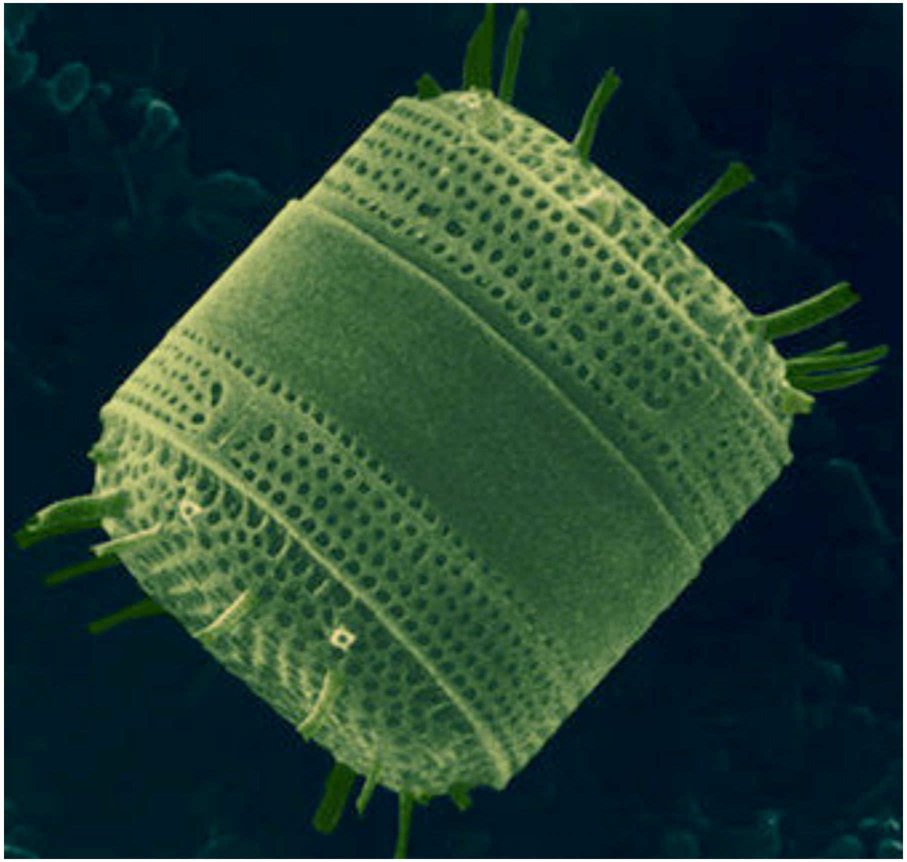


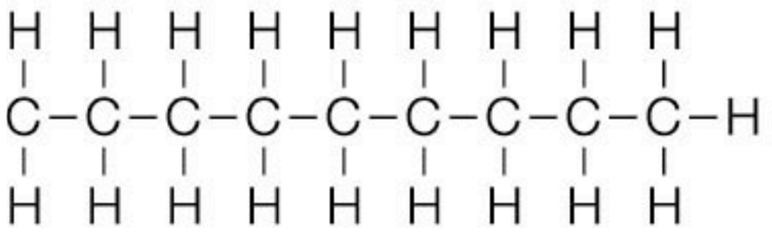
Photo: copyright Dee Berger, Lamont-Doherty Earth Observatory, 2001

Fatty acids and hydrocarbons

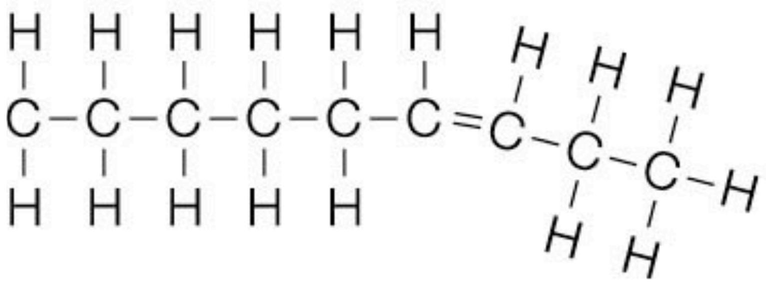
Fatty acids similar in energy density & composition to oil, but w/ carboxyl group

Remove carboxyls (COOH units) and become hydrocarbons

Saturated



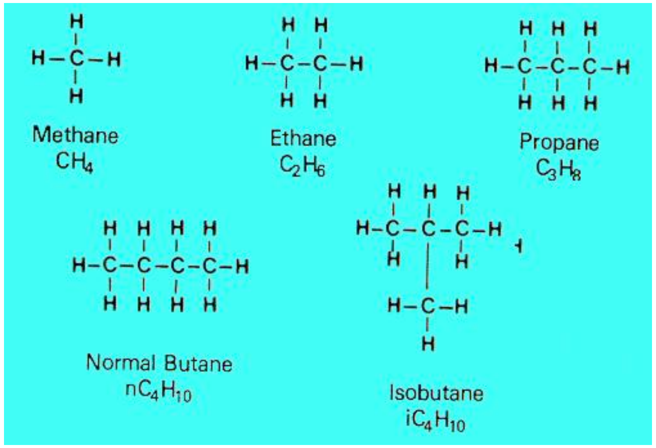
Unsaturated



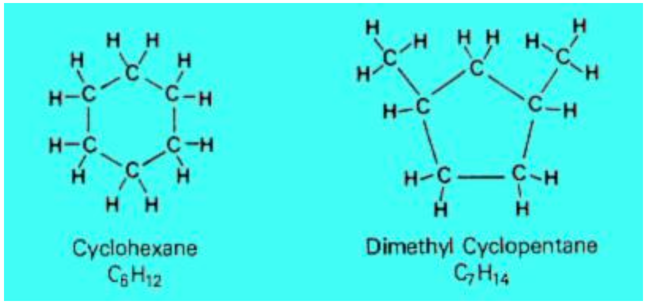
“Saturated” means no double C bonds – no extra place where a new atom could be incorporated in chain. (Each C “wants” to have four bonds).

Molecular composition of crude oil

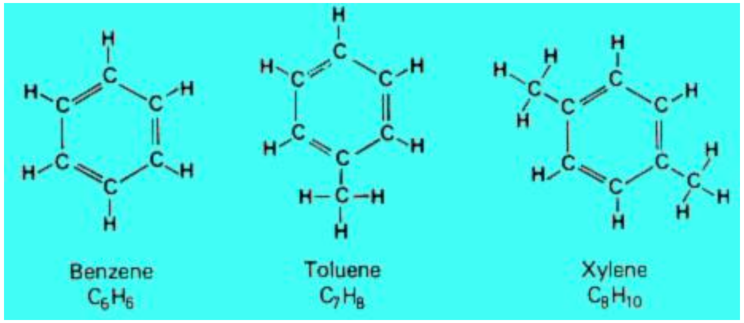
Also complex – a mixture of hydrocarbons C_nH_m of various lengths to > C_{70} (with some impurities, e.g. sulfur at S:C ~ .004-.02: 1)



Paraffins



Naphthenes



Aromatics

Crude oil includes both saturated and unsaturated compounds.

Long-chain hydrocarbons make crude viscous

Canadian crude has viscosity similar to molasses, can get 10 x more viscous

Soldiers from the South Korean army clean up crude-oil spills over Mallipo Beach after an accident involving a Hong Kong-registered tanker in Taean, about 106 miles southwest of Seoul, on December 10, 2007.

Crude oils differ widely mixture of compounds

U.S. shale oil is light crude

Distillation = separation according to volatility

viscosity (ease of flow) goes with volatility (tendency to evaporate)

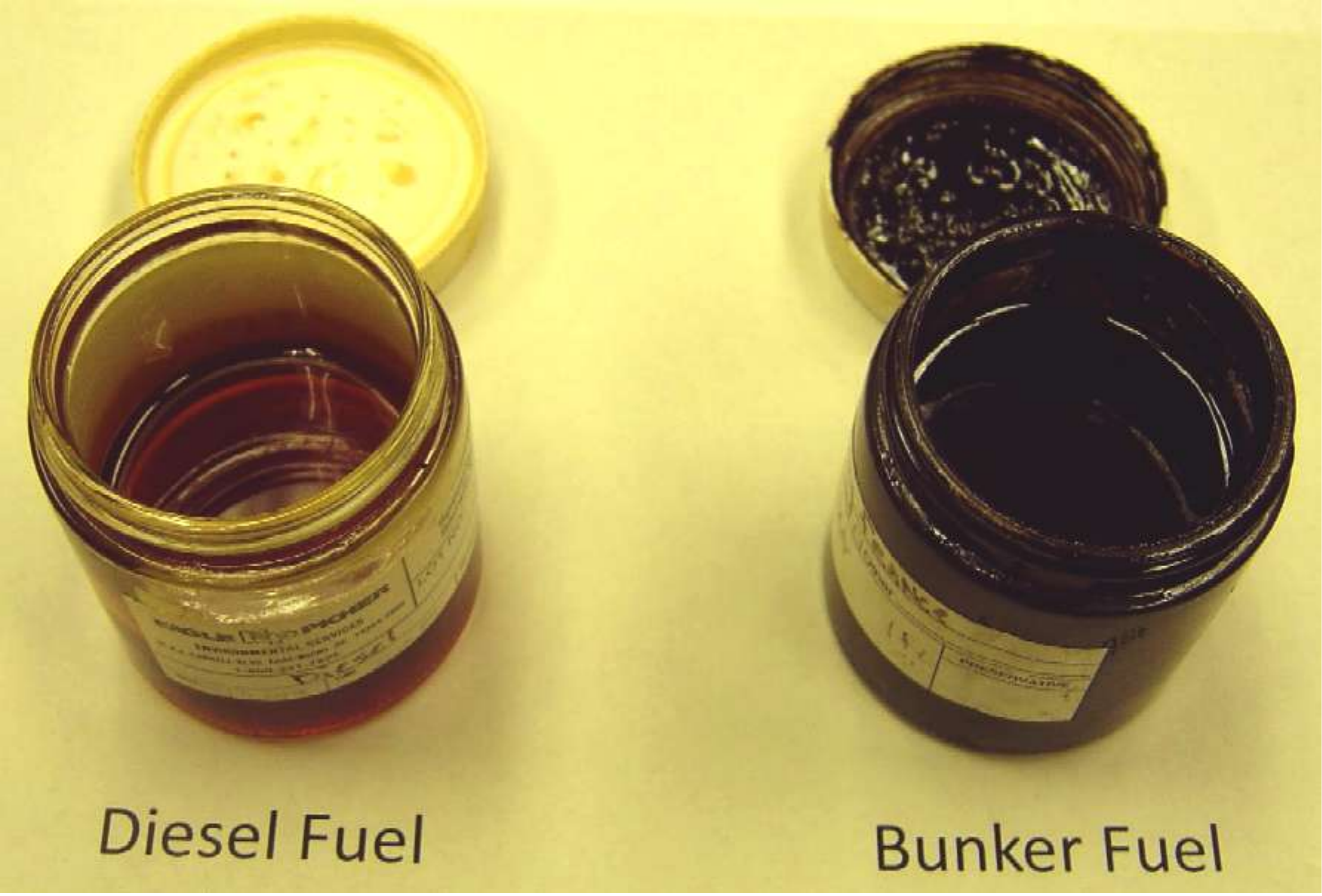
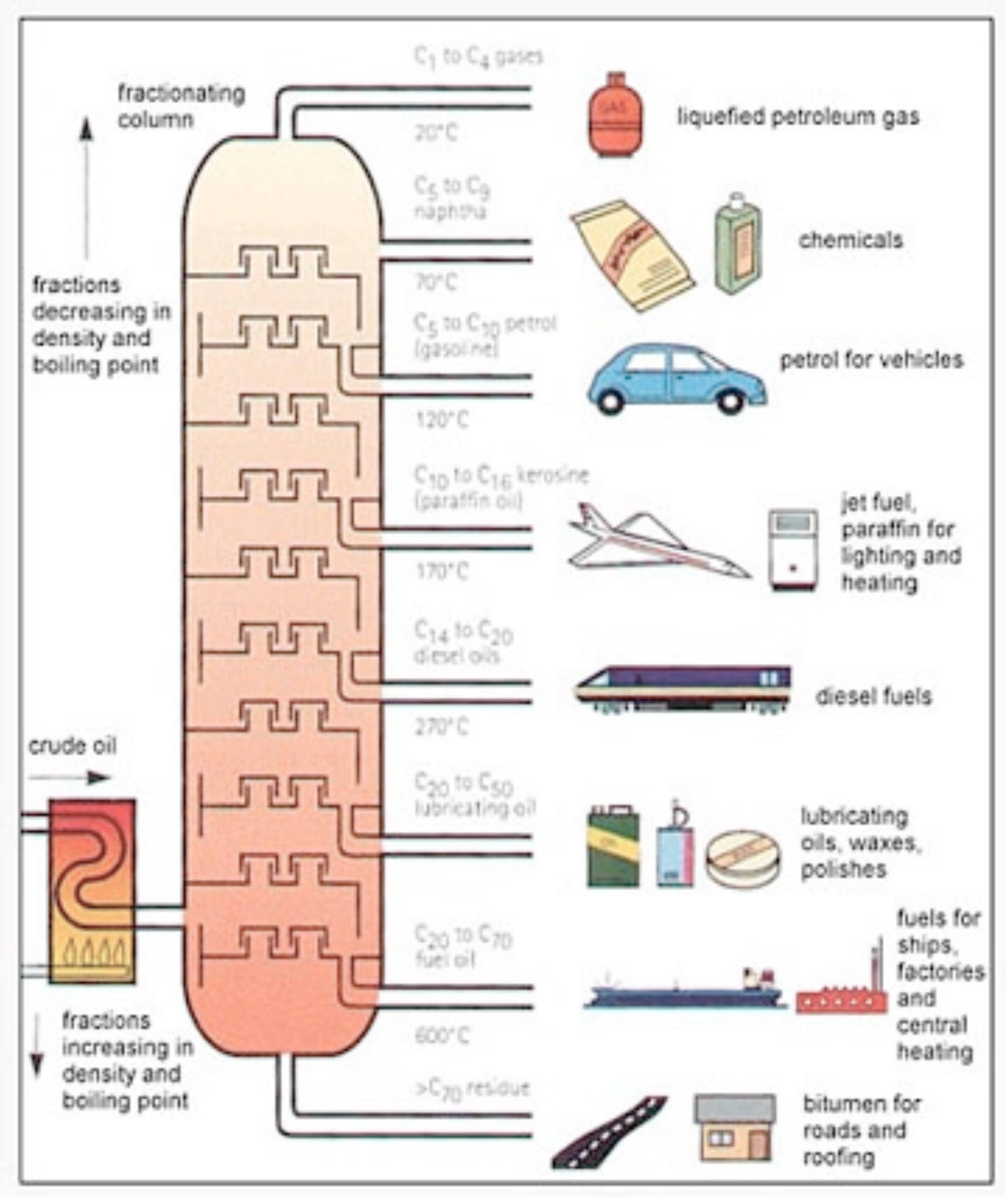


Image:

Petroleum refining = separating crude oil into components, then adjusting chemistry. “Nose to tail” use.



Distillation column. *Image: theOIlDrum.com*

1 Distillation – separating components of crude oil

2 Cracking – breaking down components

3 Reforming – combining constituents

Oil production history

Natural oil seeps were used from antiquity

Genesis 6:14

Make thee an ark of gopher wood; rooms shalt thou make in the ark, and shalt pitch it within and without with pitch

Exodus 2:3

And when she could not longer hide him, she took for him an ark of bulrushes, and daubed it with slime and pitch, and put the child therein …

Uses: sealing boats and baths, glue, mixed with sand etc. for mortar, medicine, lamps, mummification, warfare ("Greek fire", liquid that ignited on contact with water), paintings

Tarwater Creek, Santa Cruz Mountains, CA.

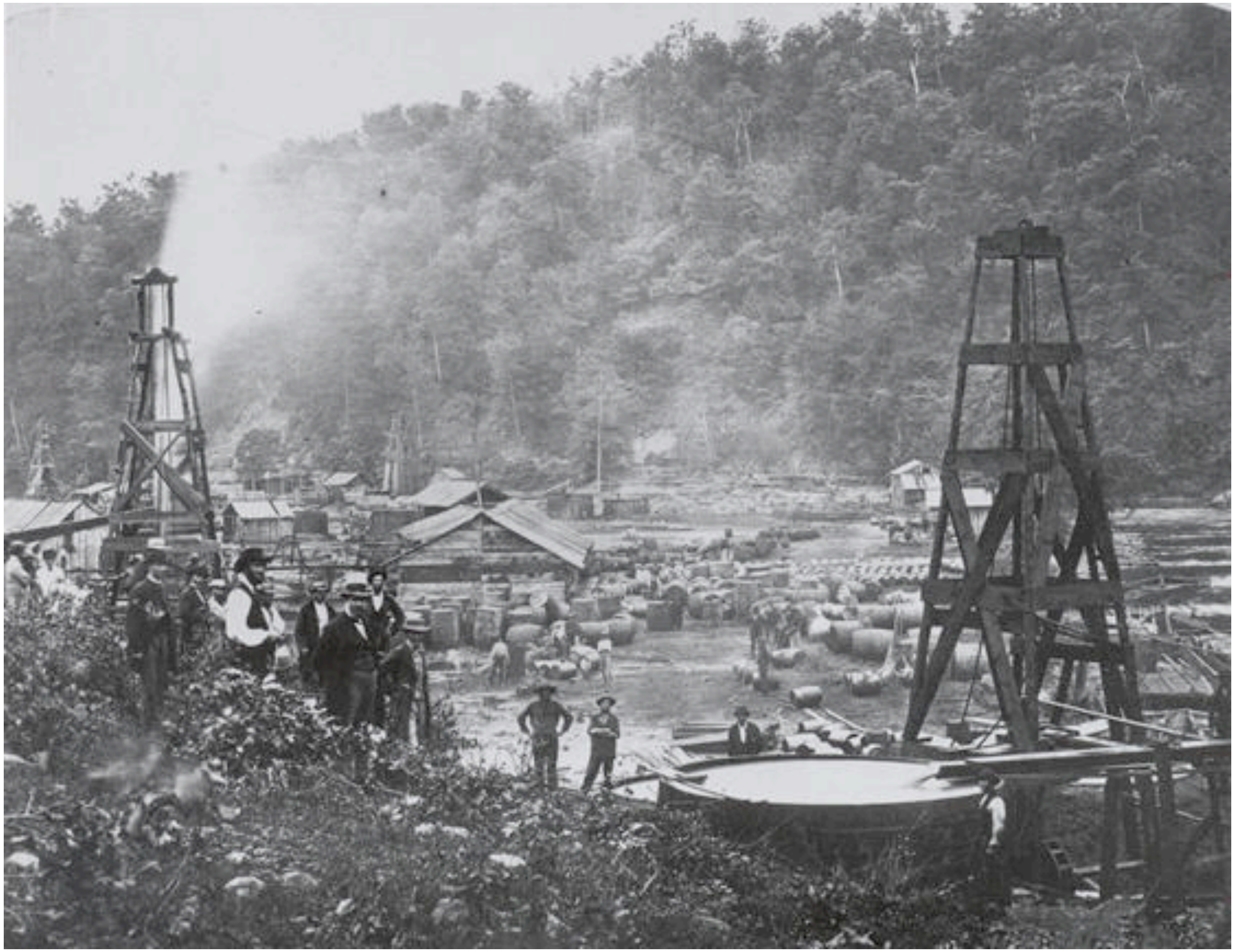
Photo: USGS

Birth of oil industry assumed Titusville, PA 1859

Site is long known "Oil Creek", oil was nuisance to local salt miners

Then, deliberate attempt to develop a well – investors funded effort.

Oil production boomed by x 1500 in 4 yrs, x 5000 in 15 years



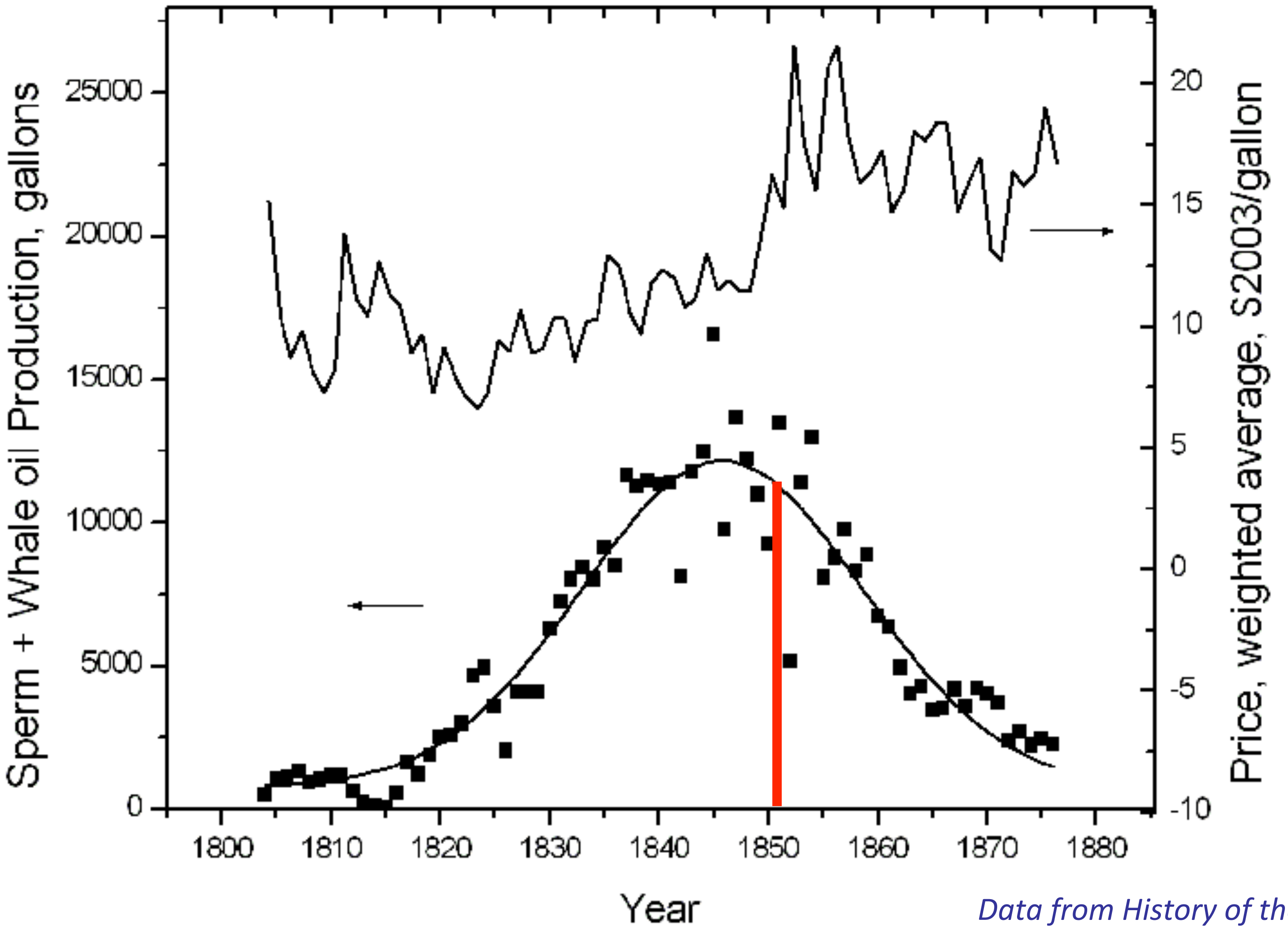
Phillips and Woodford wells on Oil Creek, PA, 1861

From [Pennsylvania Historical & Museum Commission](), Drake Well Museum Collection, Titusville, PA

Why the sudden interest in oil?

Resource limitation: fuel for lighting was running out

"Peak whale oil" ~ 1850, with expected corresponding rise in prices



"Moby Dick", Melville, 1851

Data from History of the American whale fishery" A. Starbuck, 1878. Figure from U. Bardi, ASPO

Kerosene demand drives early oil production

Refineries and pipelines by 1870s (Rockefeller's Standard Oil founded 1870)

gasoline was waste product – too volatile and flammable for use for lighting

1878: Edison's lightbulb reduces kerosene demand, causes oil industry slump

1886: invention of car provides slowly growing market for gasoline

By WWI U.S. is dominant oil producer (TX, CA) and exporter, followed by Russia

Oil barrels (1860s?)
Titusville.

As much as 50% of oil was lost to spillage in production & transport
(Paleontological Research Assn.)

Early oil production is international

First drilled oil well in Baku, Azerbaijan in 1848 (before Titusville)

Nobel oil field in Balakhani, Azerbaijan, 1890s – Swedish-owned by Nobel brothers, one of whom goes on to invent dynamite and found a famous prize…From: San Joaquin Geological Society

Early oil wells are high-pressure:

no need for pumps – derricks only

R: Baku, Azerbaijan, 1890, building levees to try to save oil from gusher. *Image from: San Joaquin Geological Society*

L: The famous 1901 Lucas gusher in Spindletop dome, Texas, gushing more oil than the rest of the country's production together. *Image from: American Petroleum Institute*

No more gushers: lower-pressure oil requires a pump

"Nodding donkeys" or "pumpjacks"

Looks like Newcomen & Watt's pumping engines!

Not a true beam engine. Don't drive beam directly with piston.

Typically use diesel engines, whose linear motion is oo fast, too short

Linear -> rotary motion and then rotary -> linear again

Image: Tony Waltham

Gearbox
http://www.youtube.com/watch?v=FU0dYV3LvAk&feature=related

Sucker rod pump
http://www.youtube.com/watch?v=SFJFiyXTOa0

Exhaustion of “easy” U.S. oil

+ OPEC embargo = turn to offshore, remote

First offshore platform off Louisiana in 1938 (100 foot depth)

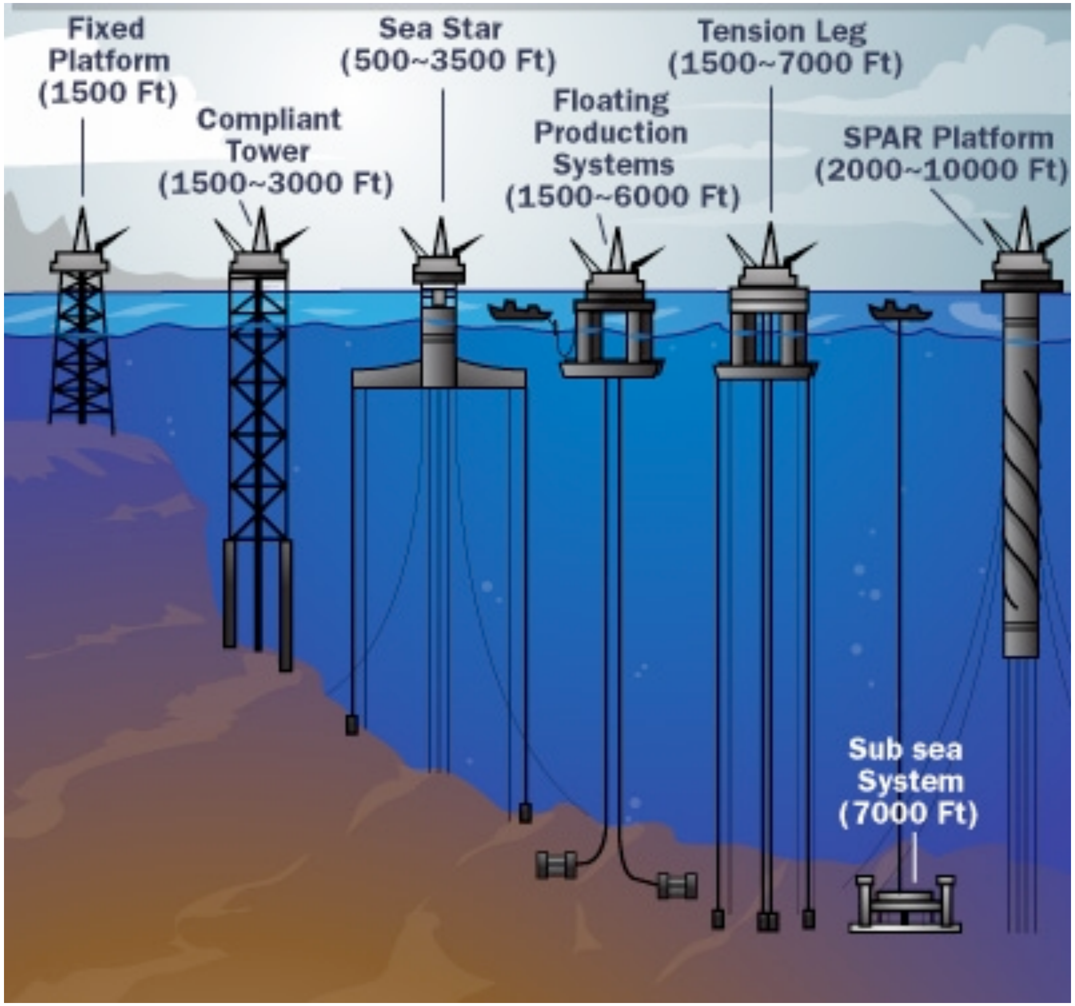
1973 OPEC embargo prompted construction of Trans-Alaska pipeline (1977)

Oil produced from deeper waters: BP “Deepwater Horizon” is 5000 ft (1500 m)
Industry projected extraction from 8000 ft water depth, wells to > 35,000 ft.

Petrobras P-51 oil and gas platform off the Brazilian coast: 180,000 barrels oil and 6M cubic meters gas per day.

Photo: Petrobras

Floating oil platforms allow deepwater production



Wells drilled from drill rigs, then replaced by production platforms.

One platform serves many slant wells.

Generally wells need pumping. (But too deep for rod pumps).

Blowout prevention system (BOP) seals well if back pressure detected.

Figure above: HowStuffWorks.com

Left: Solar Navigator.net

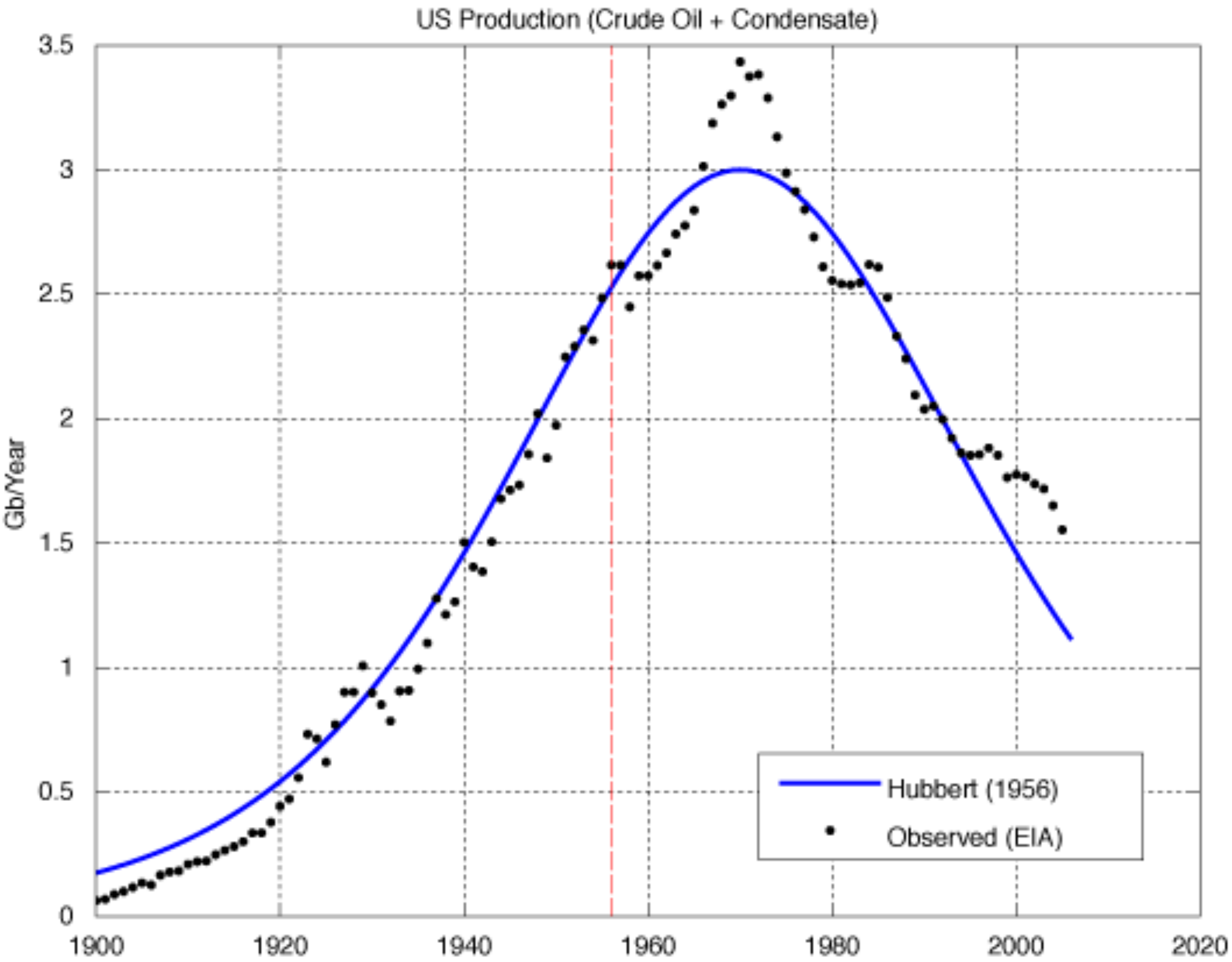
Hibernia platform, world's largest oil platform, N. Atlantic off Canada, gravity base structure, 50 wells drilled

U.S. by mid-2000s

no longer a major producer of oil and gas

U.S. oil decline: "Hubbert's peak"

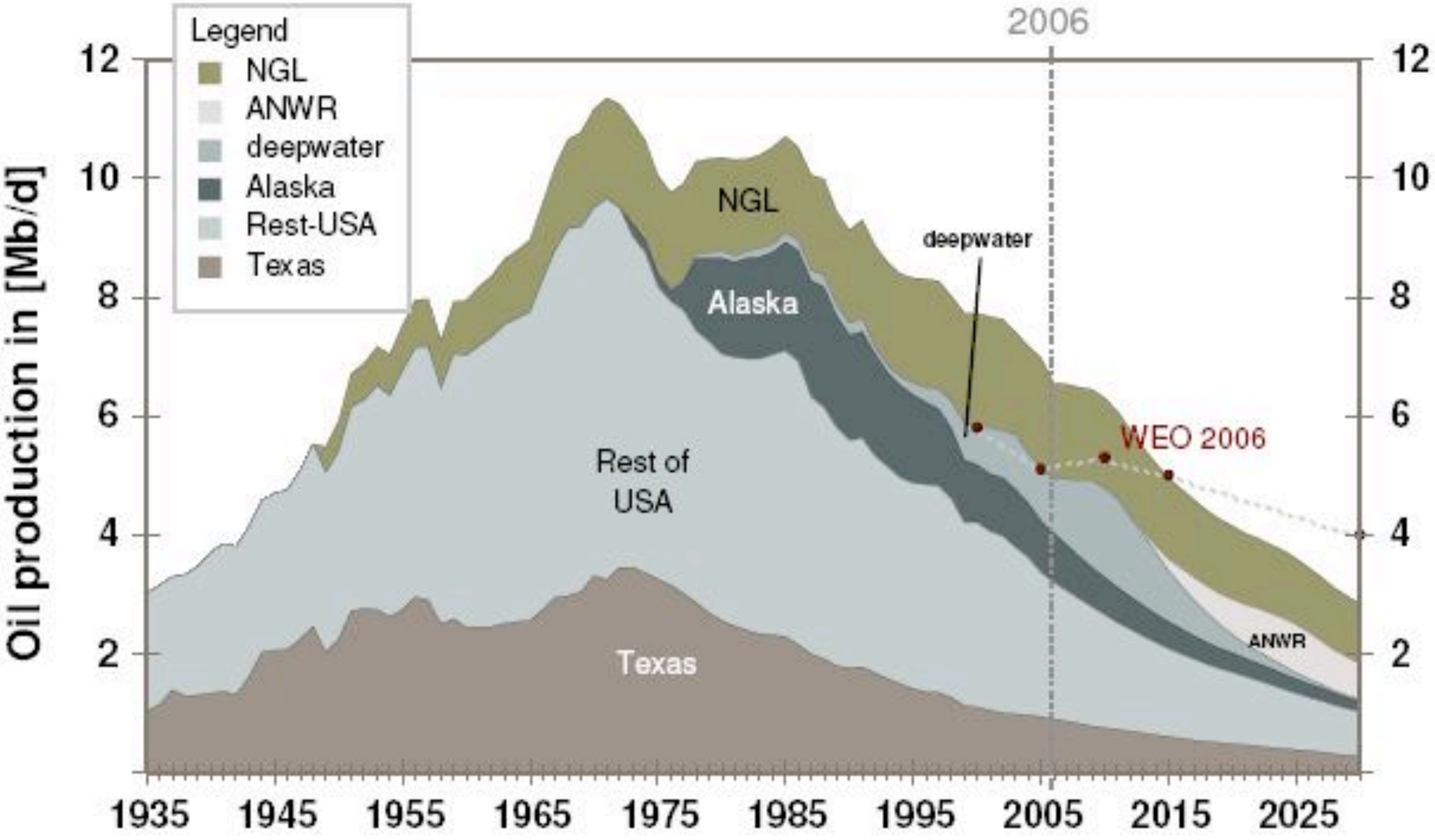
Famous prediction in 1956 by M. Hubbert, U.S. geophysicist, borne out



Data: U.S. Energy Information Agency; Image: Wikimedia Commons (S.Foucher, 2007).

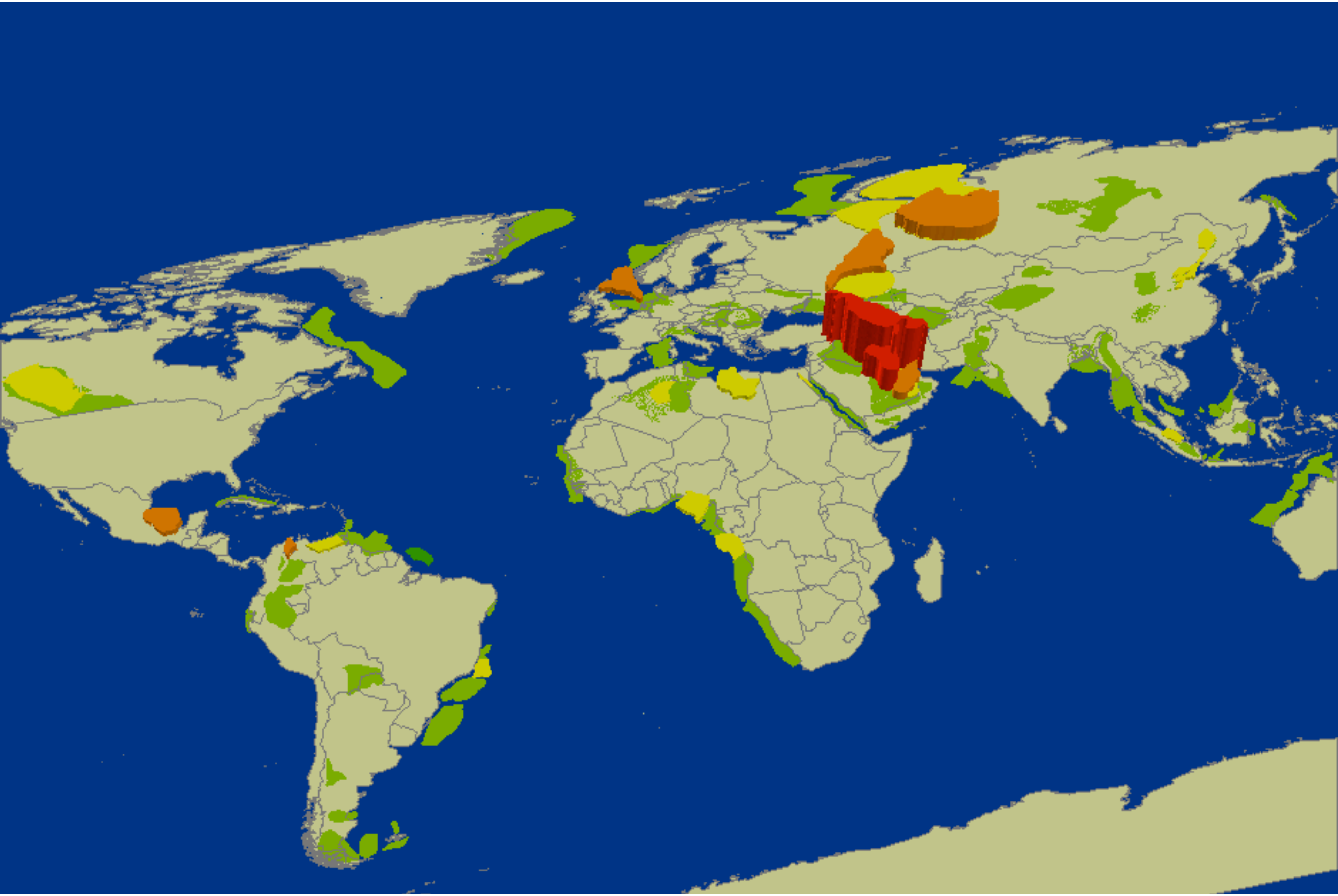
U.S. had seemed to be running out of oil

$ matter: remaining oil gets too expensive to extract



From: TheOilDrum.com (original source unknown)

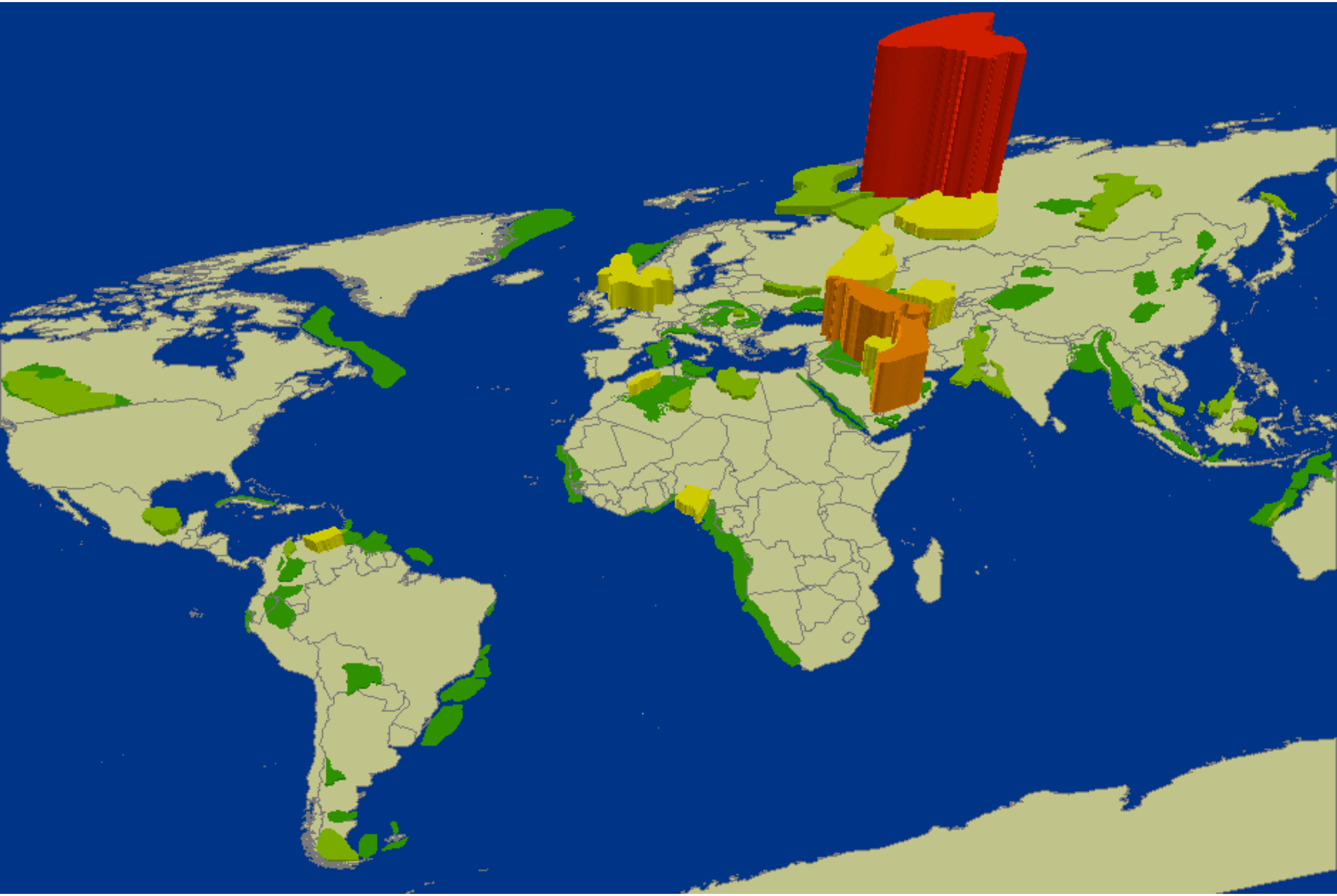
World proven oil reserves



Notice that U.S. doesn’t even register on global map.

Source: FortiusOne Data: USGS World Petroleum Assessment

World proven conventional gas reserves

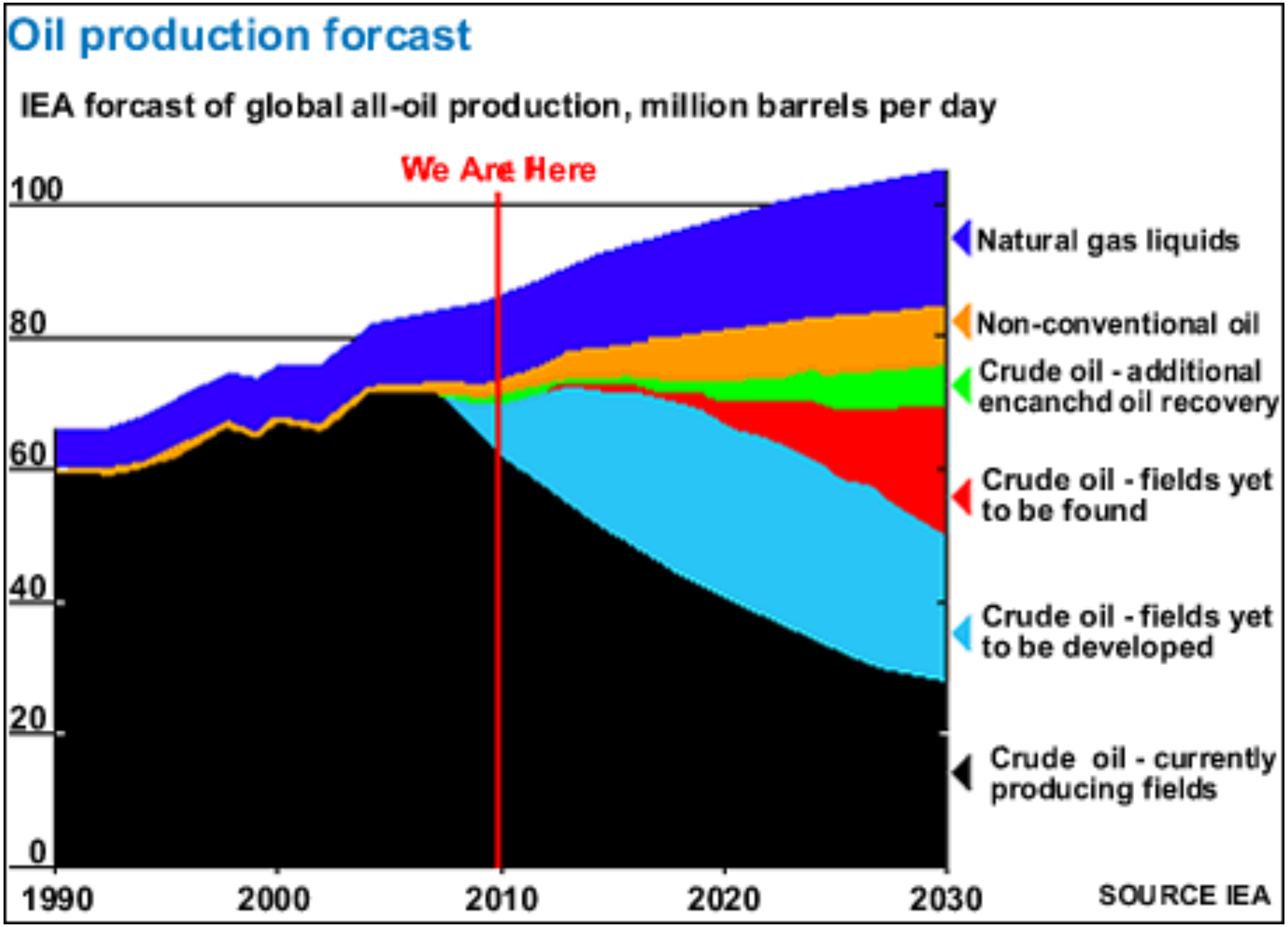


Notice that U.S. doesn't even register on global map.

Source: FortiusOne Data: USGS World Petroleum Assessment

World oil forecasts also gloomy in 2009

production growing slowly, turning to sources less easy to extract
oil price near historic highs. U.S. imports exceed production.



Natural gas was an even bigger crisis

Oil can be transported by ships, but gas best in pipelines

Canadian oil reserve:

Athabasca oil sands, Alberta

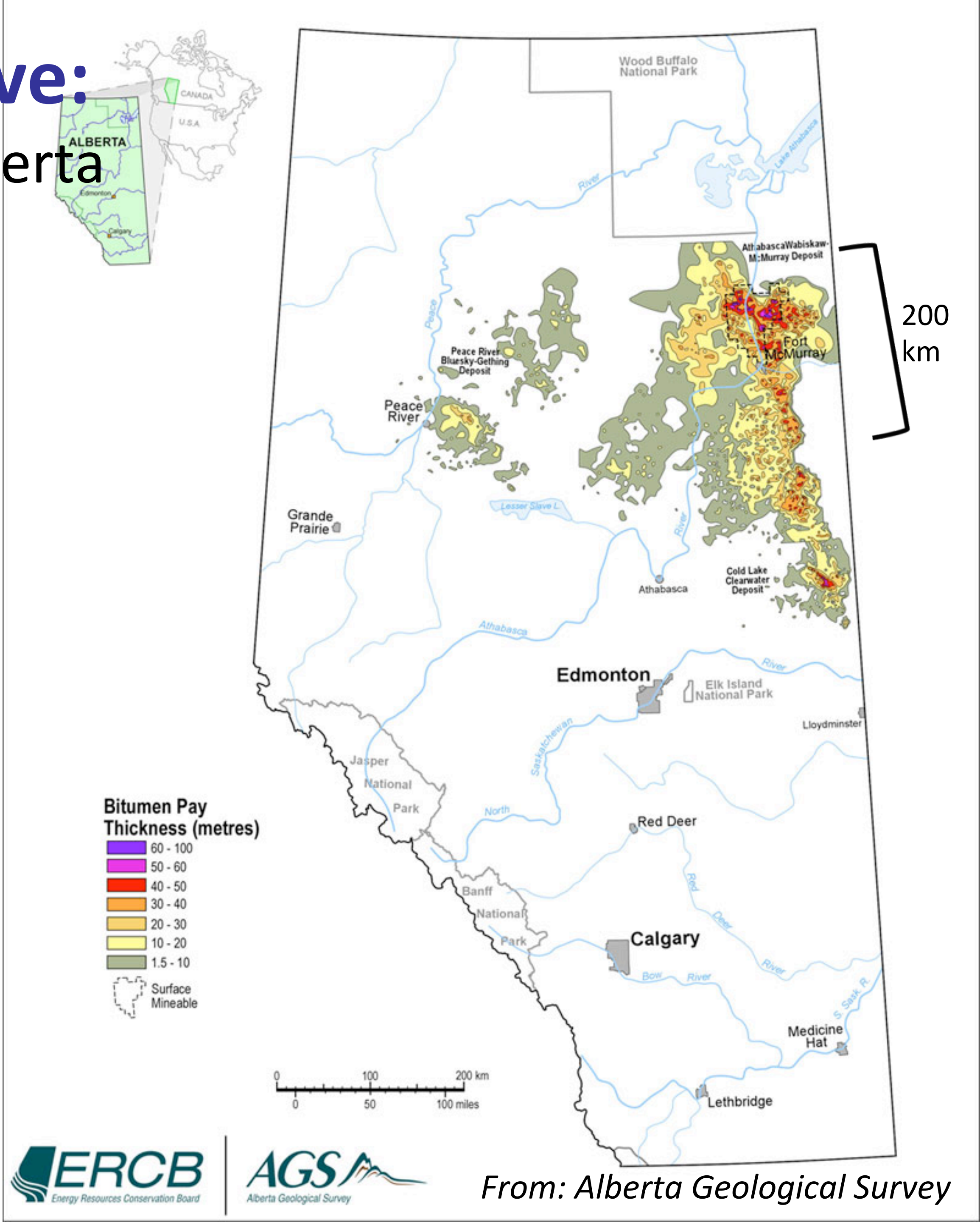
Largest bitumen deposit in world, only one accessible by surface mine

Localized deposit (but 140,000 km^2)

Total: est. 900 B barrels, *(almost as much as world conventional reserves).*

~170 B bbl economically recoverable.

Investment: $14B in 2006



From: Alberta Geological Survey

Oil (tar) sands: liquid crude (bitumen) embedded in solid matrix

Can extract by:

- Digging sands up for processing
- Underground heating by steam injection to make heavy oil (bitumen) less viscous and able to be pumped
- Underground heating by burning some of the oil sands and again pumping
- In Alberta oil is 90% of mass (other deposits can be < 10%)

Alberta tar sands, Canada: 15-65 m thick. *Photo source: Suncor Energy Inc.*

Bitumen is sticky: high viscosity, similar to asphalt

Many long-chain hydrocarbons produce high viscosity

To get bitumen to flow in pipelines, need to dilute it with lighter oil.

Photo source: Synertia

BP Whiting now processing heavy oil from Alberta

6 years: started project in 2006, production in 2012.

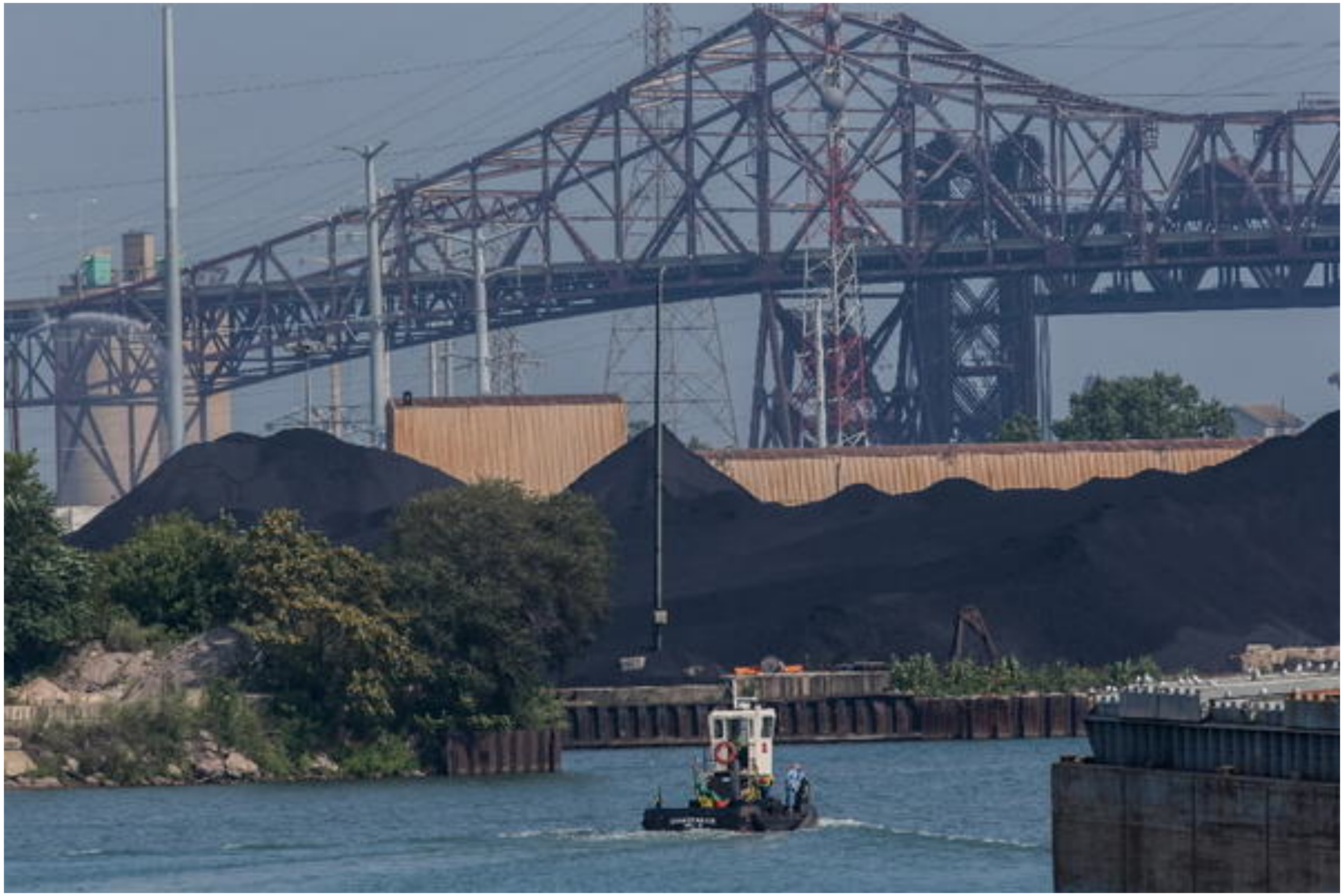
3 year delay, $1B (25%) cost overrun for total $3.8B

Heavy crude transported by Enbridge's Line 6A pipeline from Wisconsin.

Pipeline from Canada to 6A waiting for expansion permit.

BP Whiting, IN. Photo: BP.

BP Whiting: processing Alberta oil sands, but not managing "nose-to-tail" refining



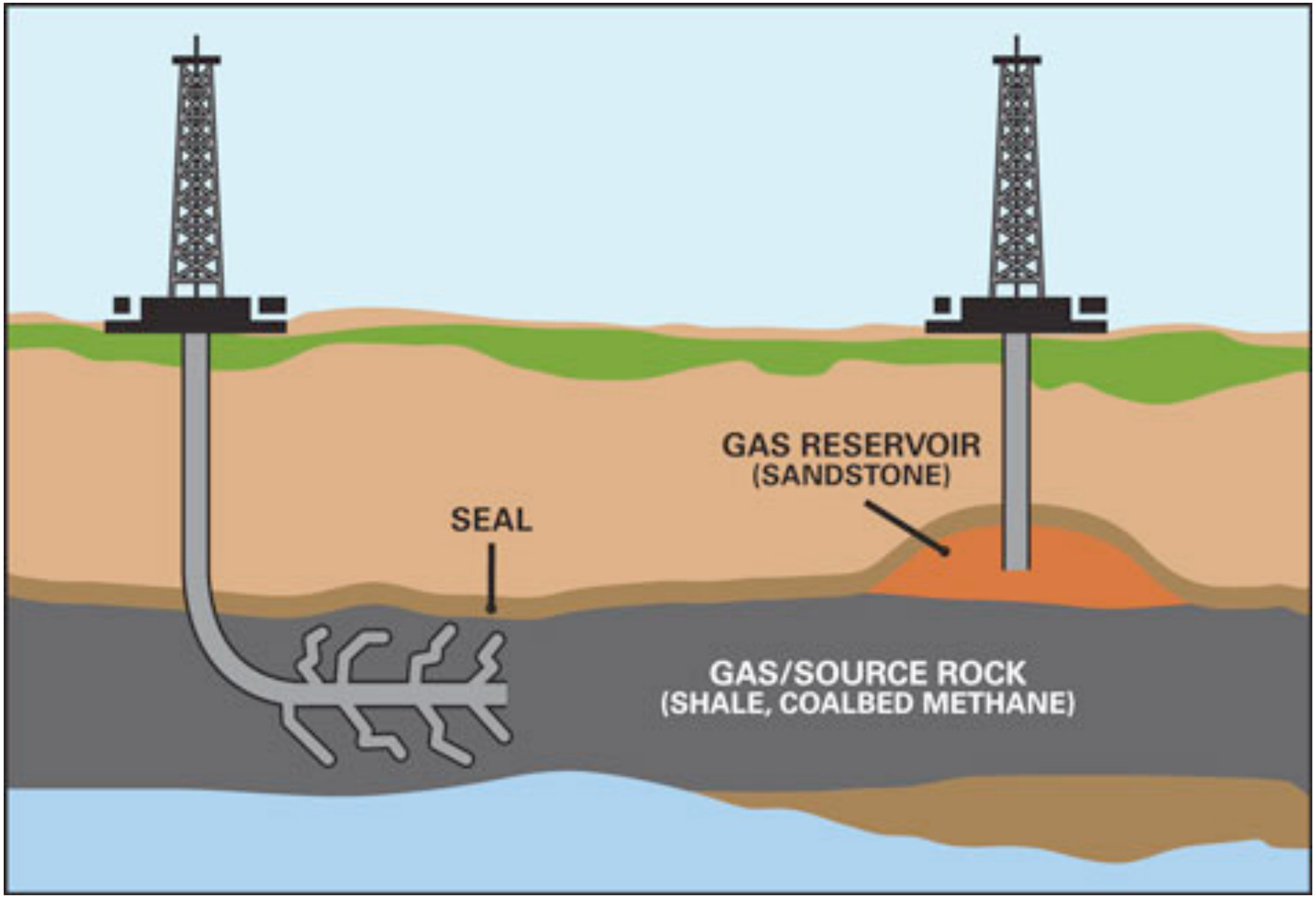
Excess production of "petcoke" – solid near-pure-C material. Can be burnt, but not enough customers. (Output tripled from 0.7 M t/yr to 2.2M t/yr). Piling up along Calumet River. Storage sites owned by Koch brothers

Photo: Zbigniew Bzdak, Chicago Tribune.

BP's oil sands expansion may have been a bad business decision.....

The revolution: hydraulic fracturing for shale oil and gas

Allows extraction of oil and gas from rock where it wouldn't otherwise flow



Hydraulic fracturing

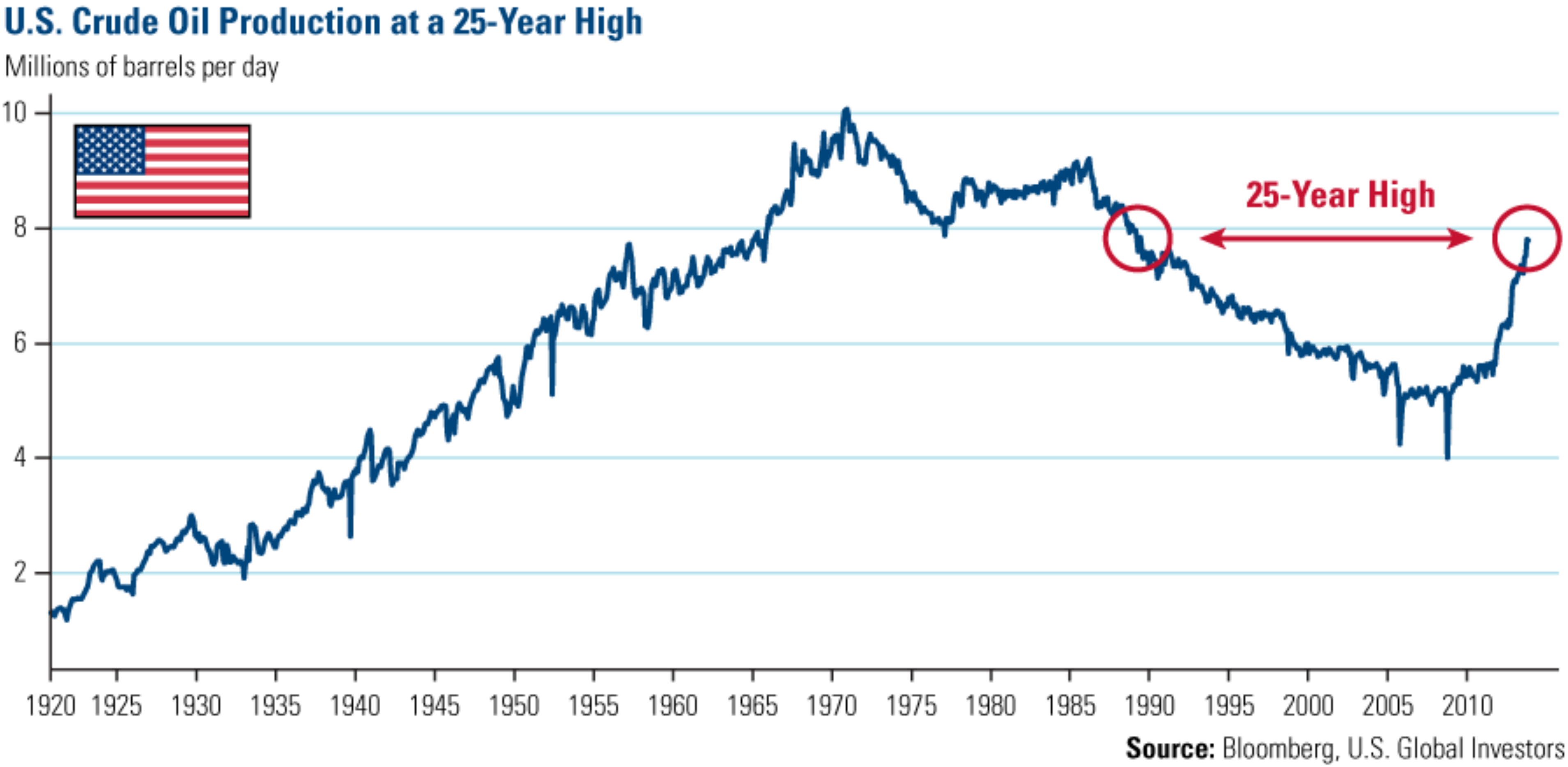
Conventional production

http://www.youtube.com/watch?v=nvnnBcxhzNA

Image from Alberta Oil

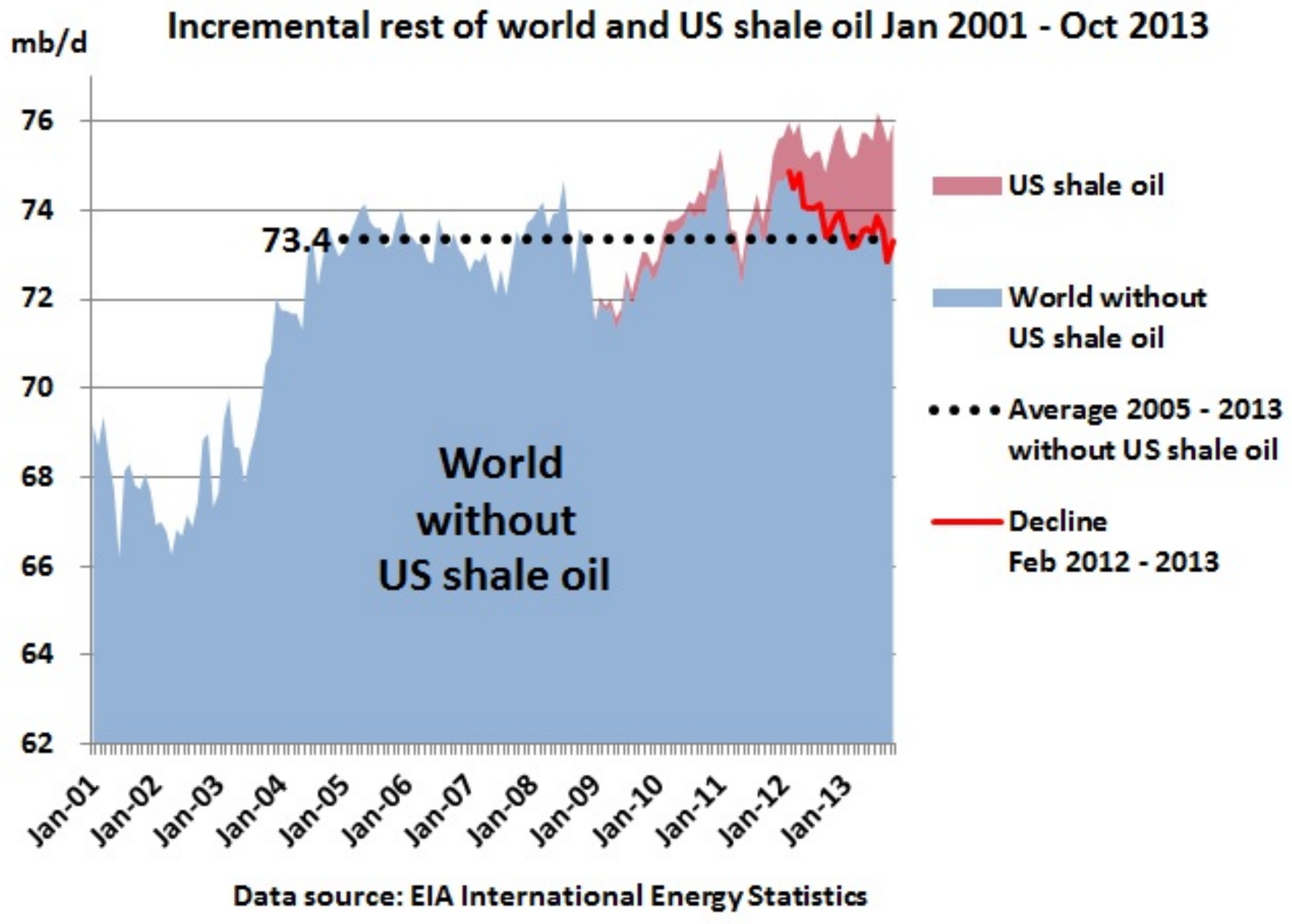
Hubbard's peak now avoided in U.S.

(for the time being)



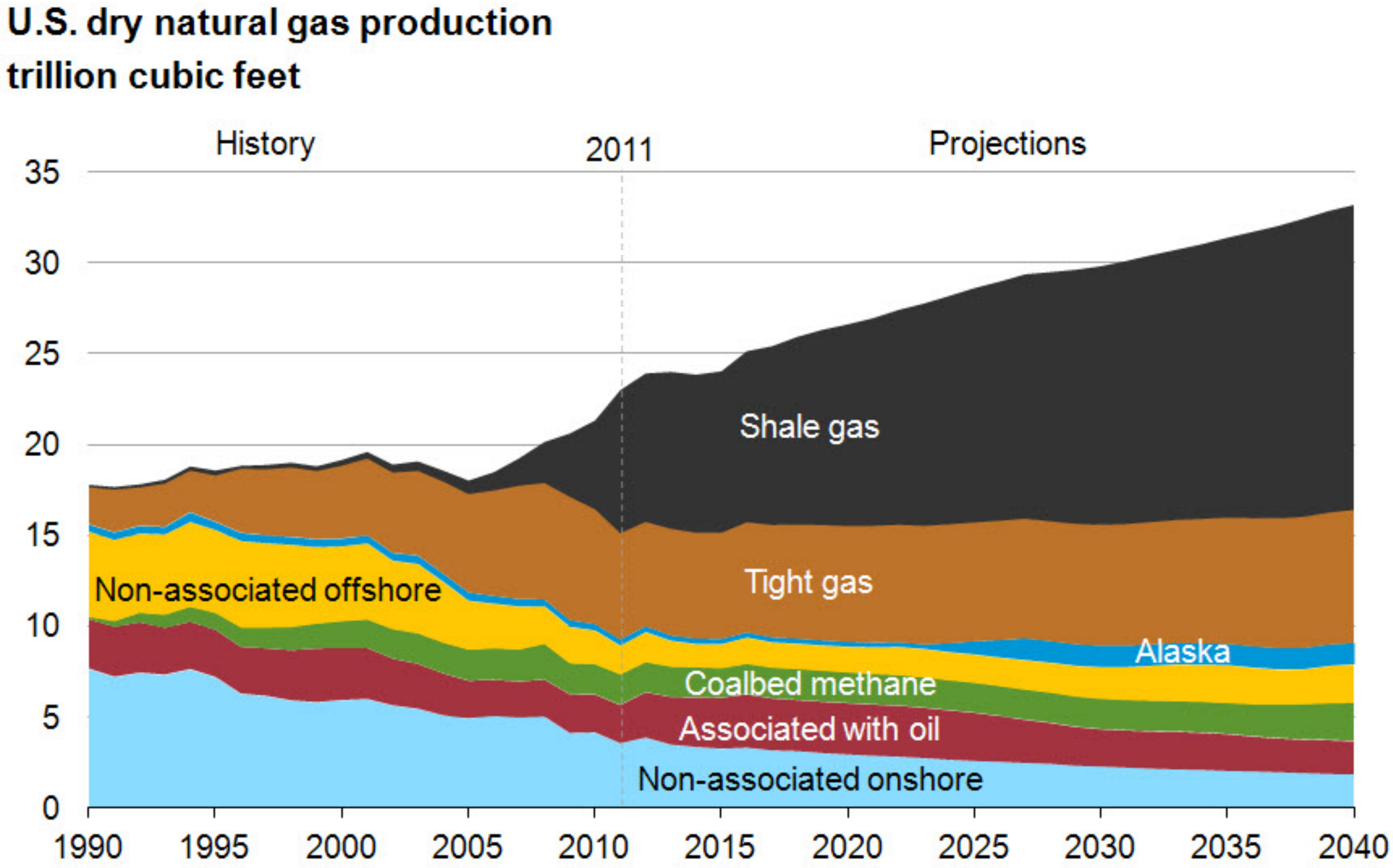
From: TheOilDrum.com (original source unknown)

U.S. production is globally significant

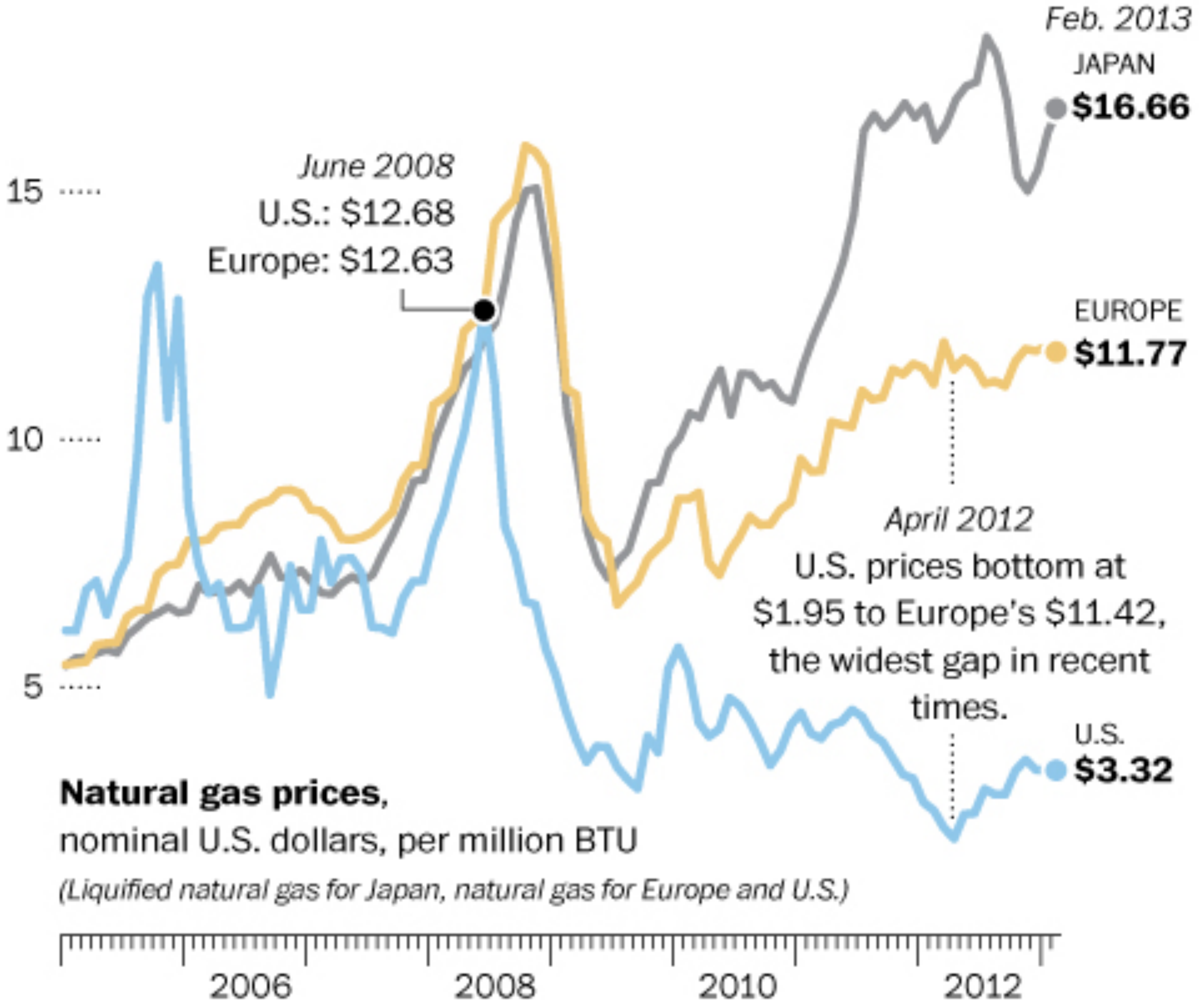


Data source: EIA International Energy Statistics

Fracking rescued U.S. from natural gas crisis



Benefits of U.S. shale gas are staying in the U.S.



Natural gas prices,
nominal U.S. dollars, per million BTU
(Liquified natural gas for Japan, natural gas for Europe and U.S.)

Figure: Washington Post, April 2013

Fossil fuels are not equally transportable

Coal

Mostly railroads overland

Little international sea transport, except to China

Oil

Pipelines -> ships (oil tankers) and sea transport

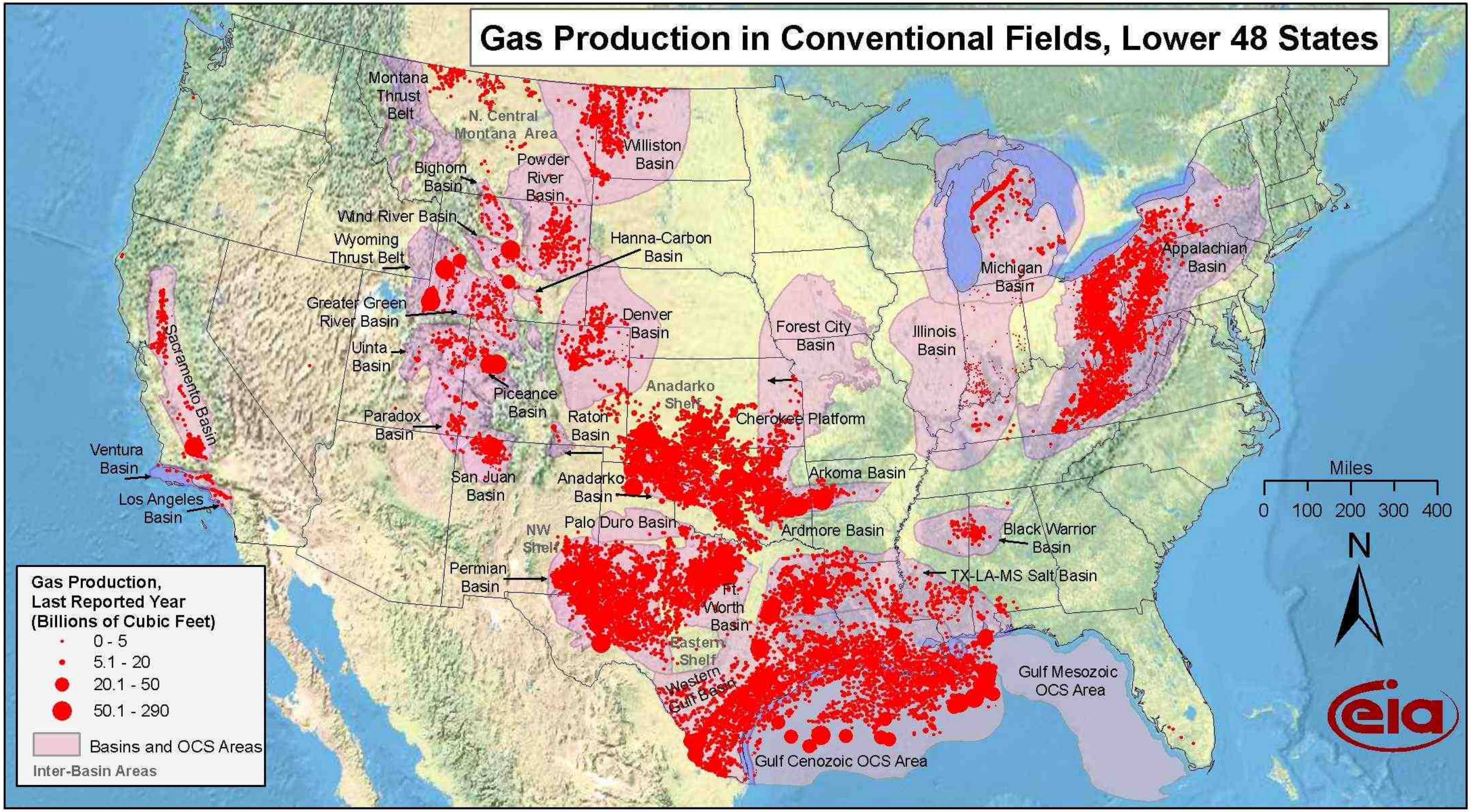
Gas

Pipelines (gas phase) overland only

Can be moved by ship only if compressed until it liquifies.

Consequence: oil prices are global, coal and gas are local

U.S. conventional gas is already in shales

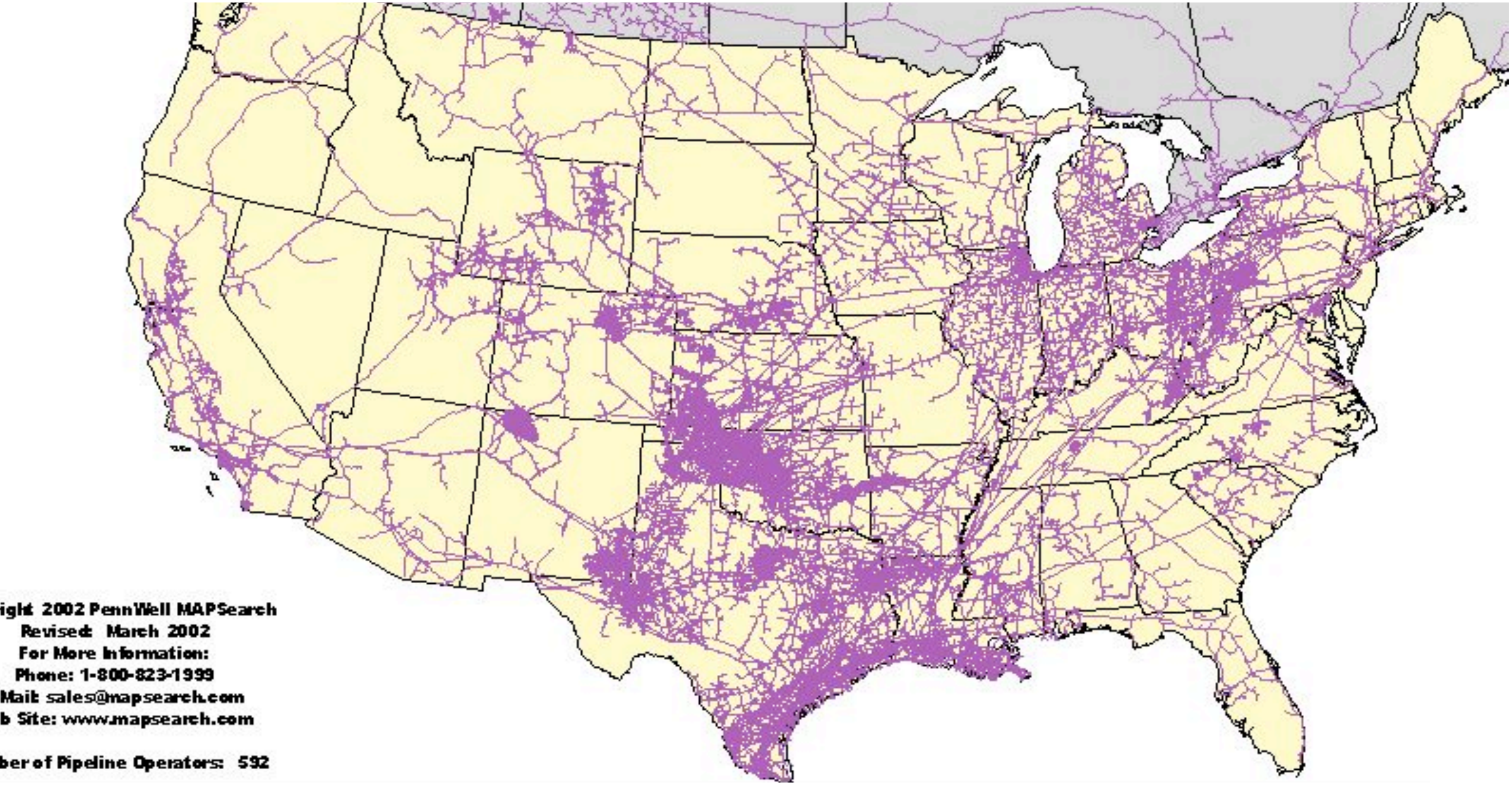


Source: Energy Information Administration based on data from HPDI, IN Geological Survey, USGS
Updated: April 8, 2009

Shale gas plays near conventional production

Source: Energy Information Administration based on data from various published studies.
Updated: May 9, 2011

Shale gas can make use of existing pipelines *but oil can't...*



ight 2002 PennWell MAPSearch
Revised: March 2002
For More Information:
Phone: 1-800-823-1999
Mail: sales@mapsearch.com
b Site: www.mapsearch.com

ber of Pipeline Operators: 592

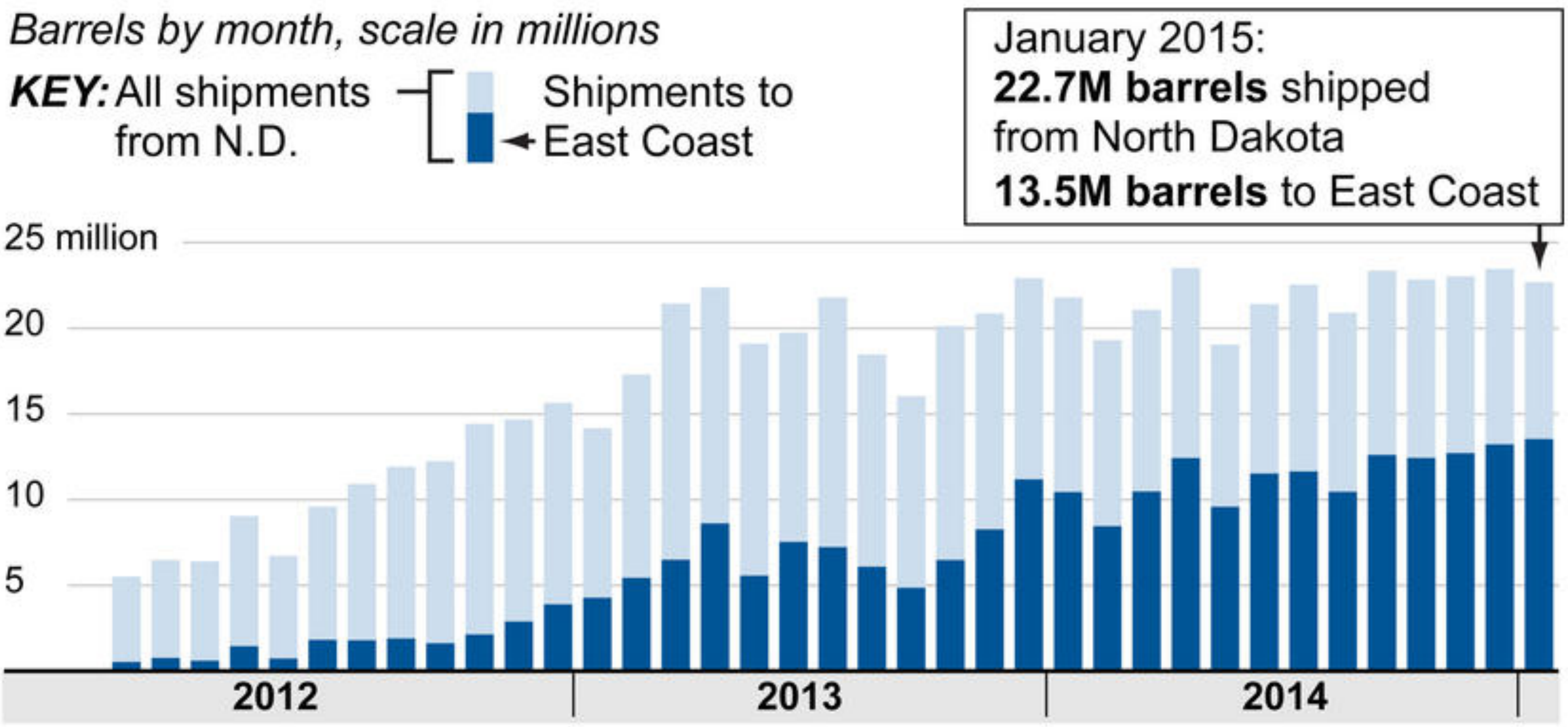
Shale gas can make use of existing pipelines

but oil can't... goes by rail instead

~ 40 trains/week through Chicago, each with ~ 100 tank cars

Oil trains, Pilsen, Chicago, April 2015. *Photo: Abel Uribe, Chicago Tribune*

Change is very, very recent



Crude oil shipments from North Dakota

Barrels by month, scale in millions

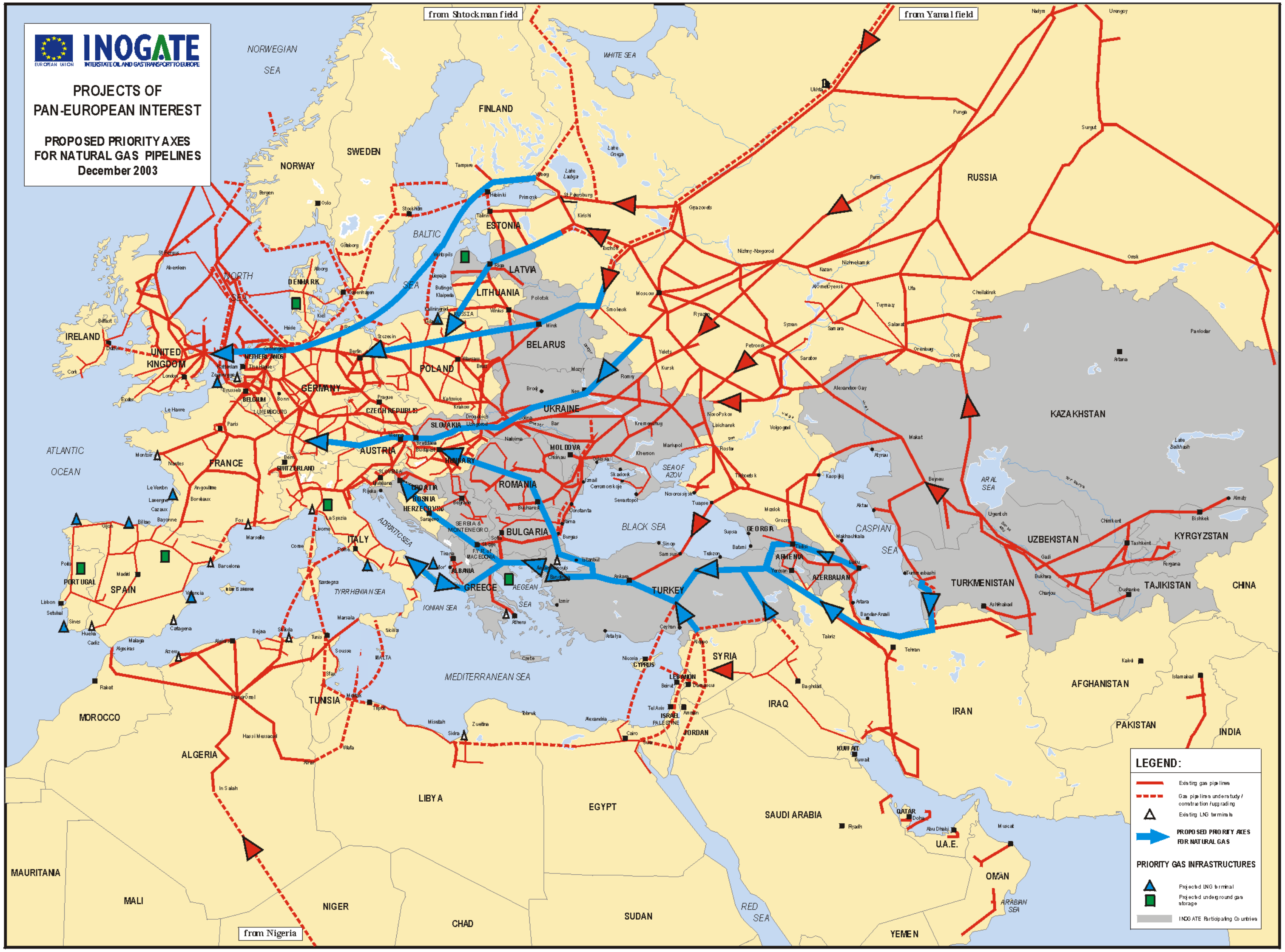
KEY: All shipments from N.D. — Shipments to East Coast

January 2015:
22.7M barrels shipped from North Dakota
13.5M barrels to East Coast

Sources: U.S. Department of Energy

@ChiTribGraphics

Europe is totally dependent for natural gas on Russia



For more information, please visit www.inogate.org

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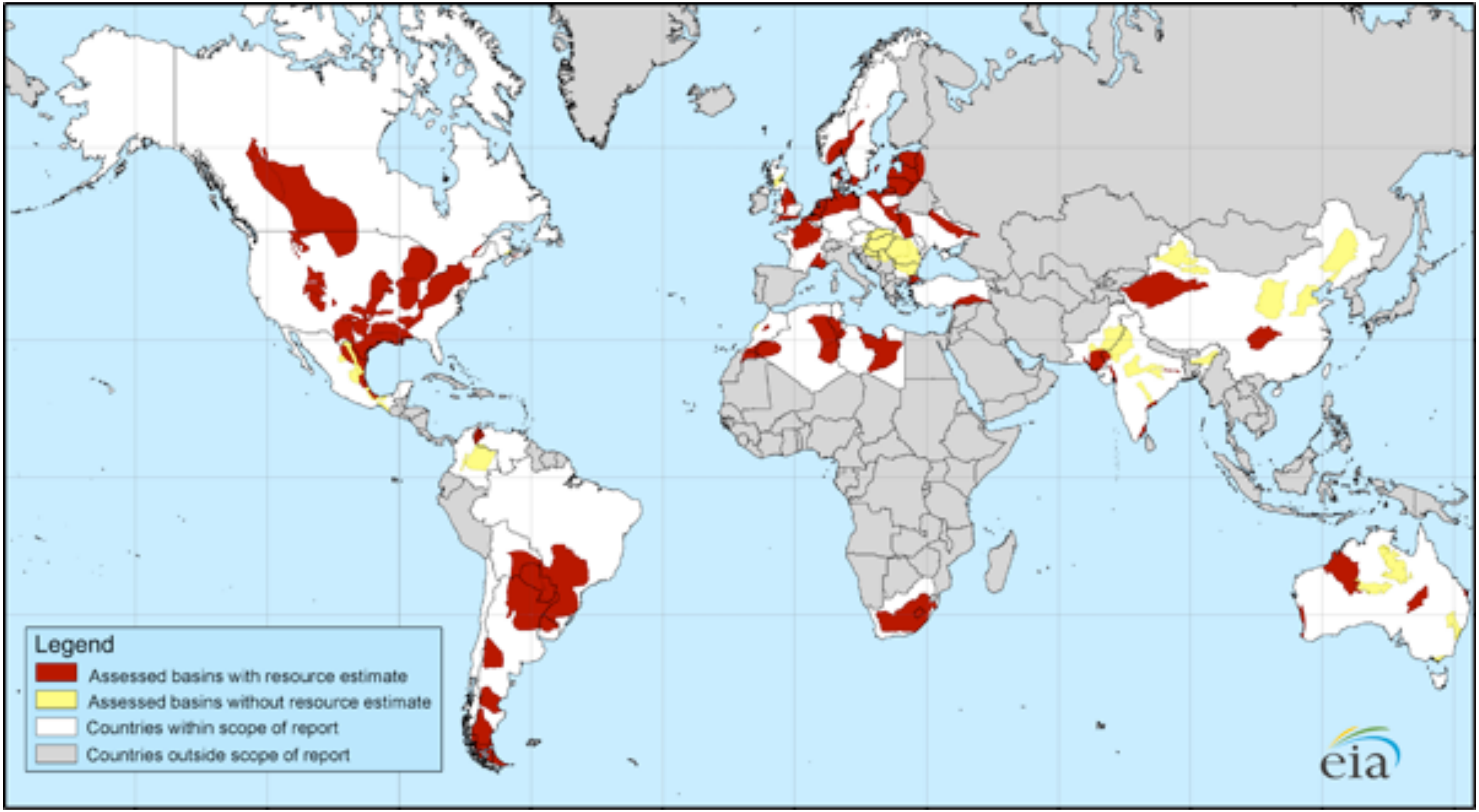
2006: Russia cuts off all gas flowing through Ukraine in dispute over prices & debts, causing shortages in European countries downstream… and interest in trans-Caspian pipelines.

But shale gas is globally significant



Local production would allow Europe, like U.S. to be energy independent for gas

How long will it last?

The EIA estimates that shale gas will provide 60 years of supply at 2030 consumption rate

.... and then what?

Fossil fuel reserve sizes not so large compared to use

Do we have one of two problems?

Either

we have plenty of fuel, and the economy is saved, but then the climate is in danger (burning all that fuel raises CO_2 too high)

Or

we are much closer to running out of fossil fuel than we thought, and the climate is saved, but the world economy is in danger

Solar power

Solar intro (very brief)

Two main energy conversions using sunlight are both called "solar"

- **Solar thermal** – use mirrors to concentrate sun and heat something and drive a heat engine, which then turns a generator and makes electricity
- **Solar photovoltaic** – convert sunlight -> electricity directly in a semiconductor via the photoelectric effect.

Solar thermal: just uses heat from sun (advantage is that you can build a better heat engine than the atmosphere)

2 of 9 (354 MW total) SEGS parabolic trough solar thermal installations in Barstow, California, starting 1984, built by Luz Int. …which went bankrupt. Still operational.

Solar thermal advantages: Proven technology (steam turbines) + heat is store-able + no exotic materials

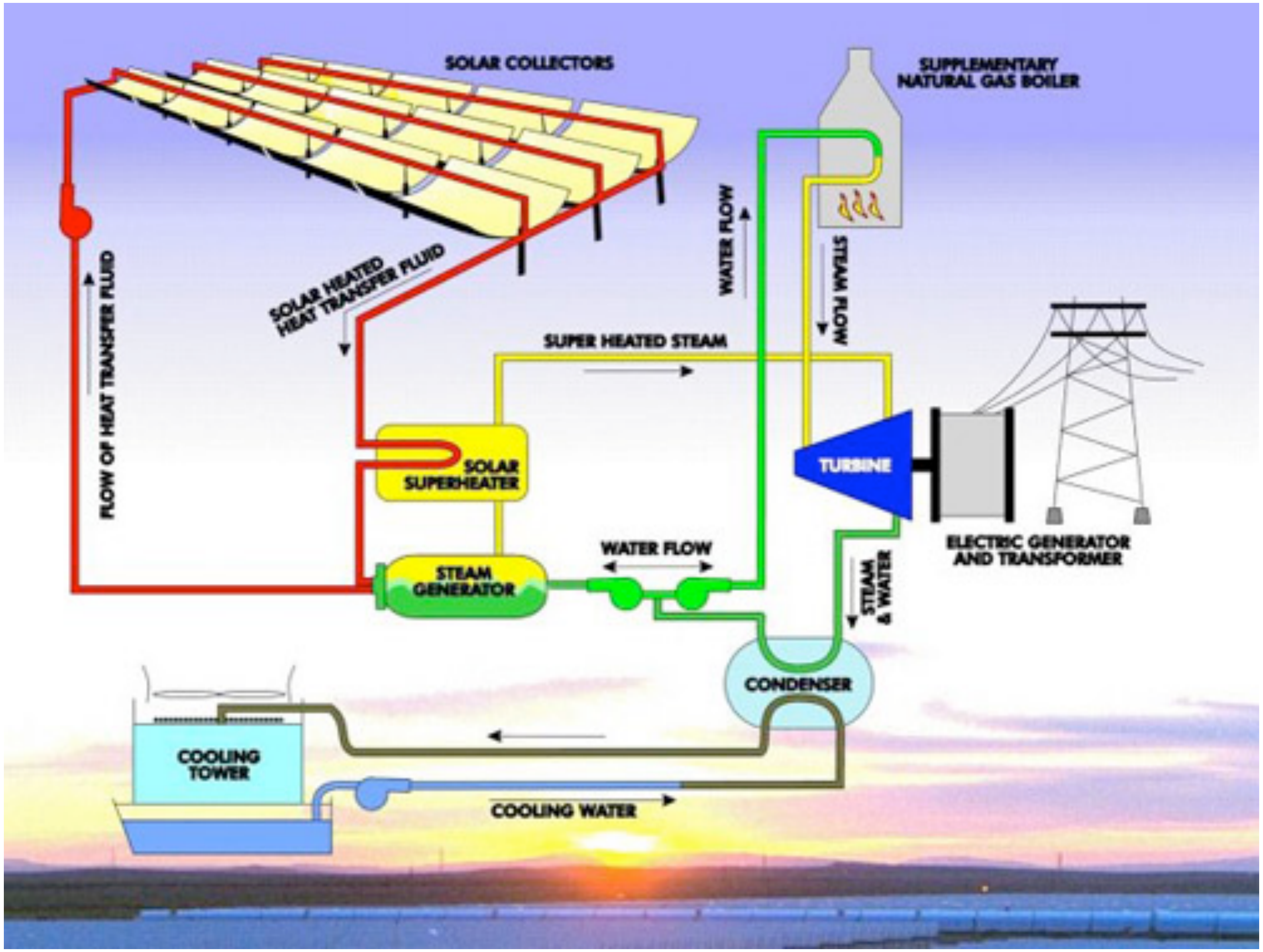


Diagram: source unknown (from the Green Technology Blog)

Power towers aim for higher efficiency

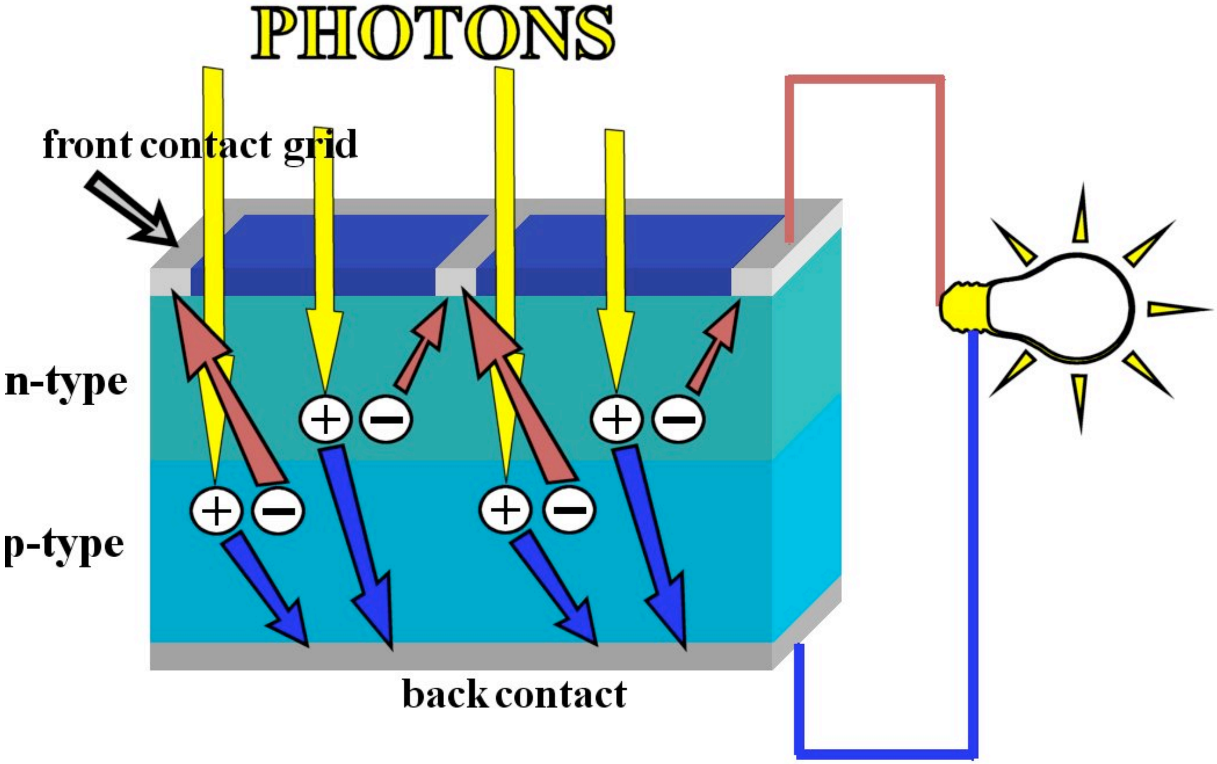
By concentrating bigger mirror area on central tower, can produce hotter temperatures and so higher Carnot limit

11 MW solar thermal PS10 "power tower" in Seville, Spain
(govt. subsidized by 27 euro cents/kWh)

Power towers aim for higher efficiency

BrightSource Solar Two power tower, near Barstow, CA. Ivanpah (400 MW capacity) is being built in Mojave now at $2.2 B cost: $5.5/W install cost. Capacity factor = ?? %. Possibly can run near full capacity with storage. CA has 33% RPS standard

Solar photovoltaic – Skip mechanical step entirely, go directly from radiation to electricity. *No turbine, no generator*



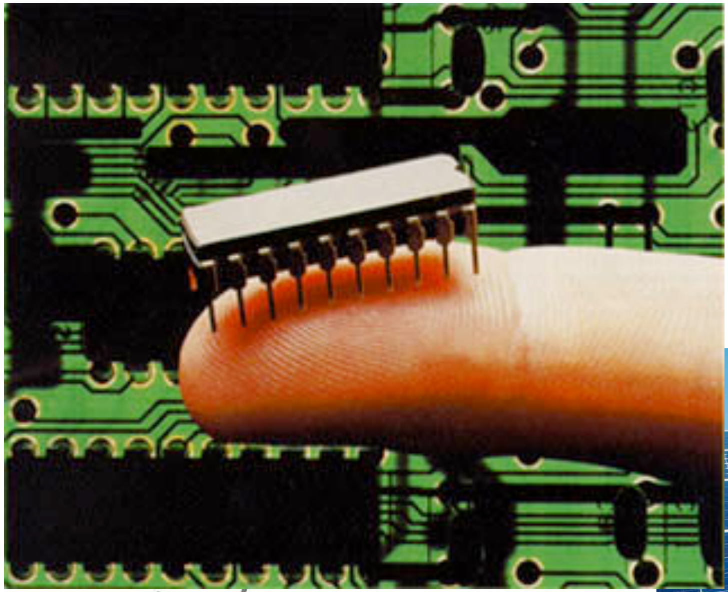
Photoelectric effect produces free electrons in semiconductor material. Current flows if given an extra conductive path. Necessarily produces DC, since current flows in only one direction. PV related to diode.

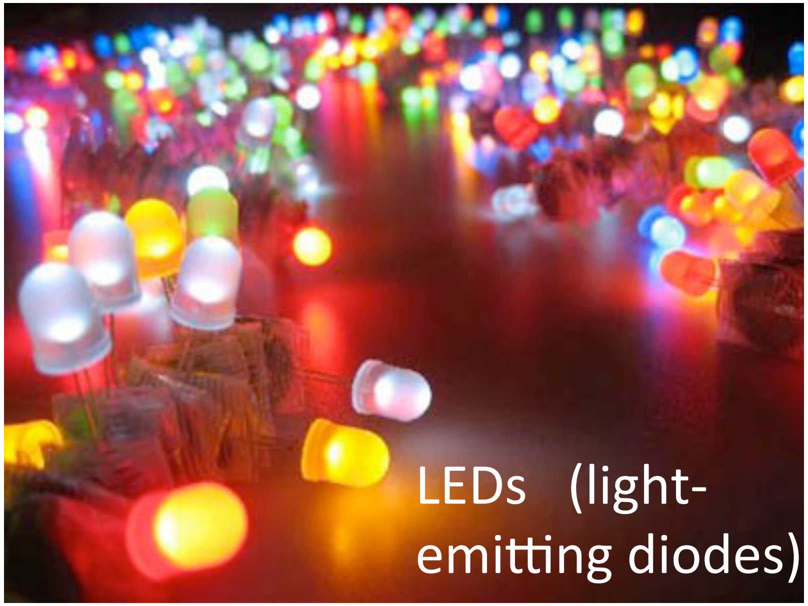
Efficiencies for commercial PV are 10-15%

What is new in the energy field?

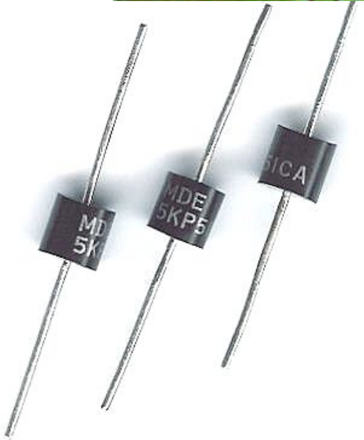
Semiconductors

Transistors





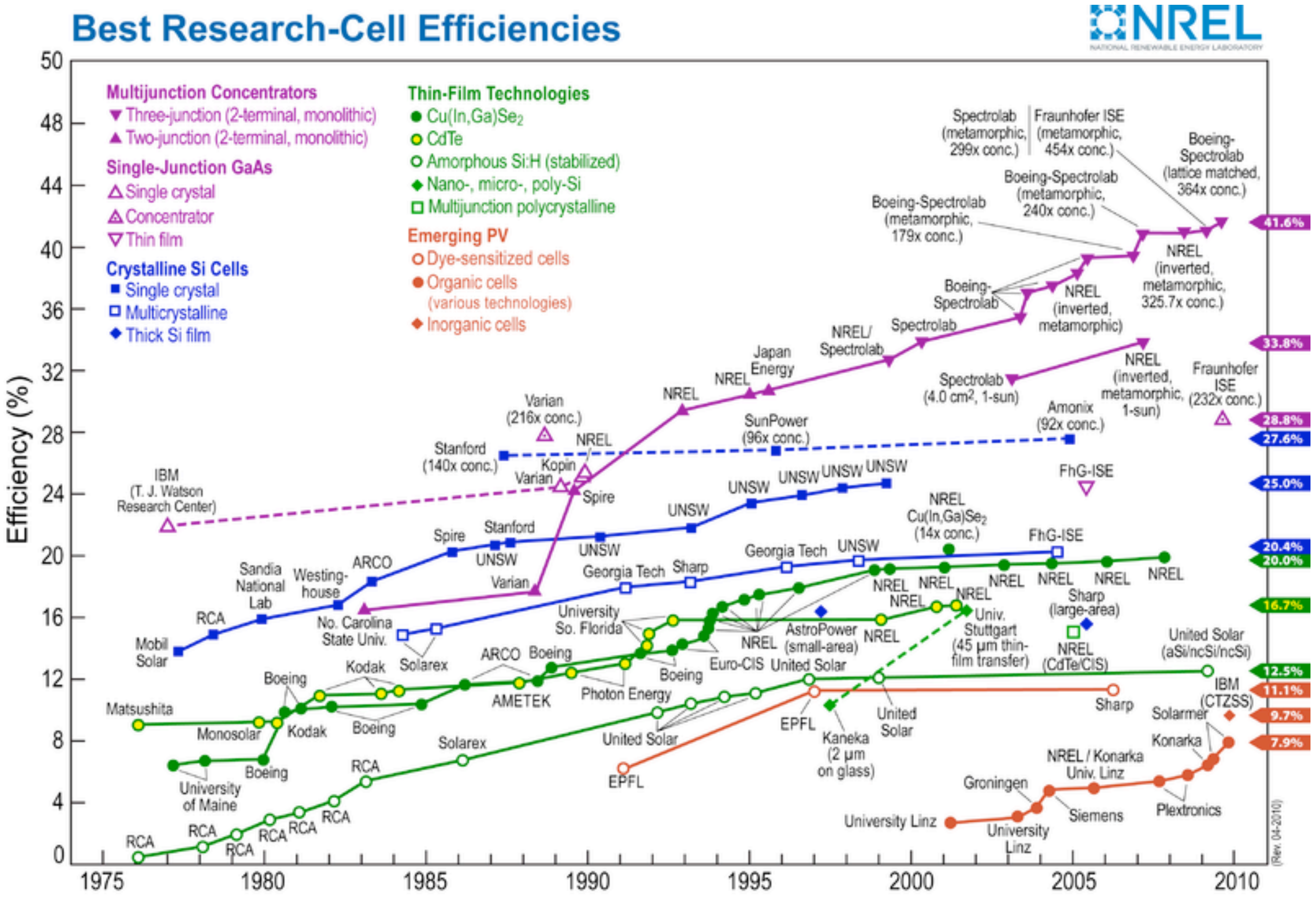
LEDs (light-emitting diodes)



Diodes

Photovoltaics

Solar PV efficiencies: up to > 40% laboratory, 10-15% commercial

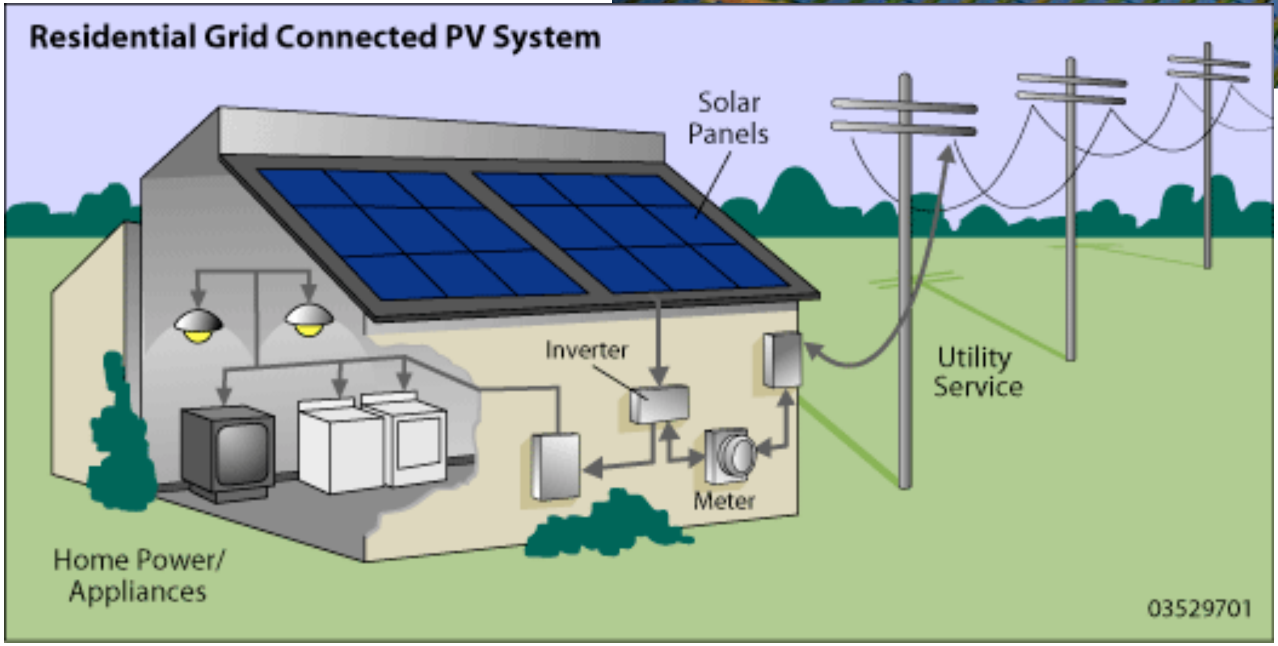


Efficiency not everything; “Thin-film cells are less efficient but cheaper

Solar PV is somewhat scale-independent

can be installed in small or large facilities (x2 cost diff.)

Residential installation typical size 1 kW. Each requires its own inverter



40 MW solar PV farm, Brandis, Germany, built by First Solar, CdTe / CdS on glass (2nd generation cells). Effective subsidy up to 45 euro cents/kWh (subsidy is 10x cost of coal-fired power)

Main barrier to use of solar photovoltaic is economics

Solar panels are more efficient at using sun’s energy than is wind… but are more expensive anyway.

How much would it cost to switch to solar?

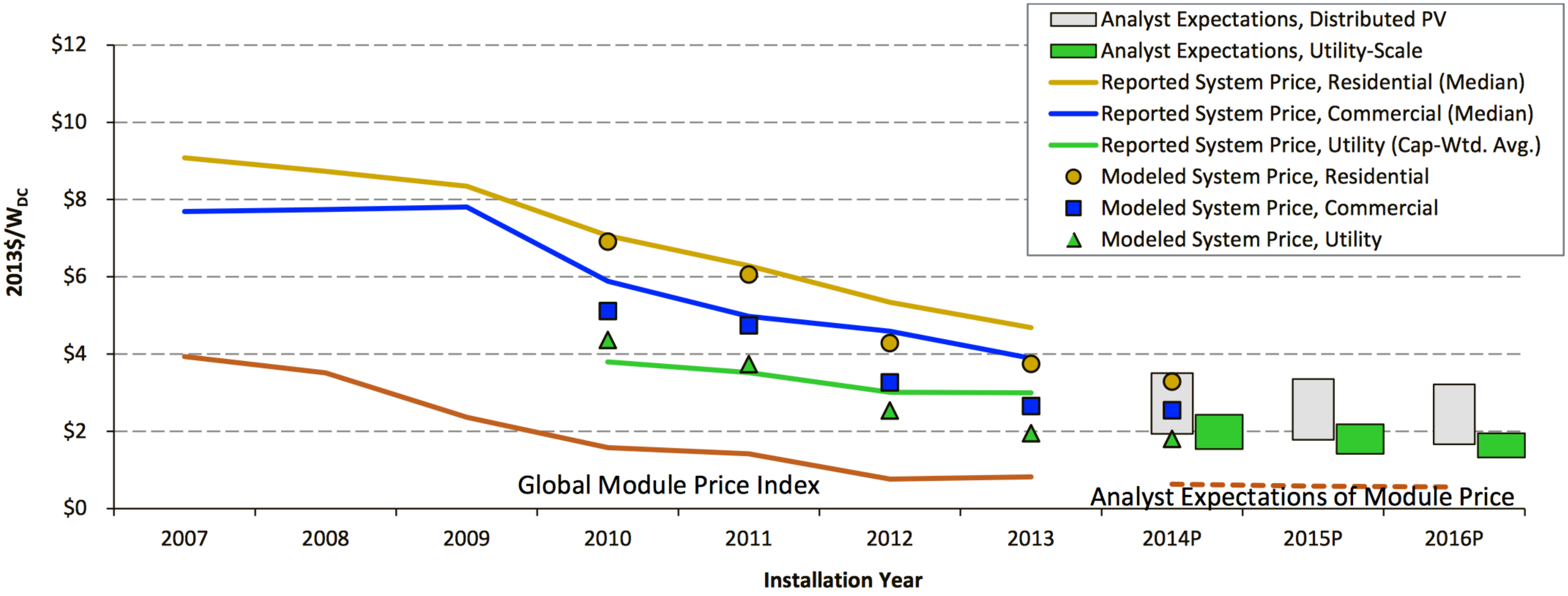
Compare to what we know (some from problem set, class)

coal at ~ $60/ton (6 cents/kg), 30 MJ/kg → ~ **0.7** cents/kWh
natural gas at ~ $4.5/mmBTU x 1mmBTU/ 293 kWh ~ **1.5** cents/kWh
mean wholesale elect. price ~ **4** cents/kWh
new coal or natural gas elect. ~ **6** cents/kWh
onshore wind elect. ~ **6** cents/kWh
solar PV elect. ~**15** cents/kWh
whole economy ~ **60** cents/kWh

If we supplied all our energy needs from solar PV, would need only ½ of current total energy.. but still spend something like 1/8 of GDP!

Current energy sector is about 7% of GDP, converting to solar would ~ double that.

Solar costs dropping – how far before bottoming out?



largest part of cost is installation, that is dropping as well

figure: US DOE

Other problems with solar PV

DC-AC conversion

- added expense

Not near demand

- transmission costs

Intermittency / storage

- added cost - harder to store electricity than heat

Costs may rise if scale up

- materials limitations may be prohibitive

Exotic materials need

- boron, gallium, antimony, arsenic, cadmium, tellurium, indium, selenium

Another problem with solar PV: exotic materials needs

Crystalline Si: purified silicon + silver
Dopants: boron, gallium, arsenic, antimony
Thin-film CdTe: cadmium, tellurium
Thin-film Cu: indium, selenium, gallium

Batteries: cadmium, lithium
Magnets / generation: neodynium
Nuclear power: uranium

NREL projection: 20 GW/yr of new solar PV build (500 GW over lifetime, meeting the U.S.-only electricity needs), would use ½ extractable total by 2060.

NREL, "PV Facts"

Critical limitations in elements if much alternative energy scaled up

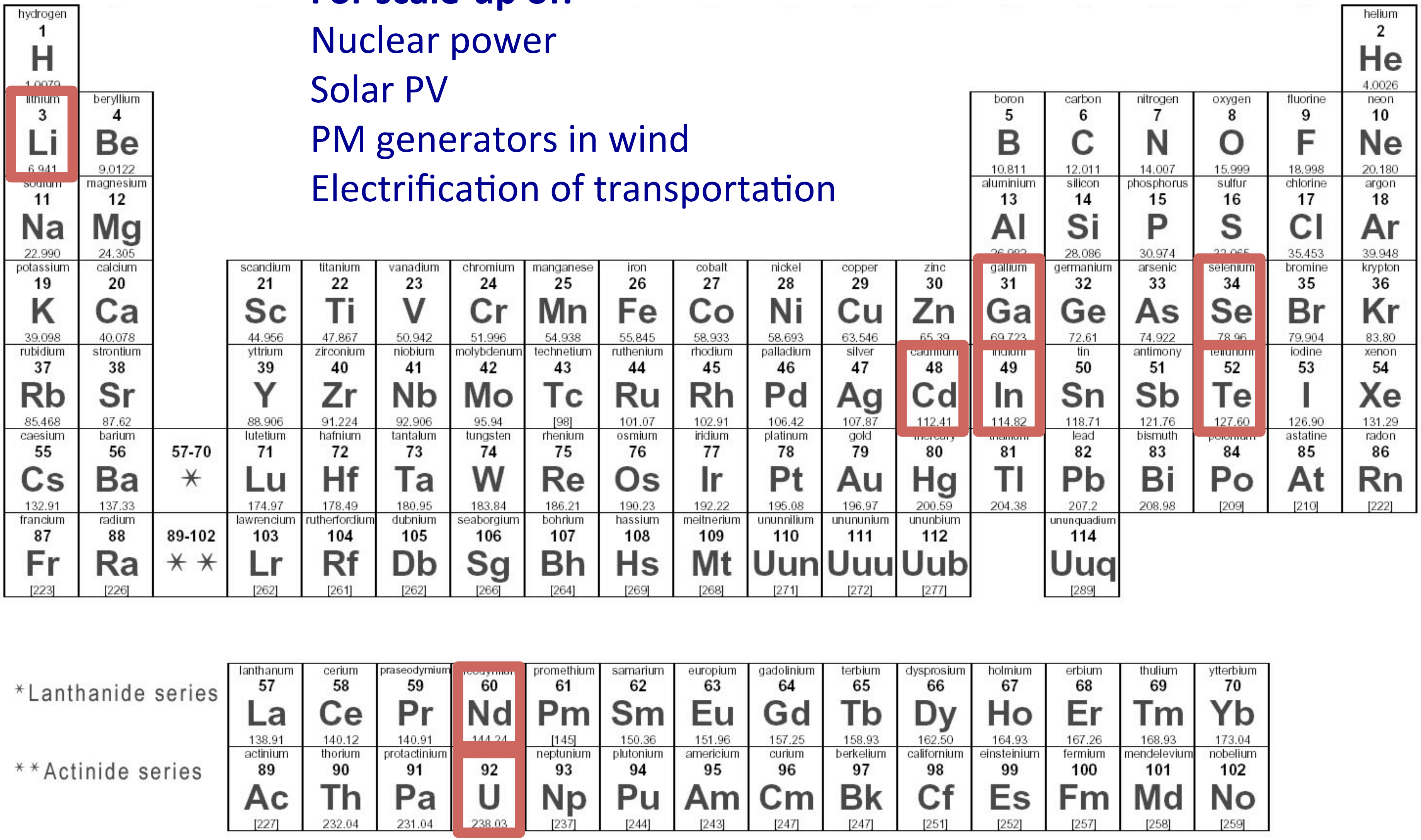
For scale-up of:

Nuclear power

Solar PV

PM generators in wind

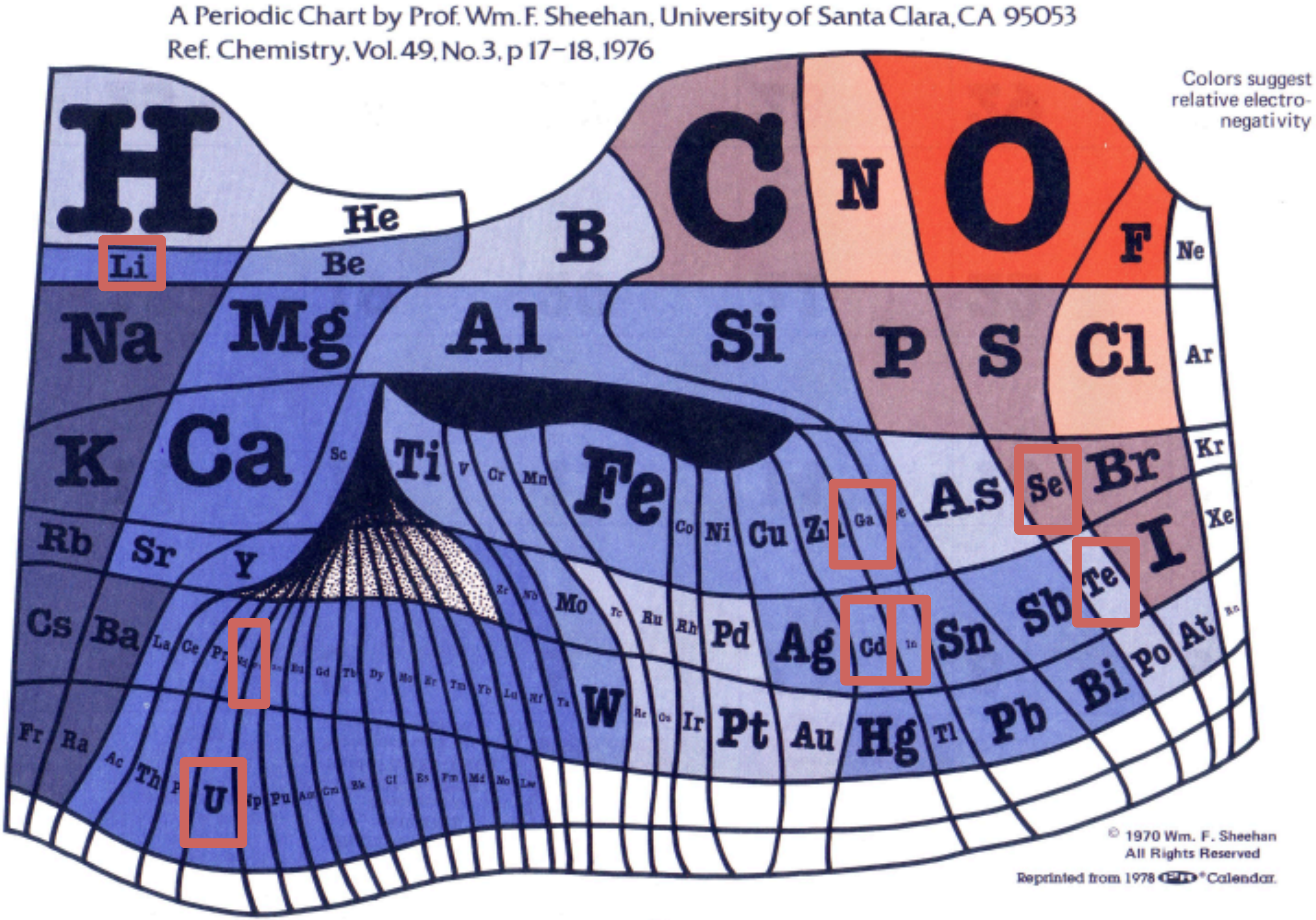
Electrification of transportation



hydrogen 1 H 1.0079																		helium 2 He 4.0026
lithium 3 Li 6.941	beryllium 4 Be 9.0122												boron 5 B 10.811	carbon 6 C 12.011	nitrogen 7 N 14.007	oxygen 8 O 15.999	fluorine 9 F 18.998	neon 10 Ne 20.180
sodium 11 Na 22.990	magnesium 12 Mg 24.305												aluminium 13 Al 26.982	silicon 14 Si 28.086	phosphorus 15 P 30.974	sulfur 16 S 32.065	chlorine 17 Cl 35.453	argon 18 Ar 39.948
potassium 19 K 39.098	calcium 20 Ca 40.078		scandium 21 Sc 44.956	titanium 22 Ti 47.867	vanadium 23 V 50.942	chromium 24 Cr 51.996	manganese 25 Mn 54.938	iron 26 Fe 55.845	cobalt 27 Co 58.933	nickel 28 Ni 58.693	copper 29 Cu 63.546	zinc 30 Zn 65.39	gallium 31 Ga 69.723	germanium 32 Ge 72.61	arsenic 33 As 74.922	selenium 34 Se 78.96	bromine 35 Br 79.904	krypton 36 Kr 83.80
rubidium 37 Rb 85.468	strontium 38 Sr 87.62		yttrium 39 Y 88.906	zirconium 40 Zr 91.224	niobium 41 Nb 92.906	molybdenum 42 Mo 95.94	technetium 43 Tc [98]	ruthenium 44 Ru 101.07	rhodium 45 Rh 102.91	palladium 46 Pd 106.42	silver 47 Ag 107.87	cadmium 48 Cd 112.41	indium 49 In 114.82	tin 50 Sn 118.71	antimony 51 Sb 121.76	tellurium 52 Te 127.60	iodine 53 I 126.90	xenon 54 Xe 131.29
caesium 55 Cs 132.91	barium 56 Ba 137.33	57-70 *	lutetium 71 Lu 174.97	hafnium 72 Hf 178.49	tantalum 73 Ta 180.95	tungsten 74 W 183.84	rhenium 75 Re 186.21	osmium 76 Os 190.23	iridium 77 Ir 192.22	platinum 78 Pt 195.08	gold 79 Au 196.97	mercury 80 Hg 200.59	thallium 81 Tl 204.38	lead 82 Pb 207.2	bismuth 83 Bi 208.98	polonium 84 Po [209]	astatine 85 At [210]	radon 86 Rn [222]
francium 87 Fr [223]	radium 88 Ra [226]	89-102 * *	lawrencium 103 Lr [262]	rutherfordium 104 Rf [261]	dubnium 105 Db [262]	seaborgium 106 Sg [266]	bohrium 107 Bh [264]	hassium 108 Hs [269]	meitnerium 109 Mt [268]	ununnilium 110 Uun [271]	unununium 111 Uuu [272]	ununbium 112 Uub [277]		ununquadium 114 Uuq [289]				

*Lanthanide series	lanthanum 57 La 138.91	cerium 58 Ce 140.12	praseodymium 59 Pr 140.91	neodymium 60 Nd 144.24	promethium 61 Pm [145]	samarium 62 Sm 150.36	europium 63 Eu 151.96	gadolinium 64 Gd 157.25	terbium 65 Tb 158.93	dysprosium 66 Dy 162.50	holmium 67 Ho 164.93	erbium 68 Er 167.26	thulium 69 Tm 168.93	ytterbium 70 Yb 173.04
* *Actinide series	actinium 89 Ac [227]	thorium 90 Th 232.04	protactinium 91 Pa 231.04	92 U 238.03	neptunium 93 Np [237]	plutonium 94 Pu [244]	americium 95 Am [243]	curium 96 Cm [247]	berkelium 97 Bk [247]	californium 98 Cf [251]	einsteinium 99 Es [252]	fermium 100 Fm [257]	mendelevium 101 Md [258]	nobelium 102 No [259]

Critical limitations in elements if much alternative energy scaled up



Environmental consequences to alternative energy

Open-pit mine for uranium, Australia
Photo: Energy Resources of Australia/SkyScans

Open-pit mine for zinc and indium: Red Dog Mine, Canada
Photo: Brodie Lee

Lithium mine, Atacama desert, Chile. (Biggest deposits in Bolivia)Photo: Robin Hammond

Industrial use (very briefly)

Industry: who uses the energy?

Energy use by industrial sector:

- Refining: 30%
- Chemicals: 27%
- Paper: 10%
- Metals: 9%
- Food: 5%

U.S. Energy Information Agency, 2002

Energy cost of materials...

In the first lecture we saw the core relationship \$3-9/yr/W
That is, using 1 W makes \$3-9 of GDP per year

put in common time units to get \$ per energy: 30 MJ -> \$3-9
or 3-10 MJ/\$

But infrastructure is more energy-intensive than the mean economy...
Rule-of-thumb infrastructure energy cost: **14 MJ/\$**

Selected industries:

- Paper: 15 MJ/\$
- Metals: 14
- Chemicals: 8.5
- Machinery: 0.7

U.S. Energy Information Agency, 2002

Calculating embedded energy in products

Example: Aleko 45W max vertical wind turbine for sale for $269 ($6/W)

Rule-of-thumb infrastructure energy cost: 14 MJ/$

→ embedded energy = $269 x 14 MJ/$
→ ~ 3.8 B Joules

Total energy produced in lifetime (say 15 years, 30% capacity factor...optimistic):

→ produced energy = 0.3 B Joules

Small wind turbine takes ~10 x as much energy to make as it could ever produce!

Not all metals are equal in energy cost

There is a reason that we recycle aluminum...

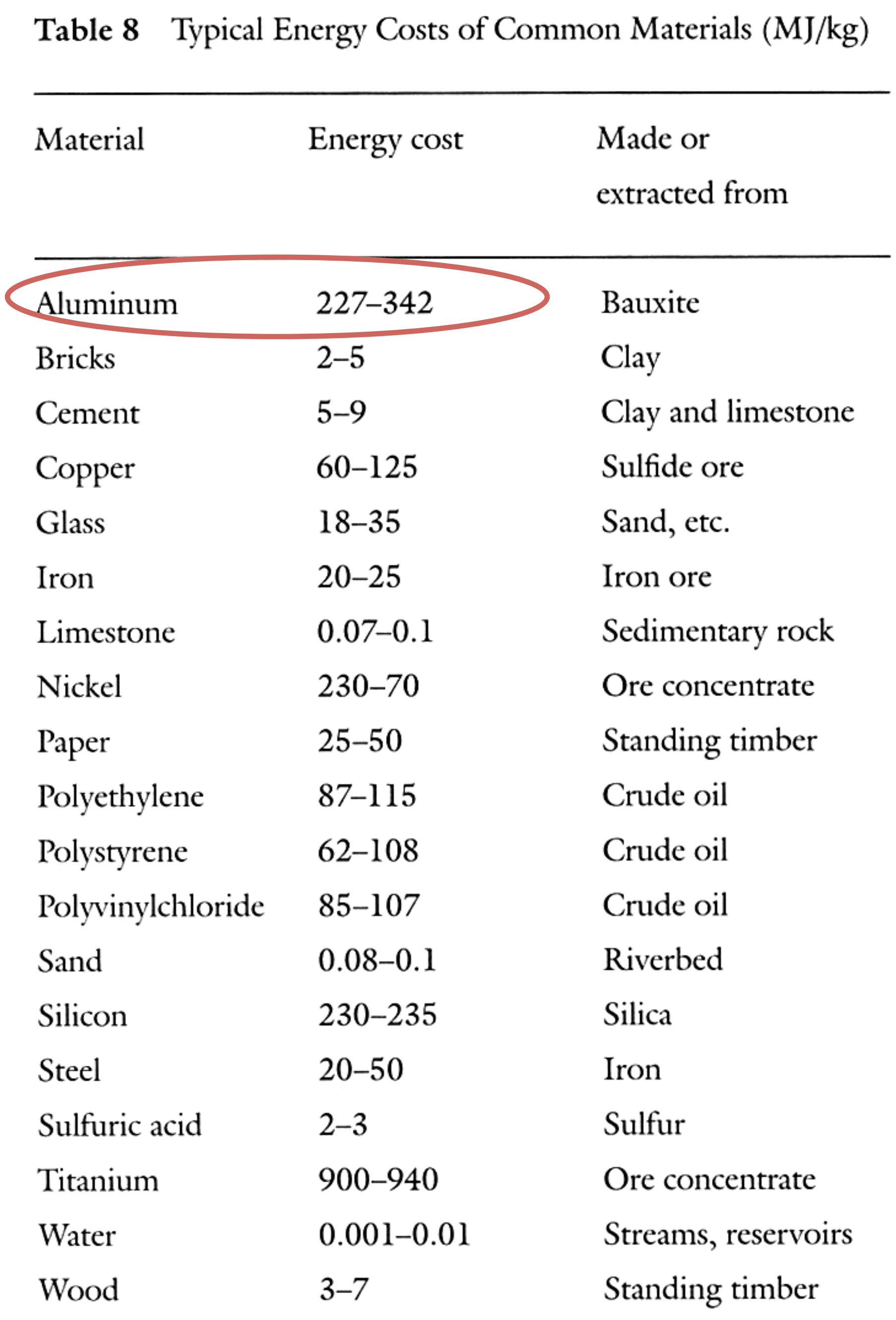


Table 8 Typical Energy Costs of Common Materials (MJ/kg)

Material	Energy cost	Made or extracted from
Aluminum	227–342	Bauxite
Bricks	2–5	Clay
Cement	5–9	Clay and limestone
Copper	60–125	Sulfide ore
Glass	18–35	Sand, etc.
Iron	20–25	Iron ore
Limestone	0.07–0.1	Sedimentary rock
Nickel	230–70	Ore concentrate
Paper	25–50	Standing timber
Polyethylene	87–115	Crude oil
Polystyrene	62–108	Crude oil
Polyvinylchloride	85–107	Crude oil
Sand	0.08–0.1	Riverbed
Silicon	230–235	Silica
Steel	20–50	Iron
Sulfuric acid	2–3	Sulfur
Titanium	900–940	Ore concentrate
Water	0.001–0.01	Streams, reservoirs
Wood	3–7	Standing timber
Fertilizer	70	

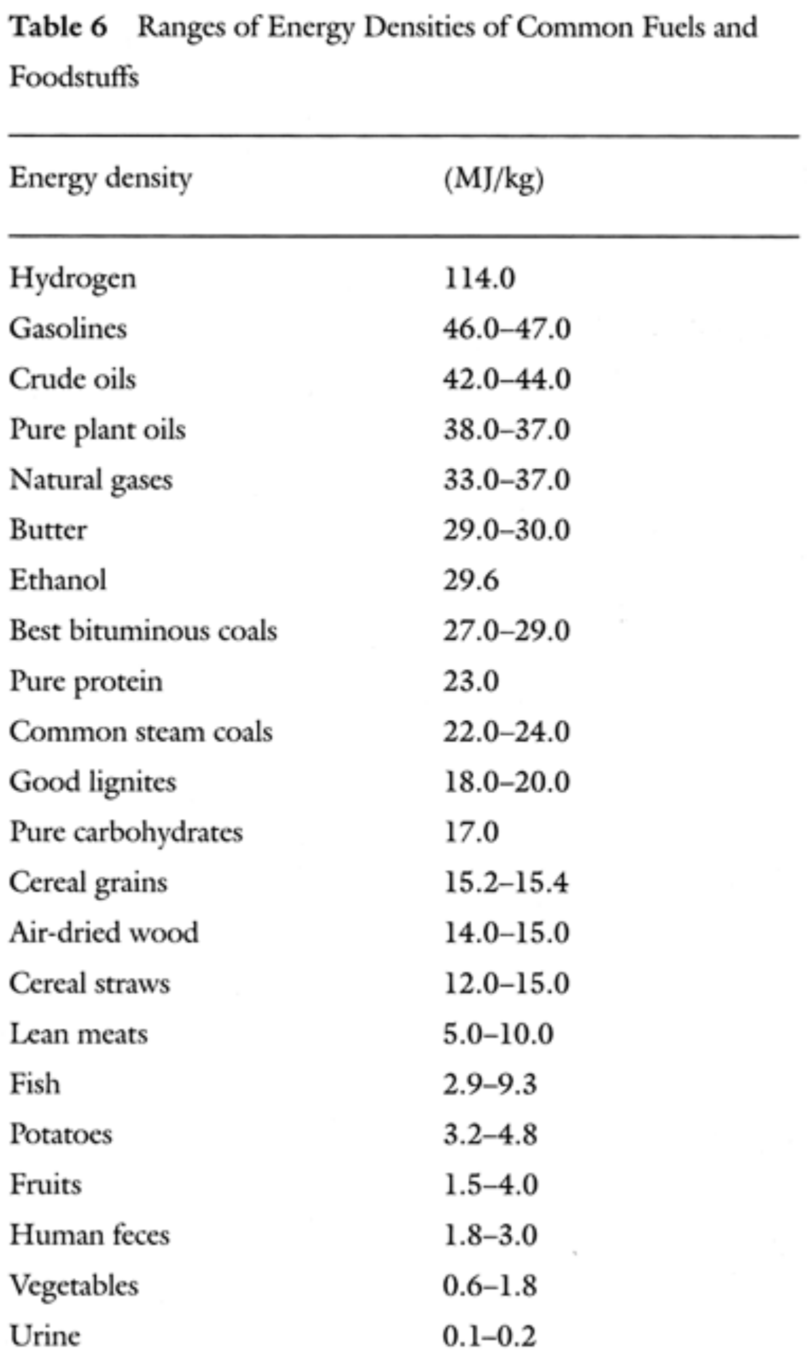


Table 6 Ranges of Energy Densities of Common Fuels and Foodstuffs

Energy density	(MJ/kg)
Hydrogen	114.0
Gasolines	46.0–47.0
Crude oils	42.0–44.0
Pure plant oils	38.0–37.0
Natural gases	33.0–37.0
Butter	29.0–30.0
Ethanol	29.6
Best bituminous coals	27.0–29.0
Pure protein	23.0
Common steam coals	22.0–24.0
Good lignites	18.0–20.0
Pure carbohydrates	17.0
Cereal grains	15.2–15.4
Air-dried wood	14.0–15.0
Cereal straws	12.0–15.0
Lean meats	5.0–10.0
Fish	2.9–9.3
Potatoes	3.2–4.8
Fruits	1.5–4.0
Human feces	1.8–3.0
Vegetables	0.6–1.8
Urine	0.1–0.2

From: Vaclav Smil, "Energies"

All metals production involves heat (smelting)

Must separate a pure metal from its ore

Always involves a change in oxidation state (from oxide or sulfide)

Typically uses high heat and a reducing agent (iron: T to 2300 C, 4200 F)

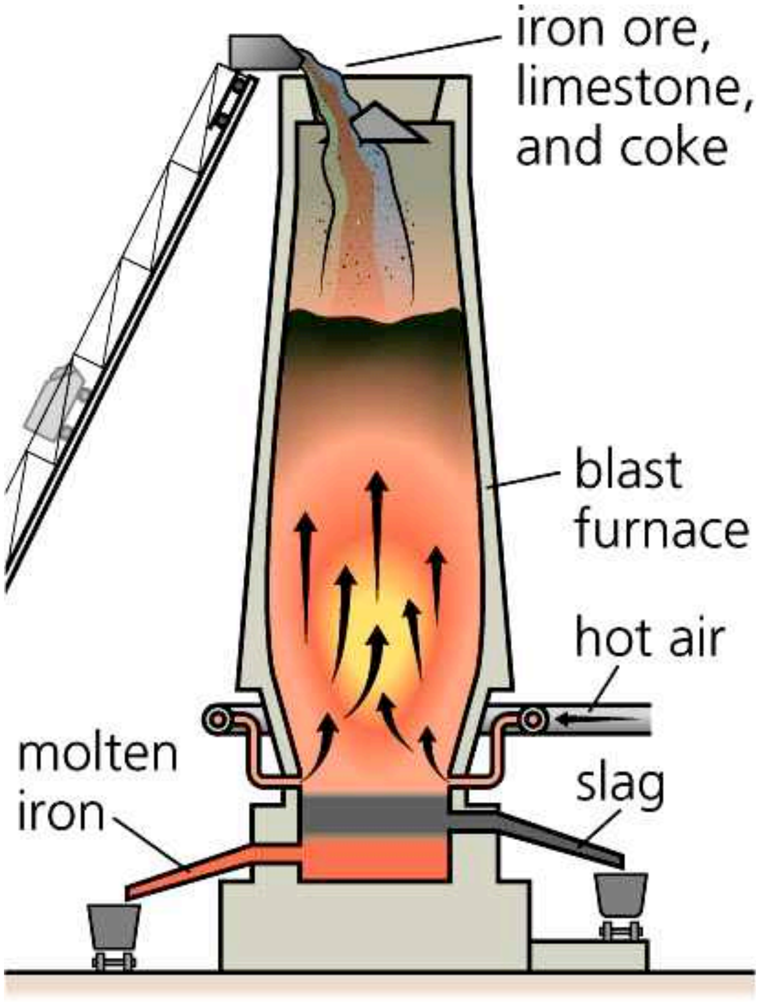
Iron: Fe_2O_3 -> Fe

Copper: $CuCO_3$ -> Cu

Lead: PbS -> Pb

Left: Blast furnace "pour". Photo from Brock Solutions

Right: Blast furnace schematic. Figure from Wealden Iron



Aluminum involves electrochemical smelting

Aluminum oxide bonds are too tight to break in normal smelting

Insanely expensive til invention of Hall-Heroult process

- Invented 1880's: Alumina crystals dissolved in molten cryolite (sodium, aluminium, fluorine) at 1760 F (960 C). Electric current (> 100,000 A at ~5V) is passed directly through molten cryolite.

Pure molten aluminum is collected at bottom of vessel

Manam, Bahrein, world's 3rd largest Al smelter

Photo from: Manufactured Landscapes

Summary: lessons from class

We can’t conserve our way out of an energy crisis

Energy is tightly tied to GDP.

Current 2%/year growth in energy use means doubling time for energy use ~ 30 yrs

Slashing energy use per GDP by a factor of two buys us just 30 years...can’t outweigh enormous growth in developing world.

Just powering the world will be difficult – switching from fossil fuels is an additional complication

Most energy technology is very old

1870's-1910	**Newer**
Hydro turbine (1848) *(a bit earlier)* Steam turbine (1884)	*Semiconductors, transistors, diodes, and all their offspring:*
AC generator and transformer (1888)	Light-emitting diodes (LEDs)
3-phase power transmission (1895 demo)	Solar photovoltaics
Induction motor (1885-1888)	Computers & electronics
Incandescent bulb (1880 commercialized)	Brushless DC motors
Internal combust. engine: Otto cycle (1876)	FACTS grid control
Internal combust. engine: Diesel cycle (1892)	DC transformers, HVDC transmiss.
Automobile (1885)	*also*
Air conditioner (1902)	Nuclear power generation
Airplane (1903)	
Hall–Héroult: aluminum (1888)	
Haber-Bosch: N fixation (1908)	

Also: phonograph (1877), telephone (18 76), movies (1877,1895), photographic film (1884), radar (1887)

Barriers to powering the world with CO_2-free energy aren't physical but economic

There is enough energy to power an advanced economy without resorting to fossil fuels

For a 2x population world as rich as the present U.S., requires ~ 10 W/m^2 or 5% conversion of mean solar flux

Current solar technologies easily exceed that target. Wind doesn't, but can contribute.

But, renewables are more expensive than fossil at present. And history shows that switching energy technology typically takes ~ 50 years.