Fossil Fuels

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Outline

The difficulty in figuring out exactly what fossil fuels are

- Because their separation from petroleum is neither simple nor specific

How we now use fossil fuels

- Including transportation's addiction to their stunningly high "energy densities"

Identifying the fossil fuels releasing the most combustion heat per amount of CO_2 liberated

Identifying the power plant technologies best at converting that heat into electricity:

- For coal: "Conventional" vs. "Ultra-supercritical" vs. "IGCC" power plants
- For natural gas: Single turbine "OCGT" vs. Dual Turbine "CCGT" power plants

The environmental impacts of fossil fuel extraction, including:

- Coal mining vs. strip mining vs. mountaintop removal
- Fracking's use of unmonitored chemicals, their "disposal" and role in earthquakes
  - And the subsequent accidental/negligent release of greenhouse bad guy, methane

(Written / Revised: July 2023)

Fossil Fuels

This note set is **primarily** about the use of fossil fuels in electrical energy production

But it also provides essential background and perspective for later note sets on

Biomass & Biofuels (pptx / pdf / key) & **Transportation** (pptx / pdf / key)

The common thread is the use of what we call **hydrocarbons**, so named

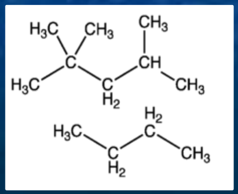
because they consist of complex carbon-carbon chain and ring structures,

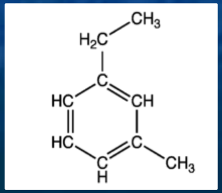
decorated primarily (but not exclusively) with H and O (as found in water)

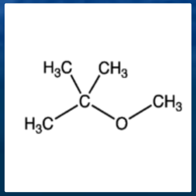
But beyond that, explanations quickly become frustratingly vague and complex

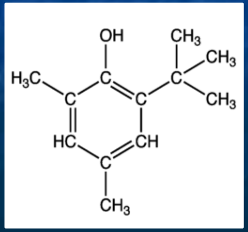
For instance, try asking Wikipedia: **What is gasoline?**

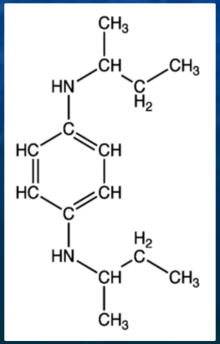
Their **still incomplete answer** spans multiple paragraphs & diagrams:











Why the complexity? Why the apparent confusion?

Most hydrocarbons are synthesized from simpler hydrocarbons [1]

Either by nature (=> fossil fuels), or at least partially by man (=> biofuels)

By either route, chemical synthesis is a surprisingly sloppy process

which very seldom creates just **one single type** of molecule

To produce a single type of molecule, human chemists spend **most** of their time

trying to separate **desired** products from **undesired** products,

using a long list of purification methods (often repeated over and over) [2]

Mother Nature generally doesn't bother to sort things out, producing instead a

gooey black mess containing hundreds (if not thousands) of different molecules

1) To view my "Cheat Sheet" explaining organic chemistry's terminology, click HERE

2) To view my tutorial on Molecular Self Assembly (from this website's Nanoscience section) click HERE

Sorting things out often depends upon "Van der Waals" bonding

In which electrons are **not shared** between atoms (as in covalent or ionic bonds)

Instead, Van der Waals "bonding" is more "mutual attraction at a slight distance"

Atoms start out with equal numbers of protons and electrons,

with those negative electrons arranged in clouds around the positive nucleus

Which could be simply represented at this: 

But at common temperatures electrons dance around, so at one instant

that atom might look like this:  and an instant later like this: 

That atom has neither gained nor lost charge, so it remains neutral

But its opposite charges are **no longer centered on the same point**

And the atom has thus become a **dipole** which can be represented as:

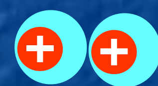
This: (+-) Changing an instant later to this: (-+)

But while "like charges repel and unlike charges attract"

That repulsion and attraction diminishes rapidly with distance, with the result

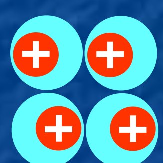
that **polarized** charge arrangements attract: (+-)(+-) Or: (+-)
(-+)

Thus electrically neutral but synchronously polarized ATOMS can attract:

As this:  Or this: 

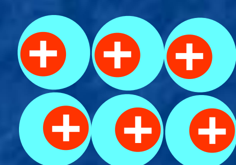
As can MOLECULES, for which attraction increases with molecular size:

Some attraction:



(+-) (+-)
(-+) (-+)

More attraction:



(+-)(+-)(+-)
(-+)(-+)(-+)

Much more attraction

(+-)(+-)(+-)(+-)
(-+)(-+)(-+)(-+)

Proof can be seen in the boiling points of similarly structured molecules:

Alkanes:	**Alcohols:**	**Amines:**
$CH_3CH_2CH_3$	CH_3CH_2OH	$CH_3CH_2NH_2$
-42.1 ºC	**78 ºC**	**16.6 ºC**
$CH_3CH_2CH_2CH_3$	$CH_3CH_2CH_2OH$	$CH_3CH_2CH_2NH_2$
0.5 ºC	**97.4 ºC**	**47.8 ºC**
$CH_3CH_2CH_2CH_2CH_3$	$CH_3CH_2CH_2CH_2OH$	$CH_3CH_2CH_2CH_2NH_2$
36.1 ºC	**117.3 ºC**	**77.8 ºC**

Within a family (column) of molecules: **The longer the chain, the higher the BP**

Between families (columns): Charges polarize differently, BP's shift up or down

A more descriptive name for Van der Waals bonding?

"INDUCED-DIPOLE BONDING"

*Which provides the basis for **Fractional Distillation***

Which is the boiling, and then selective re-condensation, of molecules

Which can separate molecules of strongly differing complexity

based on the differing NET strength of their Van der Waals "bonds"

Which is what is going on inside about half of this oil refinery's tall ugly towers:

Left: https://www.thenational.ae/business/india-expands-crude-oil-refinery-capacity-1.154077

Right: http://resources.schoolscience.co.uk/exxonmobil/knowl_old/2/pics/p_still.html

Explained schematically:

LEFT: Crude (raw) oil is heated in a furnace (its smokestack => the other towers)

More complex molecules remain liquid due to stronger Van der Waals bonding

Less complex molecules vaporize due to their weaker Van der Waals bonding

RIGHT: Vapors and hot liquids are driven into the fractional distillation tower

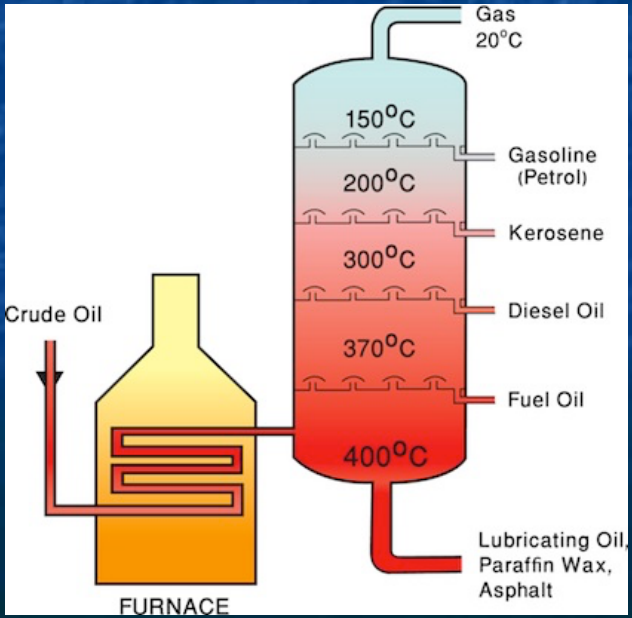
Liquids fall to the bottom and are collected

Vapors are driven up through openings in a series of stacked shelves ("trays")

which are progressively cooler based on their

increasing separation from the furnace

http://www.emec.com.eg/products-services/production-chemicals/oil-refinery-chemicals

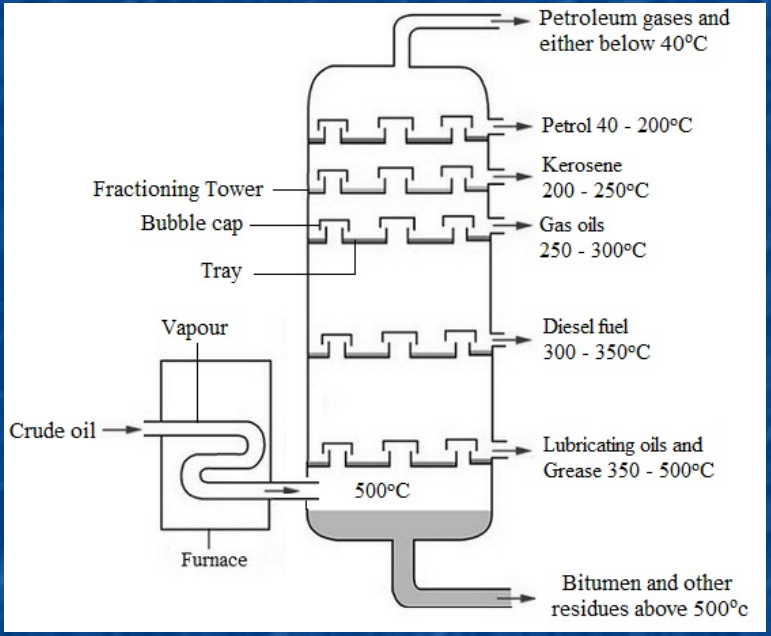


A particular molecular vapor rises until:

It passes through a shelf cooler than its boiling point,

at which point that molecule liquefies, joining any other liquids on that shelf,

which are then siphoned off through that shelf's drain



http://www.tutorsglobe.com/homework-help/chemistry/introduction-to-petroleum-chemistry-76647.aspx

More complex molecules (w/ more carbon) are picked off at lower shelves

Less complex molecules (w/ less carbon) at progressively higher shelves

*So while **this** tower's 2nd shelf is labeled "Diesel Oil"*

Its exiting **Diesel Oil** is **not one thing!** It is instead:

Molecules with comparable Van der Waals bonding and thus similar boiling points

Which typically includes molecules with **8-21** carbon atoms [1]

Similarly, the **Kerosene** shelf collects assorted molecules

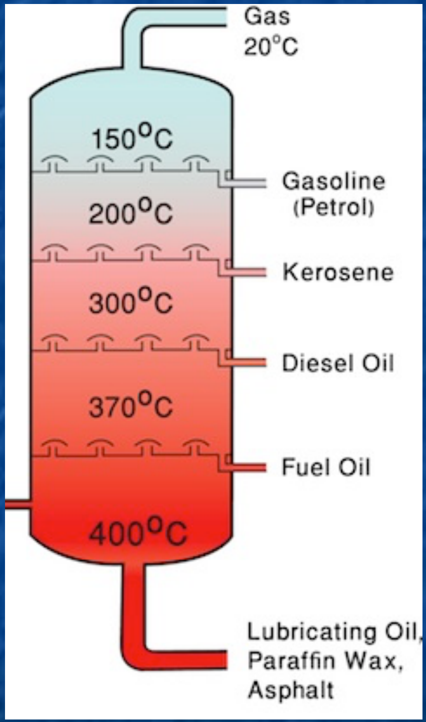
that typically incorporate **10-16** carbon atoms [2]

As the **Gasoline** shelf collects assorted molecules

that typically incorporate **4-12** carbon atoms [3]

Further refining can change that exact 4-12 carbon mixture

Producing gasoline of differing "octane" (~energy) content

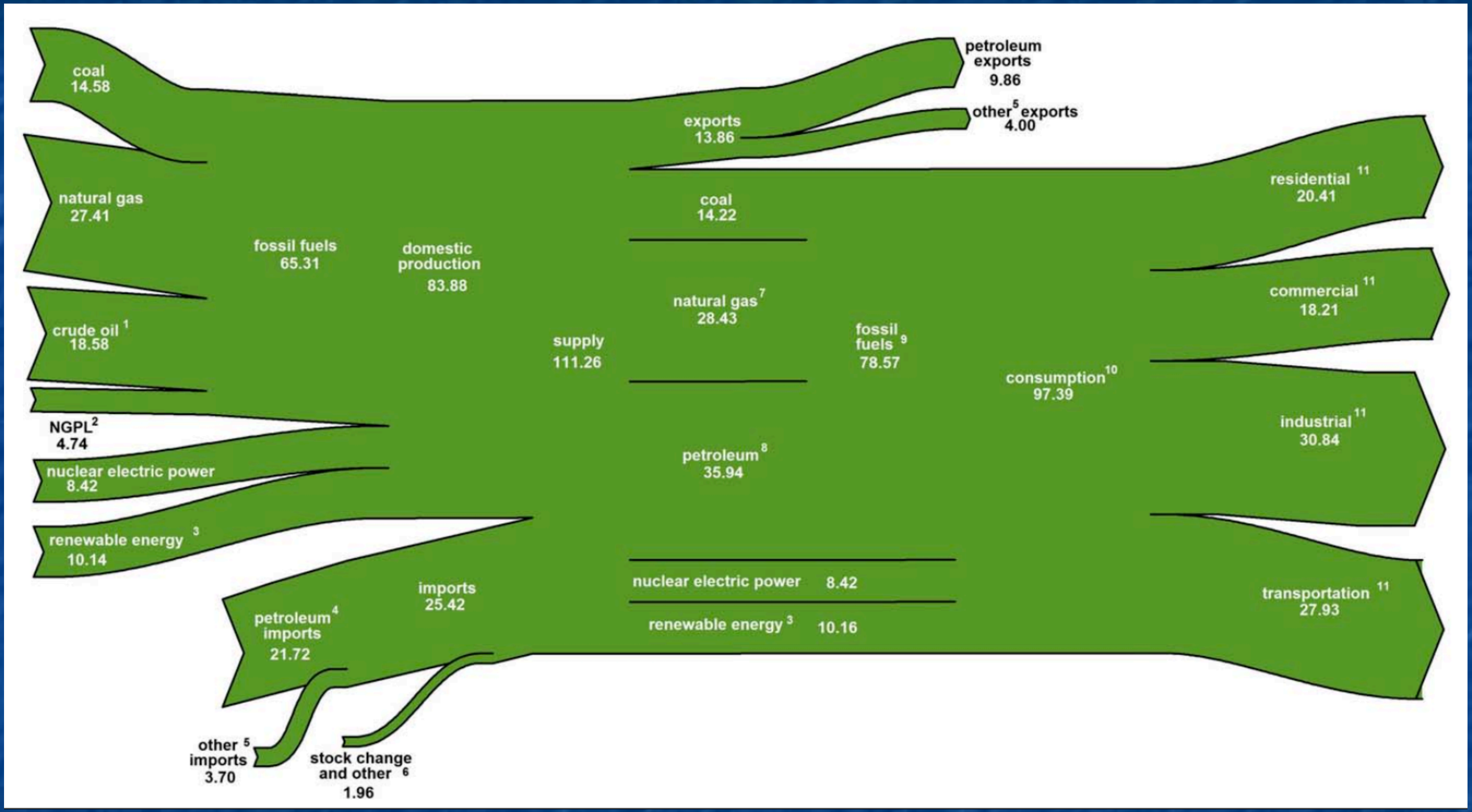


Hence the ambiguous explanations of WHAT a particular fossil fuel IS!

1) https://en.wikipedia.org/wiki/Diesel_fuel 2) https://en.wikipedia.org/wiki/Kerosene 3) https://en.wikipedia.org/wiki/Gasoline

How much of each fossil fuel do we now use? And how do we use it?

The U.S. Energy Information Administration (EIA) plots our 2016 "Energy Flow" as:



https://www.eia.gov/totalenergy/data/monthly/pdf/flow/total_energy.pdf

This boggling figure identifies our fossil fuel sources

But it fails to identify exactly how each is used

Another EIA webpage at least breaks down our use of petroleum: [1]

Petroleum products consumed in 2016

Product	Annual consumption (million barrels per day)
Finished motor gasoline[1]	9.317
Distillate fuel oil (diesel fuel and heating oil)[1]	3.877
Hydrocarbon gas liquids (HGL)	2.536
Kerosene-type jet fuel	1.614
Still gas	0.697
Asphalt and road oil	0.351
Petroleum coke	0.345
Residual fuel oil	0.326
Petrochemical feedstocks	0.323
Lubricants	0.130
Miscellaneous products and others[2]	0.096
Special napthas	0.049
Finished aviation gasoline	0.011
Kerosene	0.009
Waxes	0.006
Total petroleum products	**19.687**

But EIA elsewhere claims that natural gas is more important:

> "In 2016, most of the HGL (hydrocarbon gas liquids) produced in the United States (85%) were byproducts of natural gas processing, and the remaining 15% were from crude oil refineries" [2]

The same webpage then admits it doesn't track natural gas:

> "Because the petrochemical industry has a high degree of flexibility in the feedstock it consumes and because EIA does not collect detailed data on this aspect of industrial consumption, it is not possible for EIA to identify the actual amounts and origin of the materials used as inputs by industry to manufacture plastics."

1) https://www.eia.gov/energyexplained/index.cfm?page=oil_use (yellow highlighting added)

2) https://www.eia.gov/tools/faqs/faq.php?id=34&t=6

The "Institute for Energy Research" is a bit more forthcoming:

It breaks down our use of oil and natural gas use as follows: [1]

Oil:

45.3% - Gasoline for cars

29.8% - Heating oil & diesel fuel

19.4% - Chemicals, rubbers & plastics

9.7% - Jet fuel

2.1% - Asphalt

Natural Gas:

33% - Industrial

35% - Electrical Power

17% - Residential

12% - Commercial

3% - Transportation

But IER only notes that coal: "remains a major contributor to the world's energy pool"

A more complete profile of U.S. fossil fuel use could be assembled

by correlating data from this and the preceding 2 slides

1) https://instituteforenergyresearch.org/topics/encyclopedia/fossil-fuels/

But even without that correlation:

My yellow highlighting makes one thing very clear:

We use a VERY LARGE FRACTION of our fossil fuels for transportation

Likely more than we now use for electrical power generation

Why are transportation vehicles so enamored with fossil fuels? Because:

Highway vehicles go much farther with light and compact energy sources

Aircraft only get off the ground with **extremely** lightweight energy sources

Discussing "Why We Love Oil" in **Physics for Future Presidents**, Robert A. Muller [1]

put this into perspective by comparing the energies per mass

of many different energy sources with that of gasoline

I offer you my expanded and updated comparison on the next page:

1) Pages 66-71, Physics for Future Presidents by Robert A. Muller, Norton & Company, New York (2008)

Energy density of fuels / would-be fuels / energy sources: [1]

Substance		Energy / Mass			Energy / Volume		
	Specifics:	MJ / kg	kW-h / kg	Ratio to Gasoline	MJ / liter	kW-h / liter	Ratio to Gasoline
Hydrogen Gas (H_2) at 20°C	150 Atm. gas *	142	39.4	**3.1**	1.79	0.50	**0.05219**
	1 Atm. gas	142	39.4	**3.1**	0.0119	0.0033	**0.00035**
Methane Gas at 15°C	150 Atm. gas *	55.6	15.4	**1.2**	5.67	1.58	**0.1658**
	1 Atm. Gas	55.6	15.4	**1.2**	0.0378	0.011	**0.0011**
Natural Gas at 15°C	150 Atm. gas *	53.6	14.9	**1.16**	5.46	1.5	**0.1596**
	1 Atm. gas	53.6	14.9	**1.16**	0.0364	0.010	**0.0011**
Propane LPG	Liquid	49.6	13.8	**1.1**	25.3	7.03	**0.74**
Diesel Fuel	Liquid	45.6	12.7	**1.0**	38.6	10.7	**1.13**
Gasoline	**Liquid**	**46.4**	**12.9**	**1.0**	**34.2**	**9.5**	**1**
Jet Fuel (Kerosene)	Liquid	43	11.9	**0.93**	35	9.7	**1.02**
Fat	Animal or Vegetable	37	10.3	**0.80**	34	9.4	**0.99**
Coal	Anthracite or Bituminous	30	8.3	**0.65**	38	10.6	**1.11**
Carbohydrates	Including Sugars	17	4.7	**0.37**			
Ammonia	Liquid	16.9	4.7	**0.36**	11.5	3.2	**0.336**
Protein		16.8	4.7	**0.36**			
Wood		16.2	4.5	**0.35**	13	3.6	**0.380**
TNT		4.61	1.3	**0.10**	6.92	1.9	**0.202**
Gun Powder		3	0.8	**0.065**			
Lithium (Mn) Metal Battery		1.01	0.28	**0.022**	2.09	0.6	**0.061**
Lithium Ion Battery		0.72	0.20	**0.016**	3.6	1.00	**0.105**
Flywheel		0.50	0.14	**0.011**			
Alkaline Battery		0.59	0.16	**0.013**	1.43	0.40	**0.042**
Nickel Metal Hydride Battery		0.40	0.11	**0.0086**	1.55	0.43	**0.045**
Lead Acid Battery		0.14	0.039	**0.0030**	0.36	0.10	**0.011**
Super Capacitor		0.020	0.006	**0.0004**	0.050	0.014	**0.0015**
Capacitor		0.002	0.001	**0.00004**			
** Effective Energy / Mass is as much as 100 times smaller for high-pressure gas in heavy tanks*				*Table source: https://WeCanFigureThisOut.org/ENERGY/Energy_home.htm*			

1) Drawn from notesets: Fossil Fuels (pptx / pdf / key), Batteries & Fuel Cells (pptx / pdf / key), Hydrogen Economy (pptx / pdf / key)

*Highlighting differences by approximating those **ratios to gasoline**:*

	Energy / Mass	Energy / Volume
Hydrogen (at 1 atm. of pressure)	3	1/3000
Gasoline / Diesel / Jet Fuel	**1**	**1**
Fat / Coal	3/4	1
Carbohydrates / Protein / Wood	1/3	1/2
High Explosives	1/12	-
Lithium Ion Batteries	1/60	1/12
Flywheels	1/100	-
Conventional Batteries	1/150	1/50
Super Capacitors	1/2000	1/600
Capacitors	1/200000	1/40000

The big takeaway from the last half dozen slides?

Fossil fuels are not going to magically disappear!

We will instead remain HUGELY dependent on them because of:

Their use in producing chemicals, plastics and rubbers

Their use in ground transportation

At least until battery energy density & lifetime are significantly improved

Their use in air transportation

Where our very best battery energy densities are still **25 to 75 times too low**

And, for fundamental scientific reasons, are likely to remain too low

(As explained in my subsequent note sets on batteries & fuel cells)

Where massive high-pressure hydrogen tanks would be similarly unacceptable

And where I can't see fat, coal, carbohydrate, protein or wood ever working out!

So rather than just wishing fossil fuels away

Let's now study:

How fossil fuels are NOW used in electrical energy production

How that fossil fuel use might be reduced in the future AND/OR

How the environmental impact of that use might be mitigated

Electric power plants burn fossil fuels to produce heat:

Creating steam, propelling turbine generators (see **Generic Power Plant & Grid** (pptx / pdf / key))

To reduce fossil fuel use AND/OR mitigate environmental impact, power plants need

fuels producing more heat energy per undesirable combustion product

Where one of the most undesirable combustion products is CO_2

Electrical energy output per CO_2 output can be increased by either:

- **Using fossil fuels that RELEASE MORE heat energy per CO_2 product**
- **Using technologies that better CONVERT heat into electricity**

Fossil fuels that

RELEASE MORE heat energy per CO_2 product

For this we've got to revisit high school chemistry:

And resurrect some of its oh-so-many rules

(Which I WILL try to soften by omitting much of their arcane terminology)

RELEVANT RULES:

1) For a chemical bond to form, energy must be released: X + Y => X-Y + energy

2) For an existing bond to break, energy must be added: X-Y + energy => X + Y

3) These energies vary with the identity of the bonding atoms (X, Y)

4) These energies vary with the type of bond: single / double / triple

5) These energies vary more subtly with whatever bonds are nearby

6) To get an approximate, but likely still adequate answer, **ignore rule 5**

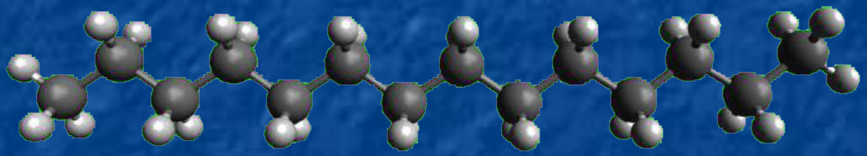
Using this to calculate heat energy release from simple fossil fuels:

The simplest, and often most concentrated hydrocarbons are **alkanes** [1]

which are also sometimes called (hydrogen) "saturated fats" or "paraffins"

which are just C-C-C-C chains (of various lengths) with hydrogens attached

Carbon's propensity for 4 symmetrically arrayed bonds leads to structures such as:



The types of bonds / energies relevant to combustion of alkanes by oxygen:

Bonds that must be broken:

C-C ΔE = 347 kJ/mole (83 kcal/mole)

C-H ΔE = 413 kJ/mole (98.7 kcal/mole)

O=O ΔE = 495 kJ/mole (118.9 kcal/mole)

Bonds that can then be made:

C=O ΔE = 799 kJ/mole (192 kcal/mole)

H-O ΔE = 467 kJ/mole (111 kcal/mole)

1) To view my "Cheat Sheet" explaining organic chemistry's terminology, click HERE

The rest is just bookkeeping:

Counting up the energies of all bonds that will be **made** during combustion

Subtracting the energies of all bonds that will be **broken** during combustion

All of which I found much easier to keep track of in a spreadsheet [1]

Input data and evaluation of combustion reactions in that spreadsheet:

n	ALKANE		Molecular Weight (g)	Melting Point (C)	Melting Point (K)	Boiling Point (C)	Boiling Point (K)	Combustion Reaction	Number of Bonds — Reactants: C-C	C-H	O=O	Products: C=O	H-O
1	Methane	CH4	16.03	-183	90.2	-164	109.2	CH4 + 2 O2 = CO2 + 2 H2O	0	4	2	2	4
2	Ethane	C2H6	30.05	-183	90.2	-89	184.2	C2H6 + 3.5 O2 = 2 CO2 + 3 H2O	1	6	3.5	4	6
3	Propane	C3H8	44.06	-190	83.2	-42	231.2	C3H8 + 5 O2 = 3 CO2 + 4 H2O	2	8	5	6	8
4	Butane	C4H10	58.08	-138	135.2	-0.5	272.7	C4H10 + 6.5 O2 = 4 CO2 + 5 H2O	3	10	6.5	8	10
5	Pentane	C5H12	72.10	-130	143.2	36	309.2	C5H12 + 8 O2 = 5 CO2 + 6 H2O	4	12	8	10	12
6	Hexane	C6H14	86.11	-95	178.2	69	342.2	C6H14 + 9.5 O2 = 6 CO2 + 7 H2O	5	14	9.5	12	14
7	Heptane	C7H16	100.13	-91	182.2	98	371.2	C7H16 + 11 O2 = 7 CO2 + 8 H2O	6	16	11	14	16
8	Octane	C8H18	114.14	-57	216.2	125	398.2	C8H18 + 12.5 O2 = 8 CO2 + 9 H2O	7	18	12.5	16	18
9	Nonane	C9H20	128.16	-51	222.2	151	424.2	C9H20 + 14 O2 = 9 CO2 + 10 H2O	8	20	14	18	20
10	Deacane	C10H22	142.18	-30	243.2	174	447.2	C10H22 + 15.5 O2 = 10 CO2 + 11 H2O	9	22	15.5	20	22
11	Undecane	C11H24	156.19	-25	248.2	196	469.2	C11H24 + 17 O2 = 11 CO2 + 12 H2O	10	24	17	22	24
12	Dodecane	C12H26	170.21	-10	263.2	216	489.2	C12H26 + 18.5 O2 = 12 CO2 + 13 H2O	11	26	18.5	24	26
13	Tridecane	C13H28	184.22			234.00	507.2	C13H28 + 20 O2 = 13 CO2 + 14 H2O	12	28	20	26	28
14	Tetradecane	C14H30	198.24			253.50	526.7	C14H30 + 21.5 O2 = 14 CO2 + 15 H2O	13	30	21.5	28	30
15	Pentadecane	C15H32	212.26			270.60	543.8	C15H32 + 23 O2 = 15 CO2 + 16 H2O	14	32	23	30	32

That spreadsheet (w/ data references) can be found on this note set's Resources Webpage

Which, along with some other input data yielded:

n	ALKANE		Molecular Weight (g)	Combustion Reaction	Energy of Combustion per mole kJ/mole Alkane	Energy of Combustion per Mass kJ/kg Alkane	Energy of Combustion per CO2 Yield kJ/kg CO2
1	Methane	CH4	16.03	CH4 + 2 O2 = CO2 + 2 H2O	824	51397	18723
2	Ethane	C2H6	30.05	C2H6 + 3.5 O2 = 2 CO2 + 3 H2O	1441	47940	16366
3	Propane	C3H8	44.06	C3H8 + 5 O2 = 3 CO2 + 4 H2O	2057	46682	15580
4	Butane	C4H10	58.08	C4H10 + 6.5 O2 = 4 CO2 + 5 H2O	2674	46031	15187
5	Pentane	C5H12	72.10	C5H12 + 8 O2 = 5 CO2 + 6 H2O	3290	45634	14951
6	Hexane	C6H14	86.11	C6H14 + 9.5 O2 = 6 CO2 + 7 H2O	3907	45365	14794
7	Heptane	C7H16	100.13	C7H16 + 11 O2 = 7 CO2 + 8 H2O	4523	45172	14682
8	Octane	C8H18	114.14	C8H18 + 12.5 O2 = 8 CO2 + 9 H2O	5140	45026	14598
9	Nonane	C9H20	128.16	C9H20 + 14 O2 = 9 CO2 + 10 H2O	5756	44913	14532
10	Deacane	C10H22	142.18	C10H22 + 15.5 O2 = 10 CO2 + 11 H2O	6373	44821	14480
11	Undecane	C11H24	156.19	C11H24 + 17 O2 = 11 CO2 + 12 H2O	6989	44746	14437
12	Dodecane	C12H26	170.21	C12H26 + 18.5 O2 = 12 CO2 + 13 H2O	7606	44684	14401
13	Tridecane	C13H28	184.22	C13H28 + 20 O2 = 13 CO2 + 14 H2O	8222	44630	14371
14	Tetradecane	C14H30	198.24	C14H30 + 21.5 O2 = 14 CO2 + 15 H2O	8839	44585	14345
15	Pentadecane	C15H32	212.26	C15H32 + 23 O2 = 15 CO2 + 16 H2O	9455	44545	14323

The key conclusions for these simple alkane fossil fuels (final two columns):

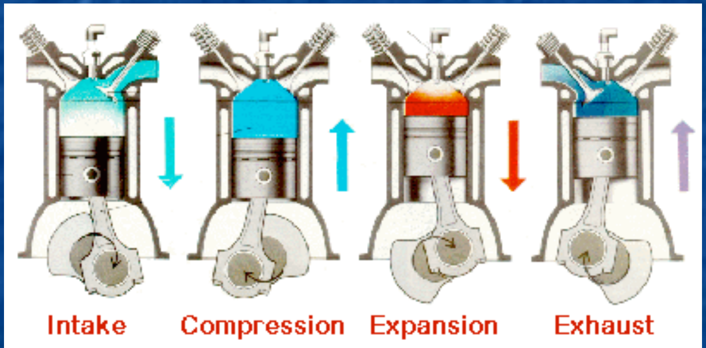
The longer the alkane, the less energy liberated per mass alkane burned

The longer the alkane, the less energy liberated per mass CO_2 released

But reflecting upon transportation's use of fossil fuels:

There, combustion must be extremely rapid, indeed almost explosive!

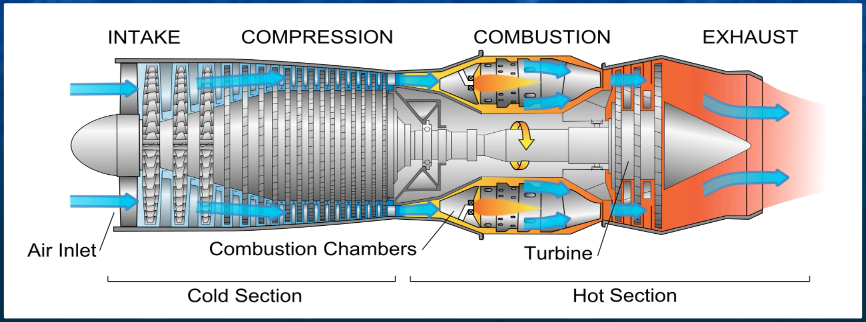
For piston engines turning at 1000's of RPM, combustion must last ~ 1/10 millisecond



http://www.ess.co.at/GAIA/CASES/MEX/spark.html

Inside the jet engines of an airliner cutting through the air at ~ 1000 kph (270 m/s)

the fuel/air mixtures must burn completely within ~ one millisecond



https://en.wikipedia.org/wiki/File:Jet_engine.svg

So transportation fuels **can't** *be burning from puddles of liquid*

A liquid puddle couldn't possibly burn so fast!

At the very least these fuels must first be "atomized" into miniscule droplets,

or possibly even completely vaporized into gas

Variable length alkane carbon chains **are** a major component of those fuels

For them to vaporize, one must again overwhelm **Van der Waals bonding**

In the short chains of methane, ethane, propane & butane, Van der Waals bonding

is so weak that they have already vaporized at room temperature

But the strengthening bonds in longer chains pushes their boiling points ever higher

So their vaporization must first require chunks of **input energy**:

- To heat them from room temperature TO their increasing boiling points

- And to then break their Van der Waals bonding (thereby boiling them)

How does this investment subtract from net combustion heat output?

The energy needed to heat a substance a certain ΔT is called its "heat capacity"

For which I found a research paper claiming a simple formula for all alkanes [1]

Accounting for the energy that would then be lost to heating & boiling each alkane,

I calculated **corrected** net energies of combustion (Col4 = Col1 – Col2 – Col3):

n	ALKANE		Energy of Combustion kJ/mole	Energy to Heat RT to BP kJ/mole	Energy to Vaporize kJ/mole	Corrected Energy of Combustion KJ/mole
1	Methane	CH_4	824	0		824
2	Ethane	C_2H_6	1441	0		1441
3	Propane	C_3H_8	2057	0		2057
4	Butane	C_4H_{10}	2674	0		2674
5	Pentane	C_5H_{12}	3290	2.34	26.42	3261
6	Hexane	C_6H_{14}	3907	9.45	31.52	3866
7	Heptane	C_7H_{16}	4523	18.00	36.57	4468
8	Octane	C_8H_{18}	5140	28.22	41.56	5070
9	Nonane	C_9H_{20}	5756	40.30	46.55	5669
10	Deacane	$C_{10}H_{22}$	6373	53.43	51.42	6268
11	Undecane	$C_{11}H_{24}$	6989	68.14	56.58	6864
12	Dodecane	$C_{12}H_{26}$	7606	83.87	61.52	7460
13	Tridecane	$C_{13}H_{28}$	8222	100.37	66.68	8055
14	Tetradecane	$C_{14}H_{30}$	8839	119.48	71.73	8647
15	Pentadecane	$C_{15}H_{32}$	9455	138.94	75.40	9241

The final column shows how the need to first **disassociate** larger hydrocarbons takes an increasing bite out of their combustion heat output!

1) https://www.sciencedirect.com/science/article/pii/S0040603199003731

Giving TWO reasons for diminished heat from more complex hydrocarbons:

1) More and more energy must be put into disassociating larger hydrocarbons

And once disassociated and fully accessible for combustion:

2) The energy put into **breaking** a larger hydrocarbon's bonds increases faster than the energy released in **making** the bonds of its combustion products

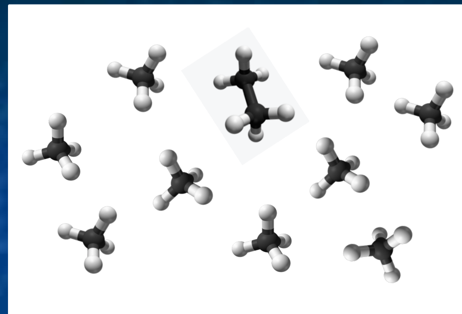
Thus:

INCREASINGLY complex hydrocarbon have a strong tendency to yield DECREASING net combustion energy per mass

And POWER PLANT hydrocarbon fuels can be VERY complex:

Complexity of the common power plant fuels vs. net combustion energies: [1]

Natural Gas:

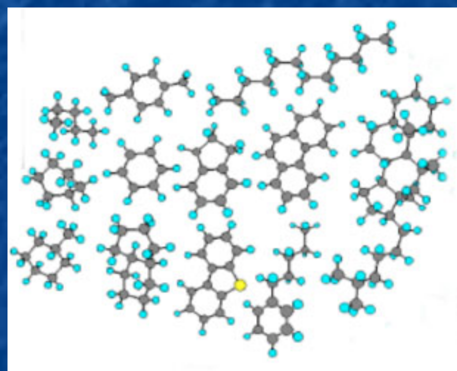


Gas (87 to 97% Methane - typically 93.9%) [2]

Zero disassociation Energy

Net combustion Energy: **54.4 MJ / kg**

Fuel oil:

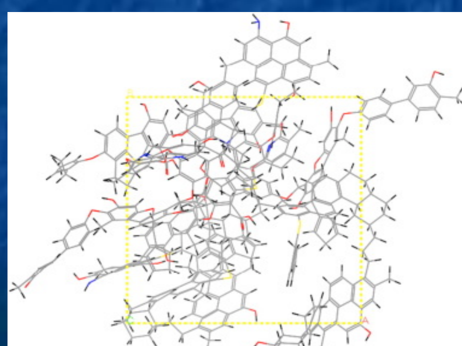


Complex **liquid**

Medium disassociation energy

Net combustion energy: **45 MJ / kg**

Bituminous Coal:



Extremely complex **solid**

Large dissassociation energy

Net combustion energy: **29 MJ / kg**

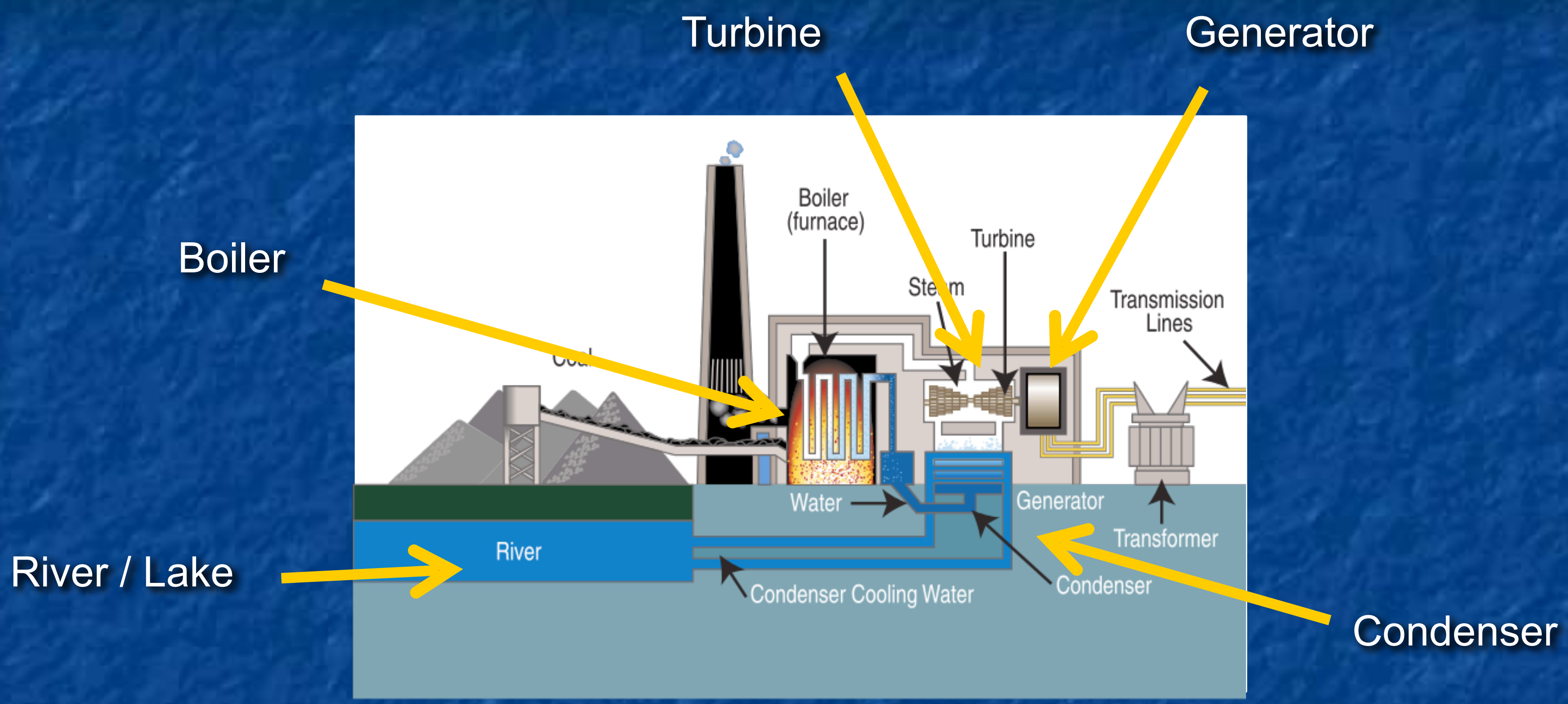
1) Sources: A variety of energy system textbooks, particularly: Introduction to Energy & the Environment by Edward S. Rubin
2) https://www.uniongas.com/about-us/about-natural-gas/chemical-composition-of-natural-gas
Middle figure adapted from http://energy.usgs.gov/GeochemistryGeophysics/GeochemistryResearch/OrganicOriginsofPetroleum.aspx
Bottom figure from: https://www.sciencedirect.com/science/article/abs/pii/S1004954116304359

Technologies that better

CONVERT heat into electricity

This depends on the characteristics of each fossil fuel

So, going fuel by fuel, here is the **traditional type of COAL power plant**:



To the essential heat + boiler + turbine + generator components,

a lake or river-cooled condenser is added to reclaim and recirculate the steam

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

As discussed in my ***Generic Power Plant and Grid*** *(pptx / pdf / key) notes:*

This type of power plant **converts more** of its fuel's combustion heat energy when that energy is used to drive steam to higher temperatures

Heat conversion efficiency varies roughly as: $(T_{steam\ max} - T_{steam\ min}) / T_{steam\ max}$

However, because steam pressure increases with temperature, higher efficiencies then require more massive (and expensive) high-pressure piping and boiler

The temperatures/pressures chosen for use in older coal-fired power plants yielded **combustion energy to electrical energy conversion of about 33-35%**

Pollution control then slowed development of newer coal plants and, more recently, natural gas priced coal out of many electrical power markets (e.g., the U.S.)

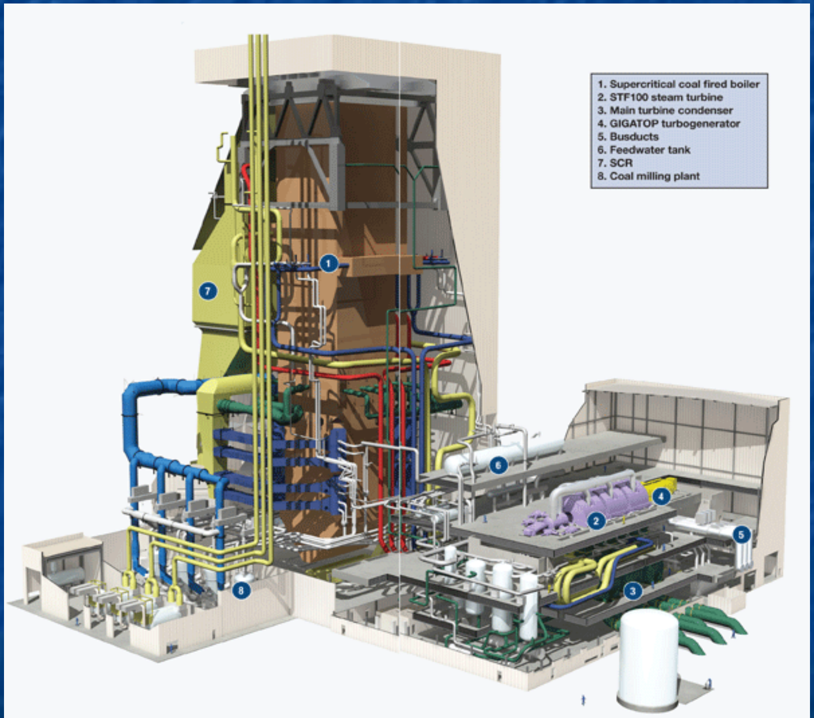
There are, however, a few exceptions to that otherwise pervasive trend:

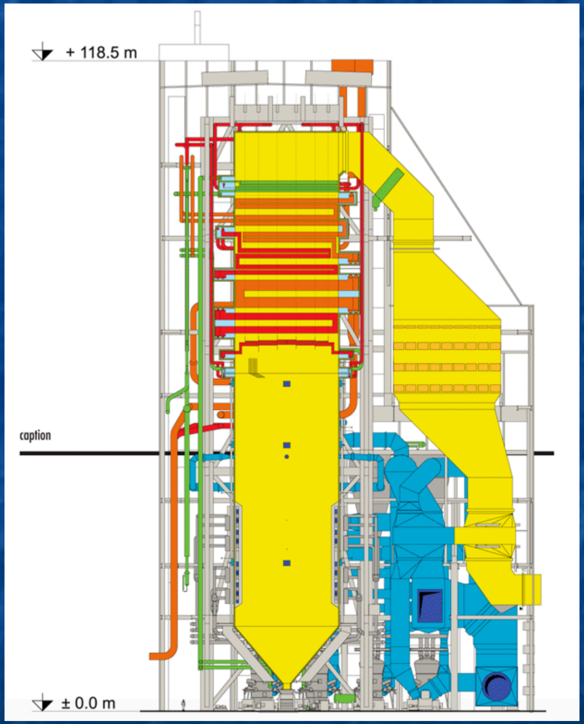
Exceptions include new **ultra-supercritical** *coal plant designs:*

Which use **extremely** high steam temperatures and pressures, such as:

Karlsruhe Germany's huge new 912 MW producing RDK-8 plant which reported a

47.5% heat to electricity conversion using 620°C / 270 atmosphere steam [1, 2]





Ref 1 & figures) http://www.powerengineeringint.com/articles/print/volume-18/issue-5/Special_Project_Report/rdk-8s-three-little-words-efficient-reliable-and-flexible.html

Ref 2) https://www.ge.com/reports/supercritical-thinking-this-coal-power-plant-applies-bullet-like-pressures-to-steam-to-achieve-worlds-best-performance/

This efficiency is ~ 1.5 times that of traditional coal power plants:

Which means that for the same electrical energy produced,

this coal plant should burn 2/3's the coal, and emit 2/3's the pollution

However, pursuit of such designs now seems largely limited to countries having:

Exceptionally abundant coal reserves AND/OR

An exceptionally strong desire to rapidly close down their nuclear power plants

(With Germany now satisfying both criteria)

For the U.S., it's easy to find lists of coal power plant **closures**

but difficult to track down information on any recent U.S. coal plant **openings**

One I did identify, Duke Energy's 2013 Edwardsport Indiana plant, [1]

uses an entirely different strategy for mitigating environmental impact:

1) See for example: Will the U.S. Ever Another Big Coal Plant? – Scientific American, August 2017

Integrated Gasification (IG) of COAL

Rather than burning coal as dense, low surface area, impure, solid chunks

IG converts coal into a pure, more efficiently & cleanly burning gas

How? By exposing its powder to heat + oxygen + moisture

Which **doesn't** convert it to the obvious alternative of methane: CH_4

INSTEAD, during gasification oxygen is TRANSFERRED from water to carbon:

Outputting "Syngas" (H_2): 3C (coal) + O_2 + H_2O => H_2 + 3 CO

Then converting the CO to CO_2: CO + H_2O => H_2 + CO_2

IMPORTANTLY: Only H_2 is then burned (producing nice friendly H_2O)

The CO_2 byproduct CAN then be CAPTURED & SEQUESTERED

Although it may **NOT** be, as it is **NOT** at the Edwardsport power plant [Ibid]

But even without sequestration there **is** *a way of reducing emissions:*

By **converting more combustion heat energy** via a **Combined Cycle (CC)**

The combustion heat energy of a fossil fuel can be used in two ways:

1) To heat and expand **combustion gases** to drive the turbine generators

2) To heat and expand **steam** to drive the turbine generators

Standard fossil fuel plants EXPLOIT ONLY ONE of these expansions

Most commonly, that of steam

How can you identify steam plants?

If the plant has cooling towers, or is on a waterfront, it's re-condensing **steam**

Combined Cycle plants instead use BOTH of these expansions

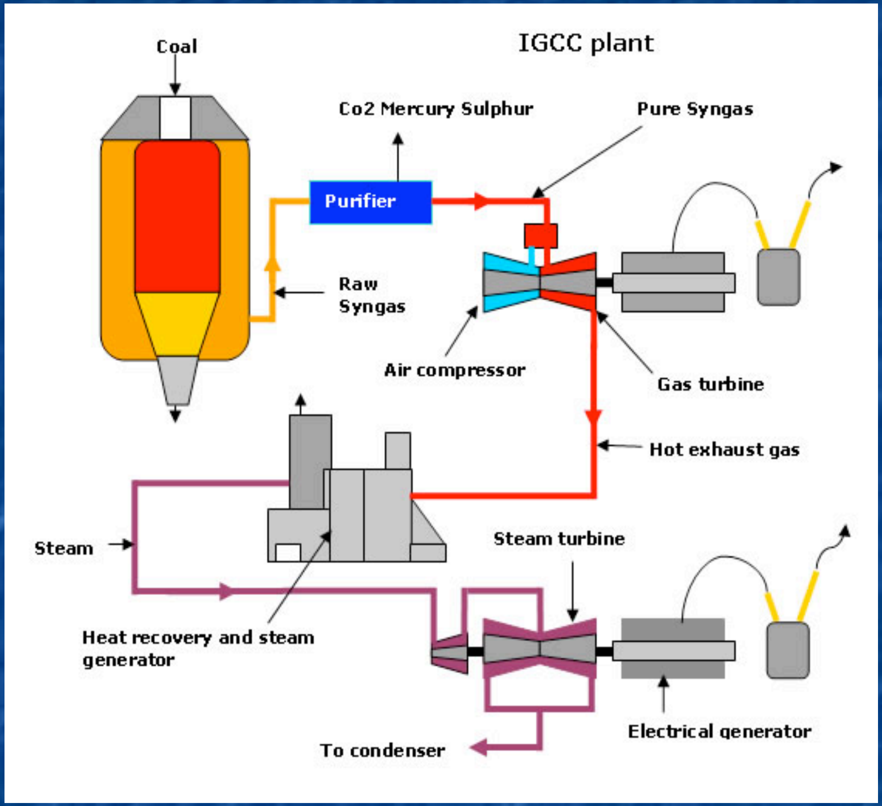
Expansion of combustion gases drives a **FIRST** turbine generator

Its hot exhaust is THEN used to boil (or at least preheat) water into steam

The expansion of which drives a **SECOND** turbine generator

Yielding an IG + CC = **IGCC Coal Plant**

Integrated Gasification + Combined Cycle:



http://www.climateandfuel.com/pages/electrical.htm

Coal gasification produces Syngas (H_2)

Its combustion/expansion drives 1st turbine:

=> **Electrical Power out**

Exhaust gas heat from that 1st turbine:

Boils water into steam

(possibly helped by burning more fuel)

Which then drives the 2nd turbine:

=> **More electrical power out**

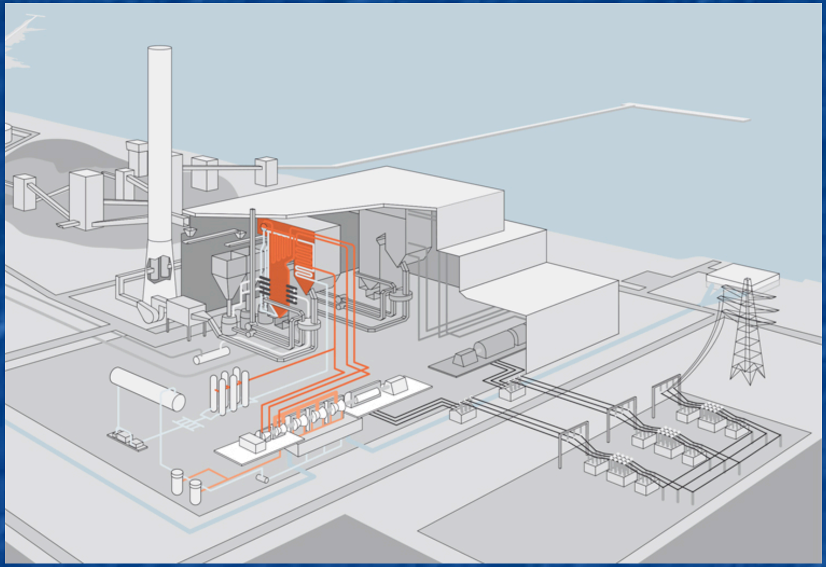
Producing a net heat to electricity conversion efficiency of ~ **43%** (U.S. DOE)[1]

1) https://www.netl.doe.gov/research/coal/energy-systems/gasification/gasifipedia/clean-power

Pictorial contrast of a Conventional vs. IGCC Coal Plant:

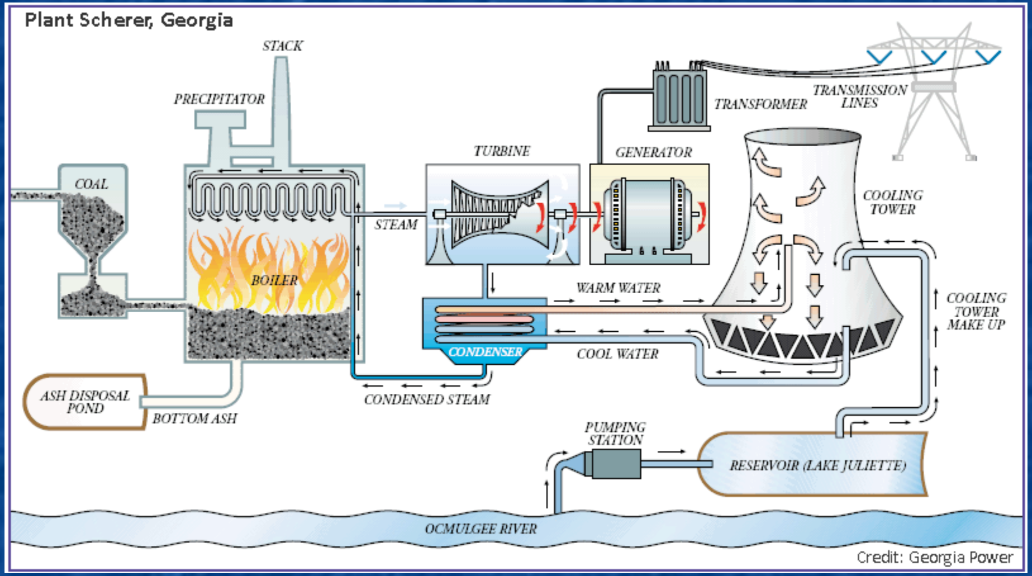
Conventional Coal Plant

Bird's eye view:



http://vantagegraphics.co.uk/project/power-station/

Schematic of plant:



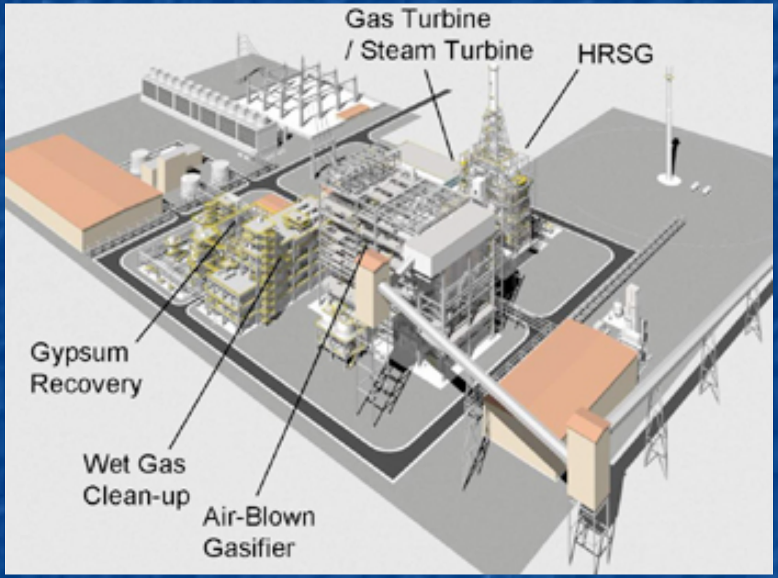
http://water.usgs.gov/edu/wupt-coalplant-diagram.html

Versus an Integrated Gasification Combined Cycle (IGCC) coal plant:

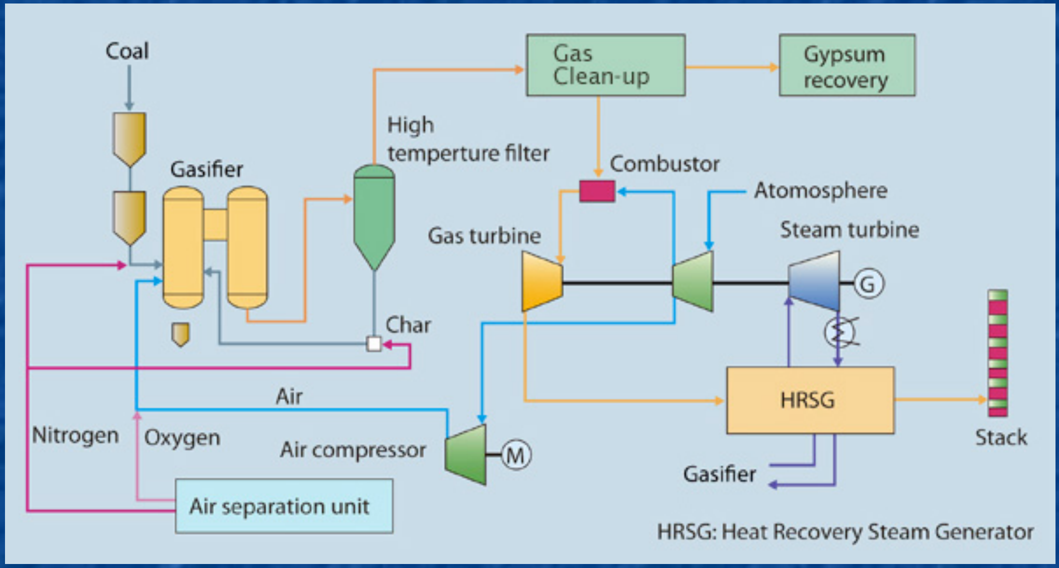
Central (rectangular) building **alone** is ~ same as preceding conventional coal plant

ALL of outlying buildings/processes must be added to make it an IGGC coal plant

Bird's eye view:



Schematic of that same plant:



https://www.mhps.com/en/products/category/integrated_coal_gasfication_combined_cycle.html

Explanation of the "Gypsum:" To remove SO_2 from this plant's exhaust,

they expose it to a limestone ($CaCO_3$) slurry => Gypsum ($CaSO_4 \cdot 2\ H_2O$)

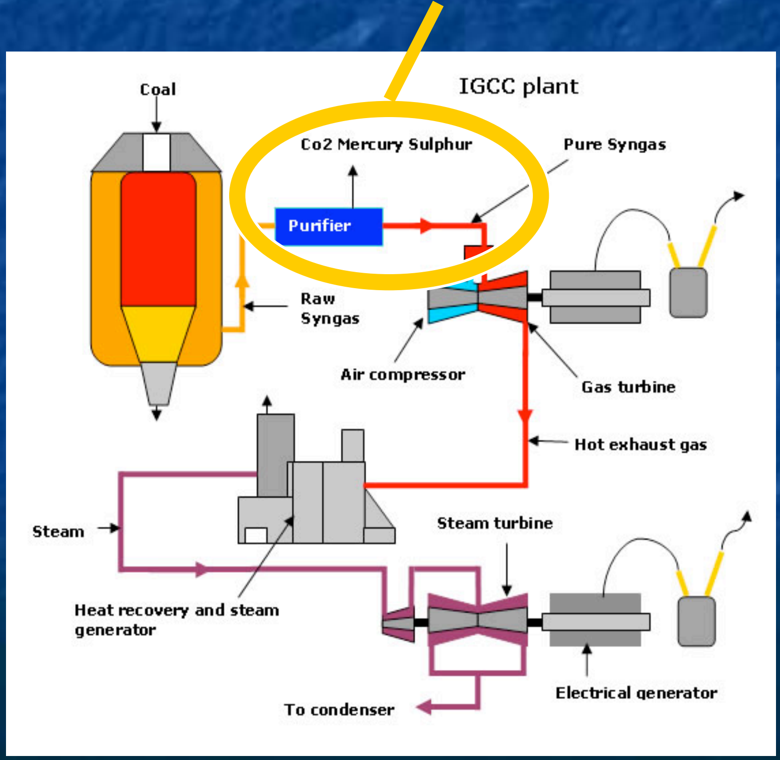
NOTE (!): The "CC" in "IGCC" does NOT refer to carbon capture!

There is a LOT of confusion about this (including in government reports!)

To the extent that IGCC DOES produce more electrical power / fossil fuel in,

it does then reduce the net OUTPUT of carbon (for the same power out)

But the possibility of true carbon "capture" instead comes in here



During gasification, coal is converted to CO_2

Which **would** then add to the carbon output

But CO_2 can be fairly easily **captured**:

by freezing, by reaction with ammonia, by . . .

Which **does** then reduce "carbon footprint"

But **ONLY** if captured CO_2 is **NOT** released later

IGCC can improve efficiency & carbon footprint, but not necessarily cost:

For details on power plant costs, see: **Power Plant Economics** (pptx / pdf / key)

But I offer you this preview on how advanced technology affects coal power:

When they last compared ALL types of U.S. coal power plant (in 2015*), the U.S. Energy Information Administration estimated electricity cost from a new plant as:

Conventional Coal Power Plants:	**$95.1 / MW-hr**
IGCC Coal Power Plants:	**$115.7 / MW-hr**
Sequestered IGCC Power Plants:	**$144.4 / MW-hr**

*Conventional & unsequestered IGCC coal plants were omitted in 2016 & 2017 reports because their new construction had been banned due to their pollution

Coal power plants are thus being priced out of the electric power market:

In 2015, power from even the cheapest/dirtiest "conventional" coal plants cost: [1]

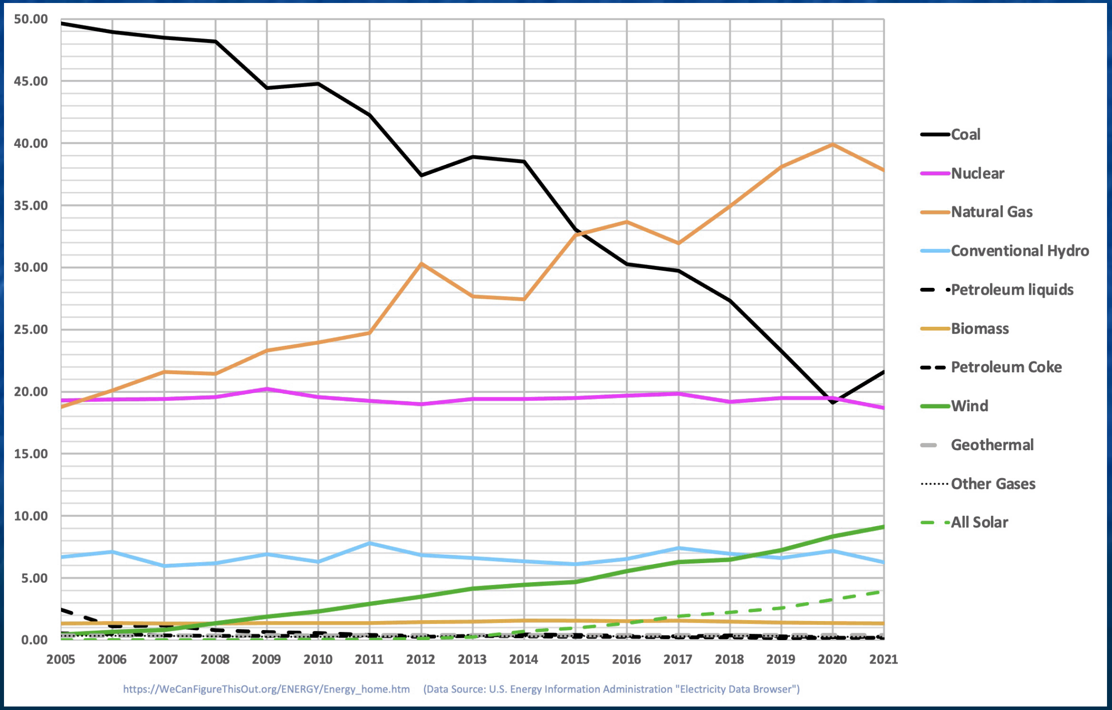
60% more than power from onshore wind farms

50% more than power from natural gas plants

40% more than power from hydroelectric plants

20% more than power from nuclear plants

Yielding its precipitous decline:



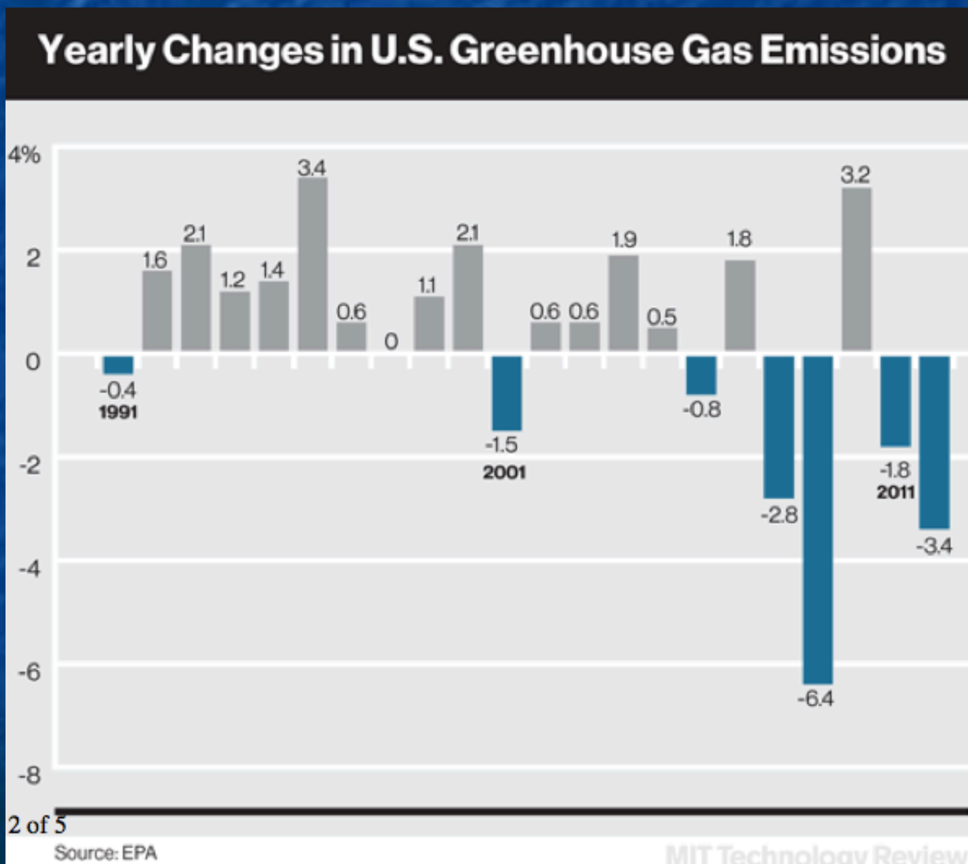
1) Cost comparisons are from my note set:
Power Plant Economics (pptx / pdf / key)

The figure is from my note set:
U.S. Energy Production & Consumption
(pptx / pdf / key)

Political pandering CANNOT trump this economic trend!

Which has led some environmentalists to announce the impending "Death of Coal"

Which **is** already a major factor in the U.S.'s declining greenhouse gas emissions:



Shame on MIT for not labeling axes!

I had to go back to their EPA source to

find that these data span ***1990 to 2013***

http://www.technologyreview.com/news/527106/how-and-why-us-greenhouse-gas-emissions-are-falling/

But before we pat ourselves on the back, note that:

What we are **now** doing is exporting our coal for **other countries** to burn:

Associated Press (28 July 2014): "Not in my backyard - US sending dirty coal abroad" [1]

This article notes that our home state port of Norfolk Virginia **leads** in such exports:

Pictured here is Norfolk's huge coal export complex ("Pier 6")

Ironically: Norfolk is **already** endangered by rising sea levels!

Photo: http://nscorp.com/content/nscorp/en/news/norfolk-southernspier6handleslargestcoalloadinginits50yearhistor.html

The previous administration touted our declining greenhouse gas emissions

But this article revealed that U.S. data omitted the effects of our exported coal

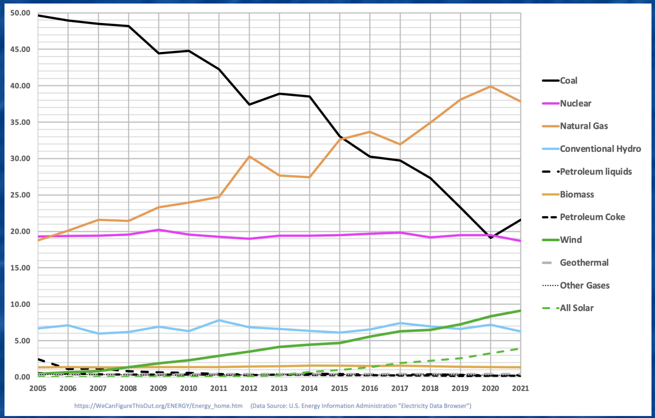
ITS greenhouse gas production may largely offset our domestic reductions!

1) *http://www.post-gazette.com/powersource/latest-coal/2014/07/28/Not-in-my-backyard-US-sending-dirty-coal-abroad-7/stories/201407280139*

*We should now discuss how to best use **oil** in power production*

But where coal APPEARS to be dying, oil is ALREADY DEAD!

Its use for power is now so small (<1%), that it was a no show in my ten year plot:



Its "death" was also driven by economics, but the reasons were more subtle

Cheaper competition (from emerging natural gas) **was** a factor

But the bigger factor was that we've got **much better uses for oil**:

- As the **feedstock** for synthesis of chemicals, rubbers and plastics
- As our still **preferred source** of ground transportation fuel
- And as our absolutely essential **single source** of air transportation fuel

Thus, for electrical power, oil's **best use** *is now effectively* **no use**

But where oil's **best use** COULD still have a major environmental impact

is in the design of more efficient **fossil-fueled transportation** engines

Specifically: In better internal combustion engines (ICE's), and in better jet engines

But their description requires background about the vehicles they power

And new designs will thus instead be discussed in my later note sets on:

Energy Consumption in Transportation (pptx / pdf / key)

and

Green(er) Cars and Trucks (pptx / pdf / key)

Moving on how to best use fuel in ***Natural Gas Power Plants:***

We saw, above, that NG combustion produces 2X the heat of coal (per mass burned)

=> Less carbon burned => Less CO_2 released into the atmosphere

More apparent good news: There is a much simpler way of burning natural gas:

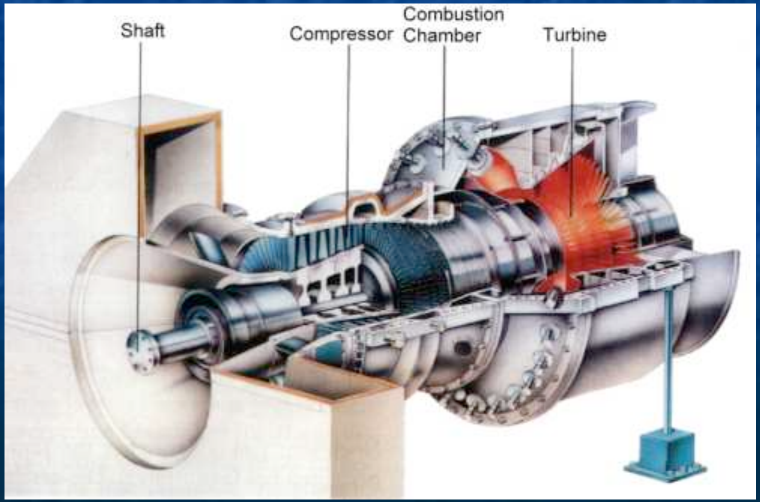
Use its expanding combustion gases to directly drive a turbine generator

This is done in what are essentially jet engines

by just substituting natural gas for their normal kerosene fuel

Connect a generator to the shaft, and this type of power plant is essentially **complete!**

http://mechangers.com/hello-world-2/



However, we need to look more closely at heat vs. carbon output:

Carbon fraction of natural gas (by weight):

Natural Gas = 71% C vs. Coal (bituminous) = 67% C

Combustion heat energy output of natural gas:

Natural Gas = 54.4 MJ / kg vs. Coal (bituminous) = 29 MJ / kg

Comparison of apparent carbon footprints:

Carbon output of **natural gas** / MJ heat = (71%) / (54.4/kg) => **13 g**

Carbon output of **coal** / MJ heat = (67%) / (29/kg) => **23 g**

Neglecting fact that some of coal's burnt carbon ends up as **solid** ash

and that this solid ash does not go out into the atmosphere

You'd expect natural gas to have ~ ½ of coal's "carbon footprint"

But common gas turbine power plants are NOT twice as clean!

Data from: **Greenhouse Gas, Carbon Footprint & Sequestration** (pptx / pdf / key)

Plant Type:	CO_2	SO_2	NO_x	Particulates
Coal fired plants	989	6.38	3.69	0.35
Oil fired plants	1,020	8.96	2.01	0.15
Natural gas fired plants	803	0.00	2.87	0.005

Natural gas plant carbon footprint = 81% that of coal, NOT 50% !

Why? Because **with a jet engine, a lot of heat goes right out the tail pipe**

And that heat energy is thereby lost

So you have to use more fuel, or run the turbine longer

To produce a given amount of electrical energy

Source: Intro to Energy and the Environment – Edward S. Rubin (p. 168)

*Schematic of a such an **OPEN Cycle Gas Turbine (OCGT)** power plant:*

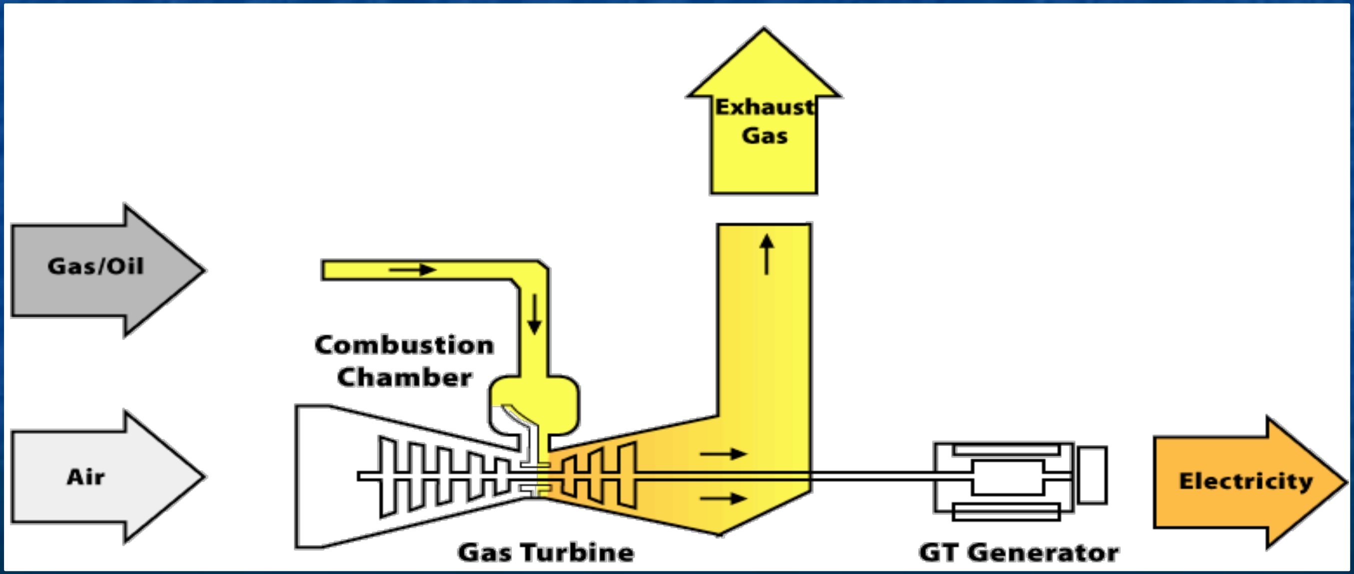
It IS about as simple as it can get:

Raw natural gas is injected directly into the jet engine

Where it burns and expands, turning that engine's turbine

Which is connected directly to the electrical generator

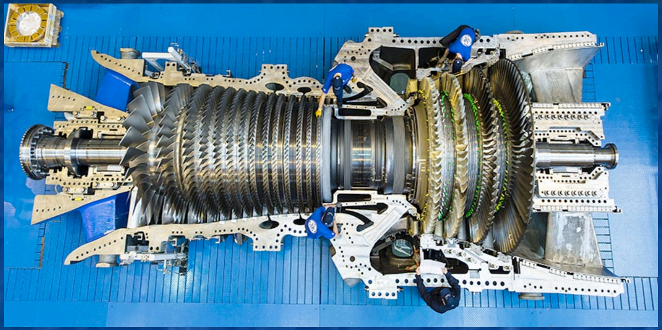
With **hot combustion gases** shooting right up the exhaust duct / smoke stack



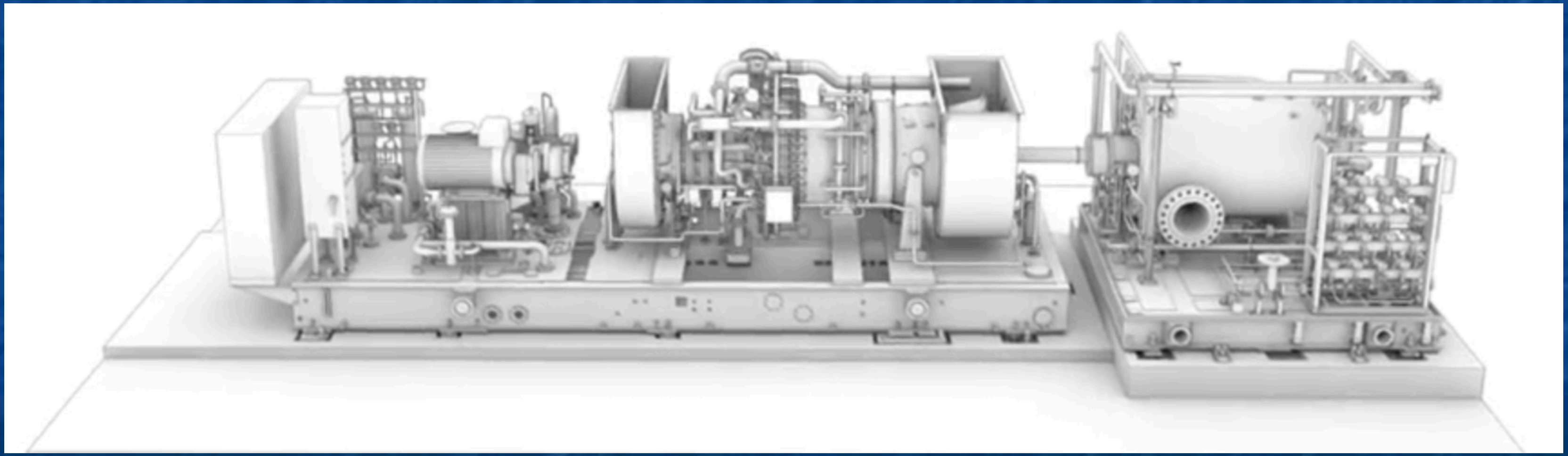
https://www.consumersenergy.com/content.aspx?id=1345

The components of an actual "OCGT" gas turbine power plant:

The gas turbine itself:



Full power train = Starter motor + turbine (output / input air ducting) + generator:

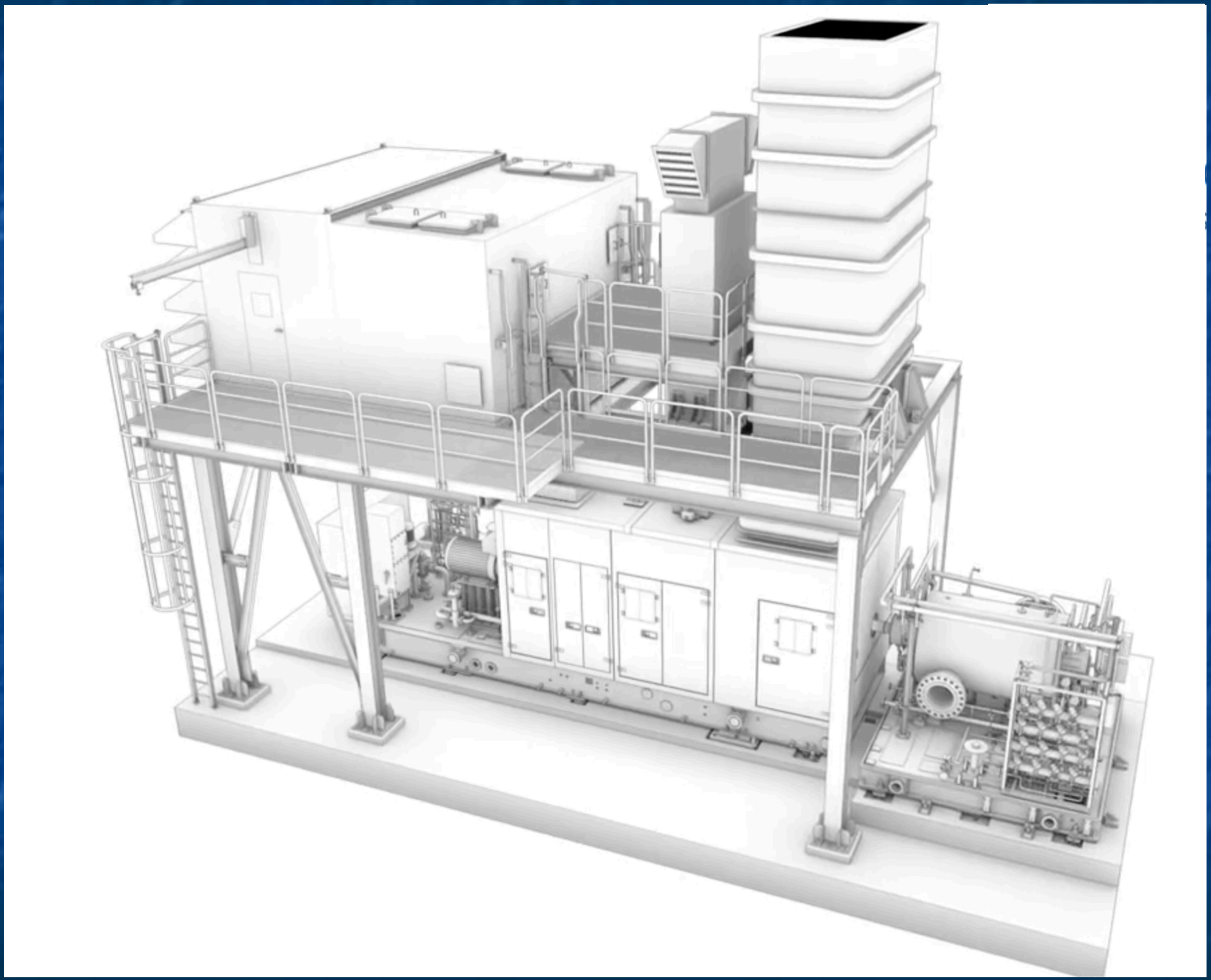


https://powergen.gepower.com/plan-build/products/gas-turbines/index.html

http://www.alternativeenergyhq.com/can-natural-gas-turbines-be-partner-to-renewables.php

https://www.youtube.com/watch?v=OkfqUSBdN8M

After safety and sound-containment enclosures are added:



https://www.youtube.com/watch?v=OkfqUSBdN8M

That is it! It's Complete!

This one is a **GE NovaLT16** (simple / OCGT) gas turbine system [1]

Note its small, self-contained, fully-connected construction

It's so small & self-contained that it might be delivered almost fully assembled

=> Radically reduced capital cost + installation cost

Power companies likely use multiple units and/or larger units

But this one (alone!) already produces **16.5 MW**:

- **Equivalent to ~ 4 modern (~100 meter diameter) wind turbines**

- And MUCH larger than many other new sustainable energy generators

This type of unit is U.S. power's **favorite choice for evening "peaking power"**

Where low capital cost is essential as it may only be used for ~ 1-3 hours a day

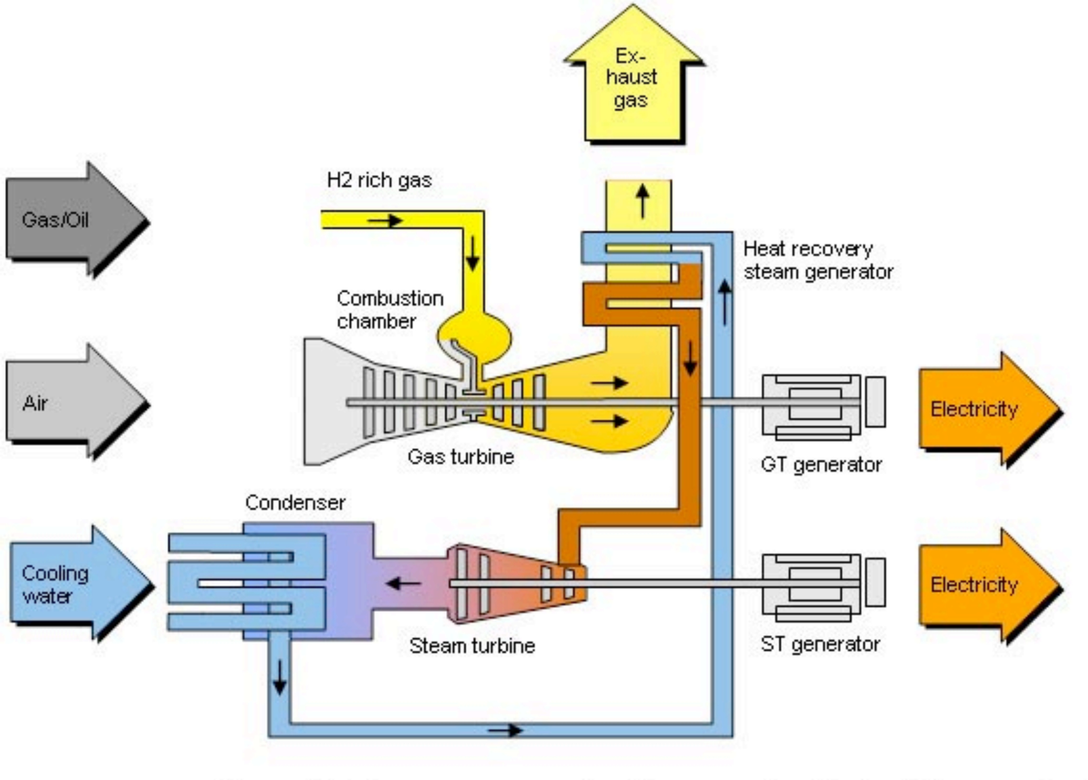
1) http://www.compressortech2.com/September-2014/GE-Launches-NovaLT16-Gas-Turbine/#.VjygroRx5Sp

But can the possibility of 50% lower carbon footprint be recaptured?

YES: By capturing most of the **heat** energy that went out the jet engine's exhaust

This is done in a **Combined Cycle Gas Turbine (CCGT)** power plant

Where 1st turbine's exhaust heat boils water into steam driving a 2nd turbine:



Source: http://www.powergeneration.siemens.com/products-solutions-services/power-plant-soln/combined-cycle-power-plants/

http://www.power-technology.com/projects/uskmouth/uskmouth2.html

*But this makes a **CCGT** power plant much more complex and expensive:*

As a manufacturer of both OCGT and CCGT plants, GE claims efficiencies of up to:

61% for dual turbine CCGT [1] vs. **36%** for single turbine OCGT [2] plants [3]

Increased efficiency => decreased fuel use => Reduced carbon footprint

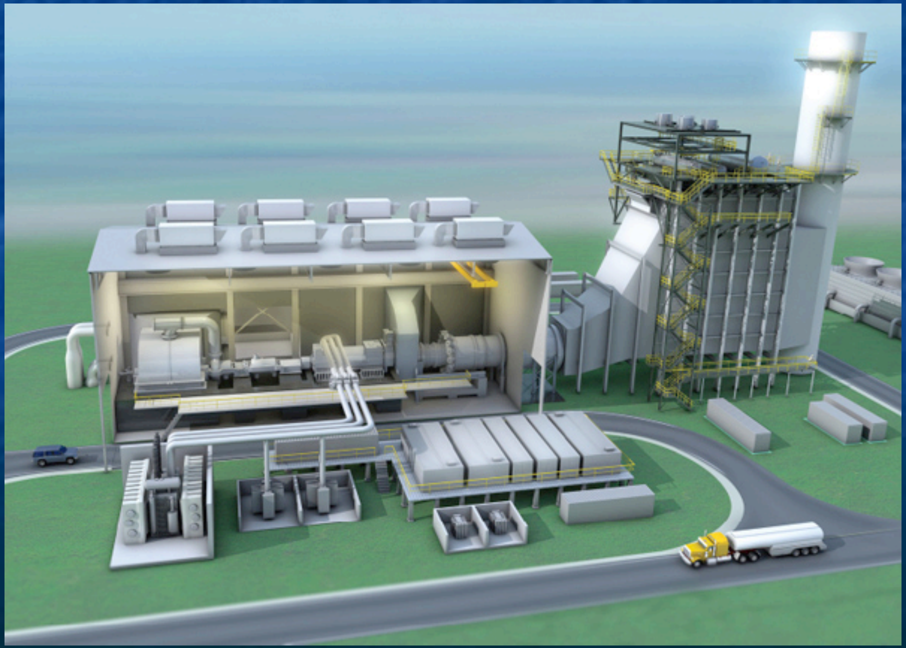
But, as seen below, OCGT is significantly more complex (and thus capital intensive)

So **instead of peaking power**, it's more likely used for steady **base power**

Ref 1 and figure: http://www.powermag.com/pushing-the-60-efficiency-gas-turbine-barrier/

2) https://www.geoilandgas.com/subsea-offshore/offshore-turbomachinery/novalt16-gas-turbine

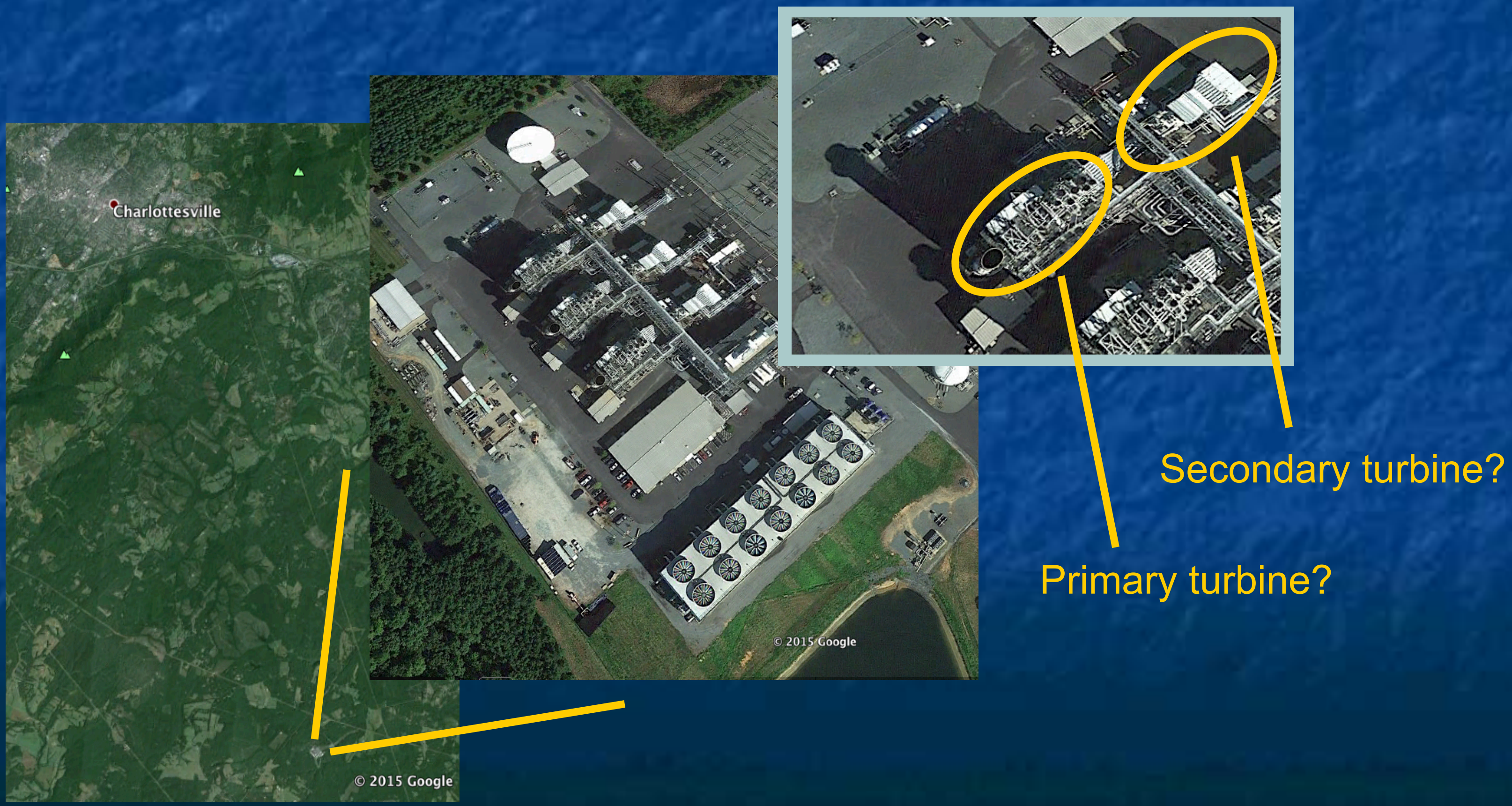
3) It's NOT that I am trying to promote GE! It's just that their marketing webpages are exceptionally rich in factoids and figures!



*Is Charlottesville's nearest power plant a triple **CCGT** ?*

Three apparently simple (OCGT) gas turbines can be seen near the plant's center

- But each of these seems to feed into a secondary structure
  - That, plus cooling towers & the lake below indicate the use of steam
    - Which **would** then make this a CCGT plant



Combining data from the preceding two sections (taken at face value): [1]

Coal's combustion heat energy is **29 MJ/kg** vs. Natural Gas's **54.4 MJ / kg**

Coal Power Plants:

"Conventional" coal power plants convert ~ **34%** of coal's heat energy

(0.34) (29 MJ / kg) => ~ **9.9 MJ** electrical energy / kg coal burned

Leading-edge ultra-supercritical and IGCC coal plants push this toward **47%**

(0.47) (29 MJ / kg) => ~ **13.6 MJ** electrical energy / kg coal burned

Natural Gas Power Plants:

Single turbine OCGT power plants convert ~ **36%** of gas's heat energy

(0.36) (54.4 MJ / kg) => ~ **19.6 MJ** electrical energy / kg NG burned

Dual turbine CCGT power plants convert nearly **60%** of gas's heat energy

(0.6) (54.4 MJ / kg) => ~ **32 MJ** electrical energy / kg NG burned

1) Many of the last section's efficiency numbers came from power equipment manufacturers and/or trade magazines. I thus suspect that these numbers tend more toward one time records than sustainable operating values.

From USE, we must now turn to the EXTRACTION of fossil fuels:

Fossil fuels are derived from the remains of ancient plants and animals

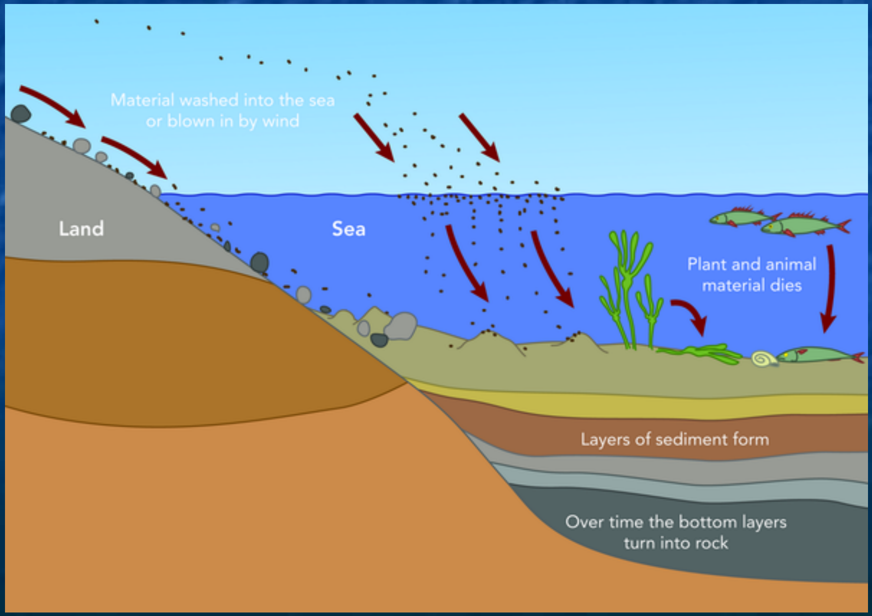
Which were often swept, by water, onto the bottom of lakes and oceans

Where they were buried by ever-deepening layers of mud and sand

There, heat from the earth's molten core drove the **geothermal gradient** which is

a 25-30°C increase in temperature for each added kilometer of buried depth [1]

Pressure + heat thus cooked and converted those remains into today's fossil fuels



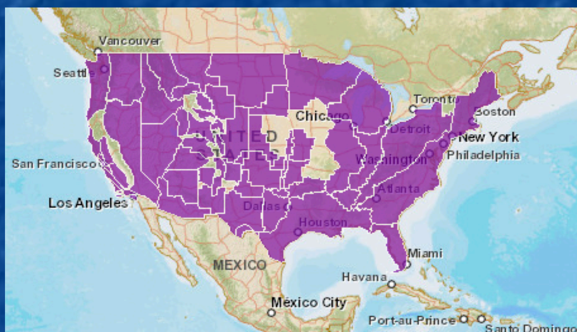
1) https://en.wikipedia.org/wiki/Geothermal_gradient

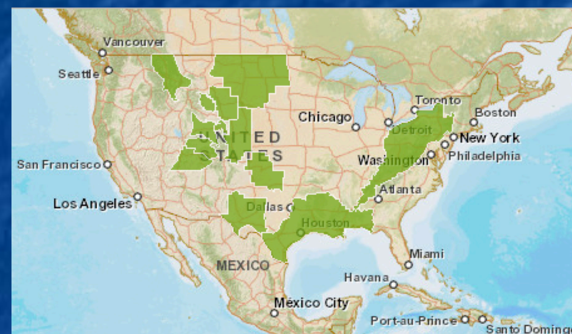
Figure: http://www.thunderboltkids.co.za/Grade5/04-earth-and-beyond/chapter3.html

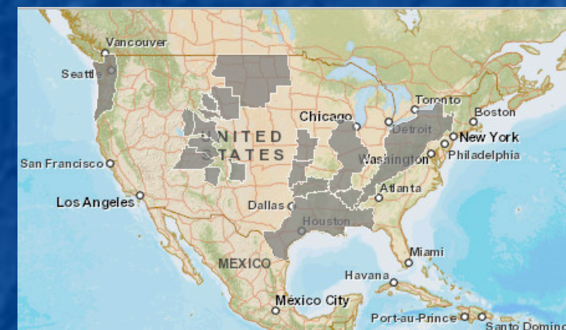
But driven by such lake & ocean-bottom sedimentation,

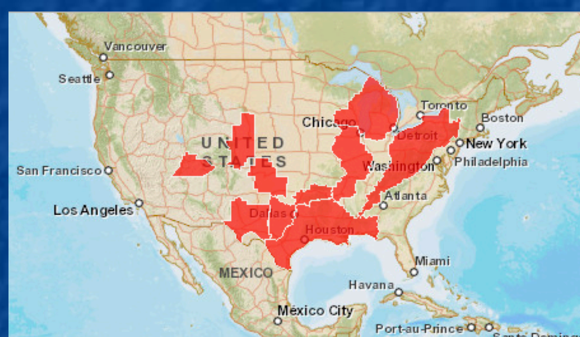
fossil fuels naturally formed in very thin widely dispersed layers:

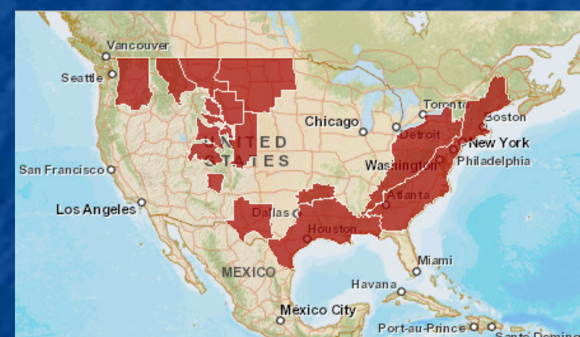
As seen in these USGS maps of our present day **oil & gas reserves**:







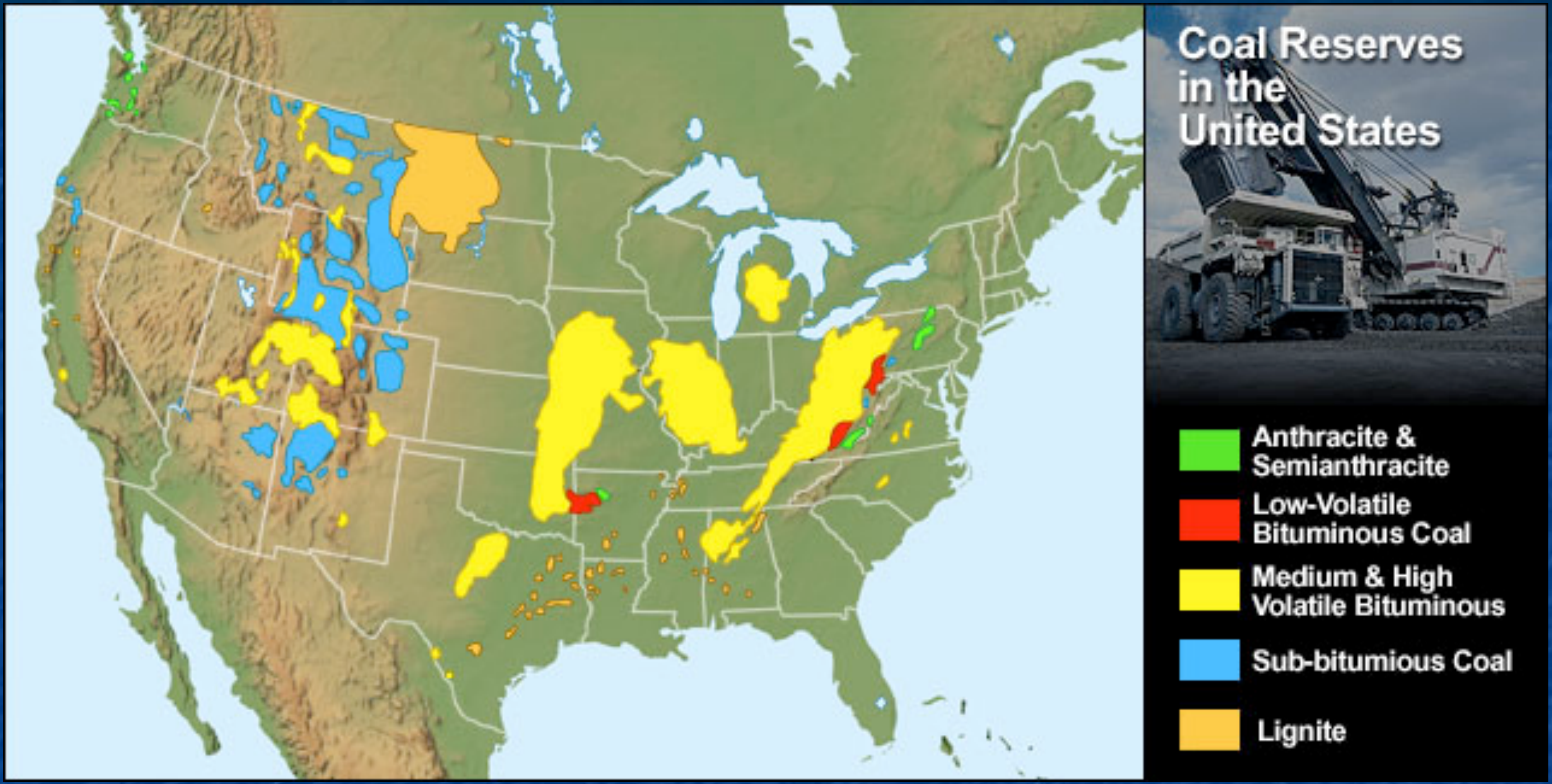




- ○ Conventional (Oil & Gas)
- ○ Continuous Oil
- ○ Coalbed Gas
- ○ Shale Gas
- ◉ Tight Gas

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

*Or in this map of our **coal reserves**:*



Extraction of thin, buried, dispersed layers poses HUGE challenges

Which I will now discuss, fossil-fuel by fossil-fuel:

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

Extraction of coal:

Deep underground mines were our classic source of coal

From the surface, such mines look like this one in Stirrat, West Virginia

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

Historically, coal mining has had a huge negative impact upon its miners

In the U.S. at least, dust & fire control measures now mitigate this impact

Underground mining's larger environmental impact was geographically limited,

coming largely via the "tailings" removed and piled upon the surface,

and their tendency to leech out toxins (or collapse upon local communities)

But where layers are flat & shallow, coal is now extracted by strip-mining:

Which uses massive earth-moving equipment to remove the non-coal "overburden"

covering shallower coal layers (as seen in the Illinois strip mine at the left):

After overburden and coal layer removal is complete, this leaves landscapes

such as those at the "Bear Run Mine" in southwestern Indiana (seen at the right)

Left Figure: http://www.athro.com/geo/trp/gub/coal.html

Right Figure: http://valleywatch.net/?p=2557

But strip mining runs into problems in more mountainous country:

Such as in West Virginia, where conventional strip mining

has been supplanted by **mountaintop removal** mining

Which consists of pushing whole non-coal mountaintops into adjacent valleys,

in order to expose and extract their previously buried coal layers

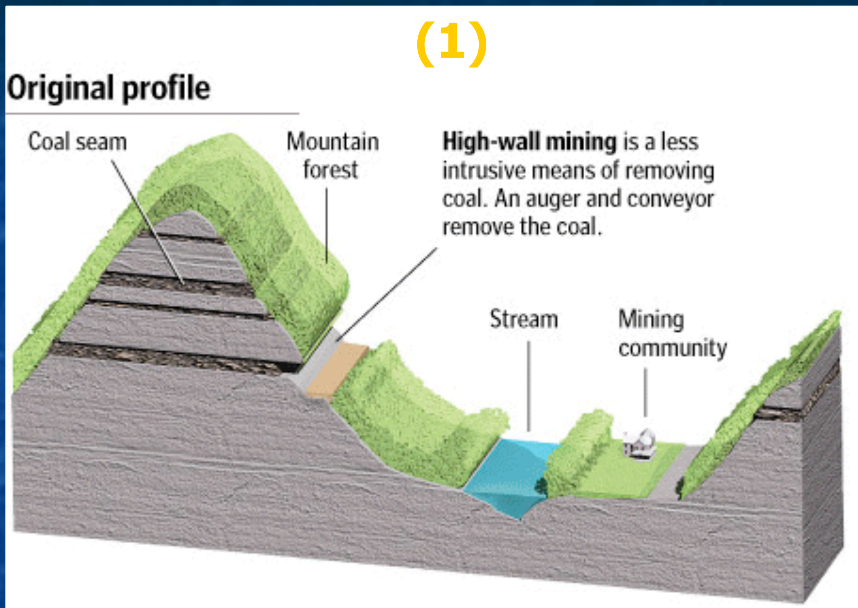
Producing landscapes like this:

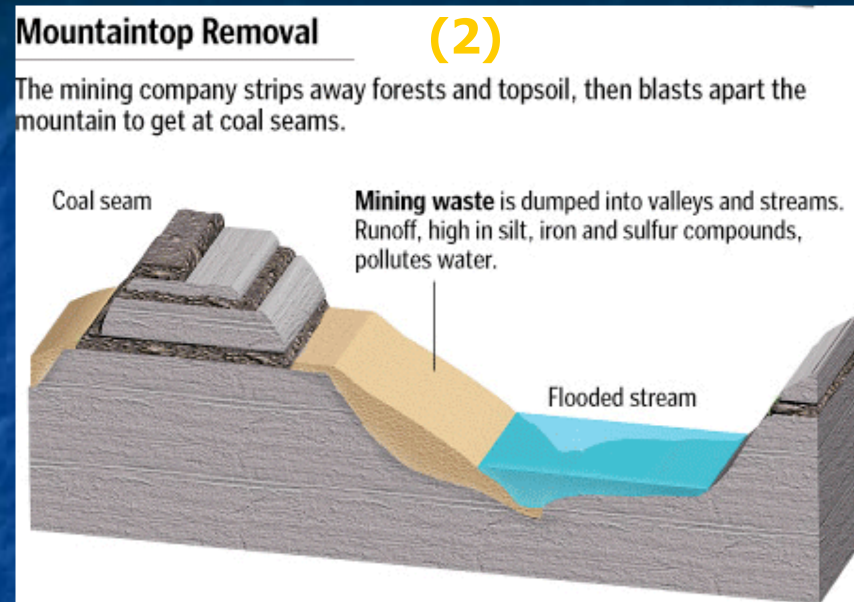
http://vault.sierraclub.org/sierra/201209/mountaintop-removal-coal-mining-west-virginia-251.aspx

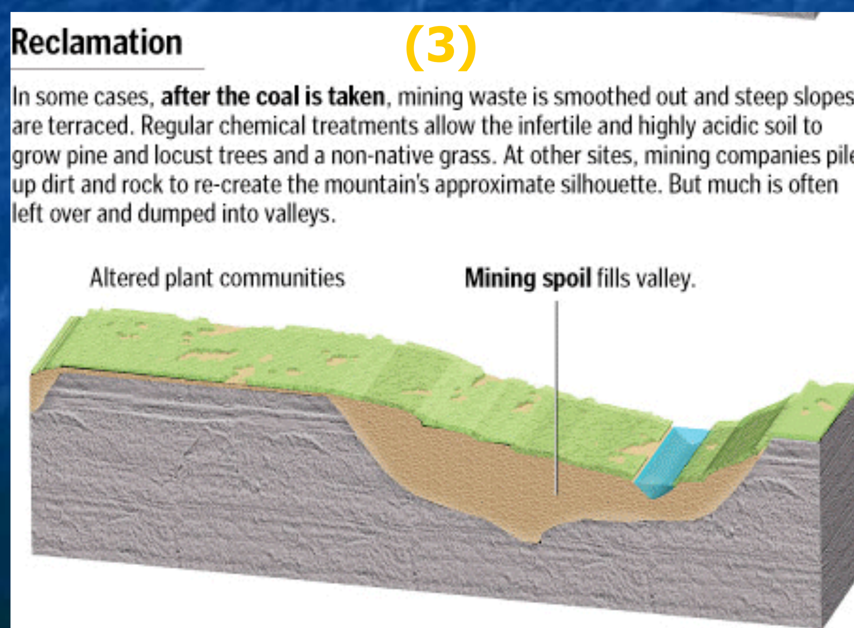
Which spread into landscapes like this:

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

Mountaintop removal described pictorially:







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

Mountaintop removal can devastate entire landscapes because:

1) The final, full reclamation steps may never occur

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

2) If reclamation does occur, the 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 then flows into now crumbled valley-filling overburden

Leaching out (previously sealed in) heavy metals

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

4) The scale and extent of mountaintop removal is HUGE:

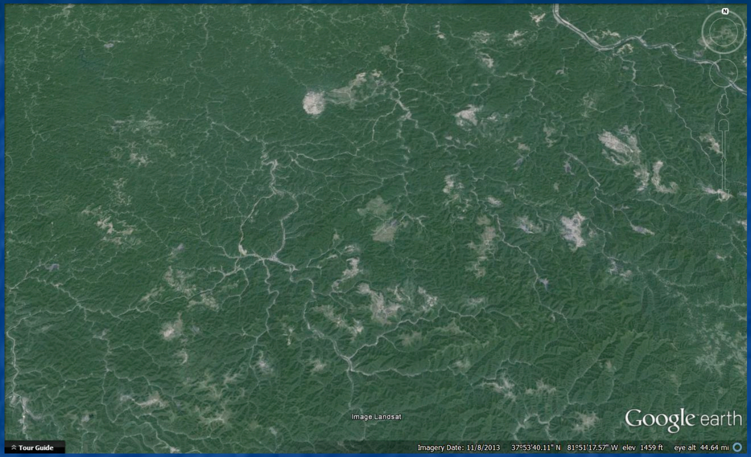
"MTR will mine over 1.4 million acres (5700 square kilometers) by 2010, an amount of land area that exceeds that of the state of Delaware." [1]

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

A collection of West Virginia satellite images:

The gray patches are NOT natural geology, they're formerly green mountaintops!

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]

Extraction of oil:

Oil's principal difference from coal is that it contains less complex hydrocarbons

Oil thus has weaker Van der Waals bonding, making it a liquid or semi-liquid

Nevertheless, oil was formed by the same sedimentation + pressure + heat process

Which means that **oil deposits are also naturally thin and dispersed**

But much of that sedimentation + pressure + heat occurred **beneath oceans**

If a smaller ocean became land-locked, evaporation could deplete it of water

This would leave behind a layer of salt

which could be much, much thicker than the proto-oil layers

Over millions of years, this sandwich of salt and proto-oil would be buried

by some combination of mud, dust and lava,

which would ultimately densify and harden into sedimentary rock

But while sedimentary rock is dense and hard, oil and salt are not

Liquid/semi-liquid oil, like liquid water, densifies very little under pressure

And as a liquid/semi-liquid it retains the ability to flow

Crystalline salt, or salt + water slushes, are also very resistant to compaction

And as a semi-solid they can also flow

Thus, millions of years later, an ocean's legacy may be

A very unstable stack of:

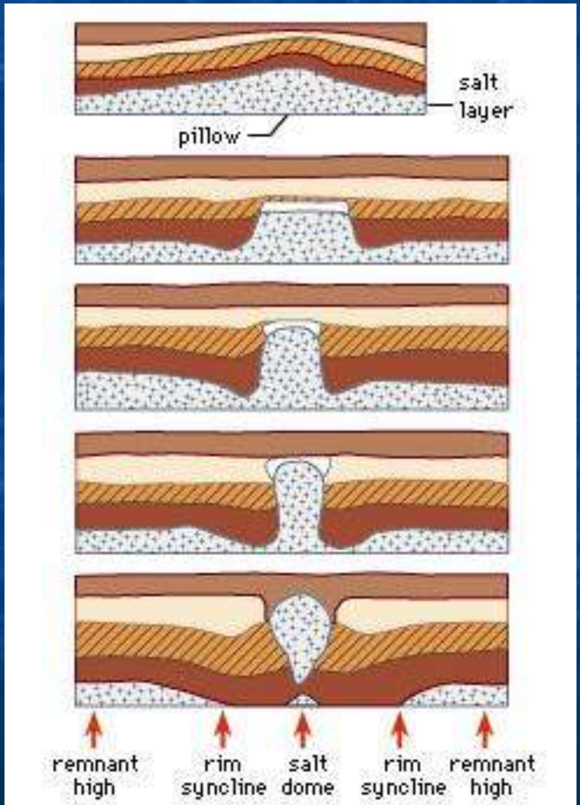
Very thick, dense, hard sedimentary rock layers above

Thick, less dense, flexible salt layers accompanied by

Thin, less dense, liquid/semi-liquid oil layers

Where the capping rock is weaker and/or thinner

the salt and oil may stage a break-out



©1994 Encyclopaedia Britannica, Inc.

https://www.britannica.com/science/salt-dome

Producing a salt dome:

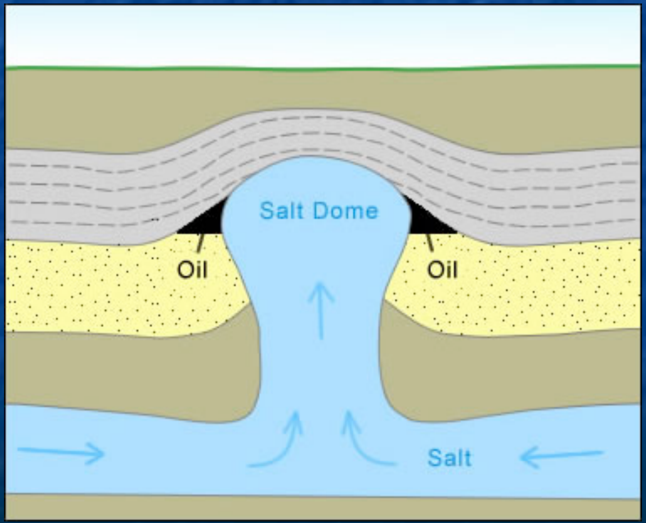
Which, if it eventually collides with an impenetrable rock layer,

can be effectively frozen in place

But buoyant nearby oil can continue flow up into the bulge created by the dome

that oil can thereby accumulate into vast underground pools

These buried pools are the classic target of oil wells



Prospectors hunt domes by setting off small explosions

or by just bouncing heavy trucks on the ground

Thereby sending pulses of sound deep into the earth

These "sonar" pulses reflect and detect the domes

(As they also once **accidentally** discovered the

buried crater of the dinosaur-killing Chcixulub meteor)

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

Where domes are located, oil wells can be simply drilled & pumped

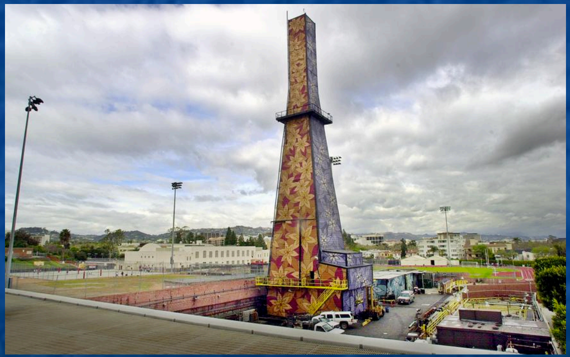
Done with a **bit of care,** this can be done with surprisingly little impact,

as can be seen in photos from my adoptive home state of California:

Unidentified LA suburb [1]

Signal Hill CA [2]

Placentia CA [2]



Beverly Hills High School
with not just pumps, but a disguised **oil derrick** [2]

1) https://www.hcn.org/blogs/goat/los-angeles-city-council-votes-for-a-fracking-moratorium-and-hopes-california-follows-suit
2) http://www.theatlantic.com/photo/2014/08/the-urban-oil-fields-of-los-angeles/100799/

*To **REALLY** screw-up an oil well requires an ocean + criminal negligence:*

Santa Barbara 1969 – **Then** the worst U.S. oil spill (now #3 behind Exxon Valdez) [1]

http://ediblesantabarbara.com/1969-oil-spill/

British Petroleum's Deepwater Horizon 2010 – **Now** the worst U.S. oil spill [2]

https://www.cnbc.com/2017/06/26/much-of-the-deepwater-horizon-oil-spill-has-disappeared-because-of-bacteria.html

1) https://en.wikipedia.org/wiki/1969_Santa_Barbara_oil_spill

2) https://en.wikipedia.org/wiki/Deepwater_Horizon_oil_spill

But while normal onshore oil wells may have relatively little impact:

Things begin to change when one "gets to the bottom of the barrel"

Or more precisely, when "lighter" more fluid oil is no longer available

To extract the remaining more viscous oil, steam must first be pumped into the wells

Which means that what emerges is then **oil + polluted water**

Steam plus a variant of strip mining also extracts oil from **tar sands** or **oil shale** [1]

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

Photo: ***The tar sand mines of Alberta Canada*** *http://priceofoil.org/2015/04/21/alberta-home-tar-sands-increasing-income-inequality/*

When steam IS used, **Energy Return on Invested Energy (EROI) plummets**

Falling from conventional oil's return ratio of ~16, to as little as 4

As discussed in my **Lifetime Energy Return on Energy Invested** (pptx / pdf / key) notes

Turning now to natural gas extraction (part I): Fracking

The history of natural gas extraction parallels that of the previous slide

Natural gas can form with oil, and then accumulate near the same salt domes

However, the quantity of such gas is limited and now substantially depleted

But within otherwise solid rock, natural gas may have accumulated in tiny pockets

These pockets can be so numerous that the net quantity of gas can be very large

But if pockets are not connected, that gas's extraction is near impossible

Hydraulic fracturing ("fracking") is a way of connecting those gas pockets:

High pressure water is pumped down wells into gas-pocket-containing rock

The water pressure is so high that the rock begins to shatter

Added sand penetrates and wedges open the newly created cracks

The water is then pumped out along with gas-containing bubbles

If real-life fracking were this simple, its impact might be limited:

Pumped back to the surface, the natural gas would just fizz out

And the water could be recycled for use at the next fracking well

But now the very non-specific process of fossil fuel formation strikes again:

The rock pockets almost certainly contain hydrocarbons other than methane

Including larger hydrocarbons kept liquid by Van der Waals bonding

Smaller hydrocarbons are thus added to the exiting water

And even larger & more viscous hydrocarbons can clog the sand-wedged cracks

But by adding strong surfactants and solvents, these can be dispersed

Surfactants, solvents & larger hydrocarbons are thus added to the water

Finally, pressure-created cracks can be enlarged by further etching away the rock

Acids, dissolved minerals and their impurities are thus added to the water

And if that were not enough, a former student sent me a study entitled:

"Biocides in Hydraulic Fracturing Fluids:
A Critical Review of Their Usage, Mobility, Degradation, and Toxicity" [1]

Which begins:

Biocides are critical components of hydraulic fracturing ("fracking") fluids used for unconventional shale gas development. Bacteria may cause bioclogging and inhibit gas extraction, produce toxic hydrogen sulfide, and induce corrosion leading to downhole equipment failure. The use of biocides such as glutaraldehyde and quaternary ammonium compounds has spurred a public concern and debate among regulators regarding the impact of inadvertent releases into the environment on ecosystem and human health.

Bottom Line: Fracking is not just about injecting water + sand!

By the time it exits the wells, the working fluid is instead a witch's brew of:

Water + Surfactants + Solvents

+ Petroleum liquids and dissolved semi-liquids

+ Acids + Dissolved minerals and mineral impurities + Biocides

1) https://pubs.acs.org/doi/abs/10.1021/es503724k?source=cen

A more detailed listing of fracking additives from EarthWorks.org:

ADDITIVE TYPE	DESCRIPTION OF PURPOSE	EXAMPLES OF CHEMICALS
Proppant	“Props” open fractures and allows gas / fluids to flow more freely to the well bore.	Sand [Sintered bauxite; zirconium oxide; ceramic beads]
Acid	Cleans up perforation intervals of cement and drilling mud prior to fracturing fluid injection, and provides accessible path to formation.	Hydrochloric acid (HCl, 3% to 28%) or muriatic acid
Breaker	Reduces the viscosity of the fluid in order to release proppant into fractures and enhance the recovery of the fracturing fluid.	Peroxydisulfates
Bactericide / Biocide	Inhibits growth of organisms that could produce gases (particularly hydrogen sulfide) that could contaminate methane gas. Also prevents the growth of bacteria which can reduce the ability of the fluid to carry proppant into the fractures.	Gluteraldehyde; 2-Bromo-2-nitro-1,2-propanediol
Buffer / pH Adjusting Agent	Adjusts and controls the pH of the fluid in order to maximize the effectiveness of other additives such as crosslinkers.	Sodium or potassium carbonate; acetic acid
Clay Stabilizer / Control	Prevents swelling and migration of formation clays which could block pore spaces thereby reducing permeability.	Salts (e.g., tetramethyl ammonium chloride) [Potassium chloride]
Corrosion Inhibitor	Reduces rust formation on steel tubing, well casings, tools, and tanks (used only in fracturing fluids that contain acid).	Methanol; ammonium bisulfate for Oxygen Scavengers
Crosslinker	The fluid viscosity is increased using phosphate esters combined with metals. The metals are referred to as crosslinking agents. The increased fracturing fluid viscosity allows the fluid to carry more proppant into the fractures.	Potassium hydroxide; borate salts
Friction Reducer	Allows fracture fluids to be injected at optimum rates and pressures by minimizing friction.	Sodium acrylate-acrylamide copolymer; polyacrylamide (PAM); petroleum distillates
Gelling Agent	Increases fracturing fluid viscosity, allowing the fluid to carry more proppant into the fractures.	Guar gum; petroleum distillate
Iron Control	Prevents the precipitation of carbonates and sulfates (calcium carbonate, calcium sulfate, barium sulfate) which could plug off the formation.	Ammonium chloride; ethylene glycol; polyacrylate
Solvent	Additive which is soluble in oil, water & acid-based treatment fluids which is used to control the wettability of contact surfaces or to prevent or break emulsions.	Various aromatic hydrocarbons
Surfactant	Reduces fracturing fluid surface tension thereby aiding fluid recovery.	Methanol; isopropanol; ethoxylated alcohol

*This table excerpted from EarthWorks.org's: **Hydraulic Fracturing 101 - https://earthworksaction.org/issues/hydraulic_fracturing_101/***

Based on such listings, I was stunned to learn that:

Not only are fracking additives unregulated

But, in most locales, including on federally owned lands:

Fracking companies can not only add essentially anything they want,

but they need not disclose to the public or government WHAT they add

For an exceptionally comprehensive and well-referenced primer on fracking, see:

Fracking 101 from EarthWorks.org

(direct link / also cached on the this note set's Resources webpage)

Leading to natural gas extraction (part II): Fracking fluid disposal

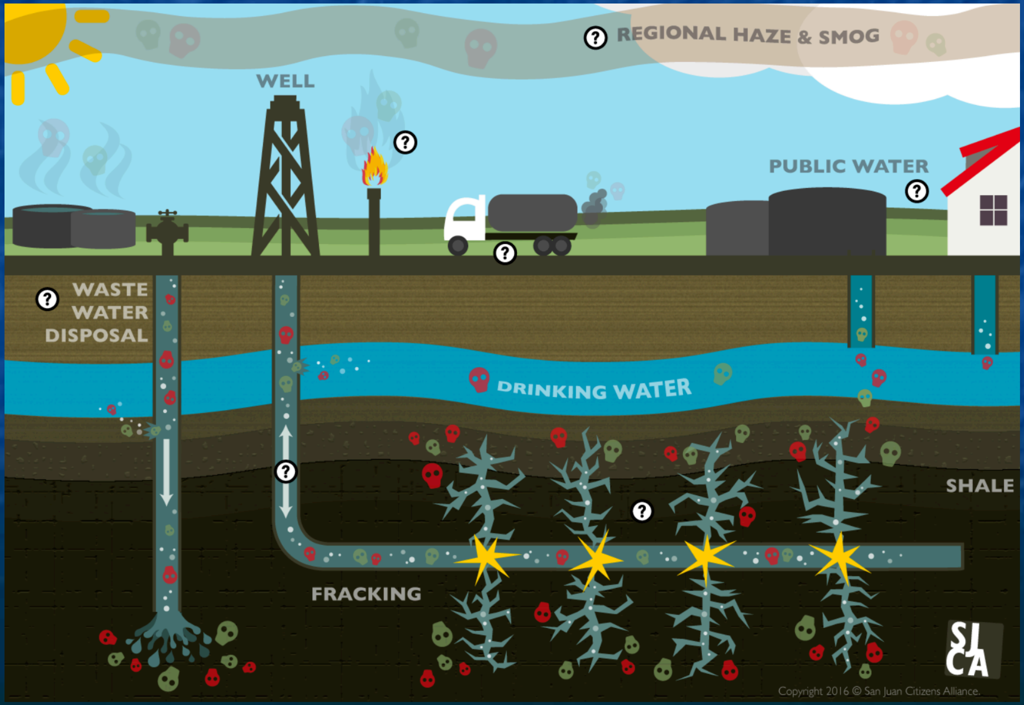
Given the resulting fracking fluid composition + today's "regulatory environment"

it is unsurprising that little (if any) effort is made to clean up those fluids

The prevailing practice is to instead hide them away by pumping them down either:

Depleted fracking wells OR Depleted oil wells

Where it is hoped that they will: **1) Stay put** and **2) Cause no further damage**



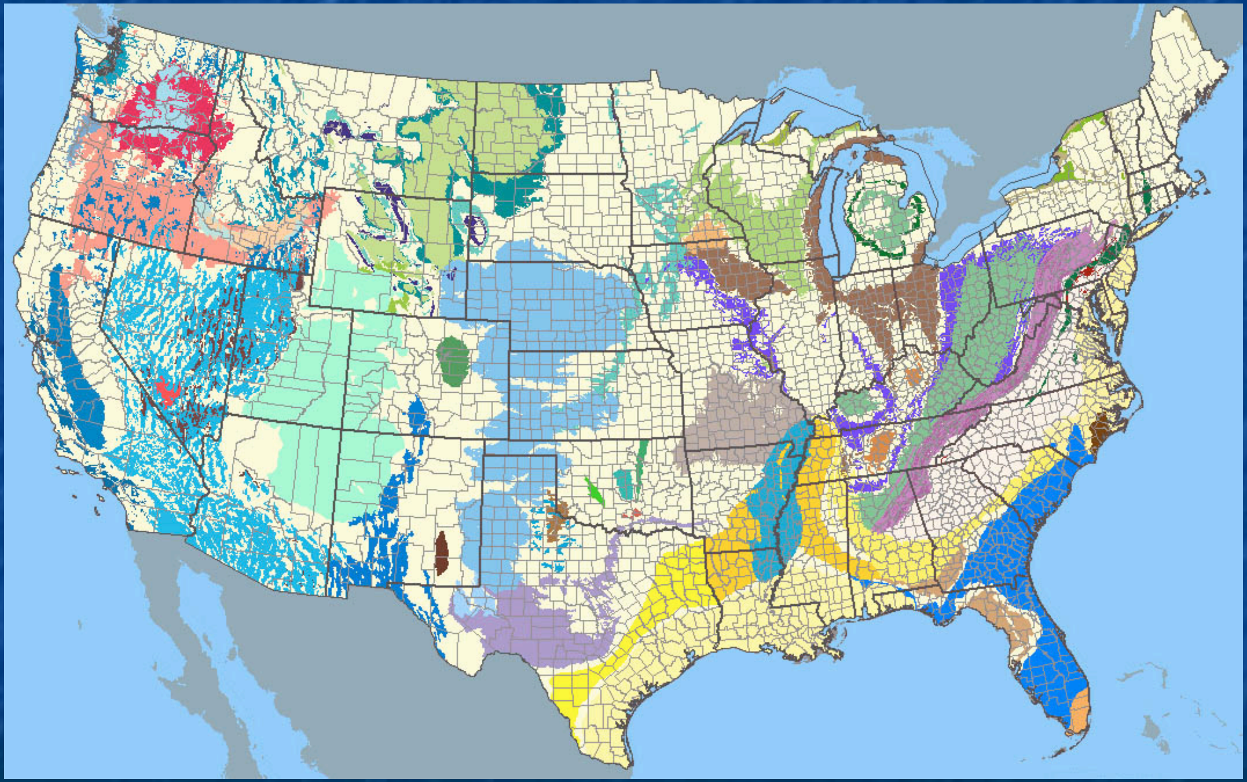
http://www.sanjuancitizens.org/fracking

Challenging such hopes is the existence of ***aquifers***:

Which are huge broad swaths of buried, naturally porous rock

into which, over many thousands of years, water has percolated creating

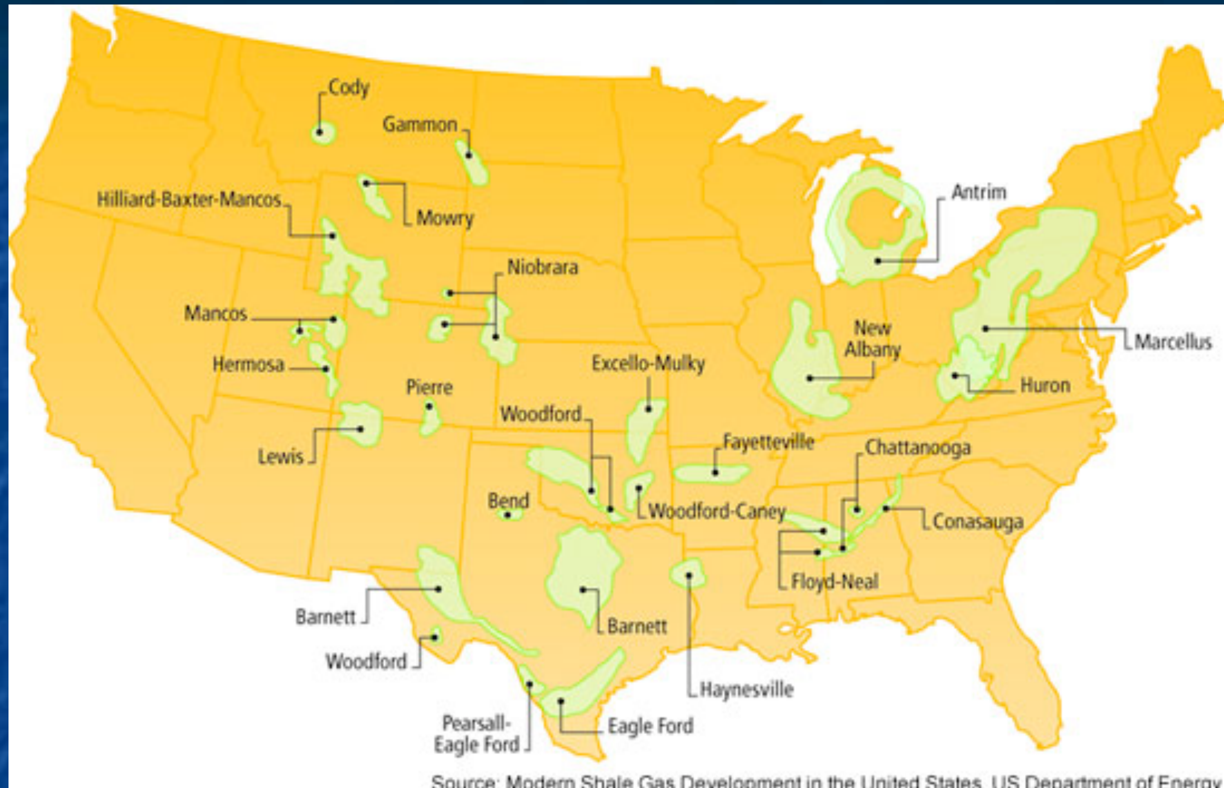
vast "underground lakes" **supplying our drinking & farm water wells**



Aquifers could widely disperse any fracking fluids leaking into them

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

Then note the geographical overlap of aquifers with fracking locales:



Source: Modern Shale Gas Development in the United States, US Department of Energy

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

Fracking groundwater pollution is already documented in Montana & Pennsylvania

While being very **strongly** suspected elsewhere

And a 5-year study already shows that mothers living within ½ mile of fracking sites are 25% more likely to have low birth weight babies than those 2 miles away [1]

1a) https://www.washingtonpost.com/news/energy-environment/wp/2017/12...of-low-birth-weight-babies-new-study-says/?utm_term=.93264ed472b6
1b) http://advances.sciencemag.org/content/3/12/e1603021

Further, if your residence was not included in the previous map:

This EIA map shows where fracking "may soon be coming to a place near you"

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

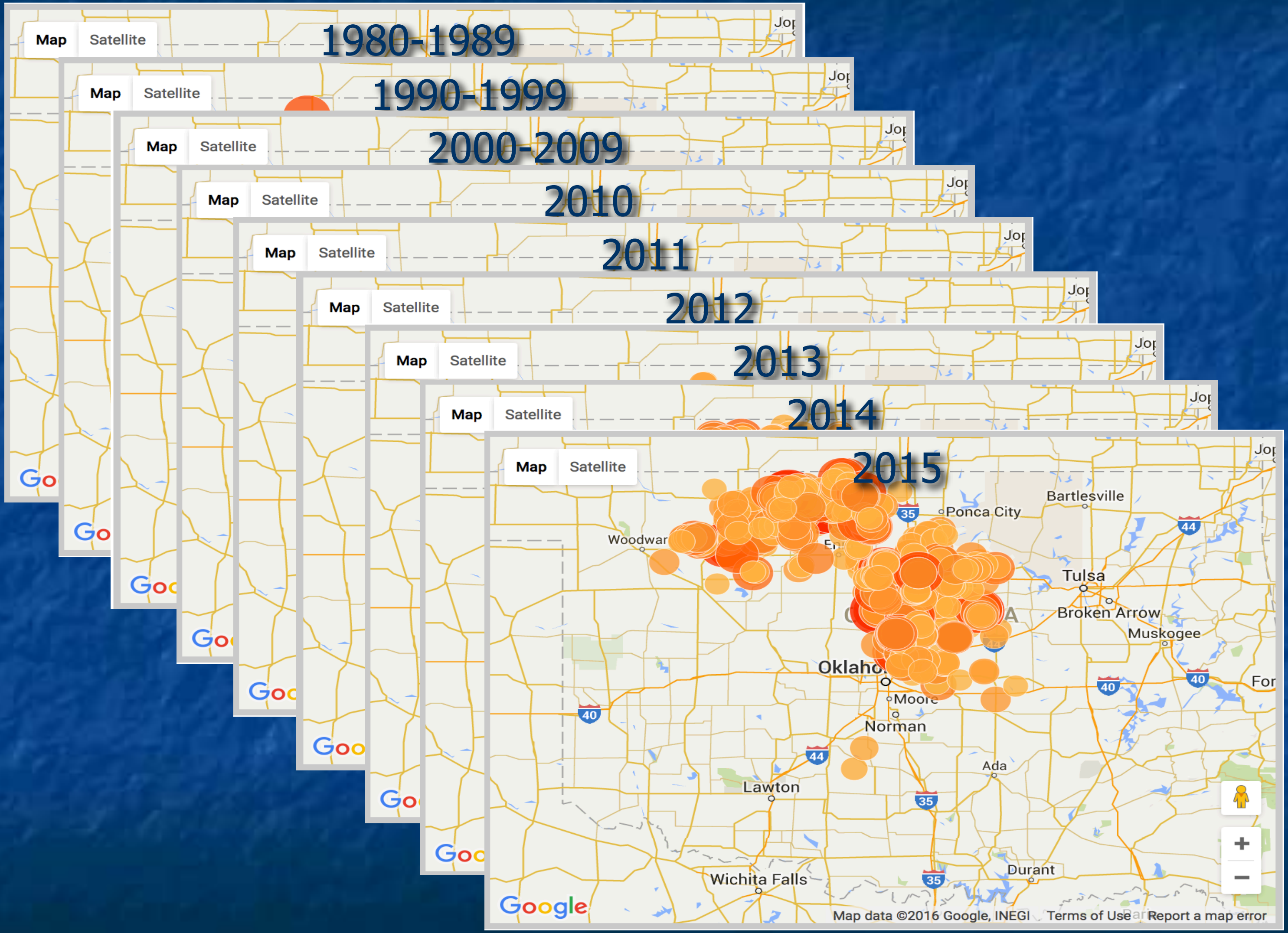
Map: http://www.eia.gov/analysis/studies/usshalegas/

Meaning that major segments of our population may soon be guinea pigs

in an essentially unregulated & unmonitored chemistry experiment

Natural gas extraction (part III): Fracking fluid induced earthquakes

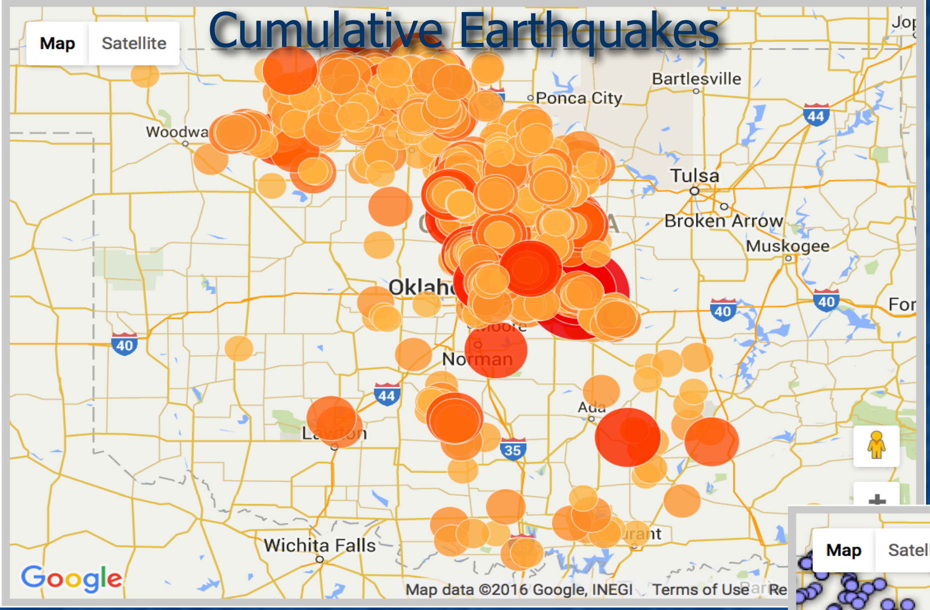
Page thru these plots of Oklahoma Earthquakes (from the Oklahoma Gov. website):

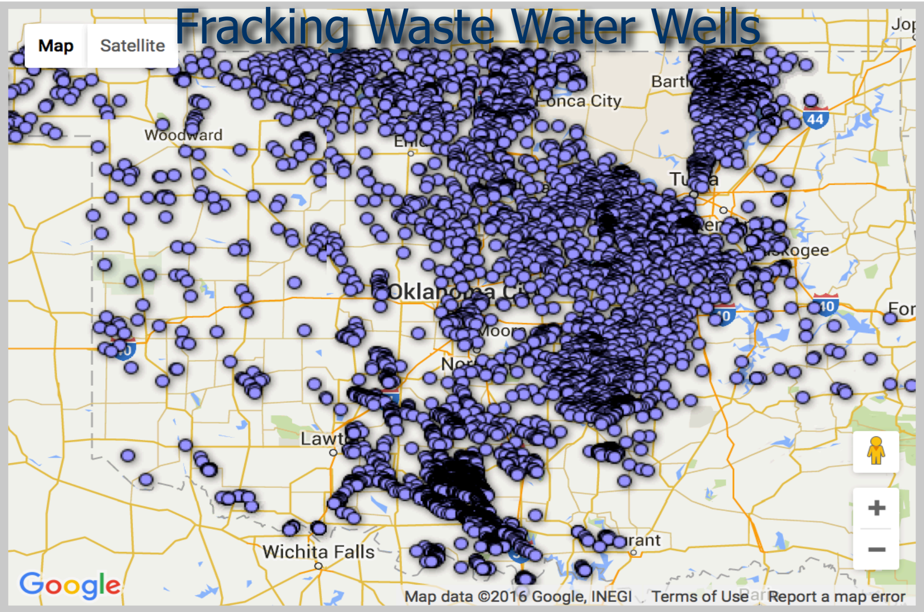


http://earthquakes.ok.gov/what-we-know/earthquake-map/

Something is clearly going on, but what is the root cause?

Might the answer lie in this final comparison from the state's website?





But backing up a bit:

Earthquakes are DRIVEN by stresses in the earth's crust

The ongoing collision of tectonic plates induces such stresses at their boundaries

As occurs along the western coast of North America

It is part of the Pacific Ocean's **Ring of Fire** tectonic boundary known for its

buildup of mountain ranges, volcanoes, and frequently severe earthquakes

But some plate stresses grew from tectonic collisions so ancient

that their locations no longer coincide with modern plate tectonic boundaries

These locations are thus NOT now known for mountains, volcanoes or earthquakes

Examples of which include the Rift Valley of northeast Africa

Or the region near New Madrid Missouri's great 1811 earthquake

Or, apparently, Oklahoma

In comparison, net fracking-induced stresses are miniscule

But fracking **does** do two things: It fractures the local rock structure

Its fluids then lubricate that broken up rock

BOTH of these facilitate earth movement that relieves latent tectonic stress

Thus fracking OR the subsequent underground disposal of its fluids

can trigger earthquakes where tectonic stress is present

This connection has now been accepted by many (if not most) seismic researchers

I grew up within walking distance of California's infamous San Andreas Fault

There, Oklahoma's biggest ~ Richter 5 earthquake would be considered trivial

But earthquake damage depends hugely upon local construction practices

Most vulnerable is un-reinforced brick or concrete construction which is thus

banned in California, but not in "earthquake free" states such as Oklahoma

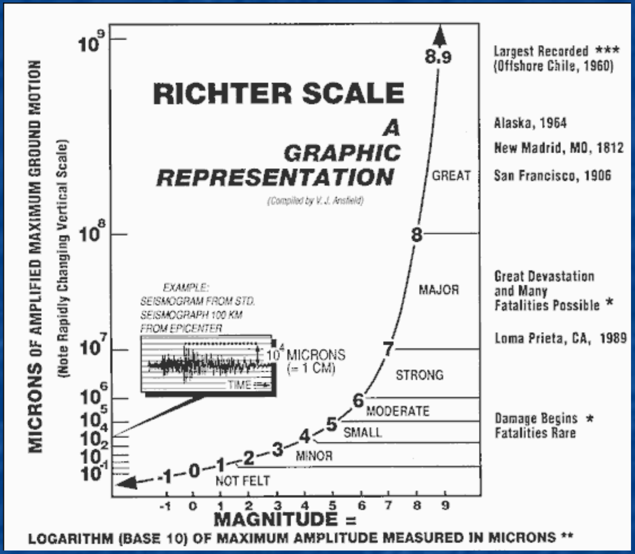
Thus Oklahoma's apparent "frack quakes" **have** in fact produced significant damage

But the greater fear is of ultimately triggering an Oklahoma "Big One"

The base 10 logarithm of an earthquake's energy => Its Richter Scale ranking

This figure, and my Californian experience, identify the danger zone as > Richter 6

- While Richter 5 = "Moderate: damage begins - fatalities rare"
- And Richter 4 = "Small"



The latter "small" designation makes sense

- Because 4's have **1/100th** the energy of 6's

Fortunately, most Oklahoma quakes were ≤ Richter 4

- Posing little threat to people or property

I would have thought many such small earthquakes might, in fact, be desirable:

- Because they might ultimately dissipate the limited tectonic stresses
  - present at that location so far from present day tectonic plate collisions

Figure: http://www.sms-tsunami-warning.com/pages/richter-scale#.VovmFsro9VI

But then I caught an excellent Weather Channel documentary entitled:

Secrets of the Earth: Manmade Earthquakes, featuring Caltech & USGS seismologists

They alluded to what I later found is called the **Gutenburg-Richter Law**:

Log_{10} (Frequency of a quake with Richter magnitude M) = a – b (M)

Which if b ~ 1 (as is apparently common) implies that:

Quake frequency drops by 10 for each 1 point increase in Richter magnitude

Thus more small quakes **do NOT decrease** the chance of a big one (as I'd thought)

More small quakes proportionally **increase** the chance of a big one

Why? By shifting adjacent short segments of a fault, a series of smaller earthquakes

can lead to an accumulation of major stress farther down the fault

thereby contributing to the probability of a larger earthquake at that point

So this former Californian stands corrected:

Science supports Oklahoma's fear of small "frack quakes" inducing a "Big One"

That show's seismologists also warned that:

Given the break-up and lubrication of local rock structure,

it would be reckless to frack near a fault overdue for a major earthquake

Geothermal power plants (**Exotics** (pptx / pdf / key)) do not similarly break up rock

But they do **similarly inject lubricating water deep underground**

So where is a major geothermal push now being made?

Near California's Salton Sea, not far from the San Andreas Fault's southern end

At least one research study already attributes mini earthquakes to that operation [1, 2]

Igniting public concern, including discussion in the LA Times [3]

And Scientific American noted a history of quakes near a N. CA geothermal plant

And that a Swiss geothermal plant was abandoned after a damaging quake [4, 5]

1) http://science.sciencemag.org/content/341/6145/543
2) https://news.ucsc.edu/2013/07/geothermal-earthquakes.html
3) http://articles.latimes.com/2013/jul/11/local/la-me-geothermal-earthquakes-20130712
4) https://www.scientificamerican.com/article/geothermal-drilling-earthquakes/
5) http://www.nytimes.com/2009/06/24/business/energy-environment/24geotherm.html?_r=1&scp=1&sq=altarock&st=cse

Natural gas extraction (part IV): Methane Leaks

Methane absorbs heat radiation as much as 70X more strongly than CO_2

But it is purged from the atmosphere ~ 10X faster

Resulting in a net greenhouse gas impact ~ 30X that of CO_2

This is potentially a **very big** deal

Which is why I devote two whole later note sets to climate modeling

It's also why the U.S. EPA ~~tabulates~~ once tabulated methane releases

Tabulations that I will present in those later lectures

However, it has now been alleged that:

Fossil fuel extraction is producing **major** "accidental" methane leaks

And that these releases have flown under the EPA's radar

The EPA ~~uses~~ used a "bottom up" method of tabulating methane releases

Which is based on identifying and sampling **known** emitters of methane [1]

And concludes that (in order of decreasing importance) U.S. methane sources are:

Livestock, natural gas production, land fills and coal mining

But a Harvard led research team instead used a "top down" method:

Based on 12,694 aircraft-borne measurements of atmospheric methane [2]

These revealed U.S. methane concentrations **50% higher than EPA estimates**

Further, the highest methane concentrations were measured over just three states

Texas, Oklahoma and Kansas

These states are among the heaviest U.S. natural gas producers

1) Emissions of Methane, a Potent Greenhouse Gas, May be Underestimated, Smithsonian Magazine, November 2013
2) Anthropogenic Emissions of Methane in the United States, S.M. Miller et al., PNAS 110, pp. 2018-22 (2o13)

Further, over these states:

The airborne gas measurements also revealed concentrations of propane

But propane is NOT produced by livestock or landfills

Which tends to exonerate those known sources of methane

Strongly implicating fossil fuel extraction as the methane source

A Stanford led study went even further in assigning responsibility: [3]

"Very high emissions rates are unlikely to be representative of typical NG system leakage rates"

"Experiments suggest that a small number of “superemitters” could be responsible for a large fraction of leakage"

That is, these potent greenhouse gas releases can be attributed to:

Rogue (particularly leaky) natural gas extraction/refining operations

3) Methane Leaks from North American Natural Gas Systems, A.R. Brandt et al., Science 343, pp. 733-5 (2014)

And that is just for the natural gas "business as usual"

To this we must now add the recent crisis at the:

Aliso Canyon Natural Gas Storage Facility

Near the **Porter Ranch** area of Los Angeles

The Background: In 1971 the Southern California Natural Gas Company

began connecting up a network of 115 depleted natural gas wells

to form a massive underground storage facility

with a net volume of 1.5 cubic miles, at ~ 1 mile depth [4]

The Intent: To accommodate gas pumped in from as far away as Canada

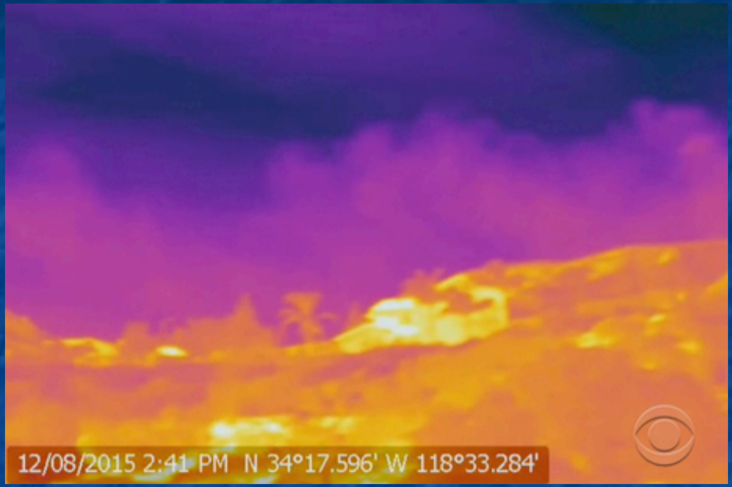
To serve 22 million gas consumers, spanning the entire Los Angeles basin [4]

On (or shortly before) 23 October 2015,
this underground network sprung a leak . . . somewhere

4) http://www.latimes.com/local/california/la-me-porter-ranch-delay-20160102-story.html

It was A VERY BIG leak:

As seen in these infrared images of the gas plume above the ridge: [5, 6]



By December, the leak rate was **110,000 pounds of CH_4 per hour** [7]

Accounting for **¼ of TOTAL California CH_4 emission** [8]

And the cumulative (5 weeks in) methane leakage was equivalent to

800,000 metric tons of the greenhouse gas CO_2 [8]

The leakage **rate** was equivalent to that produced by driving **4.5 million cars** [6]

5) http://www.cbsnews.com/news/families-uprooted-after-massive-methane-leak-in-california/
6) http://www.bbc.com/news/world-us-canada-35244634
7) http://www.latimes.com/science/la-me-porter-ranch-christmas-20151225-story.html
8) http://www.theguardian.com/us-news/2015/dec/04/california-natural-gas-leak-methane-climate-change-old-infrastructure

Which caused HUGE problems:

The total H_2S ambient was 6X higher that max allowed California limit [7]

And the leak also contained at least traces of carcinogenic benzene [9]

Stench and health concerns led the governor to declare state of emergency,

and to order the **indefinite evacuation** of more than 2000 homes [10, 6]

10k people had evacuated by 8 January, and 7k more later evacuated [11]

By early December 2015, six attempts at blocking the leakage had failed

and operators switched to the drilling of an up to 8700 foot deep relief well,

which, if they get lucky in finding the leak,

"will take 3-4 months to complete" [12]

9) http://www.theguardian.com/environment/2016/jan/14/la-natural-gas-leak-methane-benzene-health-risks-california-gas
10) http://www.latimes.com/local/california/la-me-adv-gas-leak-health-20151220-story.html
11) http://www.bbc.com/news/world-us-canada-35257861
12) http://www.latimes.com/local/california/la-me-porter-ranch-20151228-story.html

BREAKING NEWS:

February 11, 2016 (four MONTHS after the leak began)

Southern California Gas Company announced [13]

"We have temporarily controlled the natural gas flow from the leaking well"

Thus, after up to four months out of their homes,

6400 displaced families could begin to put their lives back together [14]

Although many of these families in fact chose to wait even longer until:

A **permanent** plug was installed and/or

It was proven that this single now-plugged well was the **only** leak and/or

Until their homes were certified free of trace carcinogens

13) http://www.theguardian.com/us-news/2016/feb/11/socalgas-fixes-natural-gas-methane-leak-los-angeles-porter-ranch
14) http://bigstory.ap.org/urn:publicid:ap.org:e586b063994a460fa5951198d6841b64

For a more up-to-date view of the Porter Ranch methane leak:

See Wikipedia's

"Aliso Canyon Gas Leak" webpage (link)

along with its numerous linked sources

My closing thoughts about fracking & the U.S. embrace of natural gas:

We (the U.S. public) are complicit:

It is the torrent of fracked U.S. natural gas that has driven down energy prices

And which now sustains our beloved sub $3 per gallon gasoline prices

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

The petroleum industry, with its long and dark environmental history,

to **secretly** inject potent chemicals into even our publically owned lands

Making it "**progress**" if they would now even **tell** us what they are injecting!

And that 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

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

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