Greenhouse Effect, Carbon Footprints and Sequestration

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Outline

Building a simple "do-it-yourself" model of the Greenhouse Effect based on:

- 1 color of sunlight + 1 color of earthlight + 1 greenhouse gas

Which ultimately collapses because: It's all about different colors

- Colors where gas A absorbs & emits vs. colors where gas B absorbs & emits
- Critical colors = Those where earth might radiate away heat (particular infrared colors)
  - But is now being thwarted by the addition of new atmospheric gases

Data on gases now accumulating in the atmosphere

- Including now-censored "EPA Inventory of U.S. Greenhouse Gas Emissions & Sinks"

Discussion of atmospheric gas sources, especially energy industry sources

- Possibilities of reducing such emissions
  - Or of at least "sequestering" those emissions

(Written / Revised: February 2021)

Greenhouse Effect, Carbon Footprints and Sequestration

This lecture continues our discussion of climate change

Last time I discussed how acquire long-term climate data

And provided an overview of how climate models have evolved

Today I'll dig deeper into the Greenhouse Gas Effect

Which sounds simple - and indeed the basics are

But with a realistic variety of gases, it becomes extremely complicated!

As suggested by conflicting "expert" statements, such as:

"CH_4 is 5X worse than CO_2" versus "CH_4 is 30X worse than CO_2"

And as will be seen in the "simplified" greenhouse model I'll try to develop

I'll then close by discussing Carbon Footprints and Carbon Sequestration

*Common explanations of the greenhouse effect can be **very** incomplete*

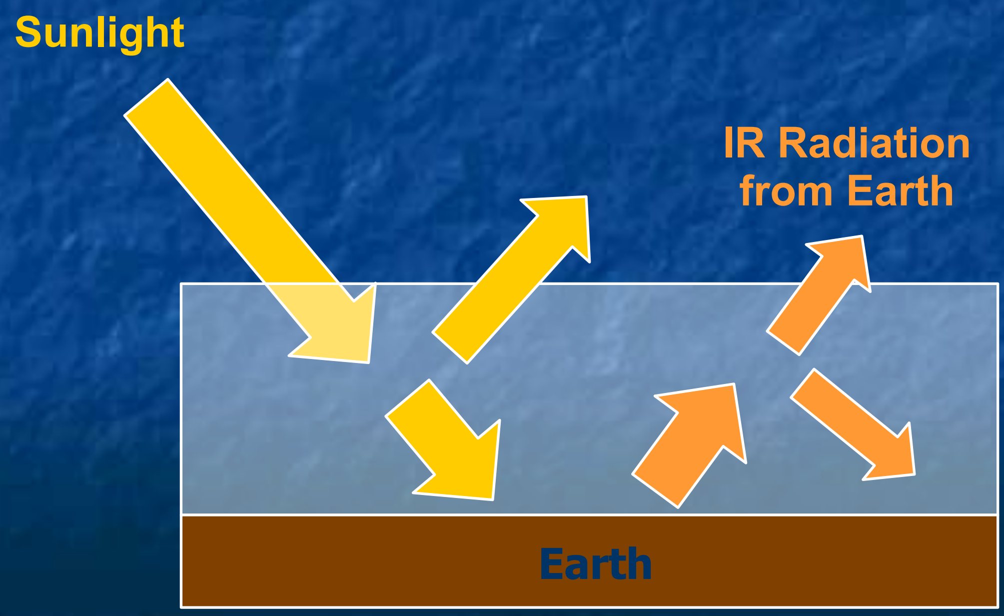
To demonstrate this, let's try to develop our own model

That model should include:

- Incoming sunlight partly absorbed/scattered by atmosphere, partly passing to earth

- Outgoing heat (IR radiation) emitted by the warm earth,

  partly absorbed/scattered by atmosphere, partly passing to out to space



To clarify our model, simplify our model:

Do this by temporarily assuming that:

- Sunlight is all one color = **$color_{sunlight}$**

- IR radiation emitted by earth is all one color = **$color_{earthlight}$**

- There is only one really important greenhouse gas = **gas**

We then need to know:

- Gas's light absorbance (per molecule or mass) at $color_{sunlight}$ = **$Absorb_{sunlight}$**

- Gas's light absorbance (per molecule or mass) at $color_{earthlight}$ = **$Absorb_{earthlight}$**

- Plus the concentration of that gas in the atmosphere

Which ought to be proportional to:

(Rate of gas introduction) x (Average gas lifetime in atmosphere)

That is: **$Concentration_{gas} = C1 \times Rate_{added} \times Lifetime$**

We would also need to know:

- Intensity of arriving sunlight (power / area) = $\mathbf{P_{sunlight}}$

- Intensity of earth's IR thermal emission (power / area) = $\mathbf{P_{earthlight}}$

The other stuff might be fixed, but this quantity will not be!

Because it will intensify if earth's surface heats up (and reverse)

So **output** of our model will be resulting value of $\mathbf{P_{earthlight}}$ as a function of time

=> Temperature of earth's surface as a function of time

So let's now see how far we can get with this simplified model:

To come up with quantitative results we'd also have to figure out a lot of constants

Taking into account things like geometries

But we just want trends now, so I'll just stick in constants as C's

Sun power flow ***downward*** *through the atmosphere:*

Power arriving at **TOP** of atmosphere = $P_{sunlight}$

In the atmosphere some **fraction** of this power will be absorbed or scattered:

$= C2 \times Concentration_{gas} \times Absorb_{sunlight}$

$= C2\ (C1 \times Rate_{added} \times Lifetime)\ (Absorb_{sunlight})$

$= C3 \times Rate_{added} \times Lifetime \times Absorb_{sunlight}$

So sunlight power passing downward **through** the atmosphere directly would be

$= P_{sunlight}\ (1 - C3 \times Rate_{added} \times Lifetime \times Absorb_{sunlight})$

However, sunlight power absorbed by greenhouse gas **eventually** has to exit

It should radiate out randomly in all directions, thus

Half re-radiates upward out into space, half re-radiates downward to earth

Sun power to earth = $P_{sunlight}\ (1 - ½\ C3 \times Rate_{added} \times Lifetime \times Absorb_{sunlight})$

*Earth IR power radiated **upward** into outer space:*

By just turning all of the arguments above on their heads, and we should have:

$$\text{Earth power to space} = P_{earth}\,(1 - \tfrac{1}{2}\,C4 \times Rate_{added} \times Lifetime \times Absorb_{earthlight})$$

Which, eventually, should balance last page's sun energy coming down to earth:

$$\text{Sun power to earth} = P_{sunlight}\,(1 - \tfrac{1}{2}\,C3 \times Rate_{added} \times Lifetime \times Absorb_{sunlight})$$

So equate, solve for P_{earth}, figure out what temperature would produce that power

What's so hard about this? To expand our model we only seem to need:

- Conversion of earth's surface temperature to power emitted

- Absorbance data for real greenhouse gases

- Concentration of real greenhouse gases

OR their rate of addition to **and** lifetime in the atmosphere

Conversion of surface temperature to power emitted:

Radiation from any heated object can be approximated by a "**blackbody**"

Which assumes that objects have all sorts of oscillators (e.g., oscillating electrons)

Some oscillate slowly, some oscillate more quickly

Oscillation of electrons => **emission** of electromagnetic radiation ("light")

Slow oscillators => Low frequency (long wavelength) light

Fast oscillators => High frequency (short wavelength) light

But these same oscillators can also **absorb** light, **including each other's light**

So heat energy is **shared around** between these oscillators

Sharing => Final balance of light from slow vs. faster oscillators

Analysis of sharing + dose of quantum mechanics => **"Blackbody Curve"**

Blackbody Curves:

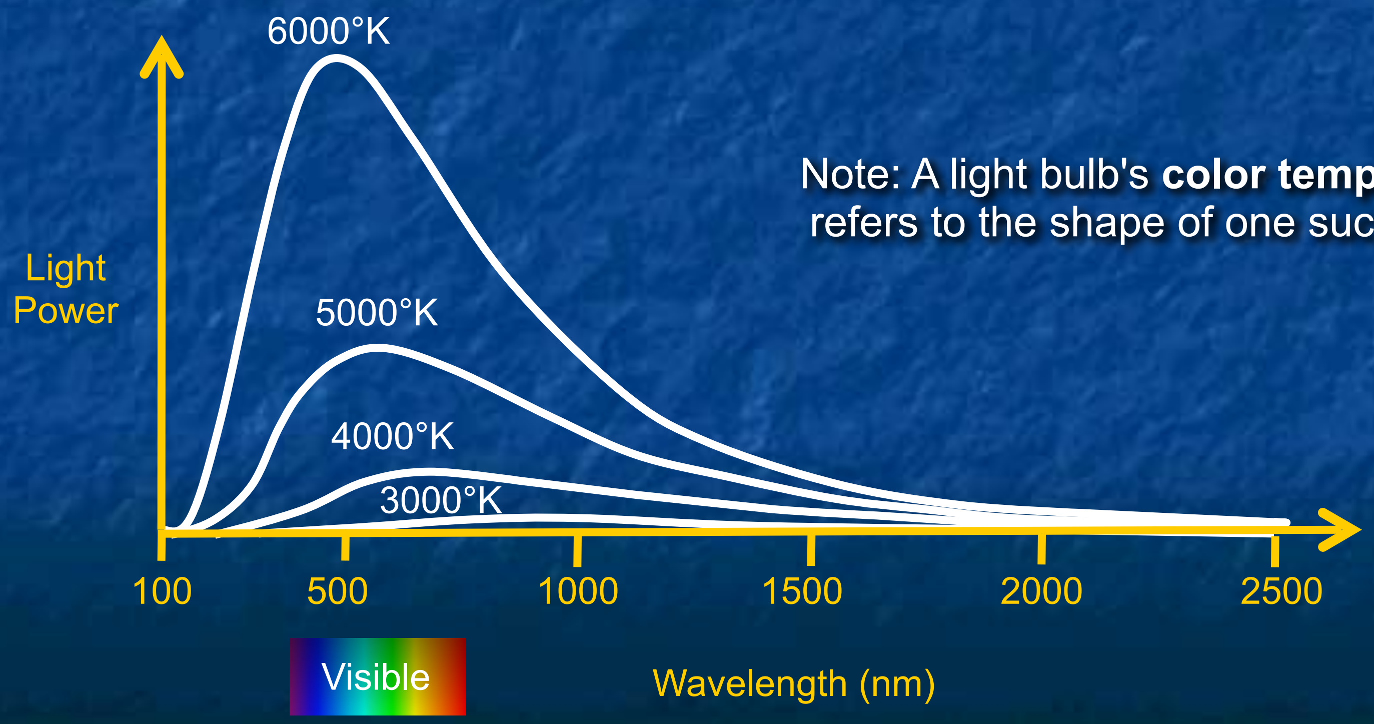
Planck's Blackbody Law:

Light Intensity $(W/m^2\text{-}\mu m) = A / \lambda^5 [e^{B/\lambda T} - 1]$

Where λ = Wavelength, T is temperature of the object (in °K)

$A = 3.742 \times 10^8\ W\text{-}\mu m^4/m^2$ $B = 1.44 \times 10^4\ \mu m\text{-}K$

Which generates curves like this for objects of different temperatures:



Note: A light bulb's **color temperature** refers to the shape of one such curve

Characteristics of which:

Roughly match our personal experiences:

As object gets hotter, it emits MORE total heat energy

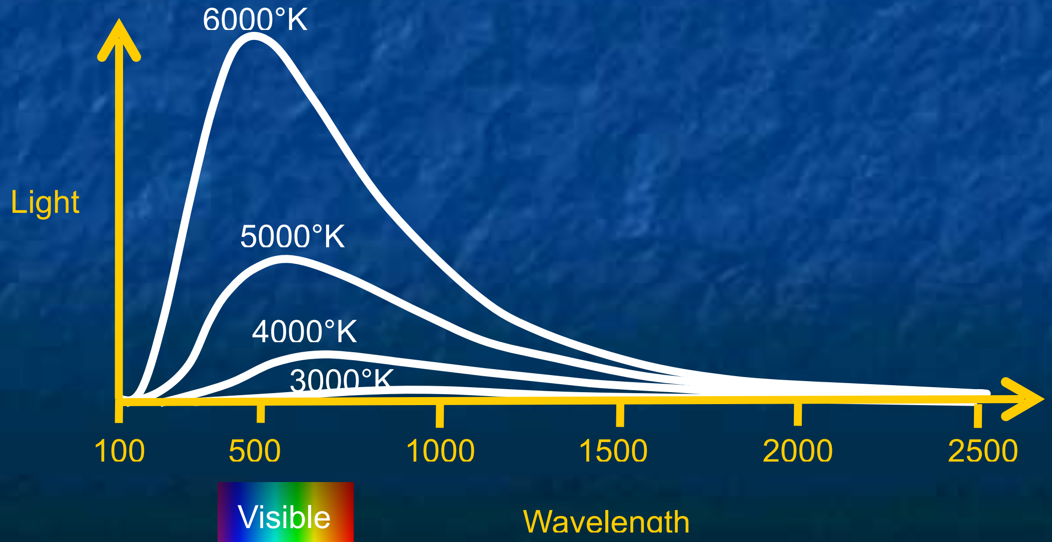
As object gets hotter, its color changes from red => orange => yellow . . .

From blackbody curves, those observations can be quantified in the:

Stefan-Boltzman Law = Total blackbody energy **=** Total heat emitted **= σT^4**

$\sigma = 5.670 \times 10^{-8}\ W/m^2/(°K)^4$

Wien Displacement Law = Peak blackbody wavelength **= 2896 µm / T (in °K)**



Implications for our model:

- We approximated sunlight's true spectrum as a single color

- We also approximated earth's (mostly IR heat) spectrum as a single color

We could still use the new laws by lumping each spectrum into one color. That is:

Sunlight spectrum ~ 6000°K Black body curve, so using Stefan-Boltzman and Wein:

$P_{sunlight} = \sigma (6000°K)^4$ ~ 70 million W/m^2 (at sun's surface)

$Color_{sunlight}$ ~ $Peak\_wavelength_{sun}$ = 2896 μm / 6000 ~ 0.5 μm

Earth spectrum, keeping earth's surface temperature as variable to be solved for:

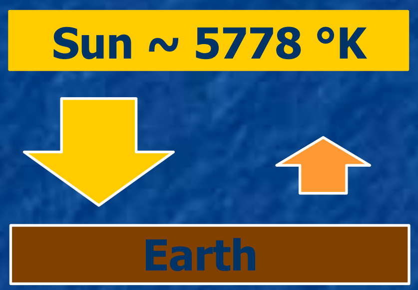
$P_{earth} = \sigma (Temperature_{earth})^4$

$Color_{earth}$ ~ $Peak\_wavelength_{earth}$ = 2896 μm / $Temperature_{earth}$

*To see how we could solve for T_{earth} , **really** simplify:*

For instance, by eliminating the atmosphere

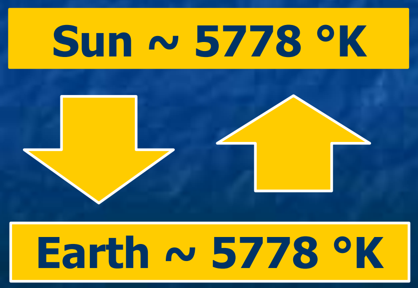
And assuming flat sun right next to flat earth:



But cooler "Earth" receives more heat than it emits!

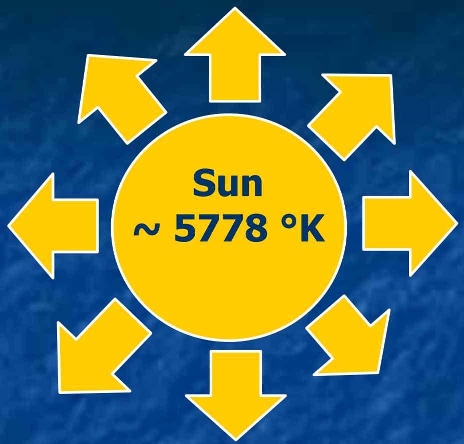
So, it would heat up until incoming and outgoing heat flows balanced

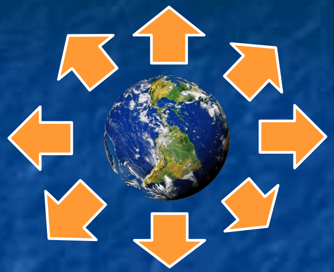
Stefan-Boltzman Law, in this geometry, would require equal temperatures:



=> **Extreme case of ~~global~~ planar warming**

Or we could use a more realistic geometry:





With its light spreading out, sun delivers far less power/area to earth's atmosphere

Earth then re-emits that energy in all directions (not just side receiving sunlight)

So balance of heat flow to and from earth' surface is achieved with

earth surface temperature far less than sun's 5778 °K surface temperature

And we all know balance comes with earth surface temperature of **about** 300 °K

But that "about" is all important to those of us living on the earth!

But that's getting ahead of ourselves, we still need more input data:

One of the things still needed is the concentrations of real greenhouse gases

A **naturally occurring** but extremely important greenhouse gas is **water vapor**

For which I could use measured concentrations + temperature trends

Hoping it does not complicate things by converting to IR reflecting clouds!

Other current atmospheric greenhouse gas concentrations:

Gas:	**CO_2**	CH_4	N_2O	CFC-11	HCFC-22	CF_4
Parts/million by volume (1994)[1]:	**358**	1.72	0.312	0.00027	0.0001	0.00007
Parts/million by volume (2014)[2]:	**395**	1.89	0.326	0.00024	0.0002	

But these are only recent concentrations, and we want to model possible changes

[1]Source: Introduction to Engineering and the Environment - Rubin (p. 471)

[2]Source: http://cdiac.ornl.gov/pns/current_ghg.html

To model possibly changing greenhouse gas concentrations:

We'd do better by using relationships like: Concentration α $Rate_{added}$ x Lifetime

So we'd first work up estimates on current and future rates of gas introduction

This is where we'd put in the effect of our industrial civilization

Then we'd need each gas's typical (average) lifetime in the atmosphere

For which I found data from various sources (ACS / Rubin textbook / ORNL):

Average greenhouse gas lifetimes in atmosphere (in years):

Gas:	**CO_2**	CH_4	N_2O	CFC-11	CFC-12	HCFC-22	HFC-23	SF_6	CF_4
Life[1]:	**50**	12	114		100		270	3200	
Life[2]:	**50-200**	12	120	50		12			50000
Life[3]:	**100-300**	12	121	45	100	11.9		3200	

[1]Source: www.acs.org/content/acs/en/climatescience/greenhousegases/properties.html

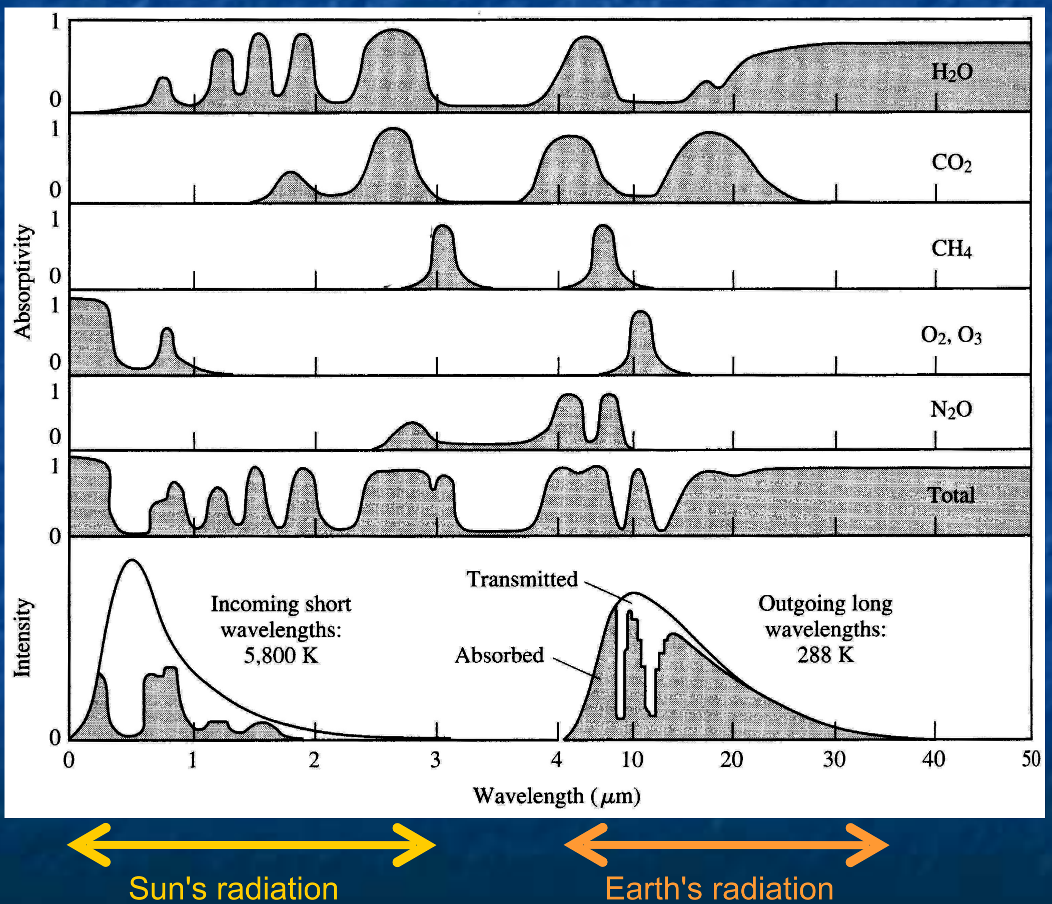
[2]Source: Introduction to Engineering and the Environment - Rubin (p. 471)

[3]Source: http://cdiac.ornl.gov/pns/current_ghg.html

Bringing me to data on real greenhouse gas absorbances

Where our simplified model runs into a non-simple wall:

Greenhouse gases absorb at all sorts of wavelengths, with huge overlaps!



Source: Introduction to Engineering and the Environment - Rubin (p. 482)

Taken from: Introduction to Environmental Engineering & Science - Masters

Implying:

Our model's single wavelength approximations are going to be **very** inaccurate

We can't just approximate sun and earth light by single wavelengths

Because **gas absorption is all across their blackbody spectra**

Effect of each greenhouse gas is also no longer independent of other gases

For one, through their absorbance overlaps, **gases can exchange energy**

But even more important is **HOW the gas absorbance bands overlap:**

Where more concentrated gas already blocks sunlight, new gas has small effect

But if new/dilute gas blocks open wavelengths, it can have a HUGE EFFECT

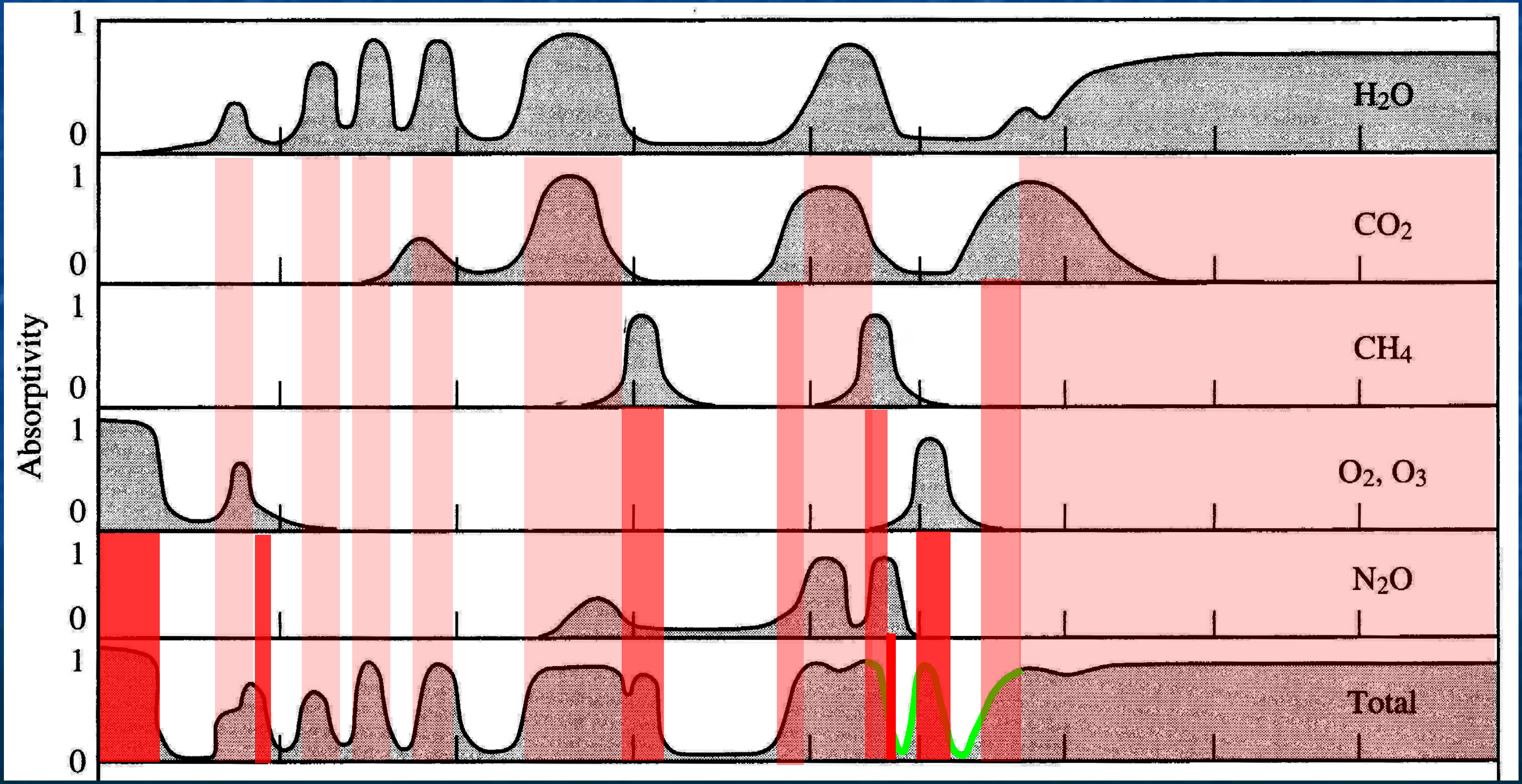
Because it closes a previously open greenhouse window!

CUMULATIVE blocking effect:

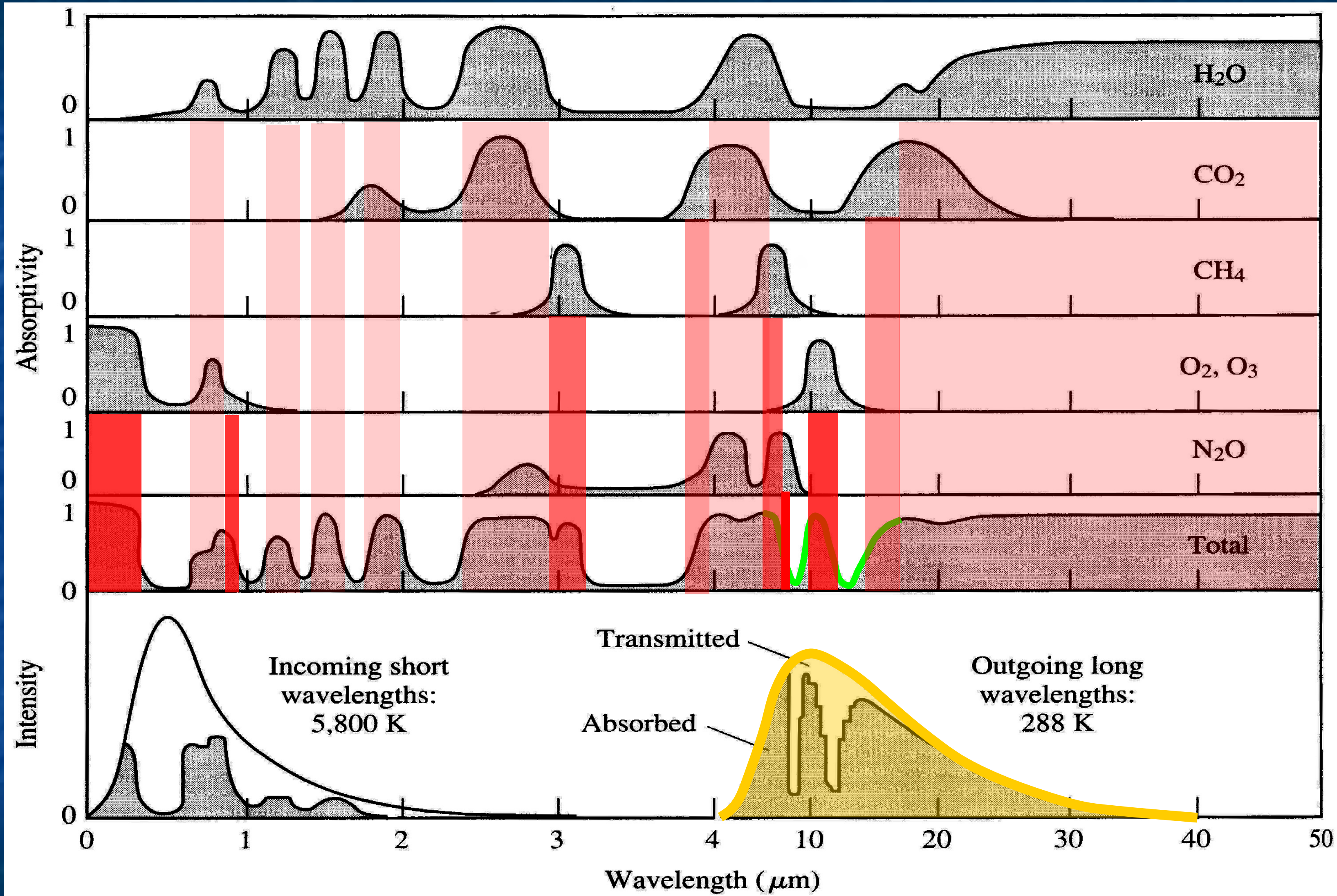
Order of chart is most concentrated gases (top) => most dilute gases (bottom)

PageDn to add red bands showing blocking due to successively more dilute gases

Green = Window for Earthlight heat loss left open by water vapor

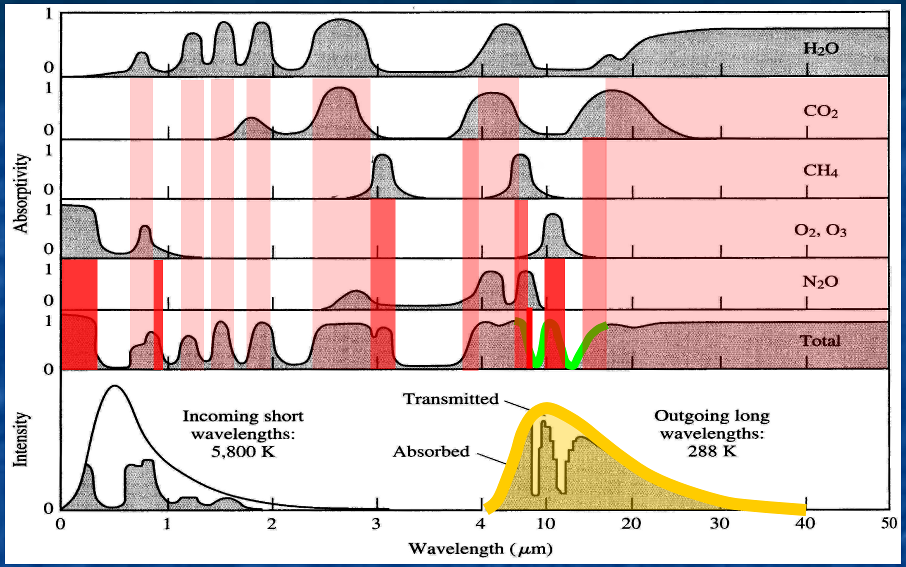


Cumulative effect of added gases on earth's heat loss window:



Heat loss window is now mostly shut by CO_2, CH_4, O_2, O_3 and N_2O

This explains the difficulty in predicting the impact of a given gas



For instance: Why I have heard methane is "5X worse" or "30X worse than CO_2"

Because it is NOT about methane's entire absorption spectrum

It's about where methane absorbs IR colors that no other gas has already absorbed

And that depends on the **absorption spectra** of ALL the other gases

And on the **concentrations** of ALL those other gases

Making this an extremely complex and tightly interwoven calculation!

Another way of looking at this is "Global Warming Potential"

For which **American Chemical Society** has a nice webpage, which I'll just quote:

"GWP is a measure of how much energy a greenhouse gas would add to atmospheric warming in a given time compared to CO_2.

A molecule's GWP depends on three factors:

1) The wavelengths where the molecule absorbs.

The absorption needs to be in the thermal IR range where the Earth emits and will be more effective if it absorbs where water vapor and CO_2 do not.

2) The strength of the relevant absorptions.

The more energy the molecule absorbs, the more effective it will be in warming.

3) The atmospheric lifetime of the molecule.

The longer the gas persists, the more warming it can produce."

http://www.acs.org/content/acs/en/climatescience/greenhousegases/properties.html

*Yielding assessments of **relative** greenhouse impact*

CUMULATIVE impact on global warming:

Gas	Lifetime (yrs)	20 yrs out	100 yrs out	500 yrs out
CO_2 (= STANDARD)	(50-300)	1	1	1
CH_4	12	72	25	7.6
N_2O	114	289	298	153
CFC-12 (CCl_2F_2)	100	11000	10900	5200
HFC-23 (CHF_3)	270	12000	14800	12200
HFC-134a (CH_2FCF_3)	14	3830	1430	435
Sulfur Hexafluoride	3200	16300	22800	32600

Remember that lifetimes are not absolute (gas doesn't then suddenly disappear)

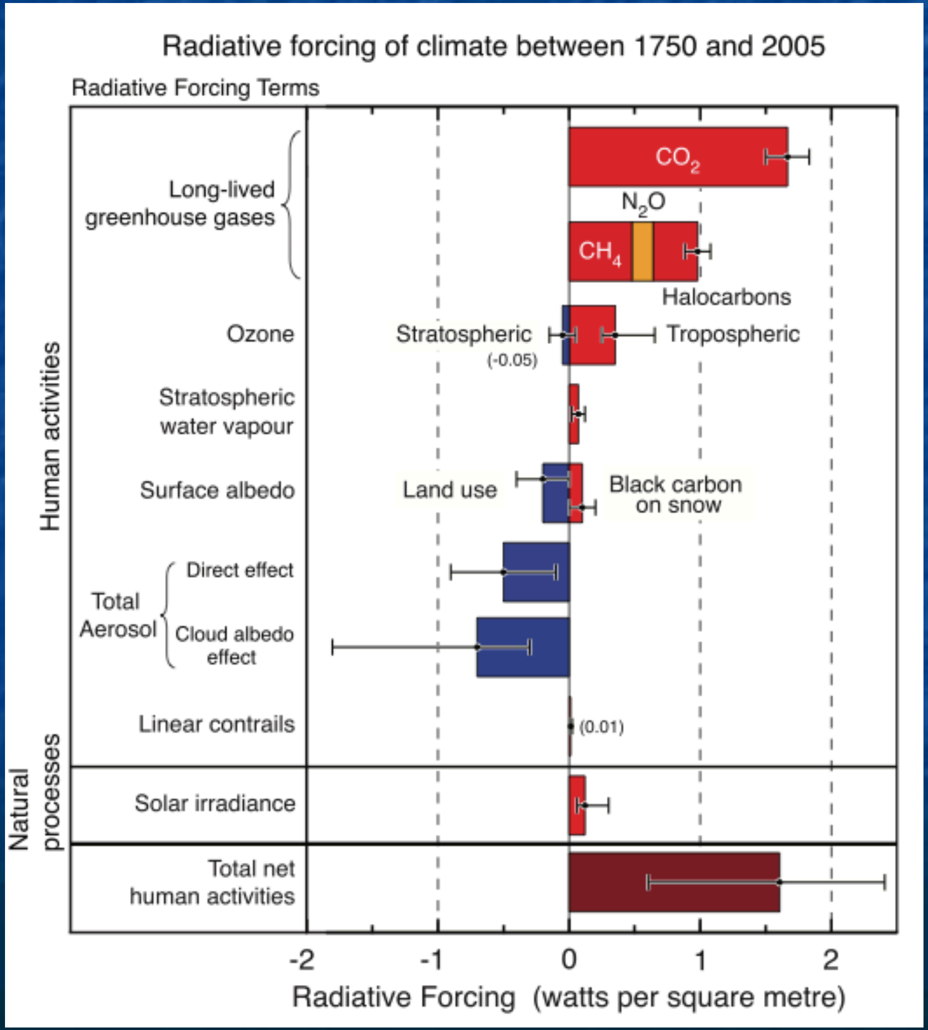
It's more like radioactive half lives, where ~ 50% will be gone in this time

http://www.acs.org/content/acs/en/climatescience/greenhousegases/properties.html

FULL effect of each gas is tabulated in IPCC's "radiative forcings"

Which go beyond GWP's by adding in relative concentrations of gases

Here showing only **manmade** forcings (i.e. above and beyond natural occurrences)



CO_2

CH_4 | N_2O | CFCs

O_3

H_2O (added by human activity)

IPCC Fourth Assessment Report - Working Group 1 2007 (p. 136)

So we now understand need for hugely complex computer models:

Which must deal with full spectra of solar and earth light/power emission

AND deal with full spectrum of a given greenhouse gas's absorption

Including possible absorption at one wavelength / re-emission at another

And deal with overlaps in absorption/emission spectra between multiple gases

Including possible blockages by more concentrated gases

And deal with complexities such as:

Water as vapor absorbs IR radiation => strong greenhouse gas => heating

But if subtle factors convert it to clouds => Reflects sunlight => cooling

Explaining uncertainties about a specific greenhouse gas's impact

Which is due to **only** small segments of its absorption bands

that peek out from behind the absorption bands of other gases

To alter projected trends

We will have to reduce greenhouse effects

Which will require reduction in following carbon footprints:

Worldwide annual greenhouse gas emissions in 1990's (in M-ton):

Source		World	US	
CO_2:	**Commercial Energy**	22,900	5,250	(US = ¼ world!)
	Cement manufacturing and gas flaring	1,000	50	
	Tropical deforestation	5,900	-	
	Total	29,800	5,300	
CH_4:	**Fossil fuel production**	100		
	Enteric fermentation	85		
	Rice paddies	60		
	Landfills	40		
	Animal waste	25		
	Sewage	25		
	Total	375	11	
N_2O:	Cultivated soils	3.5		
	Industrial	1.3		
	Biomass burning	0.5		
	Cattle and feed lots	0.4		
	Total	5.7	0.5	
Other:	CPC-11, -12, -13	0.7	0.1	
	HCFC-22	0.2	0.1	
	HFCs, PFCs, SF6		0.34	

Source: Intro to Energy and the Environment – Edward S. Rubin (p. 40), citing IPCC and others

EPA Inventory of US Greenhouse Gas Emissions and Sinks (1990-2012)

(in million metric tons CO_2 equivalent)

Source			1990	2012
CO_2:	Fossil Fuel Combustion		4745	5072
		Electricity Generation	1820	2023
		Transportation	1494	1740
		Industrial	845	774
		Residential	338	288
		Commercial	219	197
	Non-energy use of Fuels		121	110
	Steel Production / Mining		100	54
	Natural Gas Systems		38	35
	Cement Production		33	35
	Lime Production		11	13
	Ammonia Production		13	9

From table ES-2 of: http://www.epa.gov/climatechange/Downloads/ghgemissions/US-GHG-Inventory-2014-Main-Text.pdf

See note that follows

(continuing on to methane and nitrous oxide data)

Source		1990	2012
CH_4:	Enteric fermentations (a.k.a. flatulence)	138	141
	Natural Gas Systems	156	130
	Landfills	148	102
	Coal Mining	81	56
	Manure Management	32	53
	Petroleum Systems	36	32
N_2O:	Agriculture soil management	282	306
	Stationary Combustion	12	22
	Manure Management	14	18
	Mobile Construction	44	17
	Nitric Acid Production	18	15

From table ES-2 of: http://www.epa.gov/climatechange/Downloads/ghgemissions/US-GHG-Inventory-2014-Main-Text.pdf

See note that follows

A note/digression about disappearing EPA Data

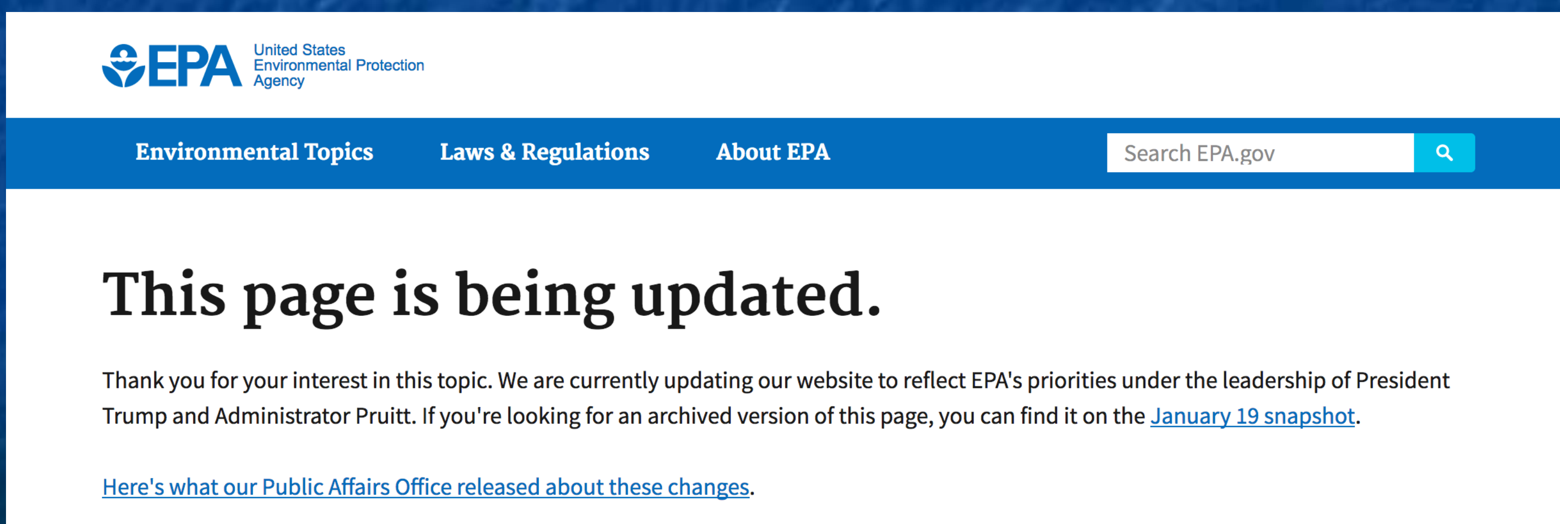
In researching this lecture note set, on 3 October 2014 I first accessed the preceding:

"EPA Inventory of U.S. Greenhouse Gas Emission & Sinks: 1990-2014"

At: http://www.epa.gov/climatechange/Downloads/ghgemissions/US-GHG-Inventory-2014-Main-Text.pdf

Re-accessing that link on 28 April 2017, the EPA server gave me a "**file not found**" error

The next day the same link returned this message:



EPA United States Environmental Protection Agency

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This page is being updated.

Thank you for your interest in this topic. We are currently updating our website to reflect EPA's priorities under the leadership of President Trump and Administrator Pruitt. If you're looking for an archived version of this page, you can find it on the January 19 snapshot.

Here's what our Public Affairs Office released about these changes.

Accessing that EPA Public Affairs Office link:

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News Releases from Headquarters > Office of the Administrator (AO)

EPA Kicks Off Website Updates

04/28/2017

Contact Information:
(press@epa.gov)

WASHINGTON – EPA.gov, the website for the United States Environmental Protection Agency, is undergoing changes that reflect the agency's new direction under President Donald Trump and Administrator Scott Pruitt. The process, which involves updating language to reflect the approach of new leadership, is intended to ensure that the public can use the website to understand the agency's current efforts. The changes will comply with agency ethics and legal guidance, including the use of proper archiving procedures. For instance, a screenshot of the last administration's website will remain available from the main page.

"As EPA renews its commitment to human health and clean air, land, and water, our website needs to reflect the views of the leadership of the agency," said J.P. Freire, Associate Administrator for Public Affairs. "We want to eliminate confusion by removing outdated language first and making room to discuss how we're protecting the environment and human health by partnering with states and working within the law."

The first page to be updated is a page reflecting President Trump's Executive Order on Energy Independence, which calls for a review of the so-called Clean Power Plan. Language associated with the Clean Power Plan, written by the last administration, is out of date. Similarly, content related to climate and regulation is also being reviewed.

Should you now encounter similar difficulty in accessing the original report,

note that I have posted my 2014 download on this lecture's "Resources" webpage: LINK

*At the top of both preceding lists: Carbon footprint of **power plants***

So let's look more closely at power plants (including info from previous lectures):

Fuels that can boil water to drive power plant steam turbine generators:

Energy Source	Carbon %	Heating Value	Carbon Intensity
Biomass	45%	10-15 kJ/g	30-45 g C / MJ
Coal	59%	24.2 kJ/g	24.4 g C / MJ
Crude Oil	85%	44.3 kJ/g	19.2 g C / MJ
Natural Gas	74%	54.4 kJ/g	13.7 g C / MJ

Lowest carbon output per heat energy output (by far) is for natural gas

Suggesting use of natural gas **should** drastically reduce power's carbon footprint

By factor of two compared to coal-fired energy!

Sources: Intro to Energy and the Environment – Edward S. Rubin (p. 214 / p. 519)

and: http://www.omafra.gov.on.ca/english/engineer/facts/11-033.htm

But US power plant emissions (gm/kW-h of electricity produced) =

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

Hold it!

Preceding table: Natural gas's "carbon intensity" (a.k.a. footprint) ~ **50% of coal**

This table: Natural gas's CO_2 output per unit of power produced = **81% of coal**

Which is it? **What's the difference?**

Answer comes from **Fossil Fuels** (pptx / pdf / key) note set:

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

*Depends on **how much of that heat** is converted into electrical energy:*

Normal **COAL** power plant just boils water => drives turbine => drives generator

Sending **a lot** of the heat energy up the smoke stack

Normal **Gas** power plant burns that gas in simple gas turbine generator (OCGT)

Sending **some** of the heat energy out its exhaust / up the smoke stack

But more recently, in the U.S. we are beginning to use our cheap gas

in more expensive & efficient combined cycle gas turbine (CCGT) plants

Boosting cost of NG power, but driving carbon footprint to ~ 50% of coal

However, in Europe, natural gas from Russia is 3-5 times more expensive

So Europeans are now **shutting down** more expensive CCGT plants

Reverting to less efficient simple gas turbines (used for **only** peak power)

With less efficient OCGT's, in Europe NG carbon footprint => ~ 81% of coal

Next biggest carbon production footprint = Cement production

Net CO_2 release is ~ 4-8% of man's carbon footprint

Which is certainly a problem to be addressed!

But are the quantities of cement used in power plants an energy system problem?

It sounds plausible:

Reactors & Dams ARE among our very largest concrete structures!

Leading many bloggers/activists to ask:

Could the carbon footprint of the concrete used in Reactors & Dams

negate their claim of having almost no carbon footprint?

To answer that question let me now revisit (and merge)

material from my Hydroelectric, Nuclear, and Fossil Fuel note sets:

What is concrete?

Concrete consists of gravel ("aggregate") glued together with a cement

Portland cement is the most commonly used modern glue

It contains calcium silicates (e.g., Ca_3SiO_5 and Ca_2SiO_4) which,

when exposed to water, form hydrates that bind the gravel together [1]

The source of that Ca is naturally occurring limestone ($CaCO_3$)

Ca is liberated by heating the limestone at 1400-1600°C in **HUGE** rotating kilns: [2]

1) Portland cement science: http://matse1.matse.illinois.edu/concrete/prin.html

2) Photo: https://www.cemnet.com/Articles/story/39950/acc-s-mega-kiln-line-project.html

Concrete's Carbon Footprint:

The above process has a huge carbon footprint due to:

- Burning of carbon fossil fuels to produce the 1400-1600°C kiln temperatures
- The need to **constantly** heat those massive kilns, even when not in production
- The release of CO_2 that occurs as Ca is liberated from the limestone ($CaCO_3$)

The now censored EPA Inventory of US Greenhouse Gas Emissions & Sinks reported [1]

that 2012 U.S. Portland cement production produced a carbon footprint of:

35 million metric tonnes CO_2 equivalent = 38.5 million tons CO_2 equivalent

Annual U.S. Portland cement production is ~ 86 million tons [2] and thus:

1 ton of Portland cement => 0.45 tons of CO_2 equivalent released

Concrete (aggregate + Portland cement) is ~ 11% Portland cement by weight [3] =>

1 ton of **Concrete** => 0.05 tons of CO_2 equivalent released

1) Deleted from the EPA website in April of 2017 "under the leadership of President Trump and Administrator Pruitt." (but my copy can still be viewed/downloaded at THIS LINK)

2) www.cement.org

3) www.cement.org/cement-concrete-basics/concrete-materials

Putting concrete's carbon footprint into an energy perspective:

What fraction of U.S. concrete production is used to produce energy?

A "typical**"** **nuclear plant** requires "**up to 350,000 cubic yards**" of concrete [1]

Which, given **concrete's density** [2] of 1.9 tons/yd^3 => 665,000 tons **Concrete**

Which is 11% Portland cement => 73,000 tons **Portland cement**

That typical nuclear plant produces ~ 1.5 GW of electrical power

Ratio of nuclear plant Portland cement use to power produced:

= 73 kilo-tons cement /1.5 GW => 0.049 tons **Portland cement** / kW

And given that Nuclear plants operate for at least 40 years, this translates into:

= **0.0012 tons Portland cement / kW-yr for a nuclear plant**

1) www.concreteconstruction.net/construction/construction-of-nuclear-power-stations.aspx
2) http://hypertextbook.com/facts/1999/KatrinaJones.shtml

Repeating that calculation for hydroelectric dams:

There really isn't a "typical" dam – designs vary too much by location

But we can use data from two large U.S. hydroelectric dams:

Hoover Dam: 3.25 million yd^3 concrete / 2.8 GW power capacity [1]

(3.25×10^6 yd^3 Concrete)(1.9 tons/yd^3)(11%) => 679,000 tons **Portland cement**

=> 0.24 tons Portland cement / kW

Bonneville Dam: 750,000 yd^3 concrete / 1.189 GW power capacity [2, 3]

(7.5×10^5 yd^3 Concrete)(1.9 tons/yd^3)(11%) => 157,000 tons **Portland cement**

=> 0.13 tons Portland cement / kW

Average is 0.185 tons Portland cement / kW

And given hydroelectric dam lifetimes of ~ 100 years, this translates into:

= **0.0013 tons Portland cement / kW-yr for a hydroelectric plant**

1) http://en.wikipedia.org/wiki/Hoover_Dam *2) http://en.wikipedia.org/wiki/Bonneville_Dam*
3) www.asce.org/People-and-Projects/Projects/Landmarks/Bonneville-Dam,-Columbia-River-System/

Finally, using those ratios to calculate carbon footprints:

From my note set on **U.S. Power Production & Consumption** (pptx / pdf / key)

Average total U.S. power is ~ ½ Tera-Watt

In 2016, nuclear plants produced 19.7% of that power => 9.8×10^7 kW

with 0.0012 tons Portland cement / kW-yr for a nuclear plant

that translates into 117,600 tons **Portland cement** / yr, and thus:

Total U.S. nuclear footprint = 52,920 tons of CO_2 equivalent

In 2016 hydroelectric dams produced 6.3% of that power => 3.1×10^7 kW

with 0.0013 tons Portland cement / kW-yr for a hydroelectric plant

that translates into 40,300 tons **Portland cement** / yr, and thus:

Total U.S. hydro footprint = 18,135 tons of CO_2 equivalent

Comparing carbon footprint of different types of existing U.S. power plants:

In **Where Do We Go from Here?** (pptx / pdf / key) analysis of carbon tax impact, I found:

Conventional Coal => 0.001 metric tonne CO_2 eq. / kW-hr => 9.6 ton CO_2 eq. / kW-yr

OCGT Natural Gas => 0.0007 metric tonne CO_2 eq. / kW-hr => 6.7 ton CO_2 eq. / kW-yr

CCGT Natural Gas => 0.00045 metric tonne CO_2 eq. / kW-hr => 4.3 ton CO_2 eq. / kW-yr

In 2016 **COAL** provided 30.4% of U.S. power => 1.52×10^8 kW

Carbon footprint = (1.52×10^8 kW)(9.6 ton/kW-yr) = 1.5×10^9 tons CO_2 / yr

= 28,300 times Nuclear's current carbon footprint

= 82,700 times Hydro's current carbon footprint

In 2016 **NATURAL GAS** provided 33.8% of U.S. power => 1.69×10^8 kW

Which, if it were produced using half OCGT and half CCGT, would represent

Carbon footprint = (1.69×10^8 kW)(5.5 ton/kW-yr) = 9.3×10^8 tons CO_2 / yr

= 17,600 times Nuclear's current carbon footprint

= 51,300 times Hydro's current carbon footprint

Comparing carbon footprint for each kW-hour of power you consume:

From top of preceding page, converting kW-yr to kW-h, and ton to kg:

Conventional Coal Power:	9.6 ton CO_2 eq. / kW-yr=>	0.99 kg CO_2 eq. / kW-hr
OCGT Natural Gas Power:	6.7 ton CO_2 eq. / kW-yr =>	0.69 kg CO_2 eq. / kW-hr
CCGT Natural Gas Power:	4.3 ton CO_2 eq. / kW-yr =>	0.44 kg CO_2 eq. / kW-hr

From two pages ago, converting GW-yr to kW-h, and ton to kg:

Nuclear Power:	52,920 ton CO_2 eq. / 98 GW-yr =>	0.000055 kg CO_2 eq. / kW-hr
Hydro Power:	18,135 ton CO_2 eq. / 31 GW-yr =>	0.000061 kg CO_2 eq. / kW-hr

Nuclear's carbon footprint / kW-hr is ~ 10,000 lower than for fossil fuels

Hydro's carbon footprint / kW-hr is ~ 10,000 lower than for fossil fuels

How can this be, given nuclear and hydro's "heavy" use of concrete?

Their concrete keeps them producing power for a VERY LONG time (40 yrs / 100 yrs)

And they use only a VERY SMALL fraction of our total 86 million tons of cement / yr

A nuclear plant requires 0.0012 tons Portland cement / kW-yr

Now producing 19.7% of the U.S.'s ½ Tera-watt, nuclear thus requires:

=> (0.0012 cement/kw-yr)(19.7%)(0.5×10^9kW) = 118,200 tons cement / yr

= 0.14% of total U.S. Portland cement production

=> Only 0.71% if we produced **ALL OF OUR POWER** via nuclear!

A hydroelectric dam requires 0.0013 tons Portland cement / kW-yr

Now producing 6.3% of the U.S.'s ½ Tera-watt, hydro thus requires:

=> (0.0013 cement/kw-yr)(6.3%)(0.5×10^9kW) = 40,950 tons cement / yr

= 0.047% of total U.S. Portland cement production

=> Only 0.76% if we produced **ALL OF OUR POWER** via hydro!

*Preceding was an example of **life cycle analysis (LCA)***

Which sometimes reveals **big differences** between:

Ongoing (operational) carbon footprint vs. life-cycle carbon footprint

Life cycle analyses (LCA's) integrate in effects of **all** materials and processes used

to manufacture **and** operate **and** decommission/dispose of that technology

Here it was suggested that zero carbon footprint of nuclear and hydro power

would, with full LCA, instead yield significant non-zero carbon footprint

But in this case I could rebut that suggestion based on only a little web browsing

Proving (once again) that for energy you can't believe all that you hear!

But principle is valid and lifecycle analyses CAN make a big difference!

LCA's also raise doubts about another green technology: Electric Cars

First LCA criticism: Their source of power

An electric car gets ITS power from a power plant

In the U.S. most of THAT power now comes from fossil fuel combustion

Coal plant power is actually **dirtier** than power from gasoline auto engines

Because we've been reducing auto emissions for half a century!

Result: Carbon footprint of gasoline burning cars can actually be LOWER than the carbon footprint of an electric car

"Won't that change as we clean up our electric power system?"

Yes, for same reasons Si PV's carbon footprint will also decrease!

Second LCA criticism of electric cars:

Their batteries require huge masses of exotic metals

- Mined at great energy and pollution costs
- Refined at great energy and pollution costs
- Transported from worldwide sources (=> more energy / carbon pollution)

World's largest source of **lithium**,
deep in Chile's remote Altacama desert:
Salar de Altacama (dry lake)

World's largest source of **cobalt**
(main component of Li battery electrodes):
Katanga, Democratic Republic of the Congo

Left photo: http://en.wikipedia.org/wiki/Salar_de_Atacama
Right photo: http://in.reuters.com/article/2013/02/19/drcongo-mining-idINDEE91I03520130219

With combined LCA issues leading to reports such as these:

In the press:

How environmentally friendly are electric cars?

(BBC News, 11 April 2013)

Buyer beware: There are shades of greenness

(New York Times, 26 January 2007)

From half million member international Institute of Electrical & Electronic Engineers:

How green is my plug-in?

(IEEE Spectrum - March 2009)

Speed bumps ahead for electric vehicle charging

(IEEE Spectrum Magazine - January 2010)

Unclean at any speed:
Electric cars don't solve the automobile's environmental problems

(IEEE Spectrum Magazine - July 2013)

The most credible major study of electric cars I’ve found:

Prepared by the U.S. National Academies of Science and Engineering:

Transitions to Alternative Transportation Technologies:

Plug-in Hybrid Electric Vehicles (2010)

They studied alternative hybrid electric car designs

Which, to minimize carbon emissions, would use ONLY batteries for early miles

Thus more numerous **short auto trips** would use zero gasoline

Alternate designs were designated:

PHEV-10 = Plug-in Hybrid Electric Vehicle – 10 initial miles on battery

PHEV-40 = Plug-in Hybrid Electric Vehicle – 40 initial miles on battery

With other acronyms:

HEV = Hybrid Electric Vehicle (non plug-in)

GHG = Green House Gas

Conclusions of this national academies report:

From "Results and Conclusions" chapter (page 33):

PHEV-10s will emit less carbon dioxide than non-hybrid vehicles, but save little relative to HEVs after accounting for emissions at the generating stations that supply the electric power.

PHEV-40s are more effective than PHEV-10s, but the GHG benefits are small unless the grid is decarbonized with renewable energy, nuclear plants, or fossil fuel fired plants equipped with carbon capture and storage systems

THAT IS: Compared to gasoline cars, plug-in electric cars will make little difference

As long as they are still charged from carbon-fueled electrical grid

Further, **this report paid little attention to carbon footprint of materials**

It's thus possible that greenhouse impact of electric cars is **now negative**

As has been suggested by a number of critics!

Leading, finally, to the topic of ***carbon sequestration***

Which is the idea that, at the carbon-burning power plants, we trap carbon gases

And somehow prevent them from entering the atmosphere

Making this easier: Coal power plant use of **IG (integrated gasification)**

Which (from carbon fuels lecture) uses heat + steam to drive these conversions:

$3C$ (coal) $+ O_2 + H_2O \Rightarrow H_2 + 3\,CO$ followed by:

$CO + H_2O \Rightarrow H_2 + CO_2$

This is done **before** the power plant's combustion/steam production step

With only the hydrogen ("syngas") then used for that combustion!

Opening the possibility of trapping that then diverted CO_2

But sequestration will be made a lot HARDER by:

(From earlier slide in this lecture)

Average greenhouse gas lifetimes in atmosphere (in years):

Gas:	**CO_2**	CH_4	N_2O	CFC-11	CFC-12	HCFC-22	HFC-23	SF_6	CF_4
Life[1]:	**50**	12	114		100		270	3200	
Life[2]:	**50-200**	12	120	50		12			50000
Life[3]:	**100-300**	12	121	45	100	11.9		3200	

That is, majority of studies / more recent studies now say that

CO_2 now in the atmosphere, will stay in atmosphere for hundreds of years

So to make a difference, we will have to sequester new CO_2 for CENTURIES

To give atmosphere time to purge CO_2 already present

[1]*Source: www.acs.org/content/acs/en/climatescience/greenhousegases/properties.html*

[2]*Source: Introduction to Engineering and the Environment - Rubin (p. 471)*

[3]*Source: http://cdiac.ornl.gov/pns/current_ghg.html*

But aren't they **already** *successfully sequestering CO_2?*

That's certainly what the advertising campaign about "**clean coal**" suggested!

Versus a 2008 Congressional Research Service Report to Congress:

Page 9:

"**Coal-fired IGCC experience in the United States is limited to a handful of research and prototype plants, none of which is designed for carbon capture**.

A commercial IGCC plant is being constructed by Duke energy . . . and other projects have been proposed. However, some other **power plant developers will not build IGCC plants because of concerns over cost and the reliability of the technology"**

Page 30:

"The estimates of the cost and performance effects of installing carbon controls are uncertain because **no power plants have been built with full-scale carbon capture**"

Page 31:

"**Amine scrubbing (of CO_2) is estimated to cut a coal plant's electricity output by 30% to 40%**

. . . cost for building a coal plant with amine scrubbing is an estimated 61% higher"

Thus while not QUITE a fantasy, "clean coal" is certainly NOT a reality!

Source: CRS Report to Congress – "Power Plants: Characteristics and Costs" (November 13, 2008) - Order Code RL34746

Suggested CO_2 sequestration techniques:

Helping natural sequestration along:

1) **Create new peat bogs:** Which are very efficient at capturing carbon

2) **Reforestation:** Another of nature's prime ways of capturing carbon

3) **Wetland restoration:**

Wikipedia reports that they store 14.5% of world's soil carbon

While occupying only 6% of land surface area

Or manmade sequestration:

4) **Iron or Urea fertilization of seas**

To induce phytoplankton growth which would then metabolize CO_2

There've been Fe trials but are strong doubts about quantities required

As well as concerns about such wholesale tinkering with seas

5) **High pressure injection into cavities created by fossil fuel removal**

Shoot CO_2 down pipes used earlier to remove oil or gas, then cap them off

Or plug up entrances to depleted coal mines, and fill with CO_2

Hold it!

I grew up atop the San Andreas Fault - I **know** how active the earth can be!

What would a big earthquake do to a CO_2 storage site?

A related idea that would use un-mineable coal seams

5b) **Enhanced Coal Bed Methane Extraction (ECBM):**

Inject CO_2 into coal seam, driving out methane absorbed to the coal

Producing methane (for use), and subsidizing cost of pumping in the CO_2

But if methane is then burned, it will then release more CO_2

So would there really be any **net** sequestration?

The estimates on ECBM carbon sequestration:

Net carbon sequestration (presumably = CO_2 in, minus methane out)[1]

For major international coal fields in designated regions:

Region	Country	Carbon Sequestration Potential	
San Juan	U.S.	1.4 giga-tonne	
Kuznetsk	Russia	1 giga-tonne	
Bowen	Australia	0.87 giga-tonne	
Ordos	China	0.66 giga-tonne	
Sumatra	Indonesia	0.37 giga-tonne	
Canbay	India	0.07 giga-tonne	**Total ~ 4.4 Gt**

From earlier in this lecture, **man's annual production of CO_2 = 29.8 Gt**

ECBM potential sounds interesting – But it would encourage coal/gas use

And are we really ready to accept the coal + gas industry's numbers?

[1]*Source: Energy System Engineering – Evaluation and Implementation – Vanek et al. (p. 215)*

BREAKING NEWS:

(revisited)

And regarding ALL "Pump a gas into the ground and forget" schemes:

Remember the 2015-16 Porter Ranch fiasco?

from my **Fossil Fuels** (pptx / pdf / key) note set:

= The **same** fossil fuel operators

= The **same** idea of pumping gas into abandoned wells

But at Porter Ranch they only tried storing the gas for a **few months**

And we're to believe they could keep gases buried for centuries?

(This didn't even require the San Andreas Fault breaking loose!!!)

6) **High pressure injection into saline aquifers**

Which are common but, because of salinity, not used for drinking or farming

It's claimed that in the US, majority of power plants are located **over** such aquifers

We'd then pump CO_2 down into aquifer water **flowing** (slowly) by

SOME of that CO_2 might eventually precipitate out as solid carbonate

Rather than capacities, test projects instead target storage **rates**[2]:

Project:	Country:	Sequestration Rate:
Brindisi	Italy	8×10^{-6} giga-tonnes/year
Porto Tolie	Italy	$< 10^{-3}$ giga-tonnes/year
Belchatow	Poland	10^{-4} giga-tonnes/year
Vattenfall	Germany	$< 6 \times 10^{-4}$ giga-tonnes/year
Luzhou	China	6×10^{-5} giga-tonnes/year

Versus man's production of CO_2 = 29.8 giga-tonnes / year

[2]*Source: Energy System Engineering – Evaluation and Implementation – Vanek et al. (p. 217)*

7) **Conversion of CO_2 into inert materials**

Finally! Something more plausible than, over the span of centuries:

- Pressurized CO_2 gas STAYING in abandoned oil/gas well or coal mine!
- Carbonated salt water NOT LOOSING its fizz!

Here, instead, CO_2 would be converted to carbonate minerals

Which are common, and are known to be stable over millennia

However: HOW will it be converted, and at what energy cost?

Converted at power plants via reactions with minerals such as Ca or Mg

Reactions don't require energy input, they release energy (albeit slowly)

So would still use heat, but get more heat back => power production

But required quantities of Ca / Mg => Major energy / environmental challenges

A more acceptable alternative?

8) **Injection into ocean bottom basalt formations**

As recently described in the New Scientist (22 July 2014) - Rock Solid Solution:

"CarbFix[3]" process pumped CO_2 into wastewater from Icelandic geothermal plant

Re-injected water into rock formations,

Where it reacted with magnesium silicates

Article claimed process could work in basalt as well as "mantle peridotite"

Basalt is what makes up most of earth's ocean bottoms

Practicality? Scalability? Hard to tell as was only interview with project leader

But to me, the idea of mimicking geological processes to solidify CO_2 makes sense

I'd also look toward possible sequestration via cultivated bacteria / algae

[3]*Website: https://www.or.is/en/projects/carbfix*

My bottom line take on current carbon sequestration ideas?

Plans to simply pump gaseous CO_2 into holes just do not seem plausible

I cannot believe that a pressurized gas will stay in place for centuries

Even if this is THE STRATEGY backed by the major fossil fuel producers

Given that time span, I believe CO_2 will have to be chemically converted/bound

There are a **huge** number of such ideas floating around

Several times more ideas than I described above!

But these ideas are immature, untested, and potentially unscalable

Leading **me** back to the one **sure** way I know of controlling atmospheric CO_2:

Radically diminishing its production . . . as soon as possible

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