Physics of Sustainabilty Energy

Course Responsible

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Energy Vault

- If each block is 1m high (and 3 x 3m wide/deep) and weights 20 tons, how high do we need to stack the blocks to have same energy as in 1L of gasoline (34.2 MJ/L). Assume Energy Vault is 100% efficient. (For simplicity assume gravity =10 m/s^2)

Energy Vault Plant, 2023

Energy Vault

$$E = mgh$$

$$E = mg\sum_{n=1}^{N} n$$

$$E = mg\frac{n(n+1)}{2}$$

$$n^2 + n = \frac{2E}{mg}$$

$$n = 18\, meters$$

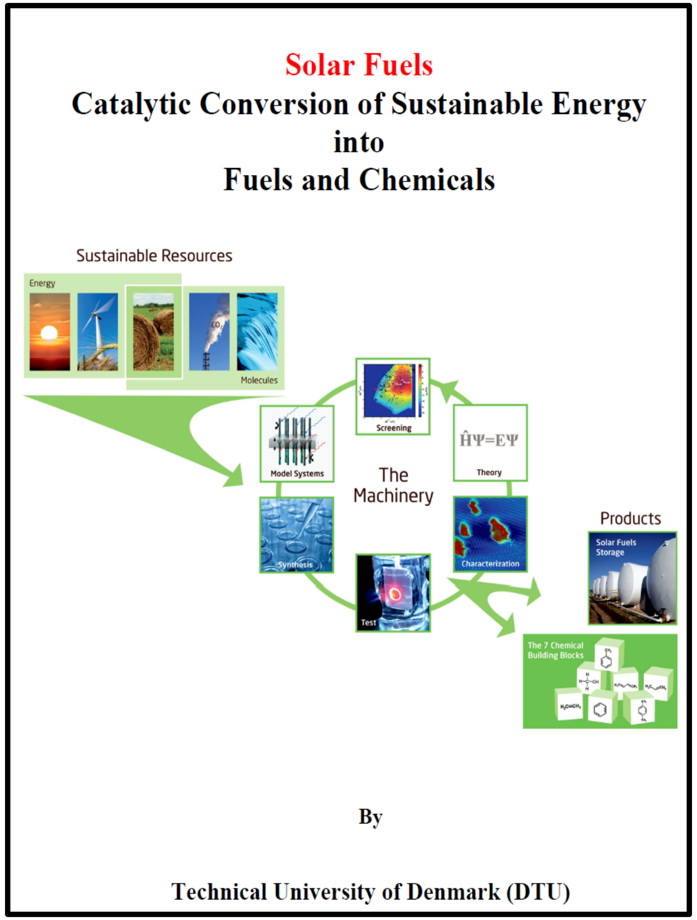
E = 34.2 MJ
M = 20 ton = 20,000 kg
g = 10 m/s^2

What this course is about

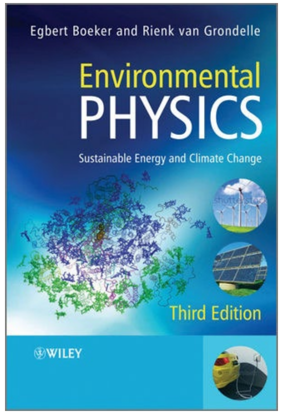
- Explaining sustainable energy technologies using physics principles.
  - Producing power from renewable energy sources
  - Converting and storing energy from renewable energy sources
  - Understanding the climate and CO_2 capture
- There will be a very small amount of chemistry, economics, biology, and geology.
- You need to get to the point where you can look at a sustainable energy project and note whether it has potential or is scientifically flawed

Text Books

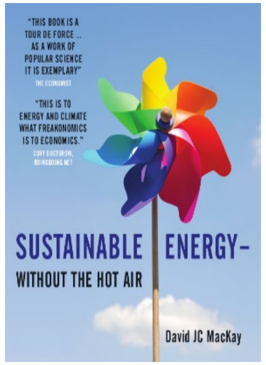
Physics of Sustainable Energy Book (On DTU Learn)



Previous Textbook



Fun to Read, no serious science



Download for free
http://www.withouthotair.com/

Syllabus

Week	Topic	Lecturer
3-9	**Introduction & Climate Effects**	Brian Seger
10-9	**Solar Cells – Detailed Balance and Improvements**	Brian Seger
17-9	**Solar Cell Junctions & Tandem Solar Cells**	Brian Seger
24-9	**Wind Power**	Brian Seger
1-10	**Electrochemistry & Batteries**	Brian Seger
8-10	**Fuel Cells & H_2 storage**	Maria Rodigues Pinto – Brian Seger
15-10	Autumn Break	
22-10	**Nuclear Power (Fission and Fusion)**	Bent Lauritzen and Volker Naulin
29-10	**Electrolysis to H_2**	Brian Seger
5-11	**Other Electrolysis (CO_2, Cl_2, NH_3) and Electrowinning**	Brian Seger
12-11	**Photosynthesis, Biomass Conversion, & Chemicals Industry**	Brian Seger
19-11	**CO_2 Capture**	Brian Seger
26-11	**Analysis Presentation Day**	Brian Seger
3-12	**Course Review and Discussion**	Brian Seger
19 -12	Final Exam	

Analysis Day

- Everyone will be part of a group (2-3 people/group) that focuses on one of our analysis problems.
- On the analysis day your group will give an approximate 8 minute presentation with 2 minutes of questions. You will also hand in a 2 page report summarizing your findings (no longer than 2 sides of a paper)
- **It is absolutely essential the report is no longer than 2 sides of 1 sheet of paper !!**
- The problems will be passed out, the week after Fall break, and the final details will be described then.
- This will contribute to a minor portion (20%) of your overall grade.

Assessment

- **<u>Written Exam</u>**: The written exam will consist of a standard 4 hour exam. Be aware of the exam date. It is on the last exam date before Christmas.
  - Most questions will be multiple choice
  - The majority will be qualitative, however there will be ~1/3 that will involve calculations. All calculations will be straightforward and can be done using a hand held calculator (as long as it has an exponential and log function). This will be provided to you at the exam.

- Evaluation and you get your grade -3, 00, 02(passed), 4, 7, 10, 12

Pre-test

- The Pre-test serves 2 purposes:
  1. To ensure that you have the proper pre-requisites to take this class.
  2. To allow us to see why you are interested in the class and potentially tailor it accordingly.

- You will have 20 minutes to take the test.

- You won't be graded on the test, but after taking it you should know whether or not:

  a) this class is what you thought it was and
  b) whether you are qualified for this class.

Slides

- White background – Normal slide
- Yellow background- Question/Exercise
- Green slide – Important / Review slide
- Grey slide- Not presented in main lecture.

Lecture - Learning objectives

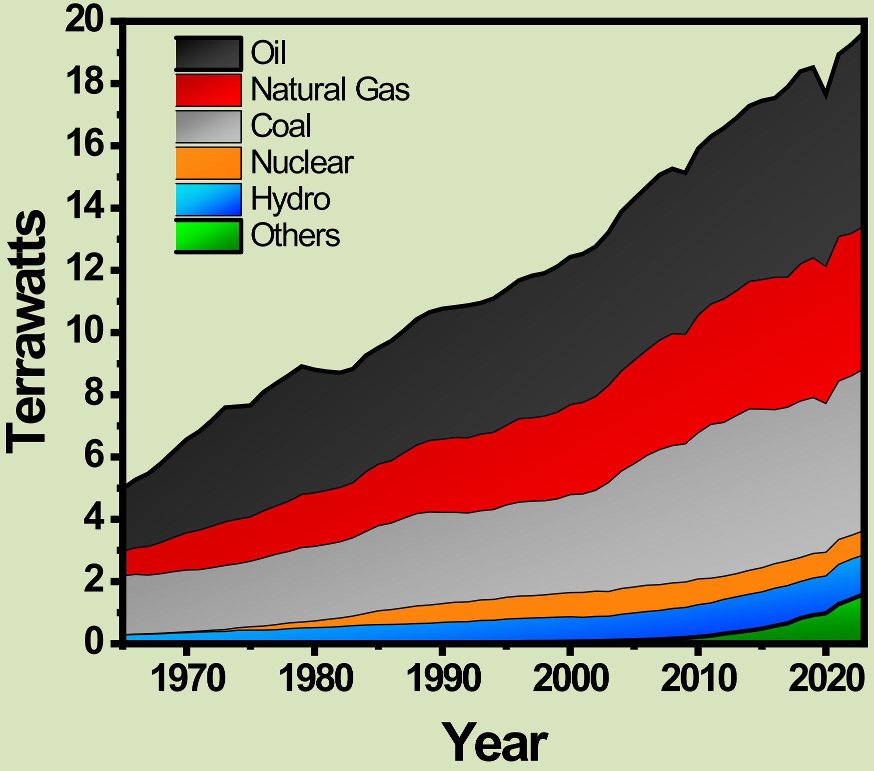
At the end of this lecture you should understand:

- The overall energy landscape
- The function of fossil fuels and all their applications
- CO_2's effect on the ocean
- Why a molecule is a greenhouse gas
- Climate modeling basics

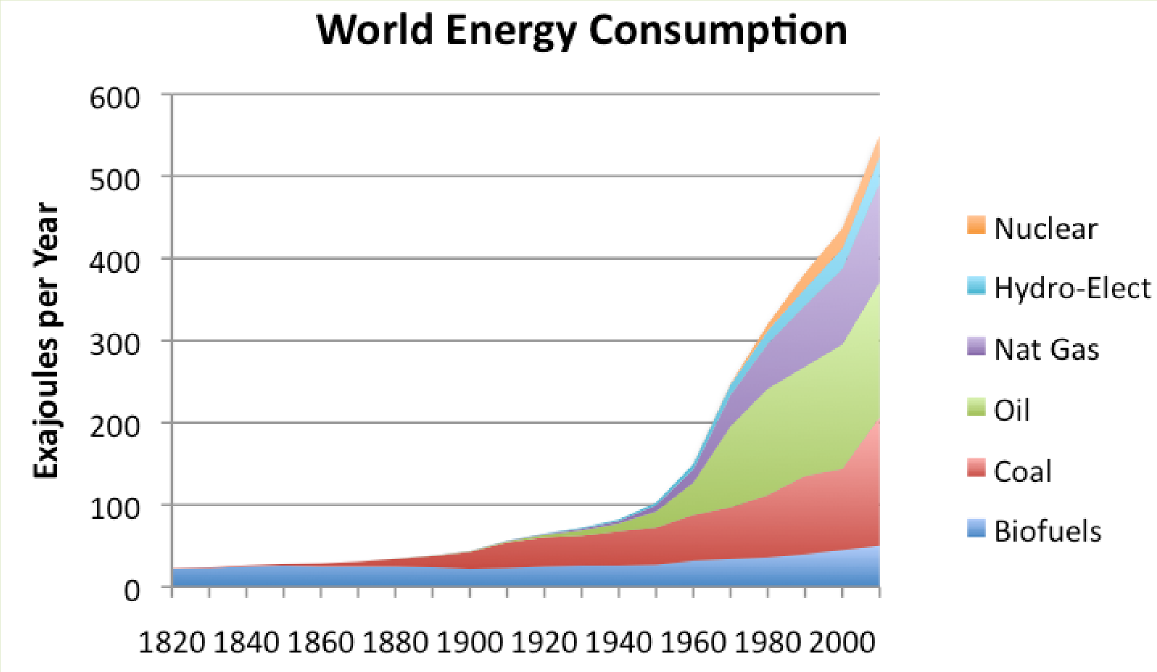
Energy Consumption

- In 2023, we used 19.6 Terrawatts with only 1.6 TW being renewables (biomass not included).

- Figures can be deceiving. On the left it seems we have linear growth, while the right shows exponential growth.



From Statistical Energy Review 2023



From finiteworld.com

Worldwide Energy Data

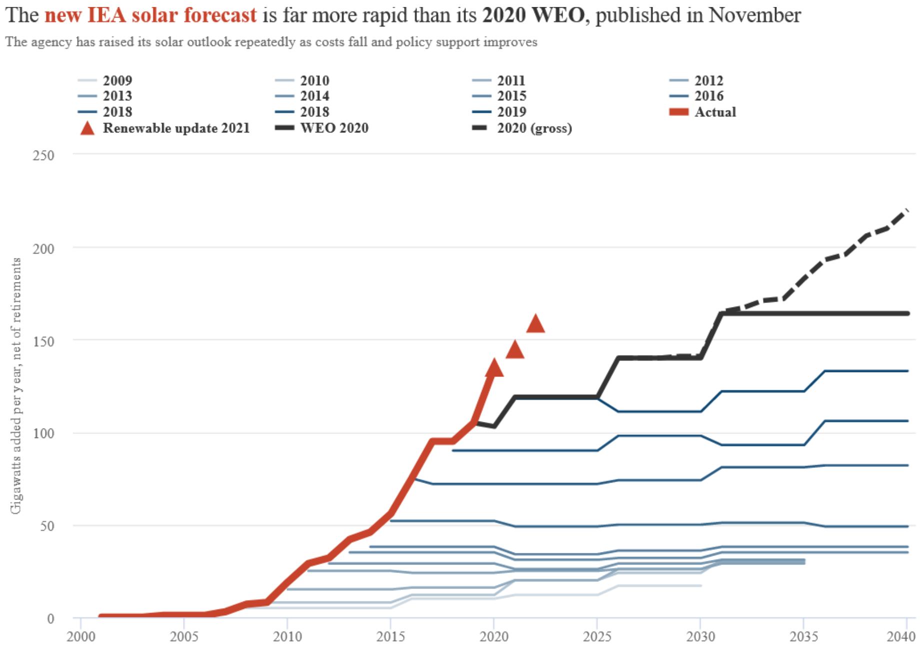
- If we want society to run completely on renewable energy sources we need to know the world energy makeup.

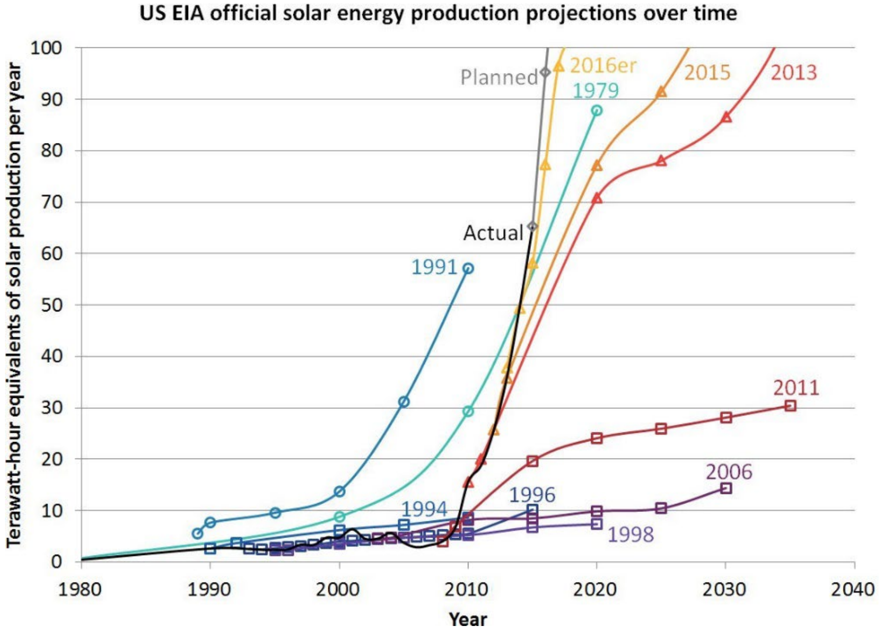
- There are 2 dominant and very similar reports that denote the world energy make-up.
  - International Energy Agency- They have a free annual report called World Energy Outlook. They split it up into US and International. IEA also has a new web-interface for energy that is useful.
  - Energy Institute Energy Report - Also a free annual energy report. Institute funded by BP, but surprisingly, this is not biased towards the oil industry.

- The world bank also has energy data as well as the Energy Information Agency (US Data only).

IEA versus EIA predictions

- The international energy agency (IEA) is bad at predictions to the point of corruption
- The US Energy Information Agency actually learns from its mistakes and is better at predicting the future.



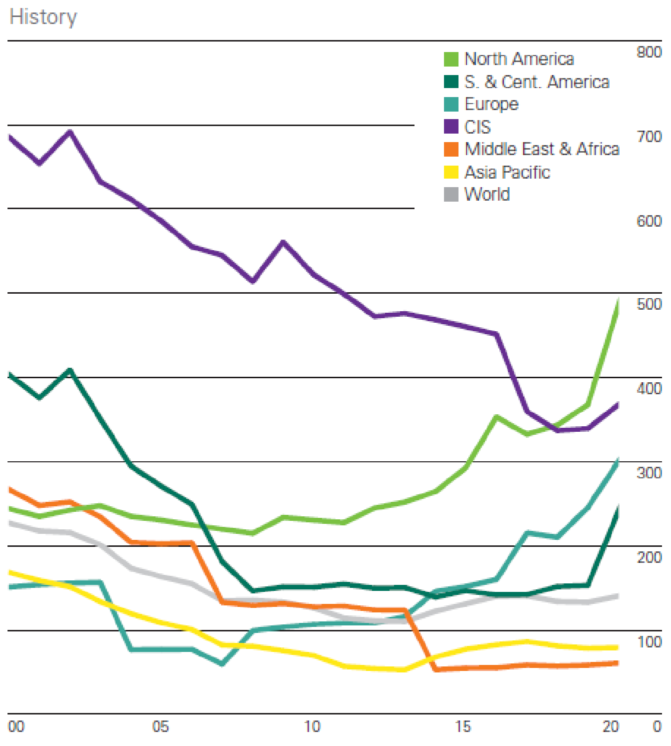


https://www.visualcapitalist.com/experts-bad-forecasting-solar/

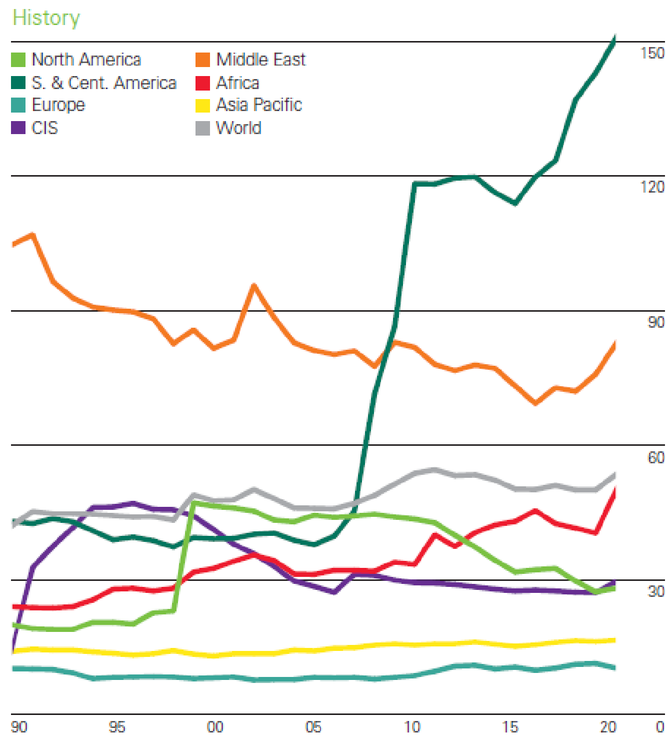
https://www.carbonbrief.org/exceptional-new-normal-iea-raises-growth-forecast-for-wind-and-solar-by-another-25

Coal, Oil & Natural Gas (CONG)

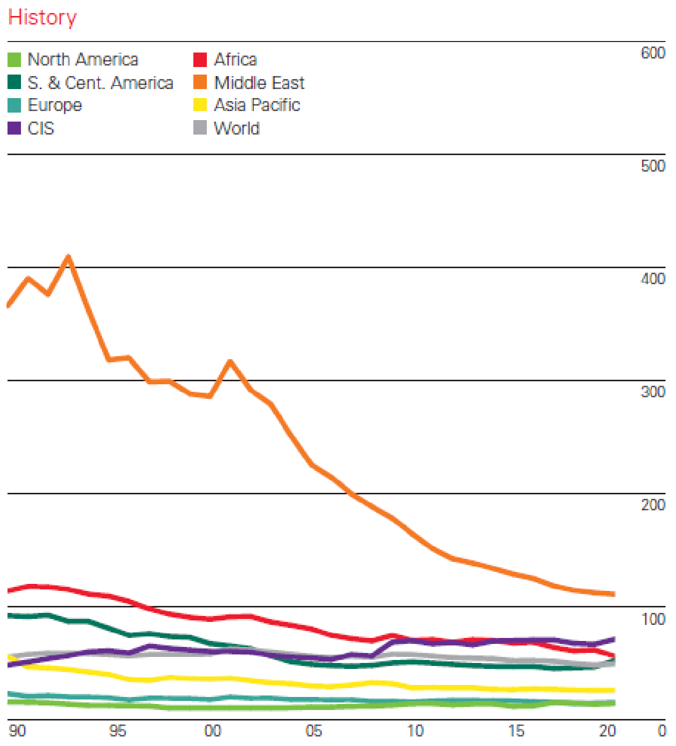
- A large portion of CONG companies worth is their reserves.
- Too high of reserves will lead to stranded assets.



Coal Reserves to Production ratio



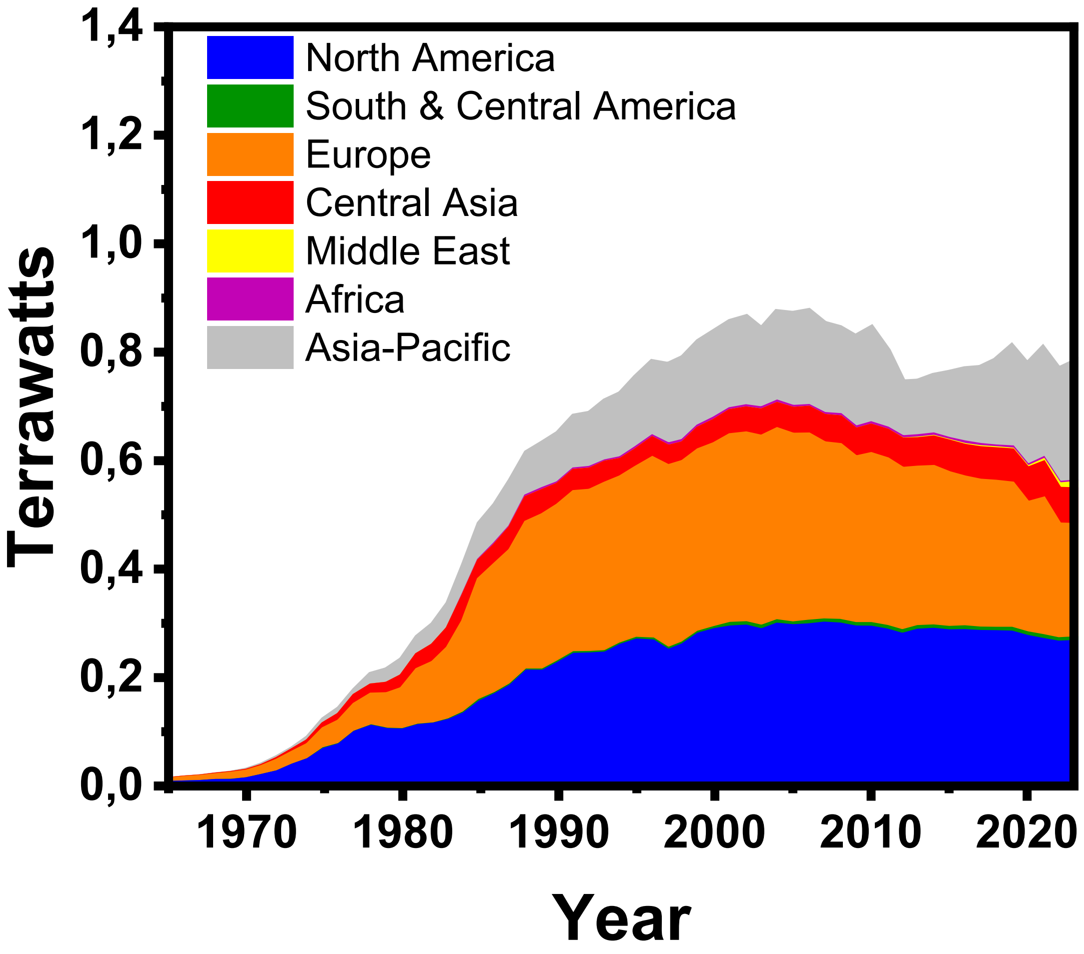
Oil Reserves to Production ratio



Nat Gas Reserves to Production ratio

Nuclear

- There are 2 types of nuclear- fusion and fission with only fission giving useful power currently.
- In theory this is a non-renewable resource because we use an isotope of Uranium and this is limited.
- We have ~200 TW-years left of Uranium.
- Nuclear waste is still an unresolved issue.
- This is becoming less and less cost-competitive



World's nuclear power ([Energy Institute 2024]())

Nuclear

- High construction costs and financial risk in 50 year projects are the main economic hinderances.

How Big Projects Performed
Source: Flyvbjerg Database

Project type	Mean cost overrun (%)	Projects (A) with ≥50% overruns (%)	Mean overruns of A projects (%)
Nuclear storage	238	48	427
Olympic Games	157	76	200
Nuclear power	120	55	204
Hydroelectric dams	75	37	186
IT	73	18	447
Nonhydroelectric dams	71	33	202
Buildings	62	39	206
Aerospace	60	42	119
Defence	53	21	253
Bus rapid transit	40	43	69
Rail	39	28	116
Airports	39	43	88
Tunnels	37	28	103
Oil and gas	34	19	121
Ports	32	17	183
Hospitals, health	29	13	167
Mining	27	17	129
Bridges	26	21	107
Water	20	13	124
Fossil thermal power	16	14	109
Roads	16	11	102
Pipelines	14	9	110
Wind power	13	7	97
Energy transmission	8	4	166
Solar power	1	2	50

Corruption

Larry Householder

- Ohio (USA) had their head of congress arrested for a 60M$ bribery for nuclear for tax breaks in summer 2020.

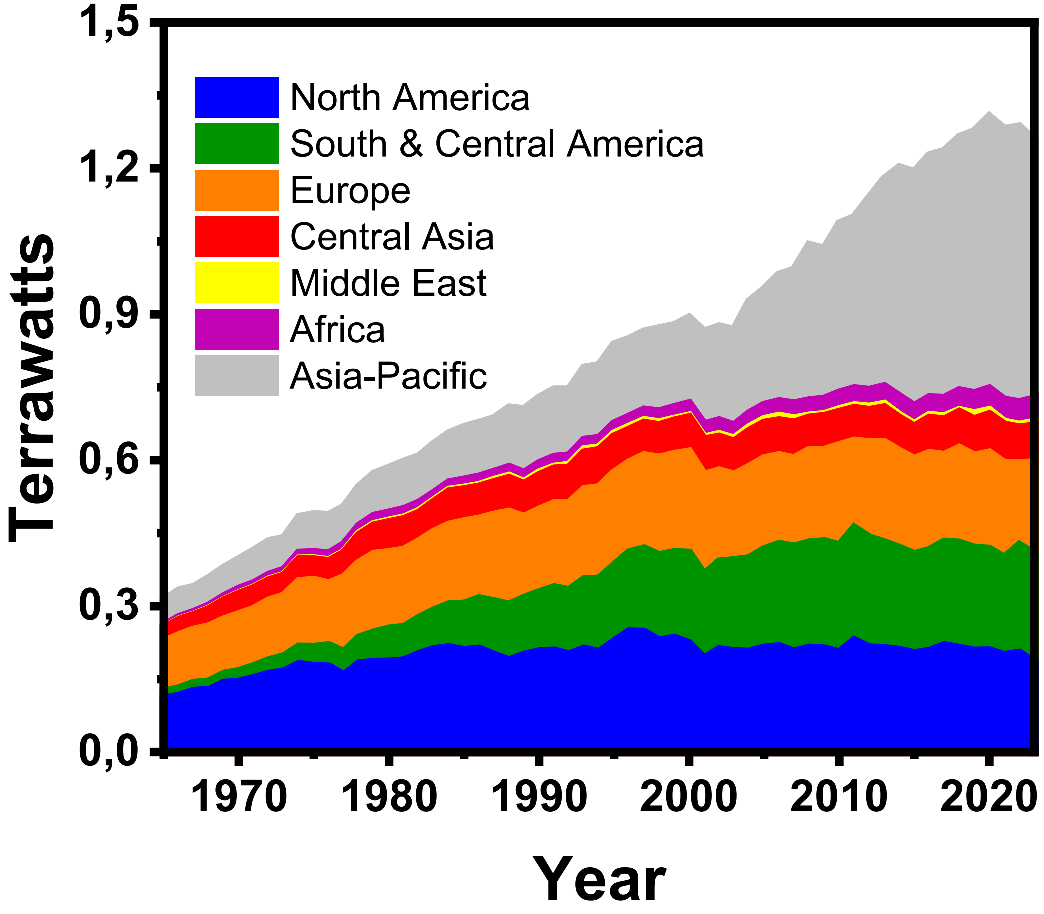
Renewables- Present Day

- Hydropower is still the largest producer of renewable energy

- Except for Asia, there has been no growth since 2000.

- Most of the best places to build hydroelectric plants have already been built.

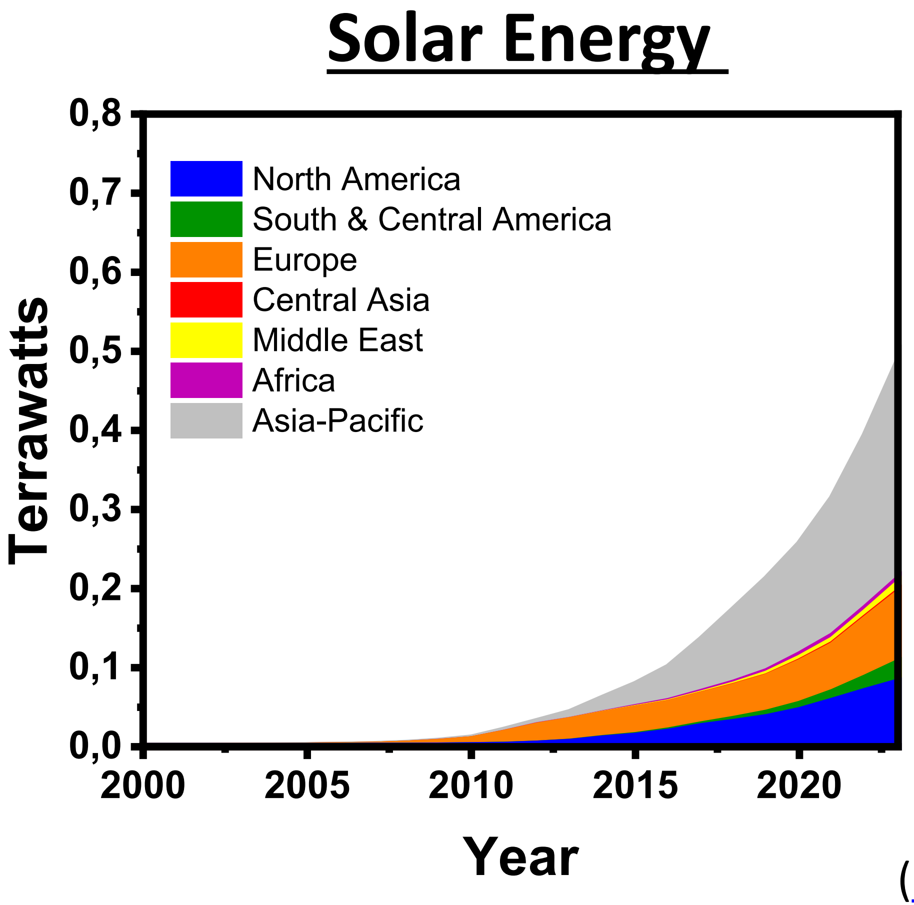
- It has been estimated that this approach can produce a maximum of 3-4 TW.

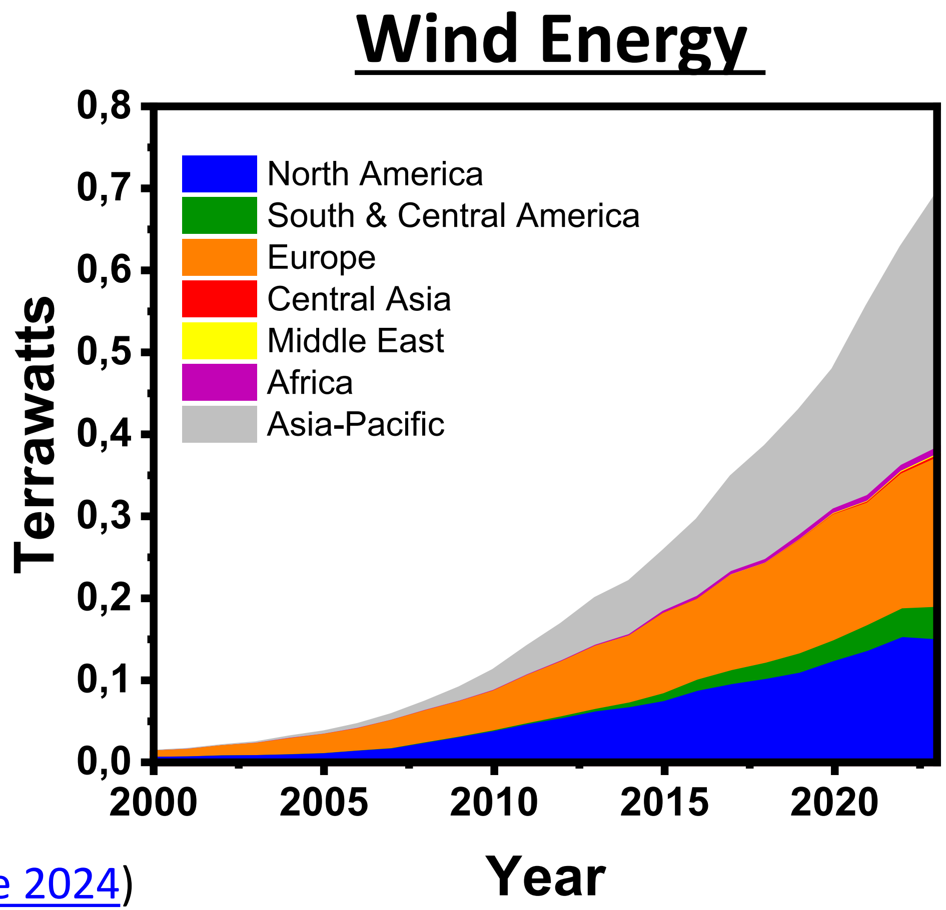


(Energy Institute 2024)

Wind & Solar

- Wind started earlier, but solar seems to be accelerating slightly faster



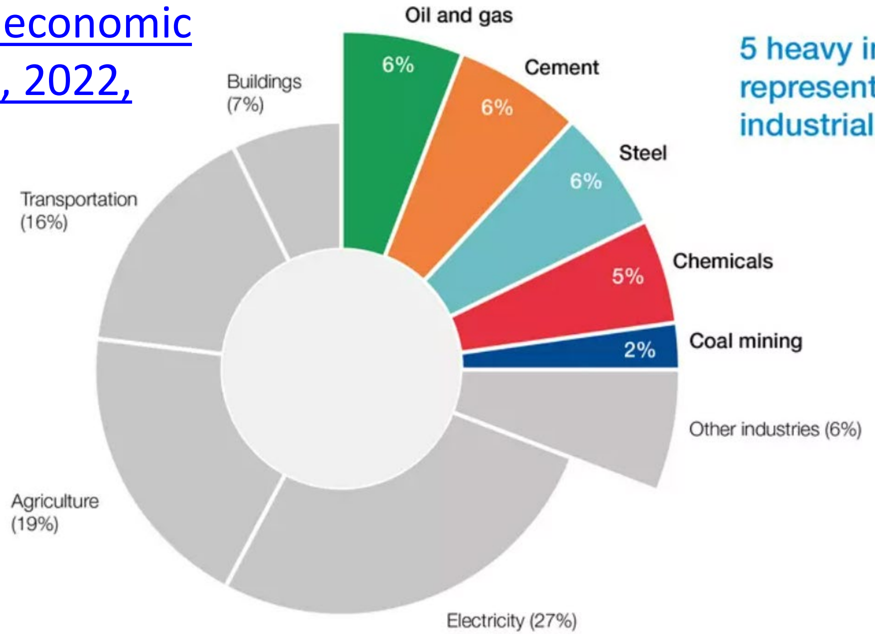


(Energy Institute 2024)

Where the energy is used and what for

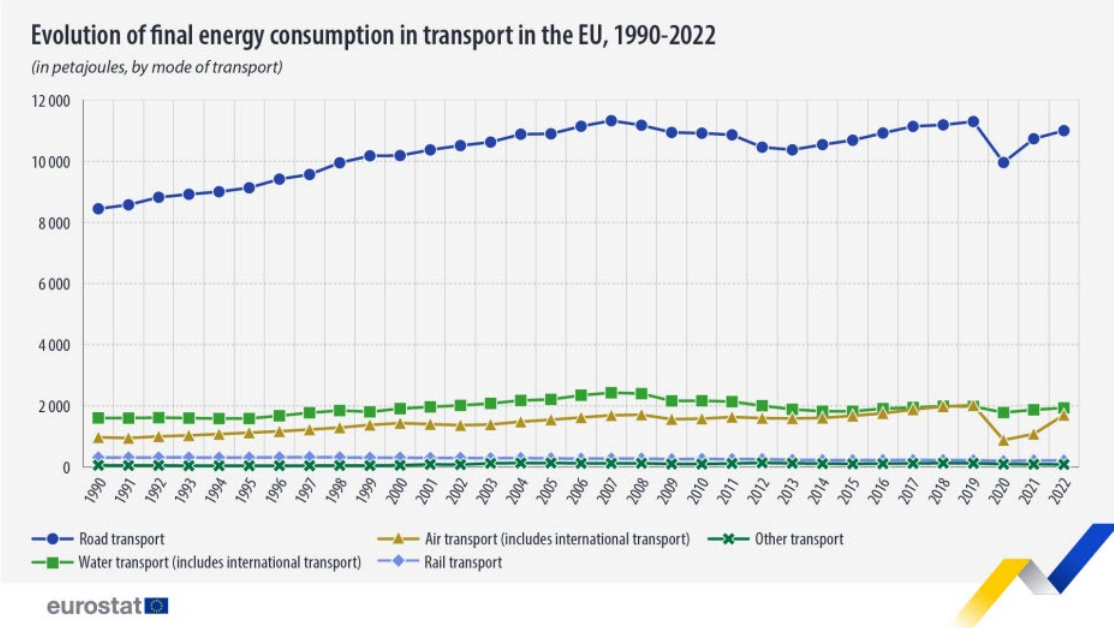
Energy by sector

[World economic Forum, 2022,](#)

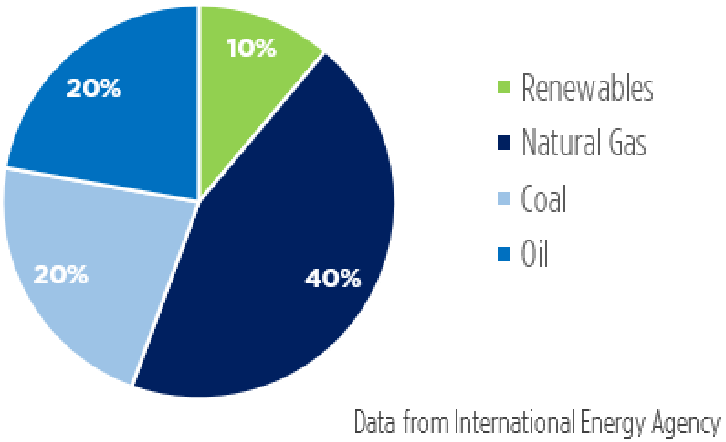


5 heavy industries represent 80% of industrial emissions

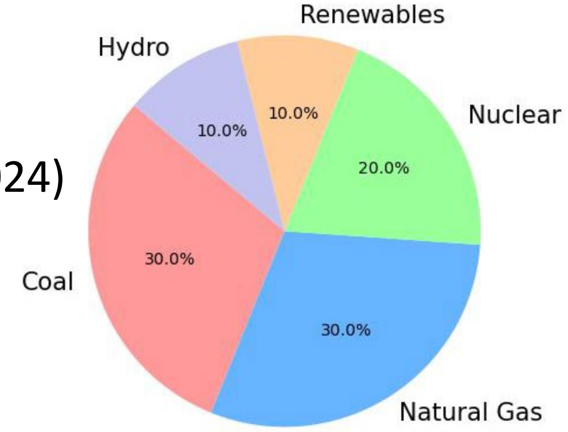
Transportation



Heating
Global
(IEA, 2020)

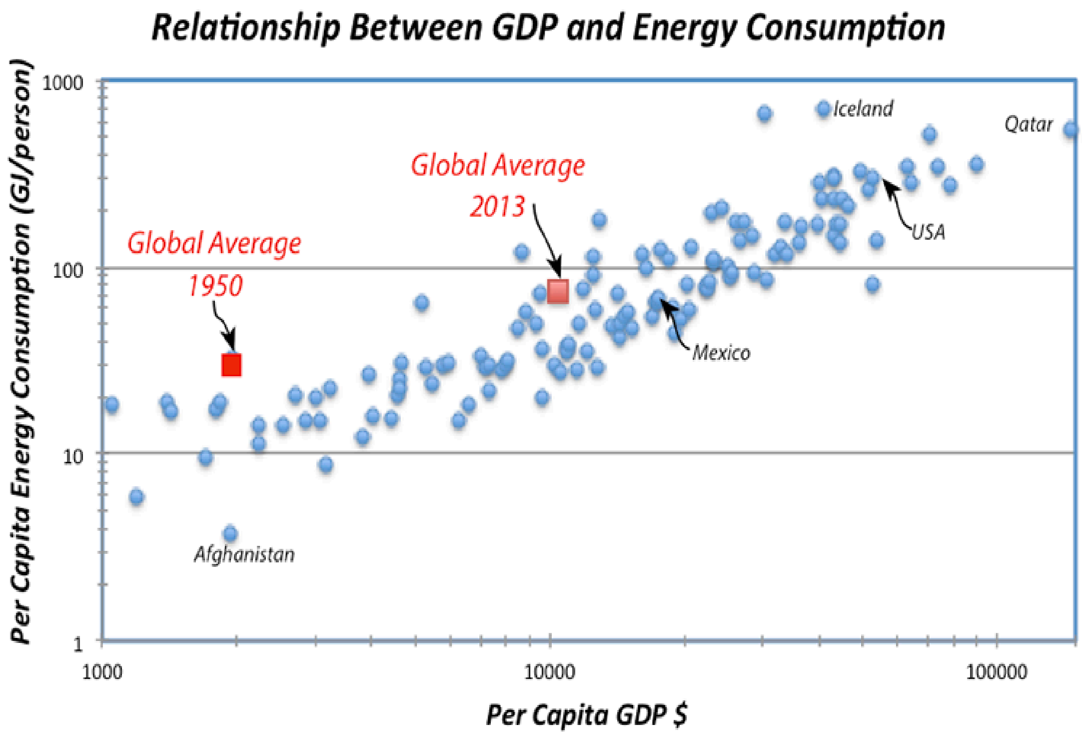


Electricity
Global
(Energy Institute, 2024)

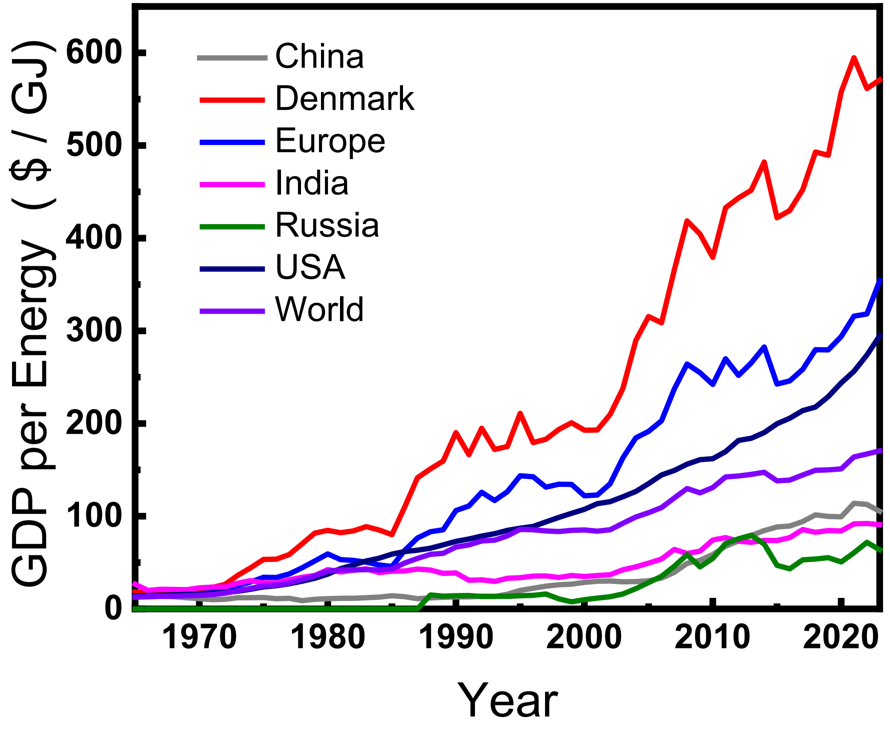


Energy vs. Economic growth

- There is a clear pattern in that countries with high gross domestic product use a lot of energy.
- This is slowly changing though.



Data from World Bank, figure compiled by David Bice



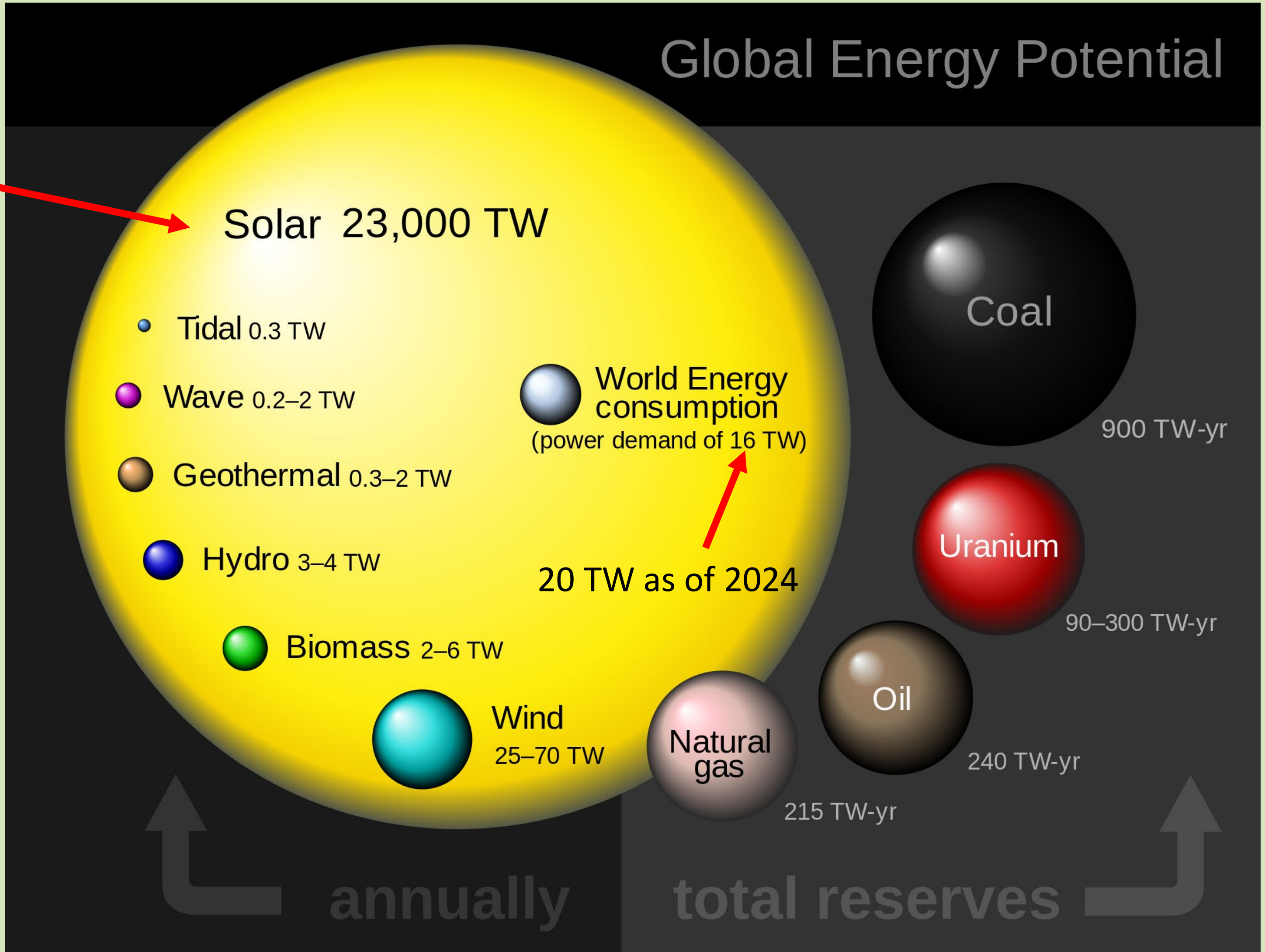
Economy Data from World Bank, Energy Data from Energy Institute

Break

Energy Sources

- This is energy sources graphically.

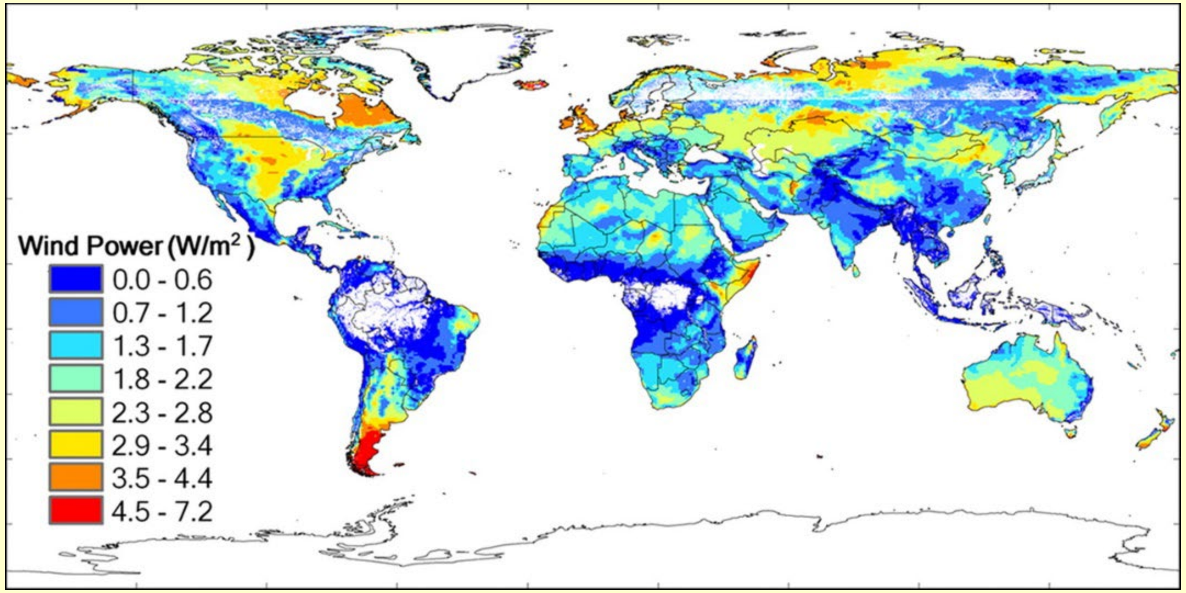
There are assumptions behind this. It can reasonably range from 14,000 to 177,000.

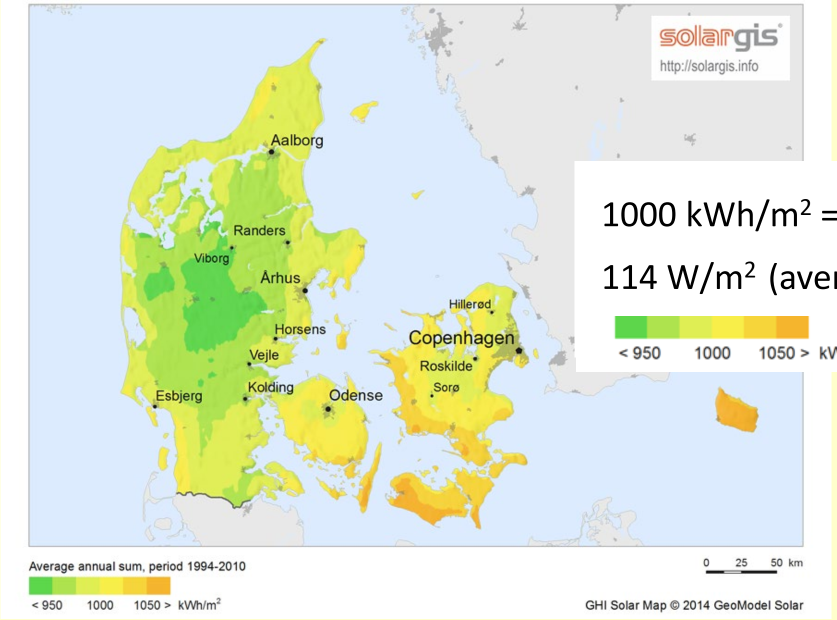


(Perez & Perez, 2013)

Wind vs. Solar in Denmark

- Denmark is one of the windiest places on Earth
- The global average energy solar energy is 200 W/m^2. (averaged over 24 hours)
- Denmark still has an order of more solar potential than wind.
- So why use wind?



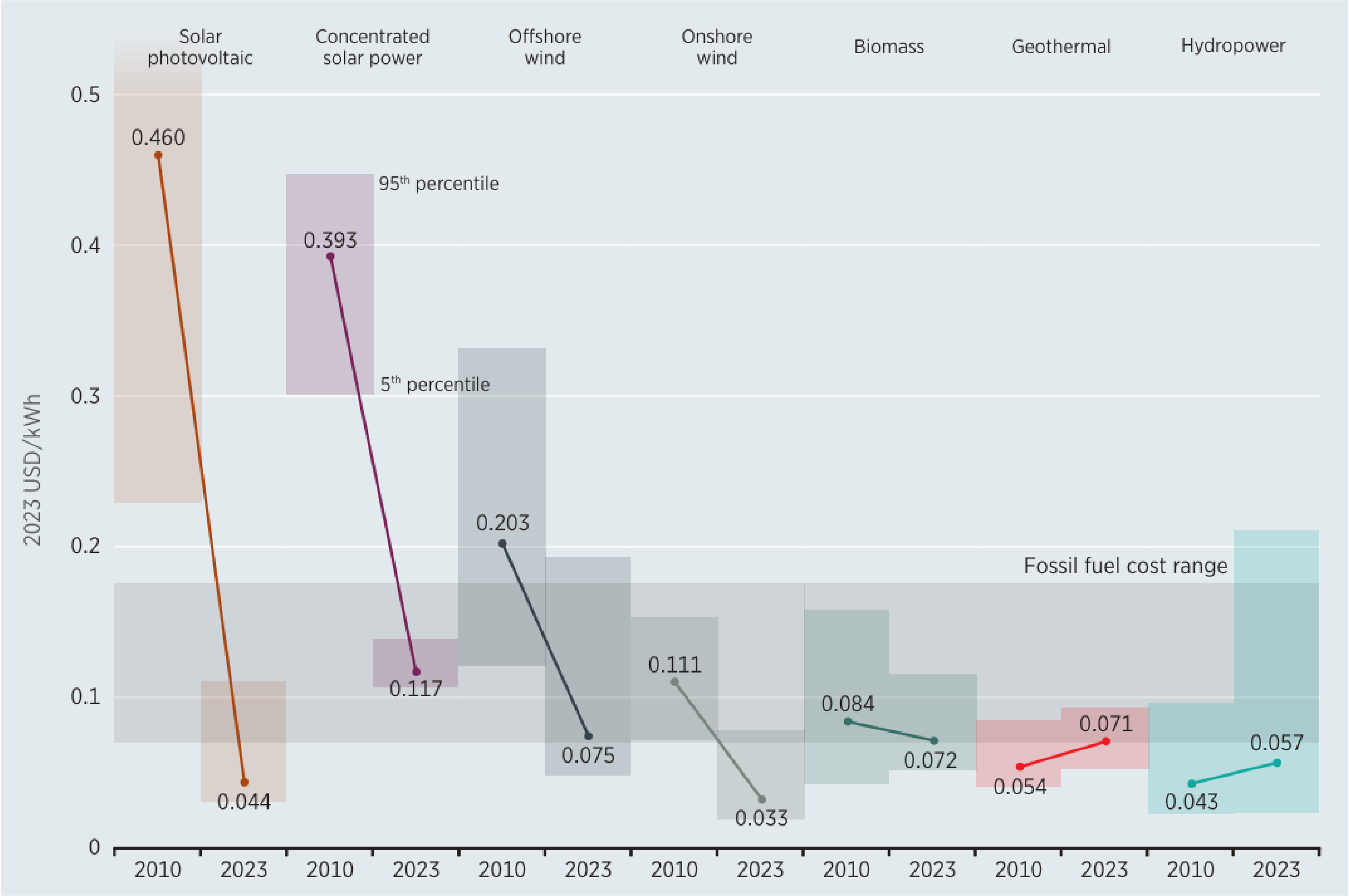


1000 kWh/m^2 =

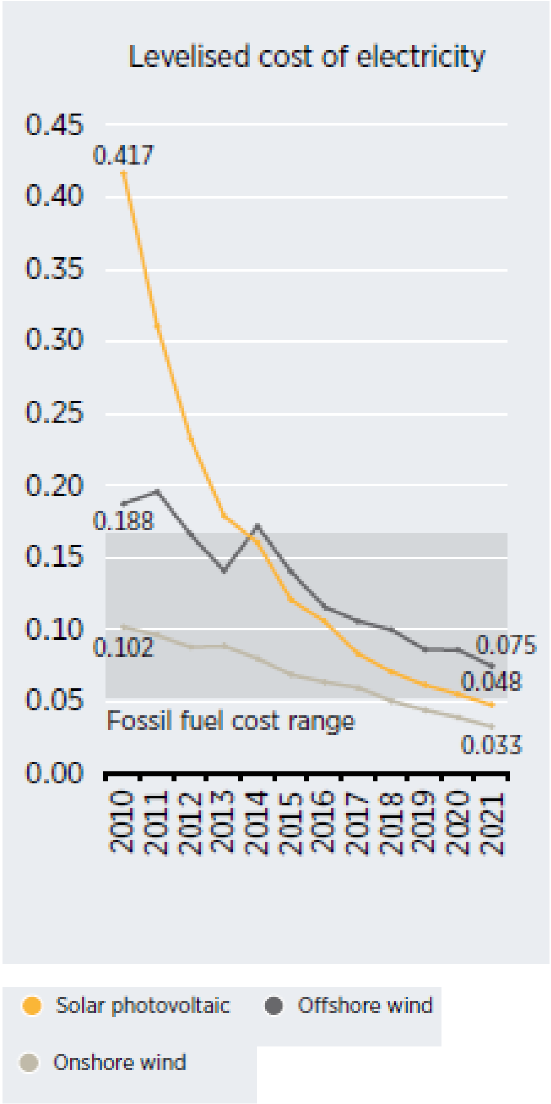
114 W/m^2 (average)

< 950 1000 1050 > kWh/m^2

Economic Competitiveness



IRENA Renewable Power Generation costs report, 2023

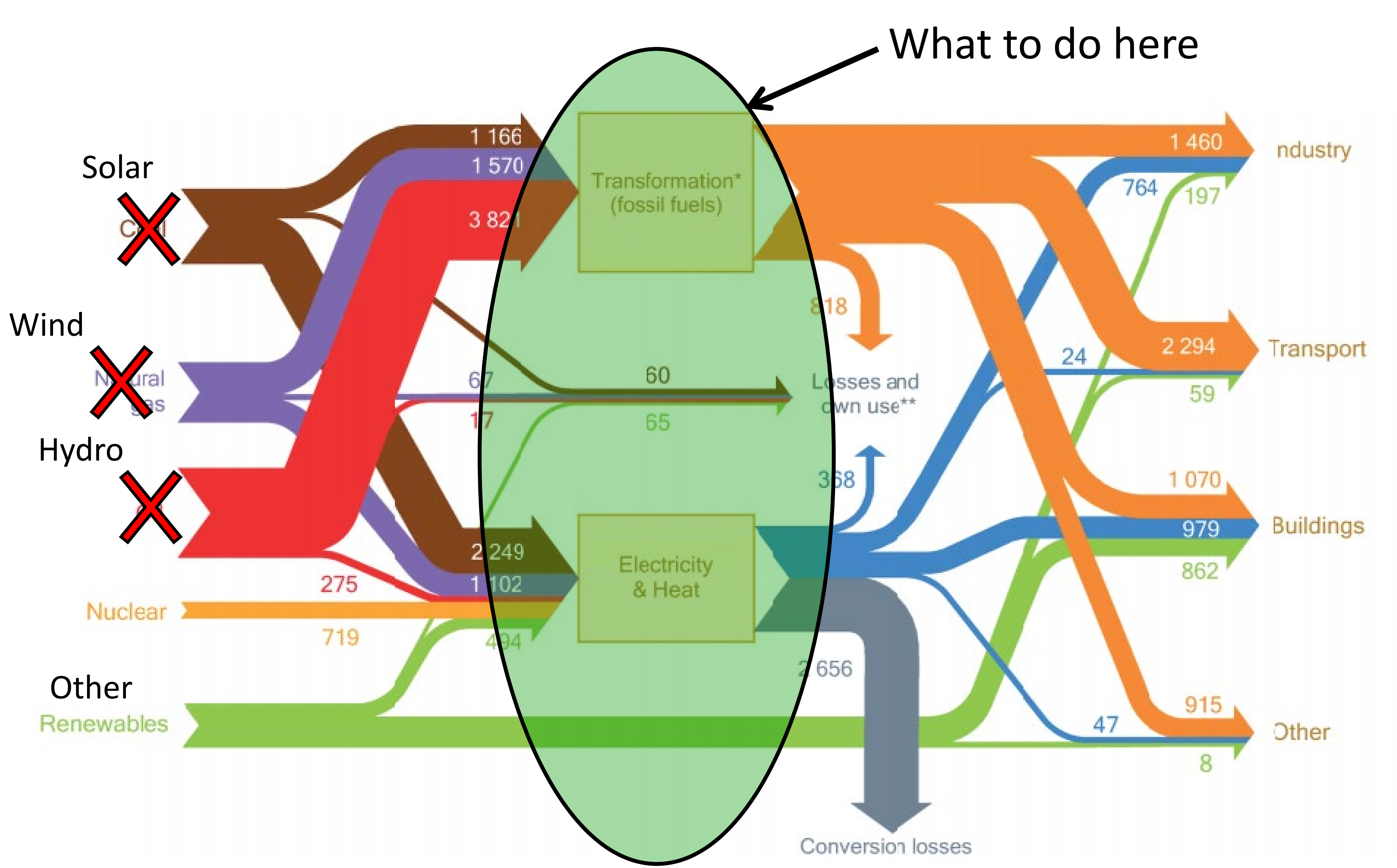


Solving the Energy Crisis

- If we produce 30 TW of renewable fuel and we need 30TW of fuel, have we solved the energy crisis.

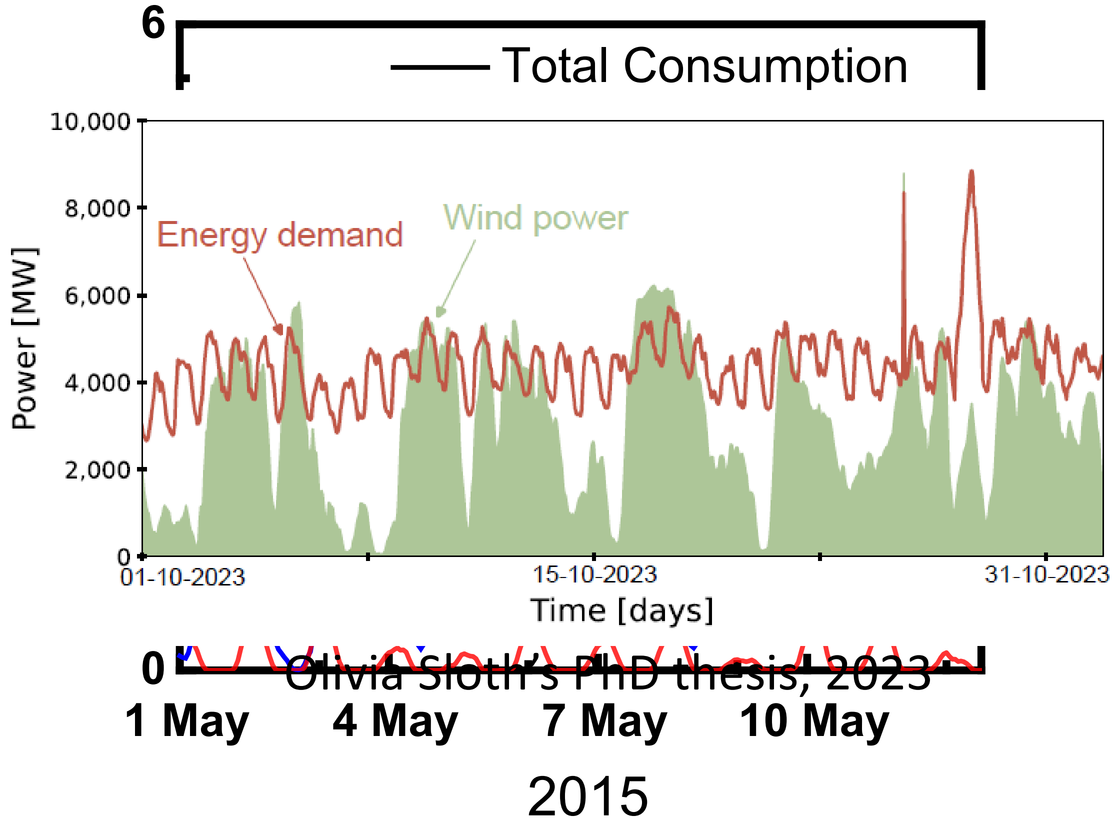
NO!

We need the inputs to match the outputs



Economic Issues

- In Denmark we have the problem where sometimes we produce more electricity than we use.
- (Electricity is ~ 1/6th of total Danish energy consumption)
- Fluctuations in supply don't match fluctuations in demand.
- Over the last decade, ~50% of its wind power was not used within Denmark.
- Economically this is bad.



Denmark electricity generation/consumption
(data from Energinet.dk)

Storing energy

- Rather than make a large excess number of solar cells/wind turbines, its *probably* economically smarter to store the energy.

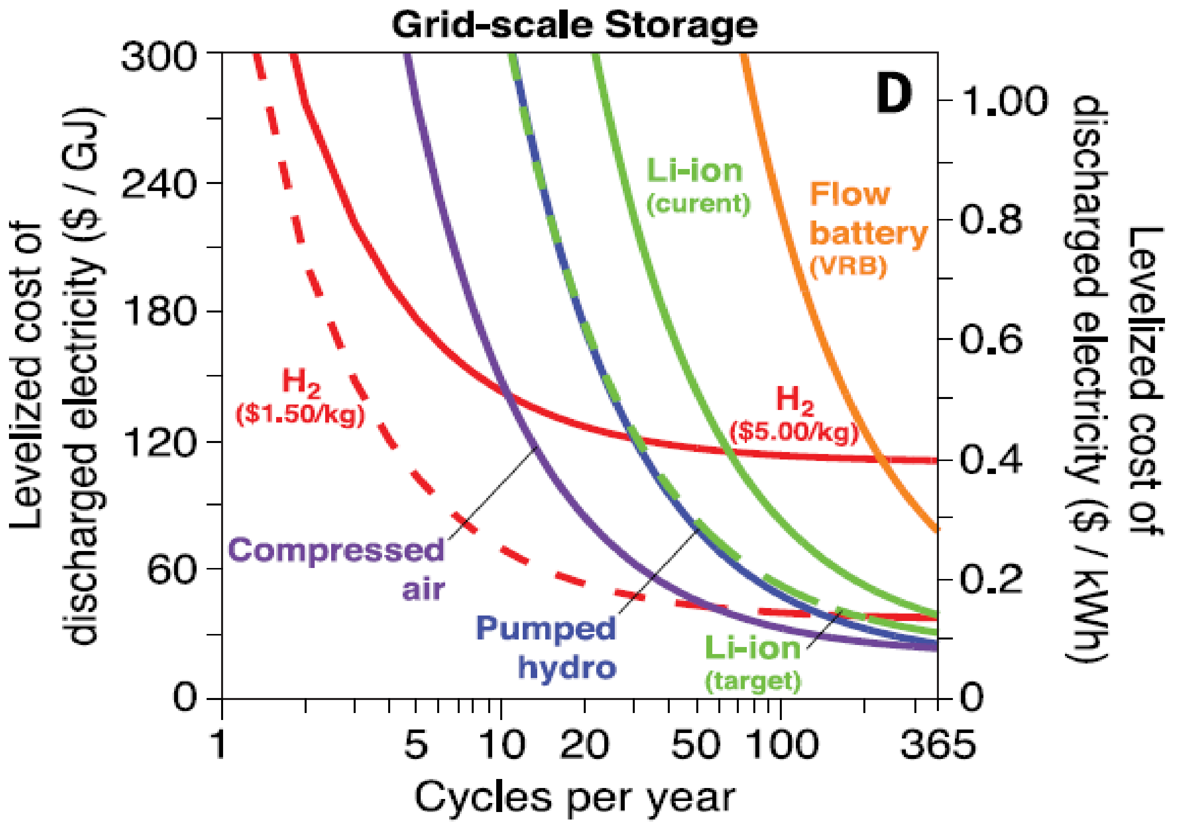
- There are 2 major approaches to storage:
  - Batteries- well developed technique, great for short times and small amounts.
  - Molecular Fuels- follows nature, underdeveloped, great for long times and large amounts.

- There are also a relatively large amount of minor approaches:
  - Pumped storage
  - Flywheels
  - Supercapacitor
  - Compressed air

How Does Storage Compare?

- The cost is a function of how often you store and release energy.
- Grid scale storage will always be cheaper than mobile storage (i.e. cars) since you don't need the flexibility
- Pumped air and pumped hydro are the most effective, but you need caves or mountains to do this.

As of 2018



DOI: 10.1126/science.aas9793

Environmental Effects

Analyzing CO_2 production

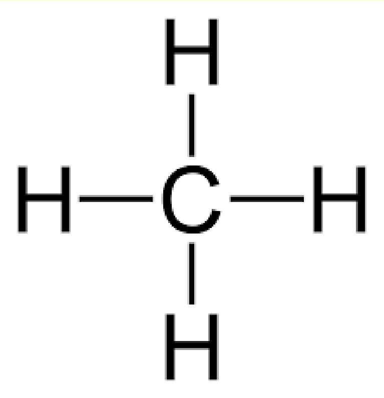
- We are only interested in energy, not CO_2.
- Do all hydrocarbons have the same CO_2/ energy?

$$C_xH_yO_z + O_2 \rightarrow \; CO_2 + H_2O$$

Generic hydrocarbon

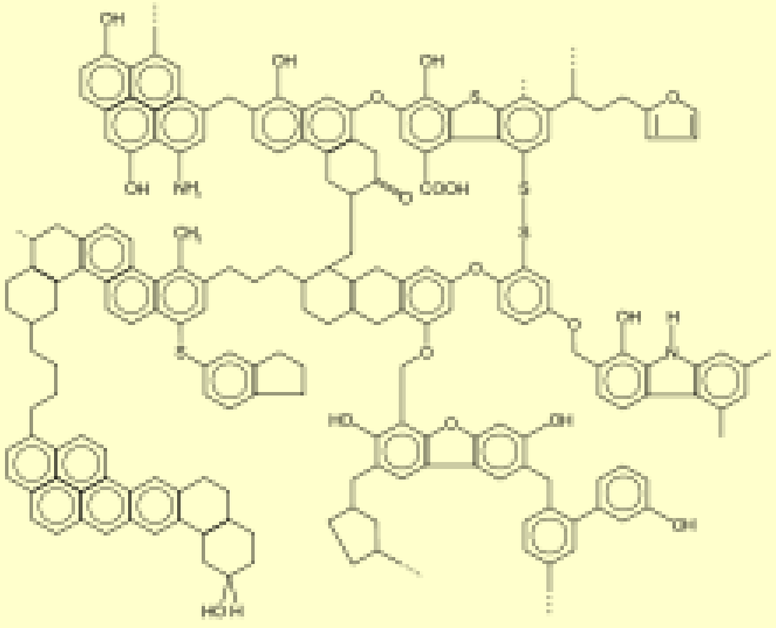
Differences in Fossil Fuels

- All fossil fuels are not created equal.
- Since they are different molecules, some will produce more energy/CO_2 than others.



Example chemical structure of natural gas

Example chemical structure of oil (octane)



Example chemical structure of coal

- Which of these gives the most energy per molecule of CO_2?

Fossil Fuels Emissions

- Determining energy produced is relatively simple.

- Take the bonds after the reactions and subtract them from the bonds before reaction. This is how much more stable your molecules are

- Stability means going to a lower energy, and emitting heat

- This is a rough approximation method, but works relatively well

Average Bond Enthalpies (kJ/mol)

Single Bonds

C—H	413	N—H	391	O—H	463	F—F	155
C—C	348	N—N	163	O—O	146		
C—N	293	N—O	201	O—F	190	Cl—F	253
C—O	358	N—F	272	O—Cl	203	Cl—Cl	242
C—F	485	N—Cl	200	O—I	234		
C—Cl	328	N—Br	243			Br—F	237
C—Br	276			S—H	339	Br—Cl	218
C—I	240	H—H	436	S—F	327	Br—Br	193
C—S	259	H—F	567	S—Cl	253		
		H—Cl	431	S—Br	218	I—Cl	208
Si—H	323	H—Br	366	S—S	266	I—Br	175
Si—Si	226	H—I	299			I—I	151
Si—C	301						
Si—O	368						

Multiple Bonds

C=C	614	N=N	418	O_2	495
C≡C	839	N≡N	941		
C=N	615			S=O	523
C≡N	891			S=S	418
C=O	799				
C≡O	1072				

Fossil Fuels Emissions

- Fossil fuels with less oxygen in them have significant lower CO_2 production per kWh of energy.

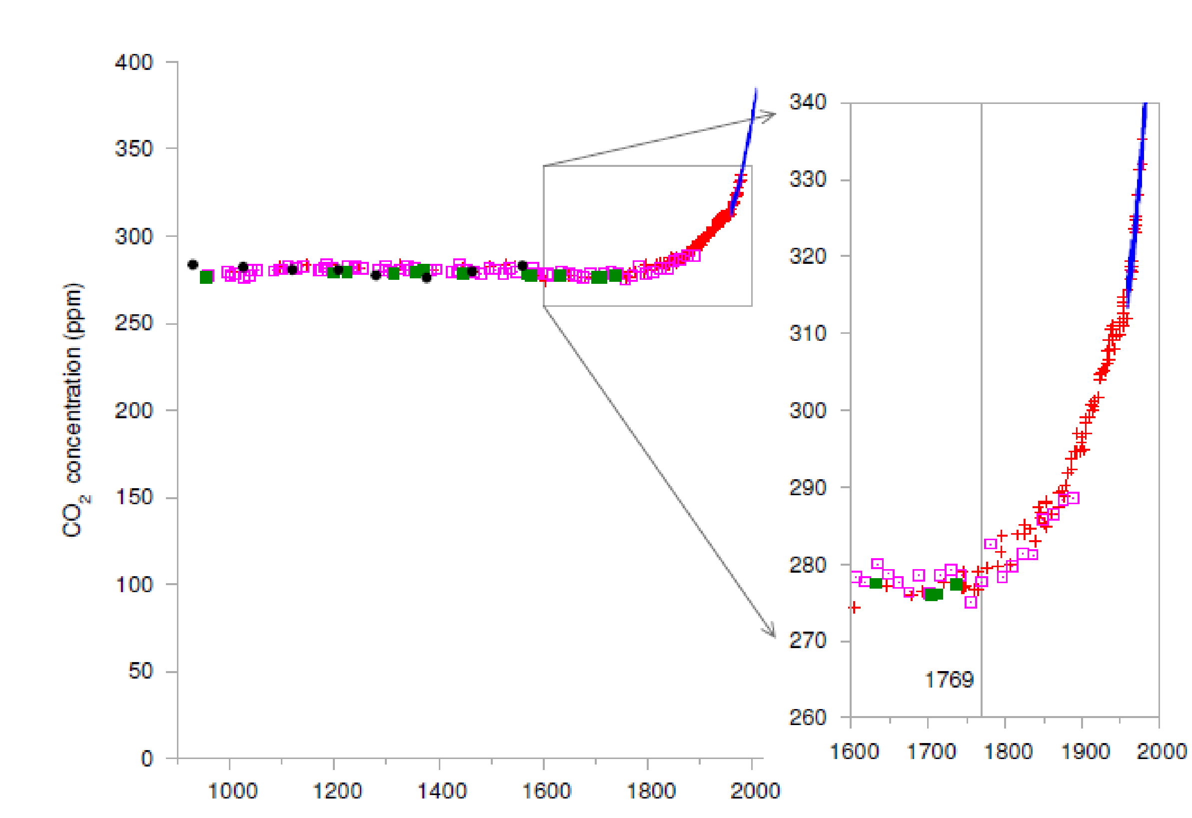
Fuel type	emissions (g CO_2 per kWh of chemical energy)
natural gas	190
refinery gas	200
ethane	200
LPG	210
jet kerosene	240
petrol	240
gas/diesel oil	250
heavy fuel oil	260
naptha	260
coking coal	300
coal	300
petroleum coke	340

Figure I.10. Emissions associated with fuel combustion. Source: DEFRA's Environmental Reporting Guidelines for Company Reporting on Greenhouse Gas Emissions.

- Short carbons have lower CO_2 / kWh than long carbon chains.
- There is a lot of oil left that has a high oxygen content, thus the CO_2 from these new sources will be more than traditional oil.
- Natural gas has the issue that we currently leaks 2% of it during extraction and production.

Historical CO_2

- By using ice-core data we can determine CO_2 concentrations well into the past.
- Since 1000 AD the CO_2 concentration has been relatively stable until about 1769. What happened in 1769?

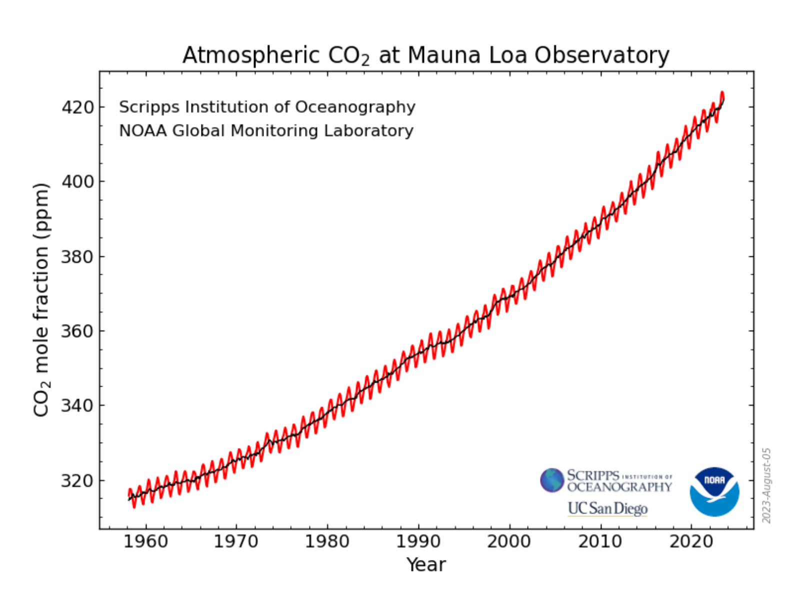


- In 1769 James Watt invented the steam engine. It's impact on the world was seen immediately.

Figure from SE book

CO_2 Concentrations

- Since we know how much energy we use (19 TW) and we know about 80% of it is from hydrocarbon combustion, we should be able to calculate how much CO_2 we are putting into the atmosphere/ year.
- Do this calculation by noting that fossil fuels typically produce 190 g CO_2/ kWh, CO_2's density is 1.98 kg/m^3, the earth's radius is 6,370 km, the pressure is 101 kPa, gravity is 9.8 m/s^2, and the average density of the atmosphere is 1.35 kg/m^3. (hint: you need calculate the mass of the atmosphere)
- The average CO_2 increase over the last decade is 2.1 ppm/year.
- Could this be due to fossil fuel combustion?



CO_2 Concentrations- Solution

Effective mass of the Earth's atmosphere

$$Pressure = P = \frac{Force}{Area} = \frac{mg}{4\pi r^2} \Rightarrow m = \frac{P * 4\pi r^2}{g}$$

$$\Rightarrow m = \frac{101x10^5 * 4 * \pi * 6.37x10^5}{9.81} = 5.25x10^{18}\ kg$$

Effective volume of the Earth's atmosphere

$$Volume = \frac{mass}{density} = \frac{5.25x10^{18} kg}{1.35\ \frac{kg}{m^3}} = 3.9 \times 10^{18} m^3$$

CO_2 Concentrations- Solution

Amount of CO_2 produced

$$19\,TW \times 80\% = 15.2\ \times 10^{12} W \times 3600\frac{s}{hr} \times 24\frac{hr}{day} \times 365\frac{day}{year} = 479 \times 10^{18}\frac{J}{Y}$$

$$190\frac{g\ CO_2}{kW \times hr} = 190\frac{s \times g\ CO_2}{kJ \times hr} \times \frac{1hr}{3600\ s} = 5.3 \times 10^{-2}\frac{mg\ CO_2}{J}$$

$$5.3 \times 10^{-2}\frac{mg\ CO_2}{J} \times 479 \times 10^{18}\frac{J}{Y} = 2.54 \times 10^{19}\frac{mg\ CO_2}{Y} \div 1.98 \times 10^{6}\frac{mg}{m^3} = 1.28 \times 10^{13} m^3$$

Volume of Earth's atmosphere: $Volume = 3.9 \times 10^{18} m^3$

Annual increase of CO_2 from Fossil Fuels

$$\frac{1.28 \times 10^{13}\frac{m^3}{y}}{3.9 \times 10^{18} m^3} = 3.30 \times 10^{-6} = 3.3\frac{ppm}{year}$$

(We measure ~2ppm, because the ocean is uptaking the rest of the CO_2.)

Ocean Acidification

- Why does CO_2 acidify the ocean?

CO_2 Equilbrium

- Here is the reactions that give us trouble.

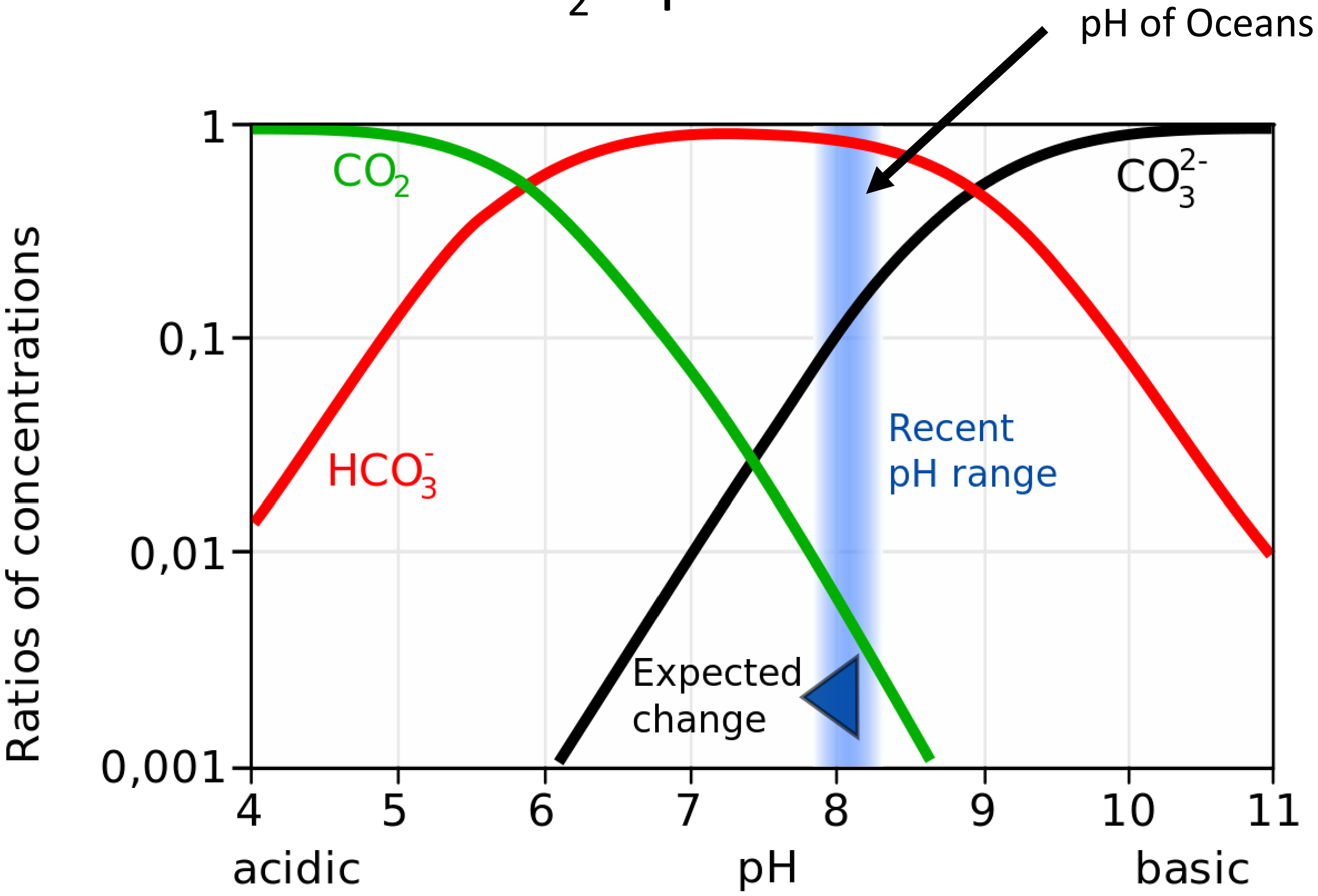
$$pKa = 6.5 = Log_{10}\frac{[H_2CO_3]}{[HCO_3^-][H^+]}$$

$$CO_2 + H_2O \rightarrow H_2\ CO_3 \rightarrow H^+ + HCO_3^- \rightarrow 2H^+ + CO_3^{2-}$$

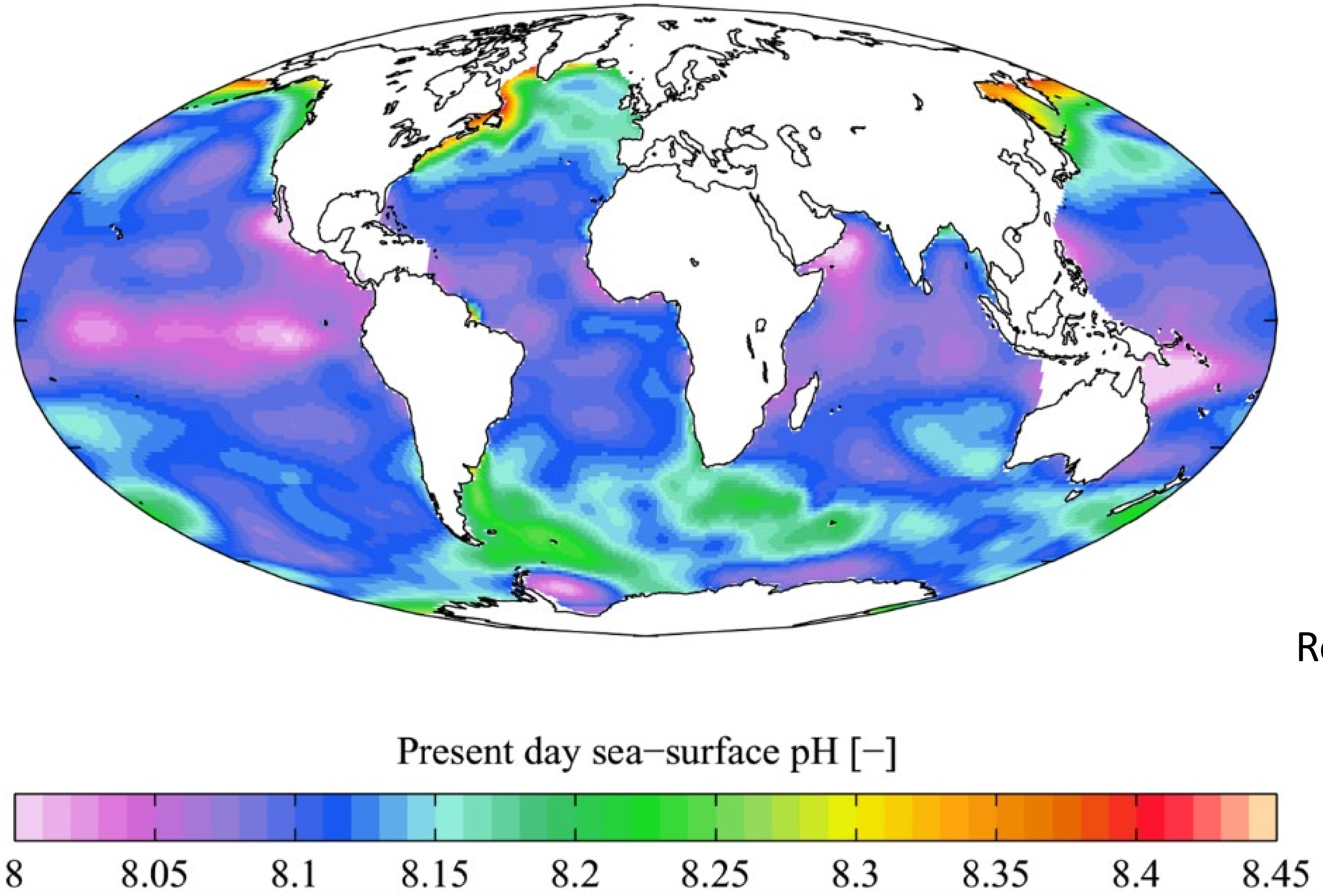
$$pKa = 10.6 = Log_{10}\frac{[HCO_3^-]}{[CO_3^{2-}][H^+]^2}$$

$$pKa = 6.5 = Log_{10}\frac{[H_2CO_3]}{[HCO_3^-][H^+]} \Rightarrow 6.5 = Log_{10}\frac{[H_2CO_3]}{[HCO_3^-]} + Log_{10}\frac{1}{[H^+]} \Rightarrow 6.5 = Log_{10}\frac{[H_2CO_3]}{[HCO_3^-]} + pH$$

CO_2 Equilbrium



CO_2 Equilbrium



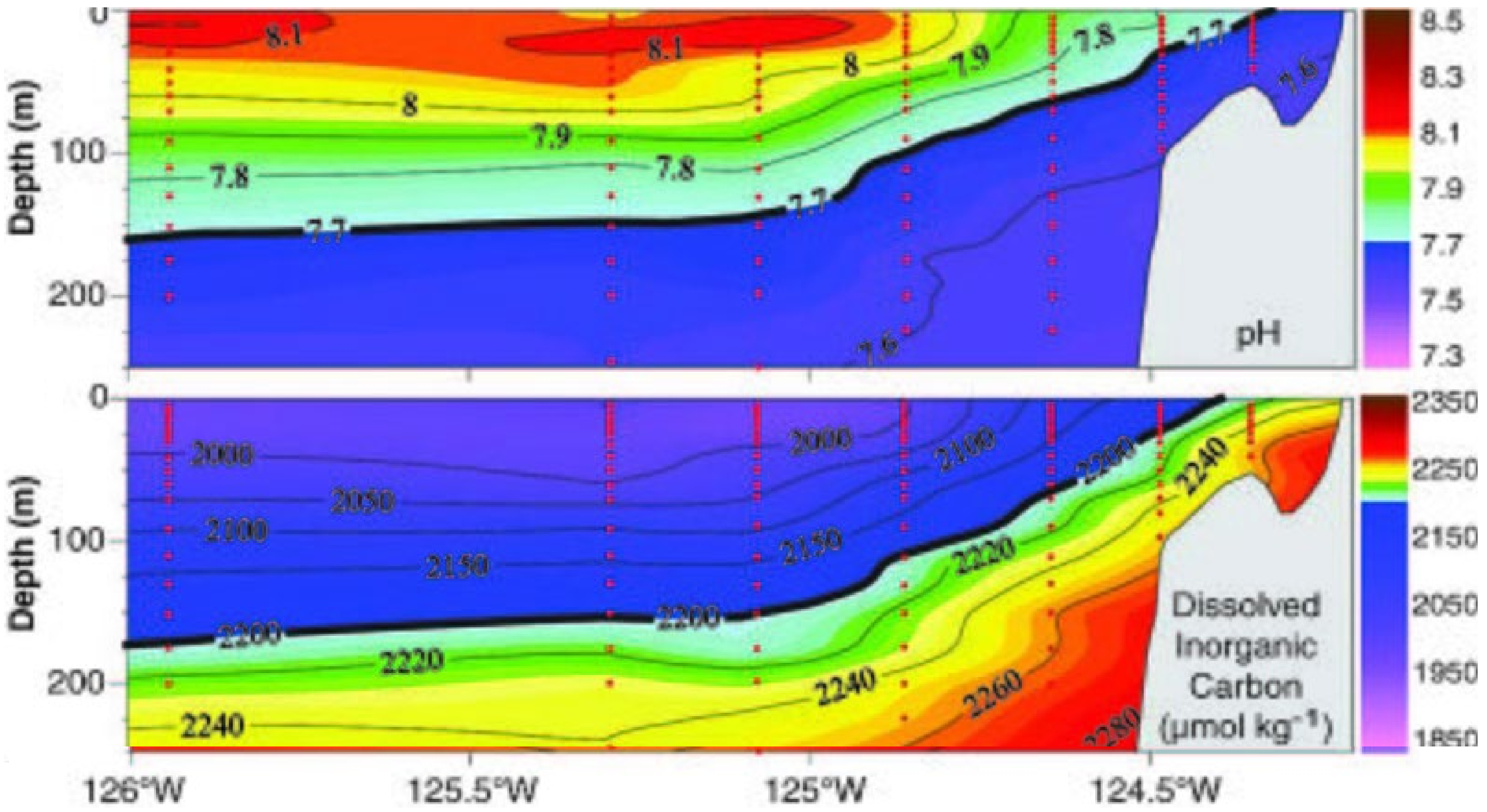
Ref: Wikipedia

$$[H]^+ = 10^{-pH}$$

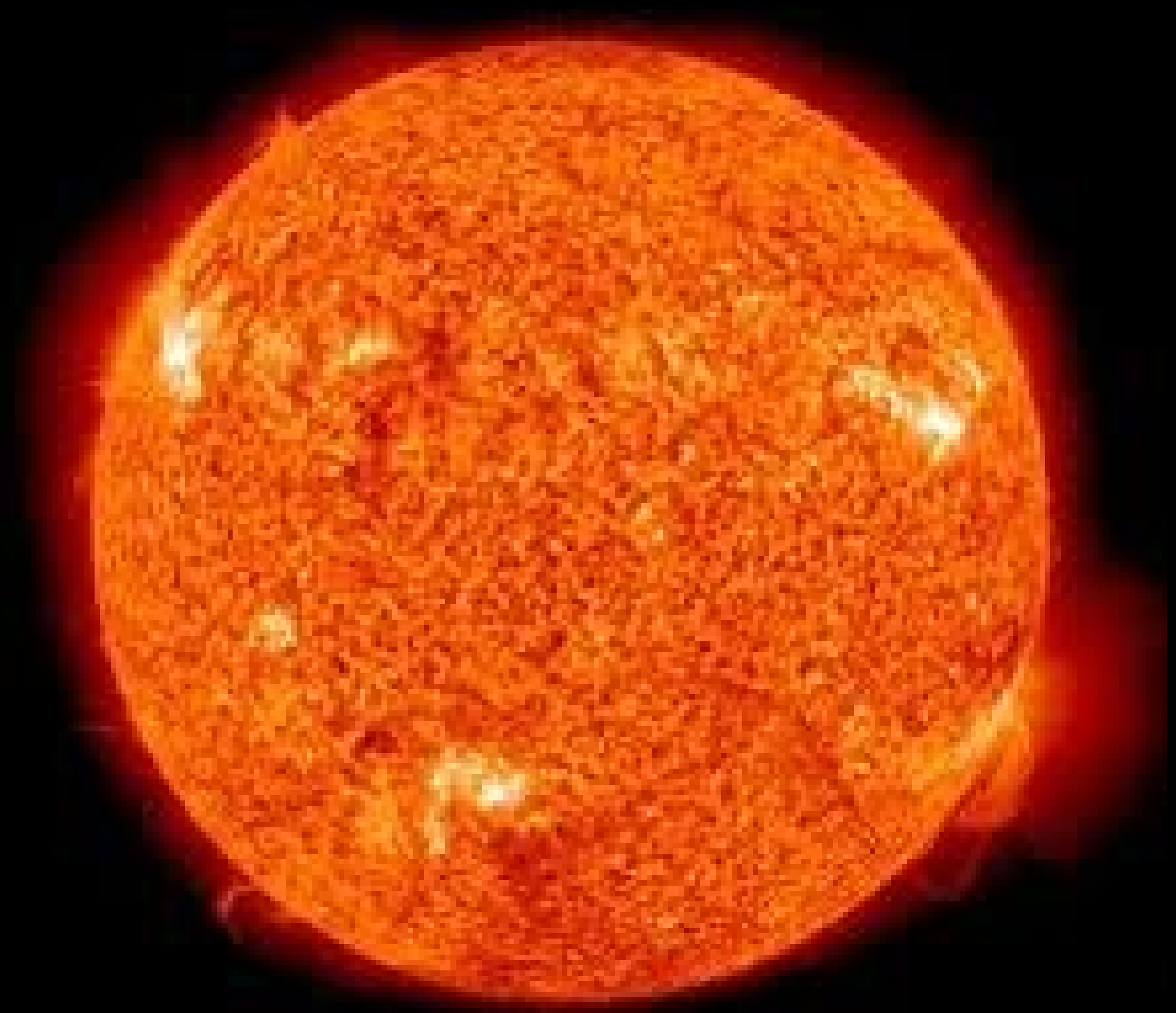
Actually activity, but basically the same

CO_2 Equilbrium

- The CO_2 balance does not penetrate that deep into the ocean.
- This shows a rough relationship between conductive mass transfer of the ocean versus CO_2 diffusion.



Solar Spectrum

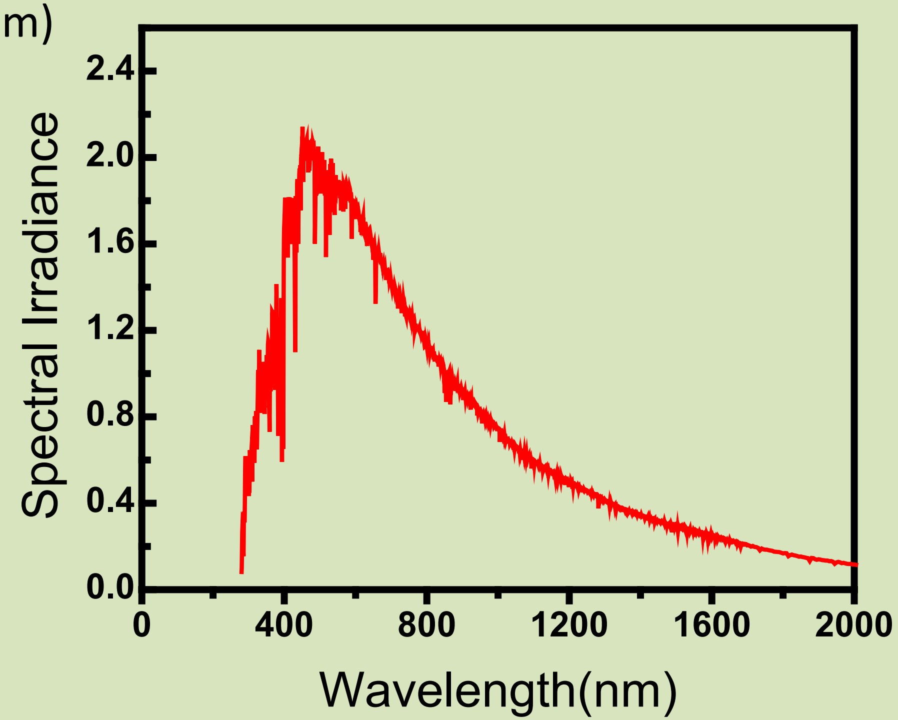


Planck's law- review

- Here is the Planck's law in convenient terms.

$$I_\lambda d\lambda = \frac{2\pi hc^2}{\lambda^5} \frac{1}{\left(e^{hc/\lambda kT} - 1\right)} d\lambda$$

Units
$(W/m^2/nm)$



- We can convert from energy to wavelength:

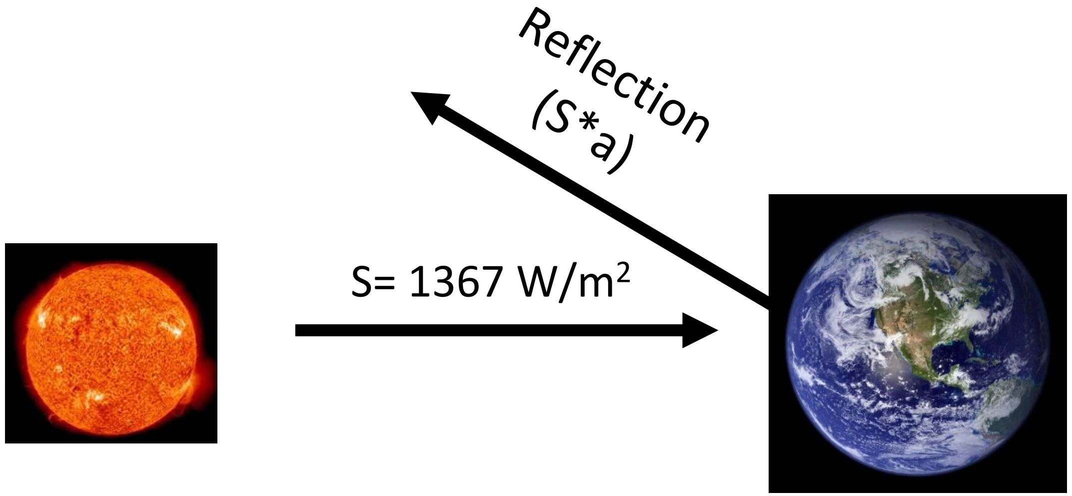
$$E(eV) = \frac{hc}{\lambda} = \frac{1240}{\lambda(\text{nm})}$$

- Stefan-Boltzmann's law is as follows:

$$I = \sigma T^4 \qquad \sigma = 5.67\text{x}10^{-4}\ \text{W m}^{-2}\ \text{K}^{-4}$$

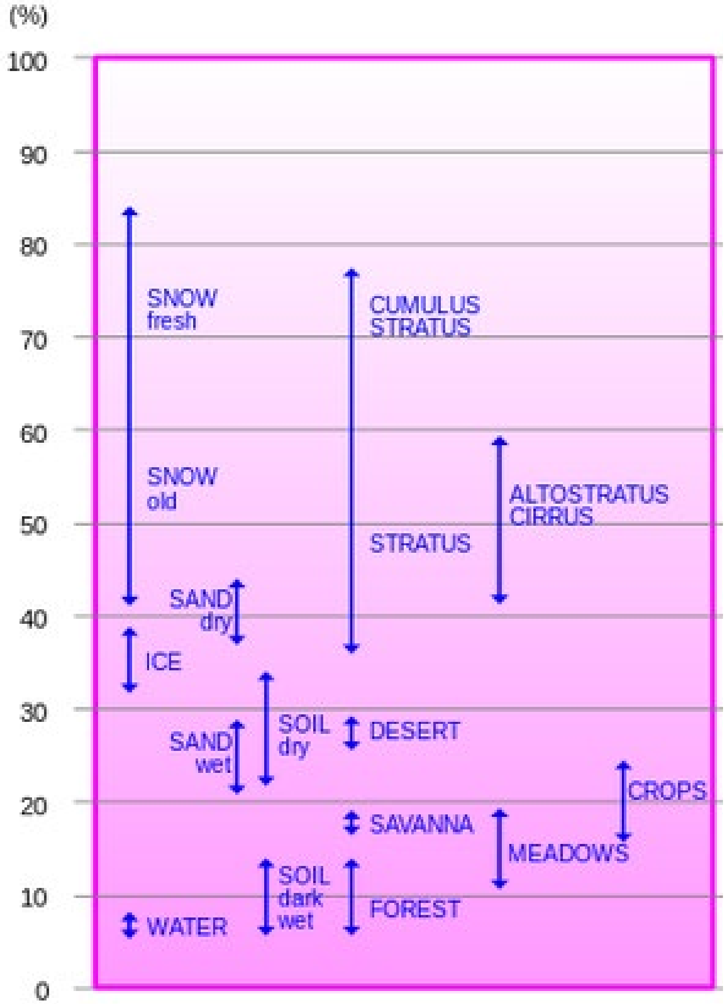
- Blackbody radiation of sun tells us it is 5800 K ⟶ Solar constant (S) of Earth = 1367 W/m^2

Earth's albedo



- Earth's albedo (*a*) is a value which is a fraction of how much solar irradiation gets reflected back into space.

- An albedo (*a*) of 100% means pure reflection of all light back into space.



Percentage of diffusely reflected sunlight in relation to various surface conditions

What about Earth's irradiance

- Earth is also a black-body irradiator.
- An energy balance on Earth, lets us denote Earth's theoretical temperature

Solar Constant (1365 W /m²)

$$Energy\ In = Energy\ Out$$

$$S(1-a) \times \pi E^2 = \sigma T_{Earth}{}^4 \times 4\pi E^2$$

E= radius of earth

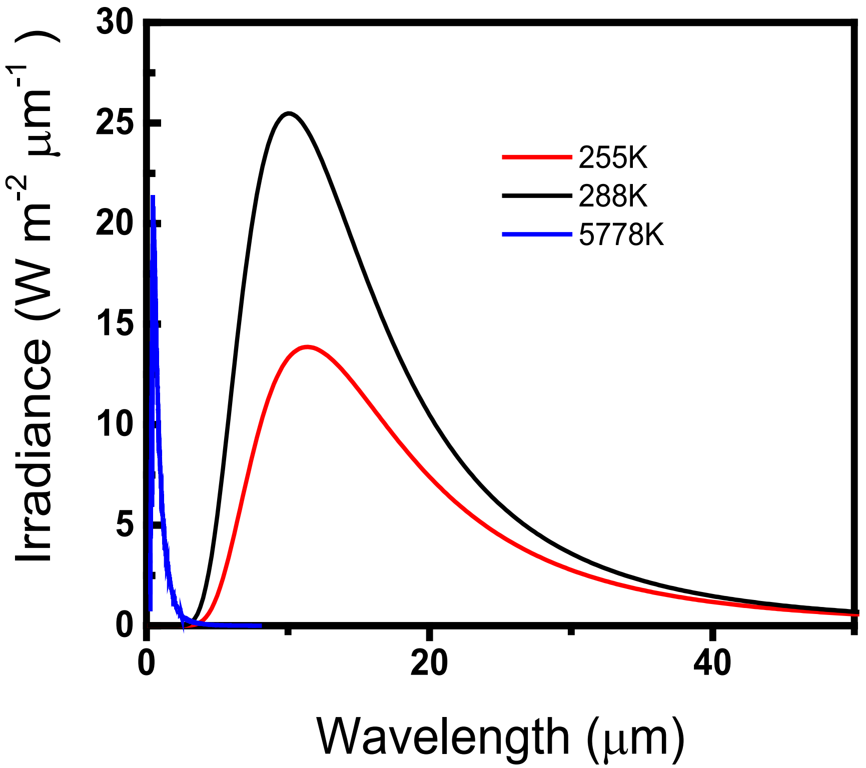
$$T_{earth} = \left(\frac{S(1-a)}{4\sigma}\right)^{1/4}$$

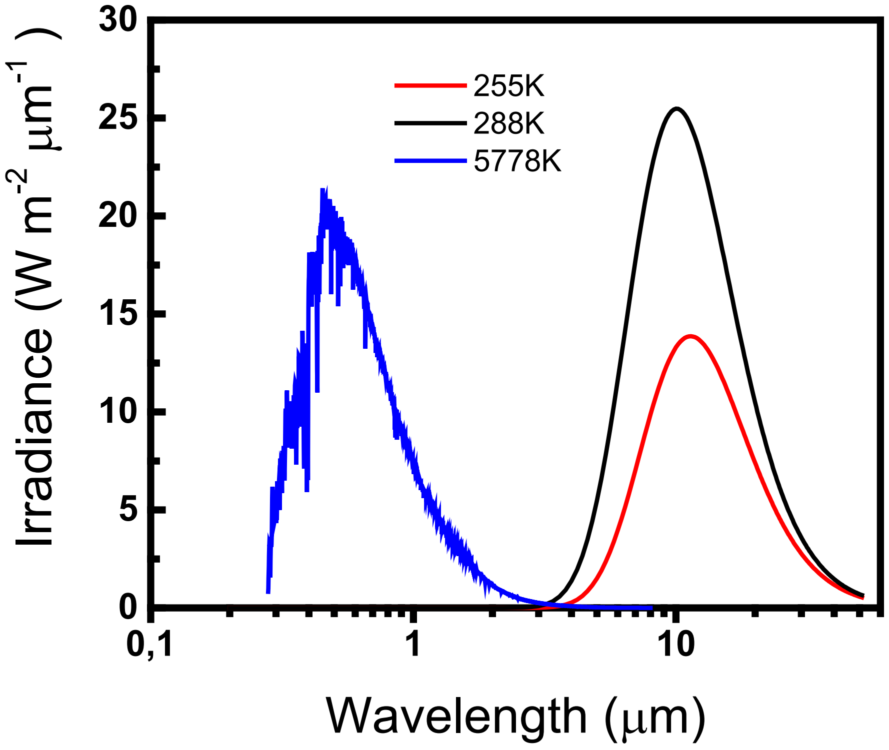
Albedo (i.e. cloud /reflections)

- This yields a temperature of 255 K, whereas the real temperature is 288 K.

Emission spectra

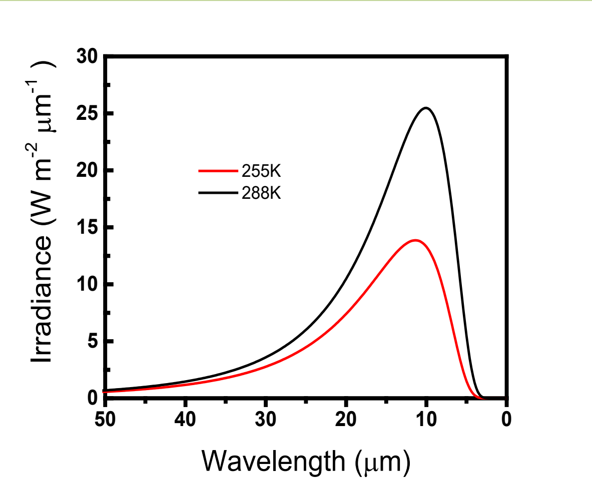
- The Earth emits at completely different wavelengths than the sun.
- There is not much variation between 255 K and 288 K.



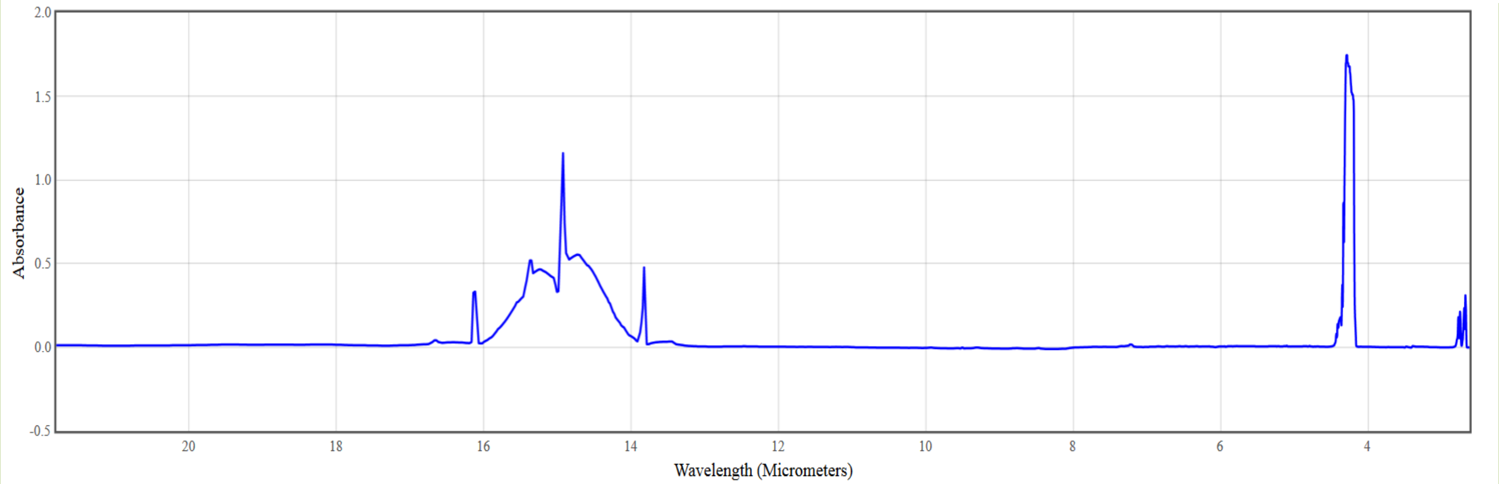


-Sun’s irrandiance power (at the sun) was scaled down by a factor of 100.

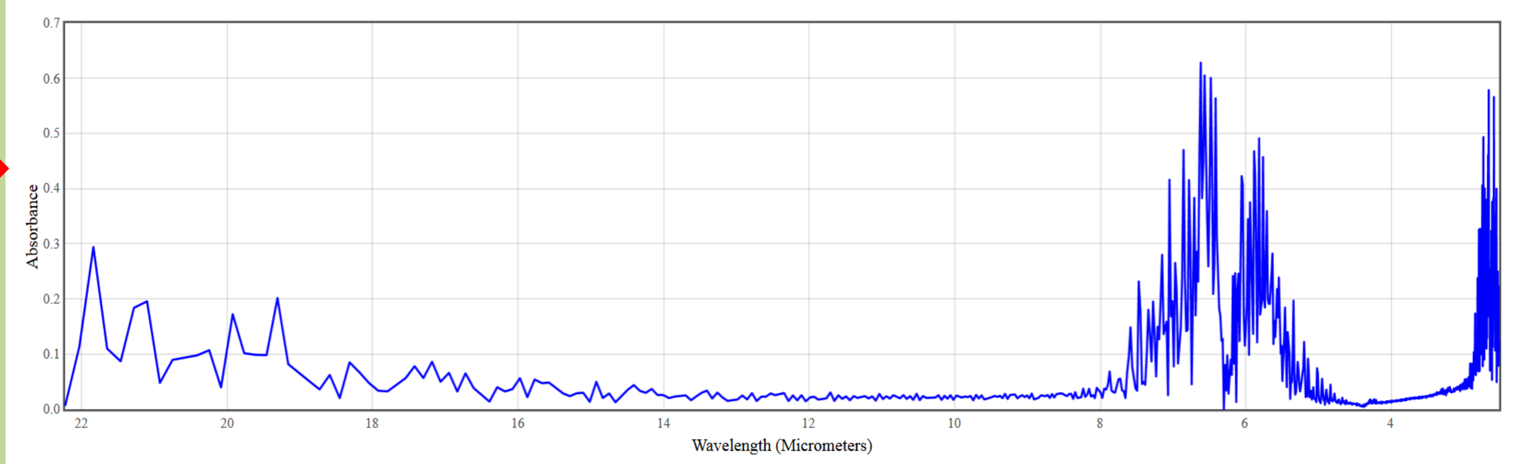
- Below is the absorption spectra for CO_2 and H_2O.
- Can you explain how these absorption spectra relate.



CO_2

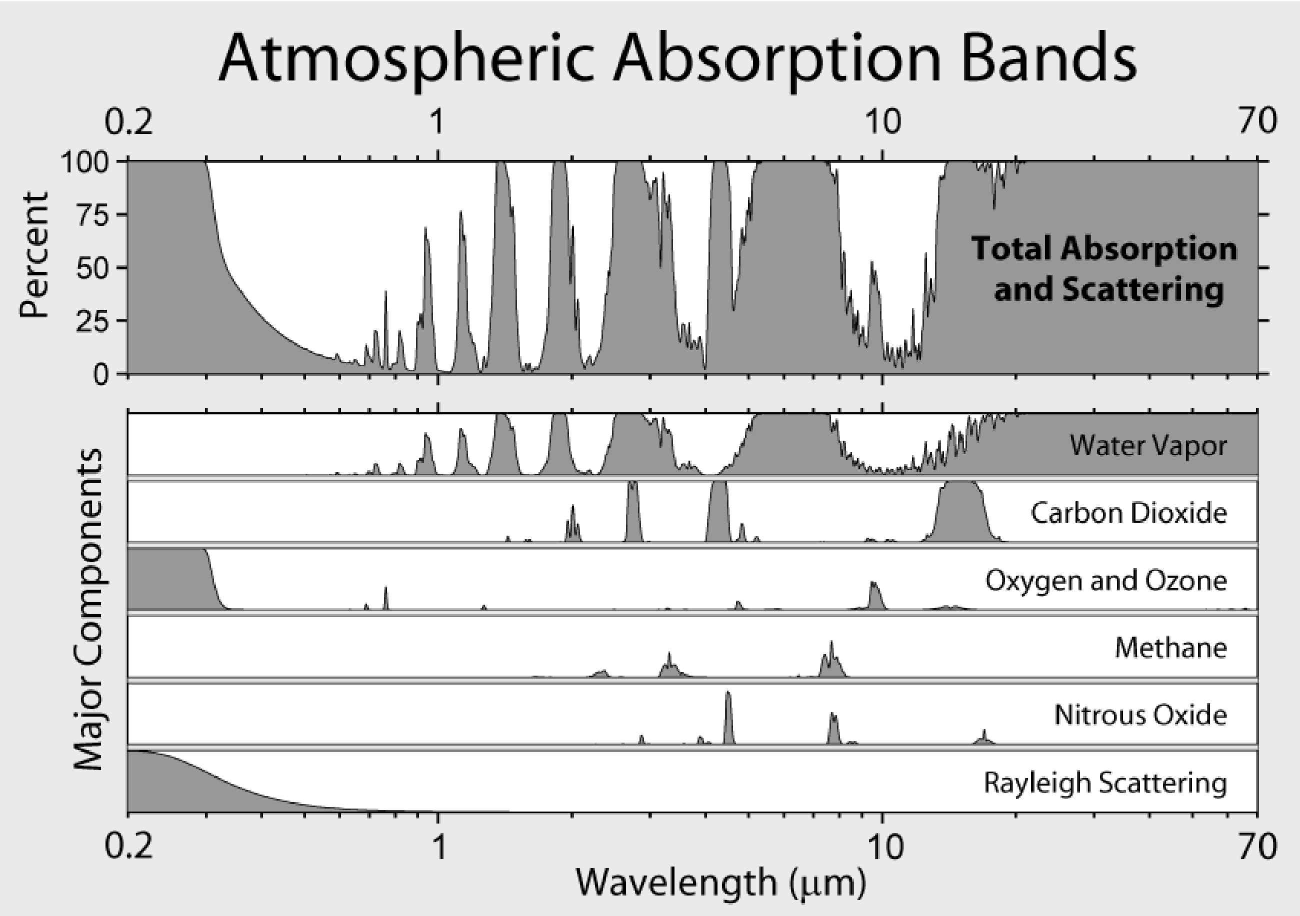


H_2O

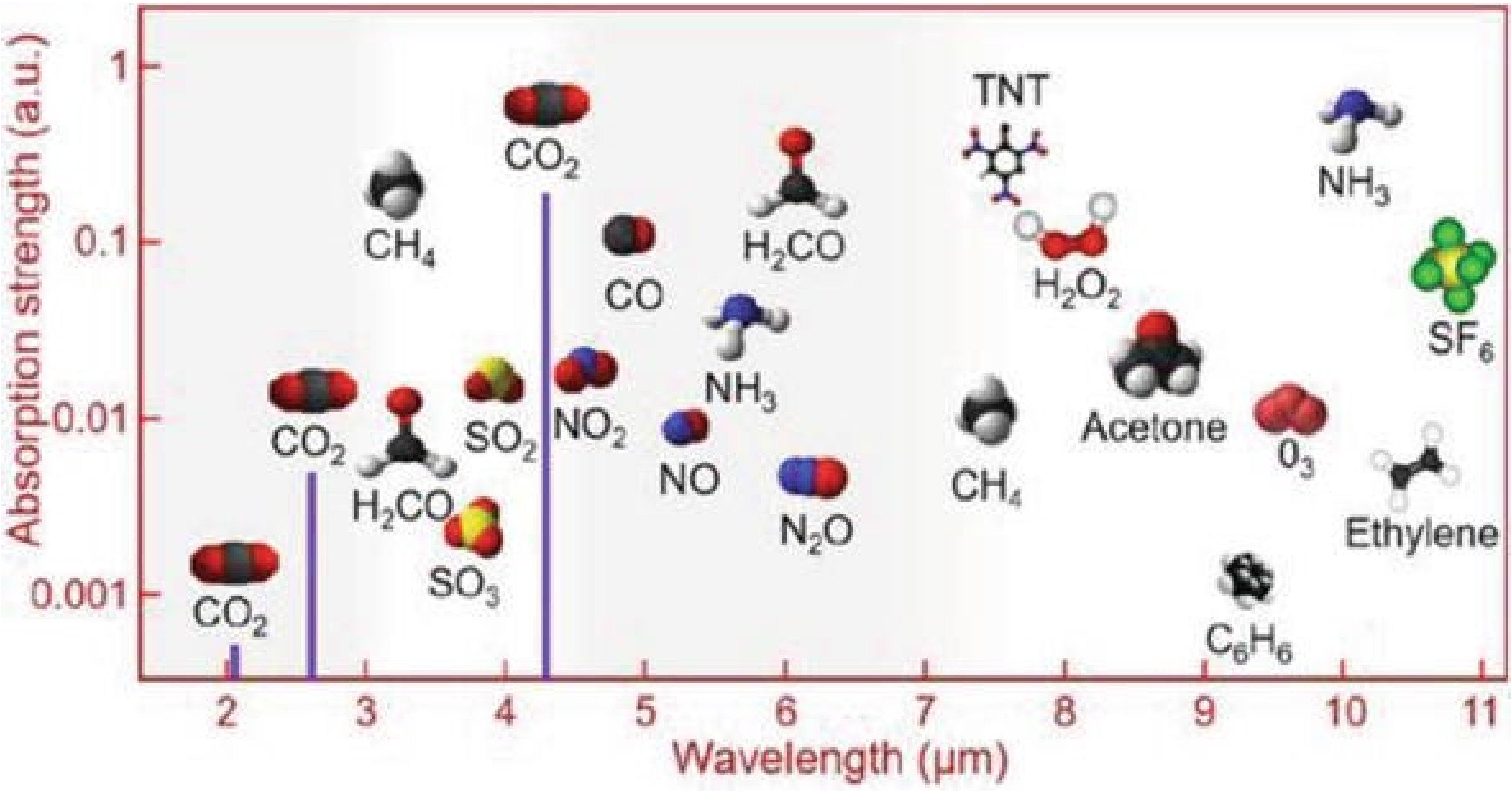


The complete picture

- CO_2 actually absorbs 100% at its peak wavelength … and always has.
- Increasing CO_2 is simply broadening the thickness in wavelengths of CO_2 absorption.



Absorption of various molecules



Why does CO_2 absorb?

- To understand greenhouse gases, we need to understand spectroscopy.
- We can go back to Hook's law and harmonic oscillators

$$\vec{F}_{spring} = -k * x$$

$$\omega = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \Rightarrow \omega = \frac{1}{2\pi}\sqrt{\frac{k(m_1 m_2)}{m_1 + m_2}}$$

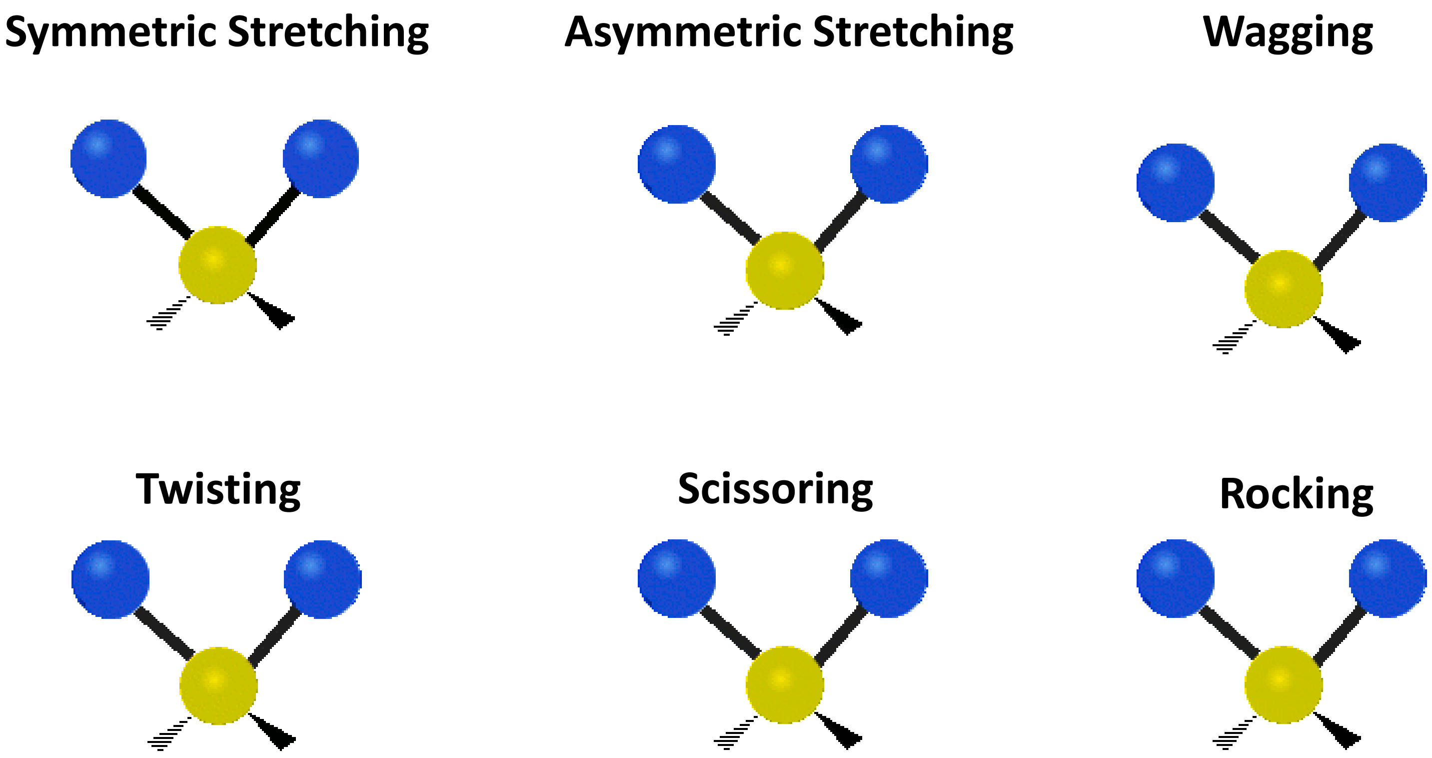
For 2 atoms

$$\omega = \frac{c}{\lambda} = \frac{E}{h}$$

- Infra-red radiation will absorb by following Fermi's Golden Rule.

Vibrational Modes

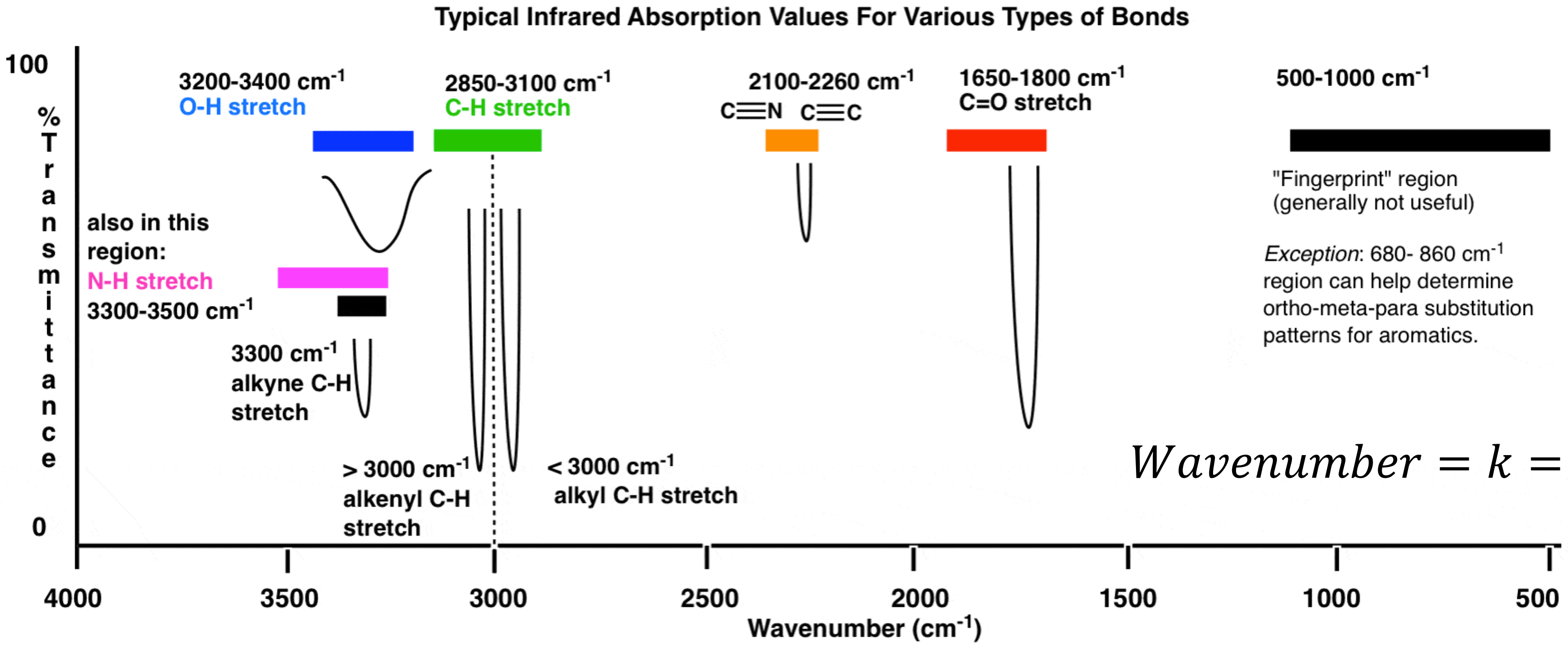
- Molecules are limited to only a few fundamental vibrations.
- Each molecule has 3 dimensions expanding the vibrations.



Six types of Vibrational Modes. Images used with permission (Public Domain; [Tiago Becerra Paolini](#)).

Spectral peaks

- The absorption for organics are very similar.



$$Wavenumber = k = \frac{2\pi}{\lambda}$$

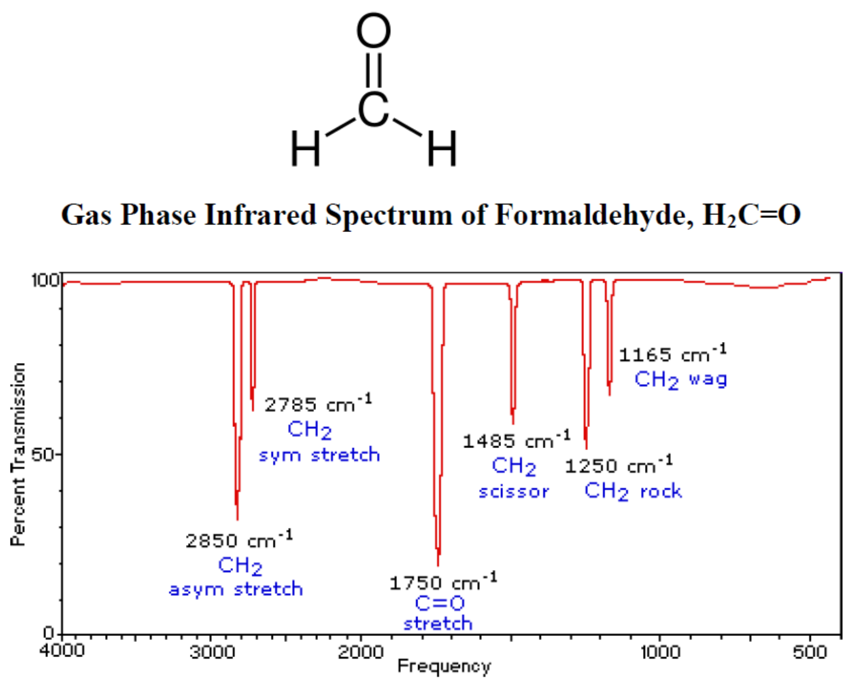
2500 3333 5000 10000 20000

Wavelength (nm)

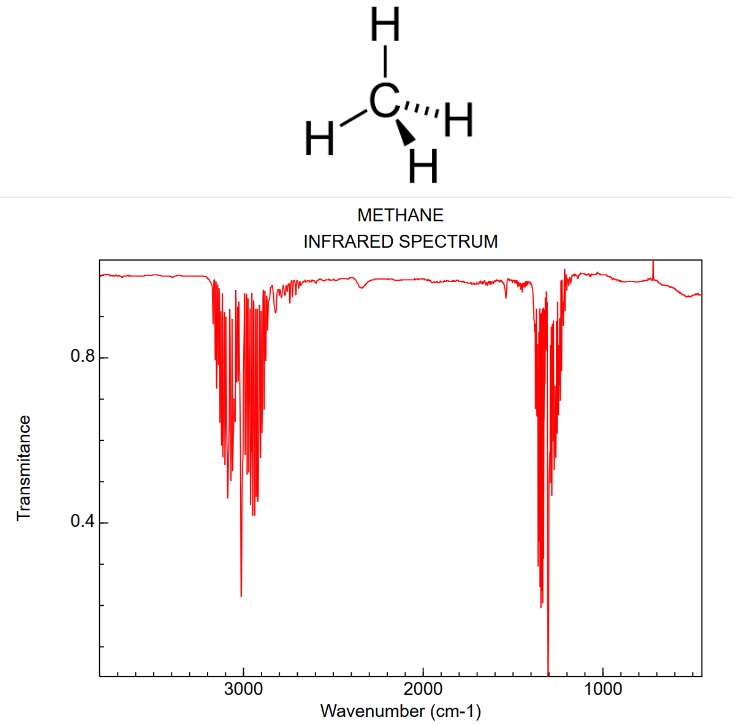
Wavelengths Earth irradiates at

Spectral peaks

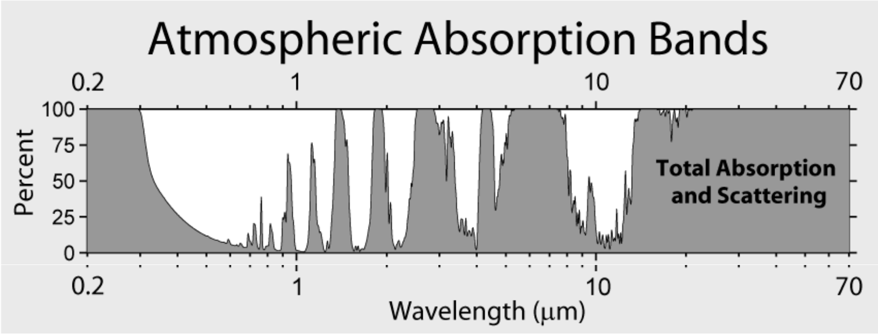
- Below is a comparison of methane and formaldehyde



[Reference](#)

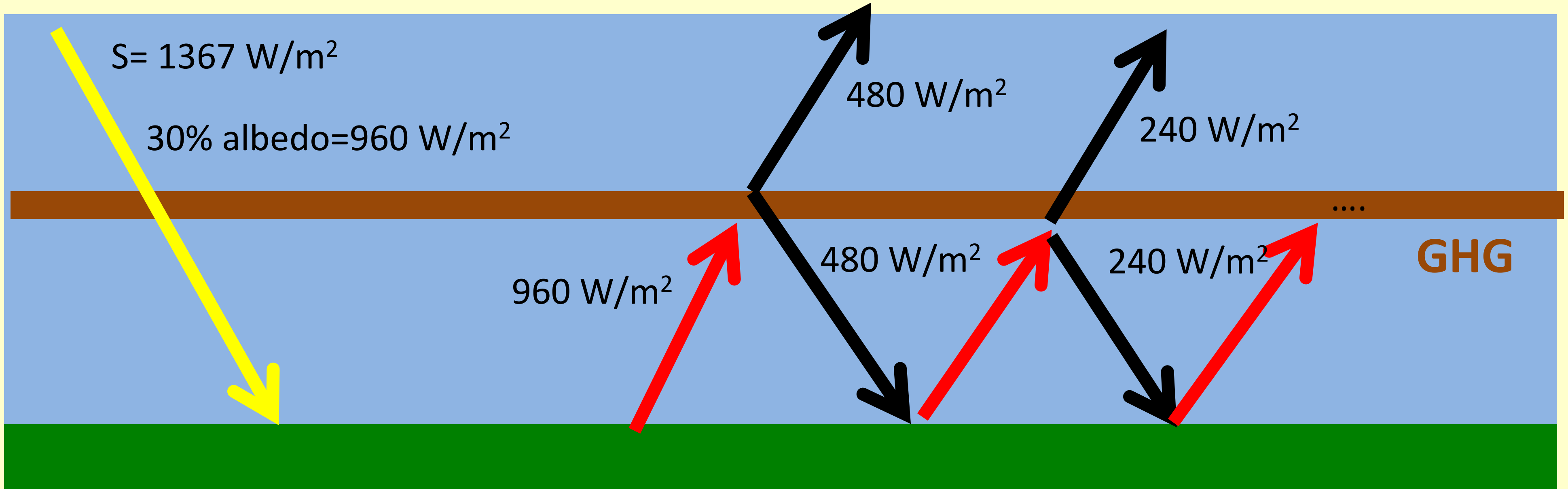


IR Data from NIST



1st order climate modeling

- Lets assume greenhouse gases (GHG) absorb 100% of Earth's outbound irradiation exactly at a set distance from earth.
- Assume 50% is irradiated out and 50% is irradiated back in (irradiation is uniform in all directions, so this is reasonable).
- What would be the temperature of Earth under these conditions?



Climate modeling calculations

- We use the same equation previously used for calculating Earth's temperature, but replace our solar constant with the incoming light.

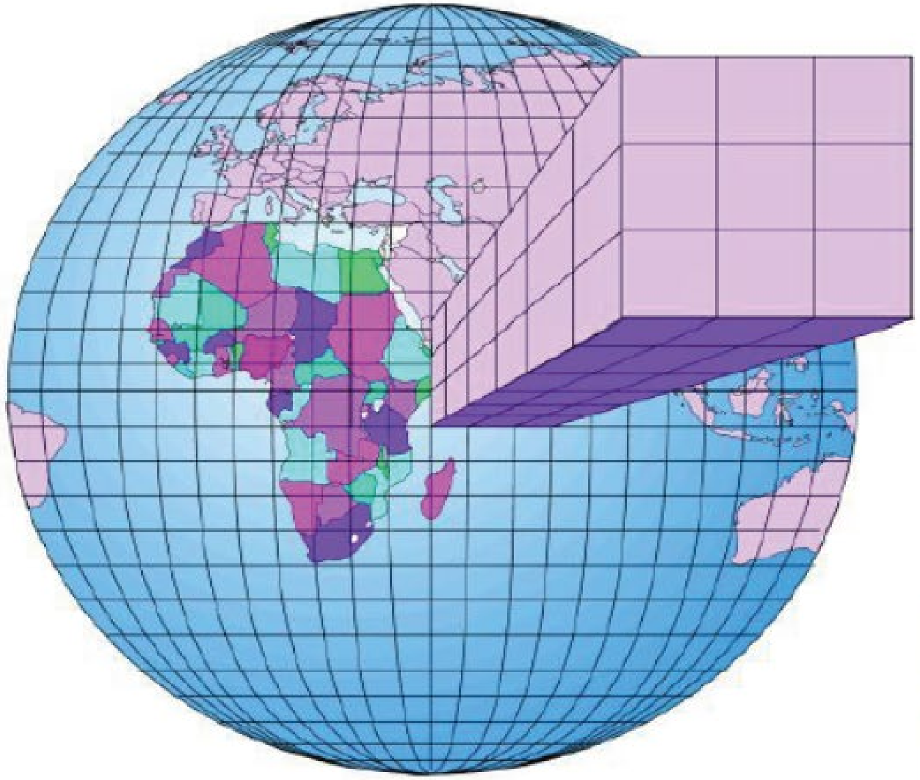
$$T_{earth} = \left(\frac{S(1-a) + GHG}{4\sigma}\right)^{1/4}$$

$$T_{earth} = \left(\frac{2*960}{4*5.67 \text{ x } 10{-}8 \text{ W m}^{-2}\text{ K}^{-4}}\right)^{1/4} = 303 \text{ K}$$

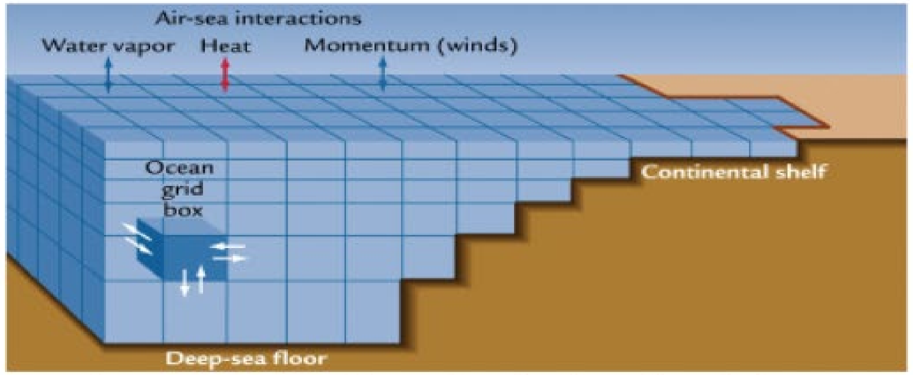
- With no greenhouse gas we are at 255K and with a single absorption (across all wavelengths) we are at 303K.

- If we model this with 2 seperate, complete layers of GHG absorption, would this increase or decrease are global warming potential?

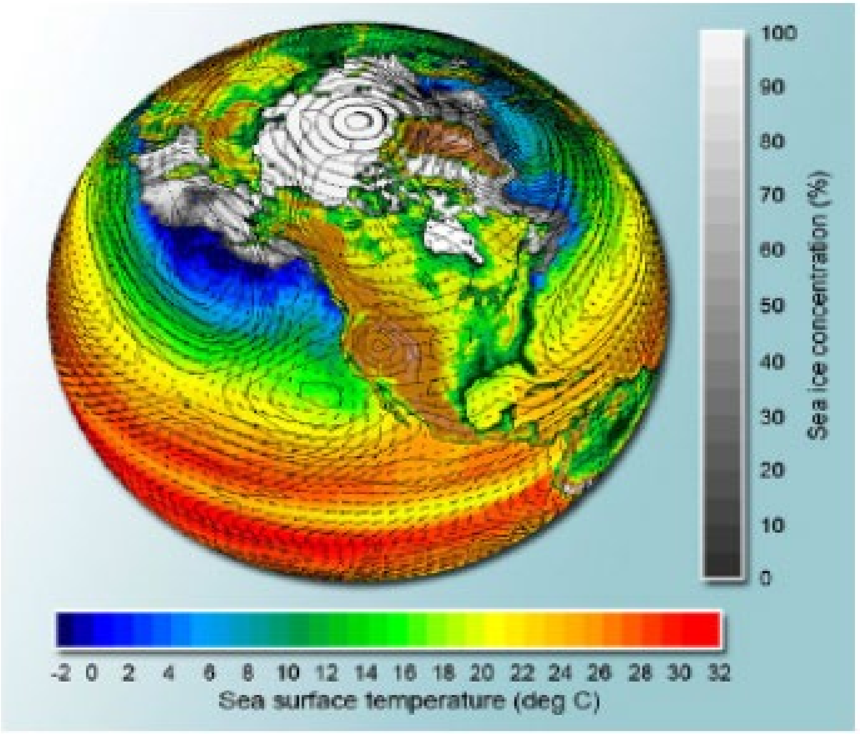
Numerical simulation

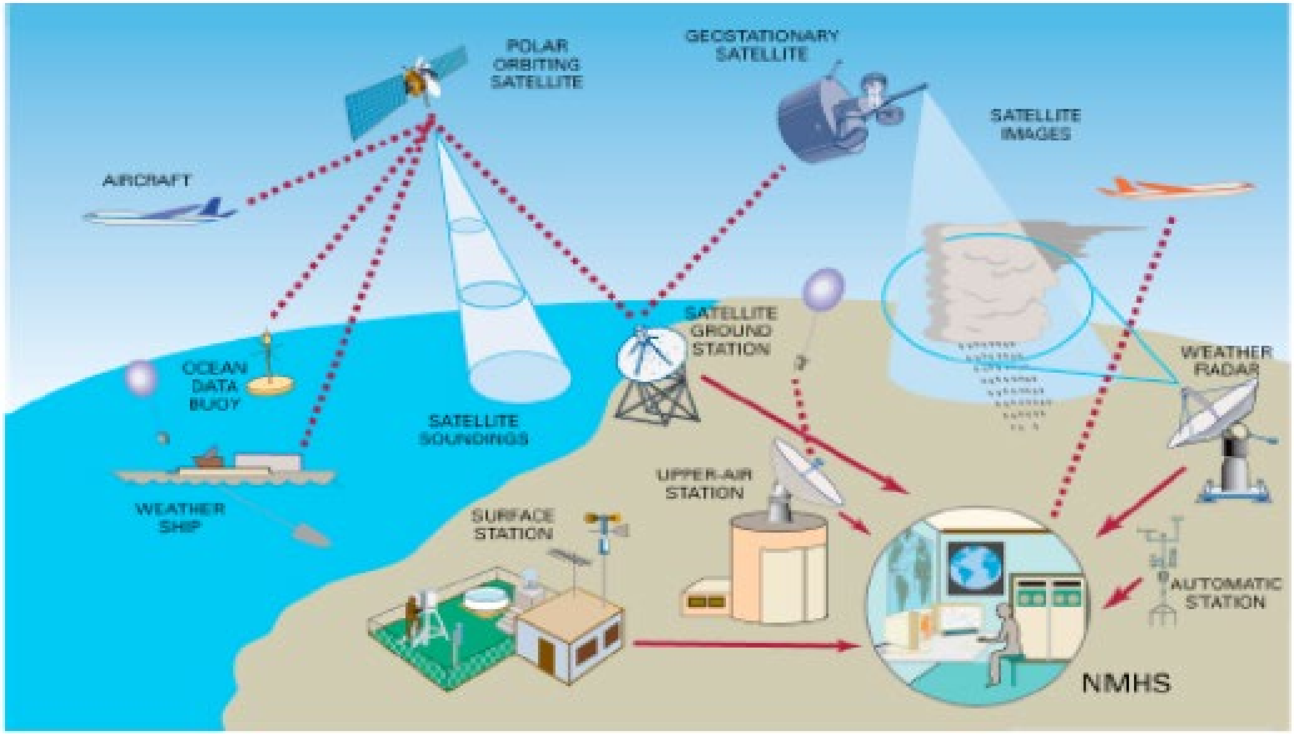


The atmosphere is devided into grid cells where the actual state of the atmosphere are known, i.e., all the variables are known at a given time step.



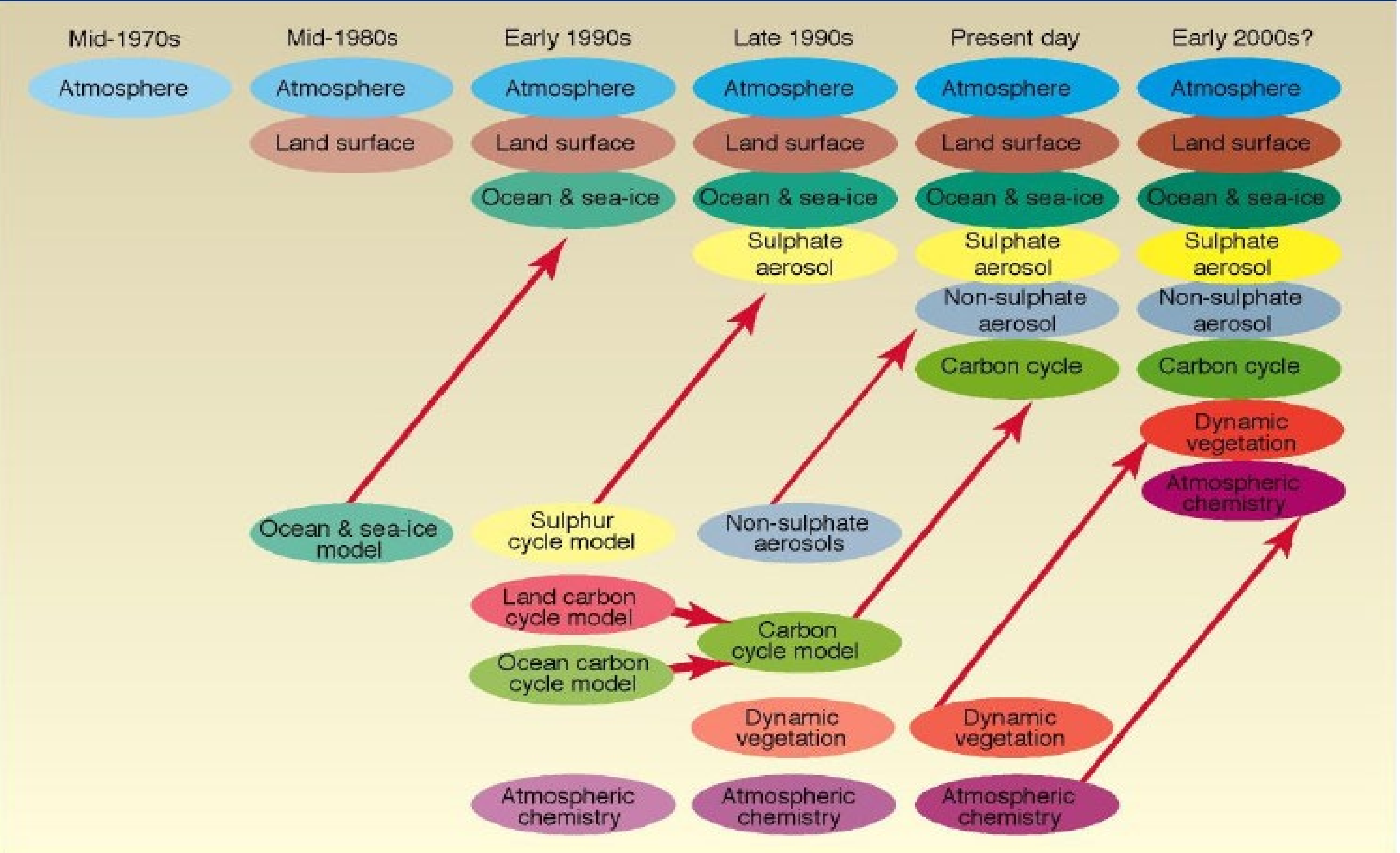
Initial conditions





To initiate a climate model or a numerical weather forecast model the three dimensional initial state of the atmosphere (and the oceans including sea ice) in all grid cells must be known. This can be obtained via a multitude of different observations. For climate models it may in fact also be obtained from the model itself.

The development of climate models, past, present and future



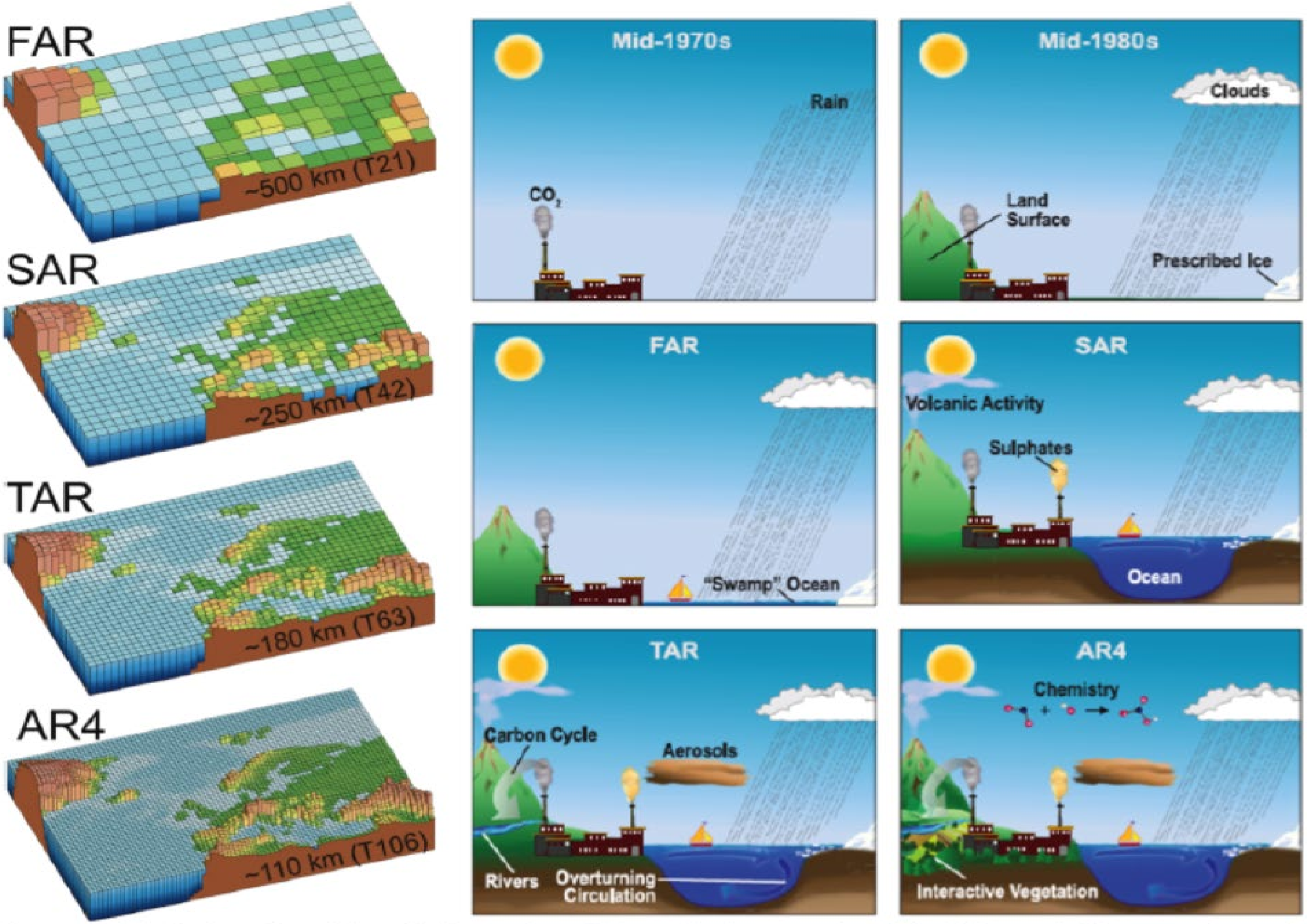
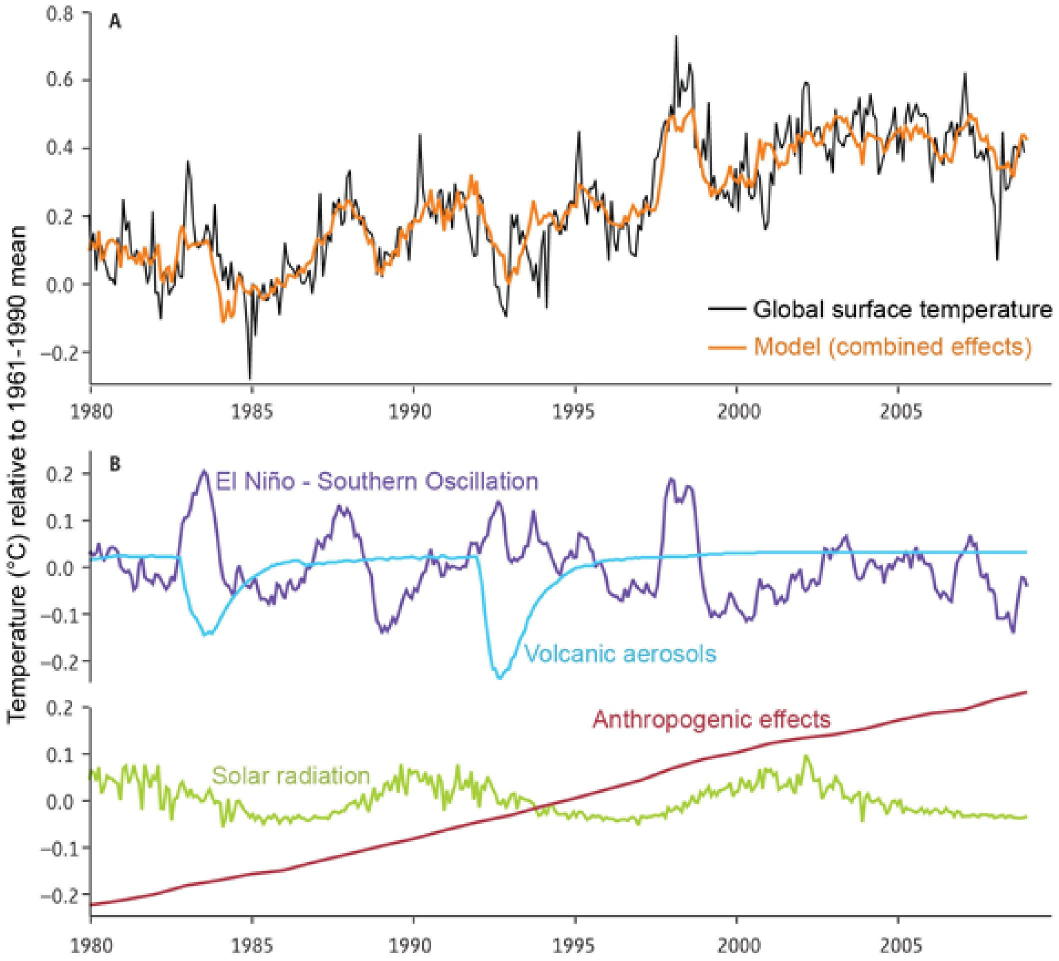


Figure 11: Evolution of model resolution and model complexity over time. The left panels illustrate the typical horizontal resolution at the time of the different IPCC assessment reports: First Assessment Report (FAR), Second Assessment Report (SAR), Third Assessment Report (TAR), and Assessment Report no. 4 (AR4. The spatial resolutions for the CMIP5 (Coupled Model Intercomparison Project phase 5) in AR5 are about the same as for AR4. It should be noted that the resolutions indicated in the figures (from AR4) are incorrect: e.g., T106 corresponds to a grid distance of ~185 km and not ~110 km.

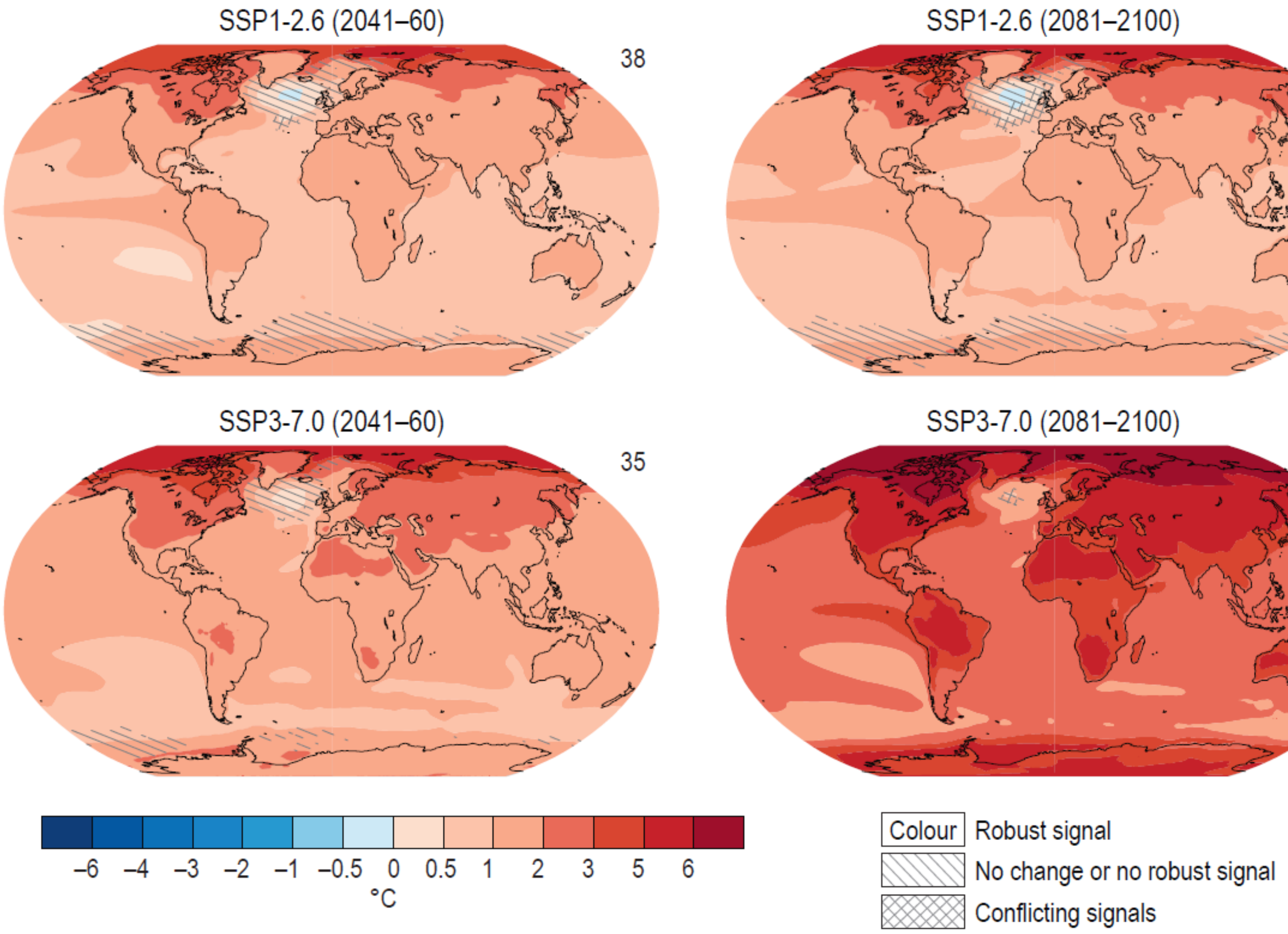
Modelling climate change

- This figures break down the different effects affecting climate.



Adapted from Judith L. Lean and David H. Rind (2009), "How will Earth's surface temperature change in future decades?", *Geophysical Research Letters* **36**, L15708

Results- Temperature



# of indepenent models used

Low CO_2 emission

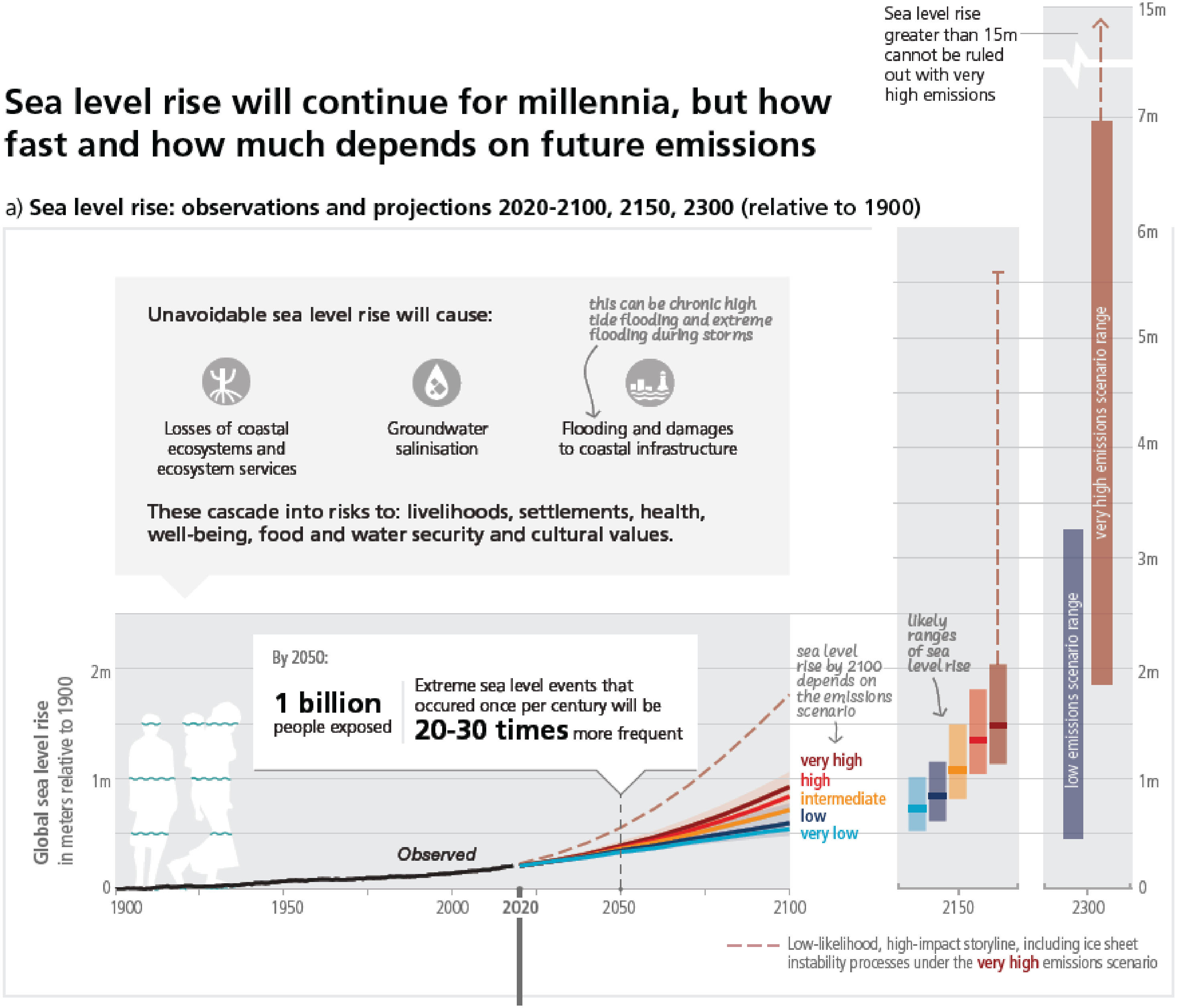
Vs

High CO_2 emissions

Whether models agree

Taken from IPCC report (AR6, Chapter 4)

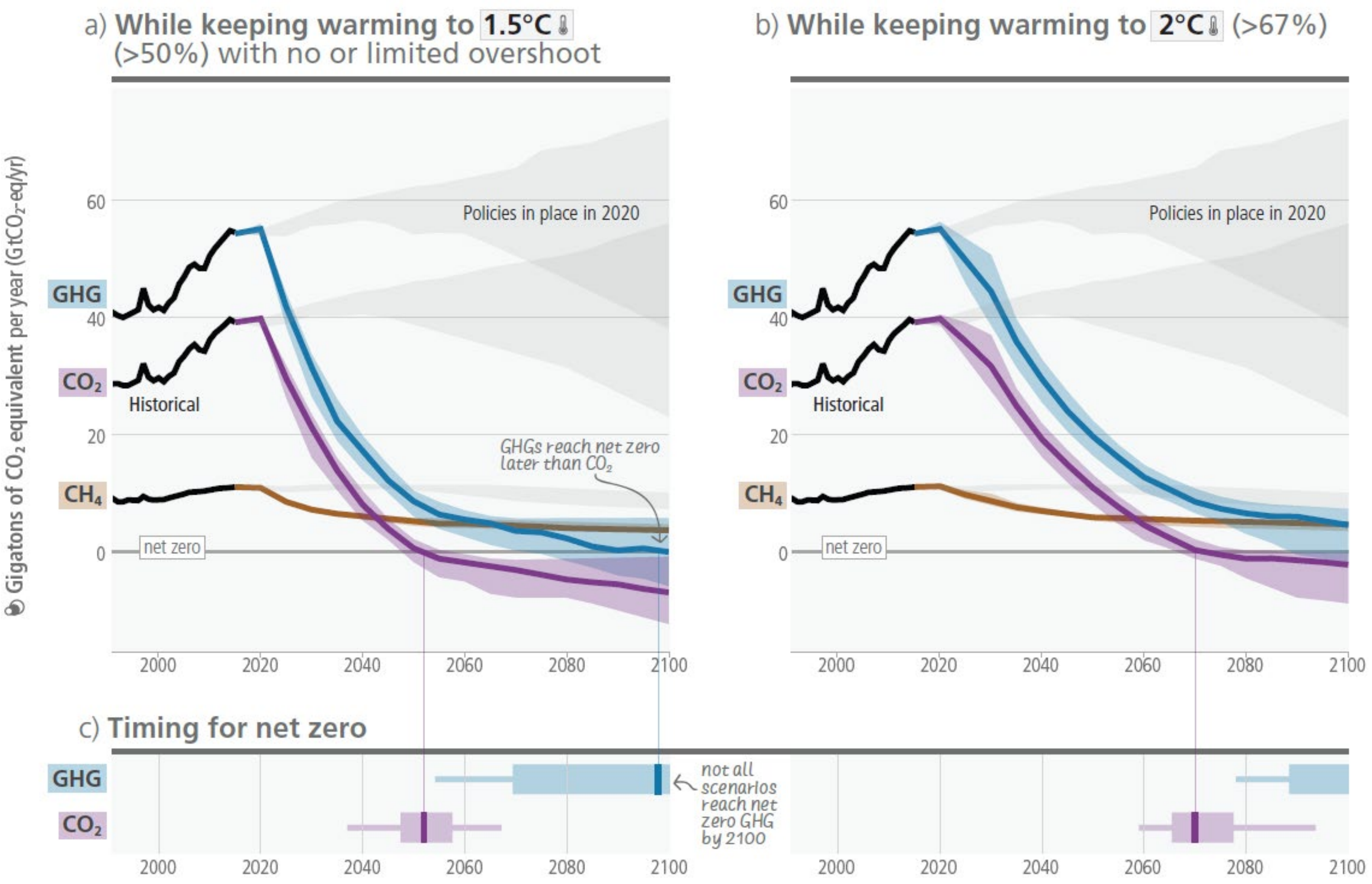
Sea levels- A delayed effect



Taken from IPCC report (AR6)

CO_2 reduction

- Models now suggest we need to go negative CO_2 in the future.



Lecture - Learning objectives

At the end of this lecture you should understand:

- The overall energy landscape
- The function of fossil fuels and all their applications
- CO_2's effect on the ocean
- Why a molecule is a greenhouse gas
- Climate modeling basics

Exercises

- What is the emissions (g CO_2/kWh) of ethanol using the bond energies of the atoms? (This is a very close, but not a perfect approximation)

- Currently CO2 only gets absorbed into the surface waters. Assume this is 1% of the total water in the oceans. Lets say we managed to inject CO_2 into the oceans to give the same pH at the surface as deeper in the ocean (Assume the surface has a pH of 8.1 and deep water has a pH of 7.6). How much CO_2 can we store in the ocean? Rather than give an answer is tons of carbon, give your answer in years operating at 18 TW operating on pure fossil fuels (use natural gas for energy/g CO2 emission)

- Find acetonitrile’s absorption spectra and determine which type of vibrations will be within the range at which Earth emits. Compare this to formaldehyde to get an indication of how absorption works and how it relates to greeenhouse gases. (Don’t worry about what formaldehyde vibrations are)