Physics for Sustainabilty Energy

Course Responsible

Brian Seger: brse@fysik.dtu.dk

Gaston Larrazabal: gaoll@fysik.dtu.dk

What this course is about

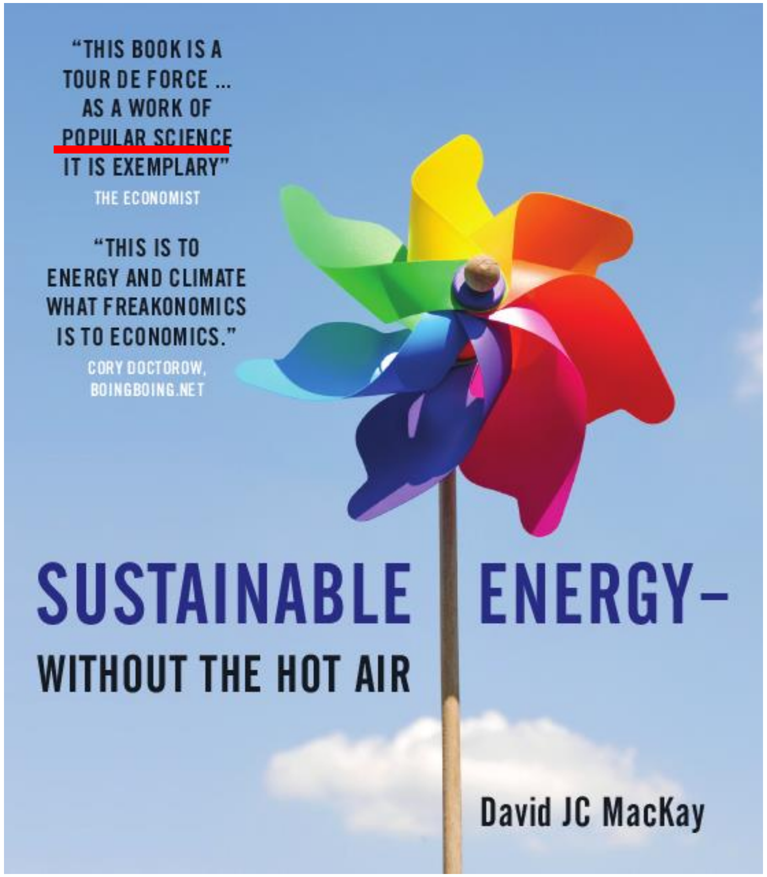
- Explaining sustainable energy technologies using physics principles.
  - Producing power from renewable energy sources
  - Converting and storing energy from renewable energy sources
  - Understanding the climate (i.e. why is sustainable energy important)
- There will be a very small amount of chemistry, economics, biology, and geology.
- This class will cover a broad variety of topics with quite varying physics.

Learning objectives

- Describe the possible sources of sustainable energy and analyze the amount of energy available in them
- Describe the climate models and identify the assumptions behind
- Explain the principles behind different energy harvesting methods
- Describe different methods for energy storage and conversion and explain the principles behind them
- Estimate and calculate the limitations of e.g. storage capacity and energy conversion efficiency based on physical principles
- Critically read, understand and analyze current literature to a level where you can evaluate its findings
- Take a project related to sustainable energy and determine the relevant data for the analysis and present this to the class.
- Analyze the link between different energy harvesting and storage methods. The student should be able to determine in which situations different methods are working together and in which situations they are competitive

Text Books

Big Picture - Motivation



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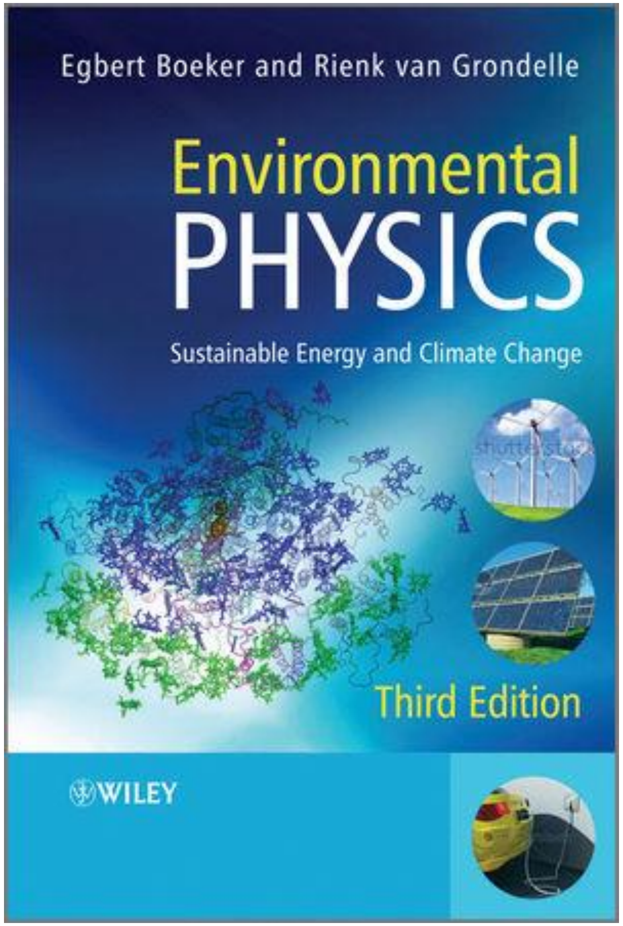
Real Physics



Also I will have detailed notes on solar cells and electrochemistry

Syllabus

Week	Topic	Lecturer
4-9	Introduction	Brian Seger
11-9	Solar spectrum and basic climate effects	Brian Seger
18-9	Solar Cells	Brian Seger
25-9	Solar Cells	Brian Seger
2-10	Wind Power	Brian Seger
9-10	Electrochemistry & Batteries	Gaston Larrazabal
16-10	Break Week	
23-10	Fuel Cells	Gaston Larrazabal
30-10	Electrolysis	Gaston Larrazabal
6-11	Sustainable Chemicals Transformation	Gaston Larrazabal
13-11	Photoelectrolyzers & Photosynthesis	Brian Seger
20-11	Heat Engines	Gaston Larrazabal
27-11	Nuclear Power	Vaulkner Naulin & Bent Lauritzen
04-12	Course Review	Brian & Gaston

Oral presentation

- Everyone will be part of a group (2-3 people/group) that presents a subject based on sustainability.
  - The topics are listed in the syllabus
  - Next week we will decide who chooses what topic.

- The week before the presentation, come to Brian to have a short 5 minute discussion about the topic.
  - The day of the presentation, you should also have a 1 page summary with 1-2 figures and 2-5 references.

- You will be directly assessed on your presentation, and parts of presentations may be on the final. The presentation will only be a small percentage of your 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/Excercise
- Green slide – Important / Review slide
- Grey slide- Not presented in main lecture.

Lecture - Learning objectives

At the end of this lecture you should understand:

- What fuels we currently use, how much of we use, how we use it, and how much is left.
- How population and economics are related to energy.
- How much CO_2 we are contributing to the atmosphere.
- What are the major sustainable energy approaches and storage mediums.

Sustainable Energy

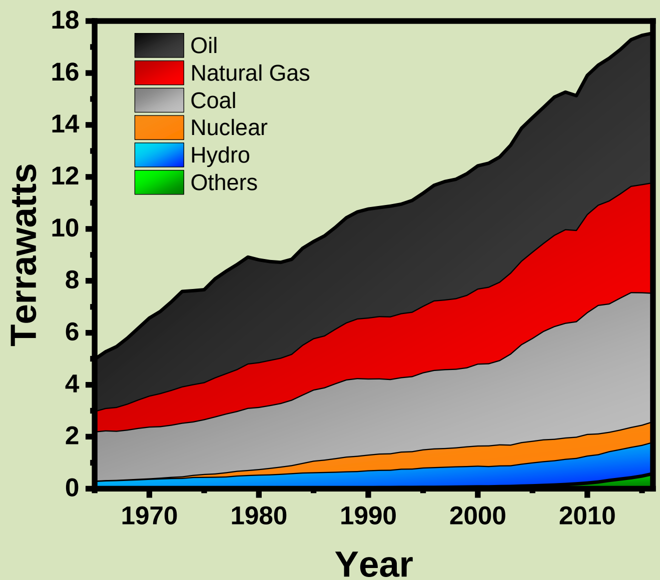
- The world is so integrated, we must look at sustainability on a global scale.
- There are many things that need to be sustainable
  - Fresh water
  - Ecosystems
  - Population
  - **Climate**
  - **Energy**
- We can’t solve the problem unless we know what it is.
- How much energy do we use, what do we use, and why isn’t it sustainable.

Worldwide Energy Data

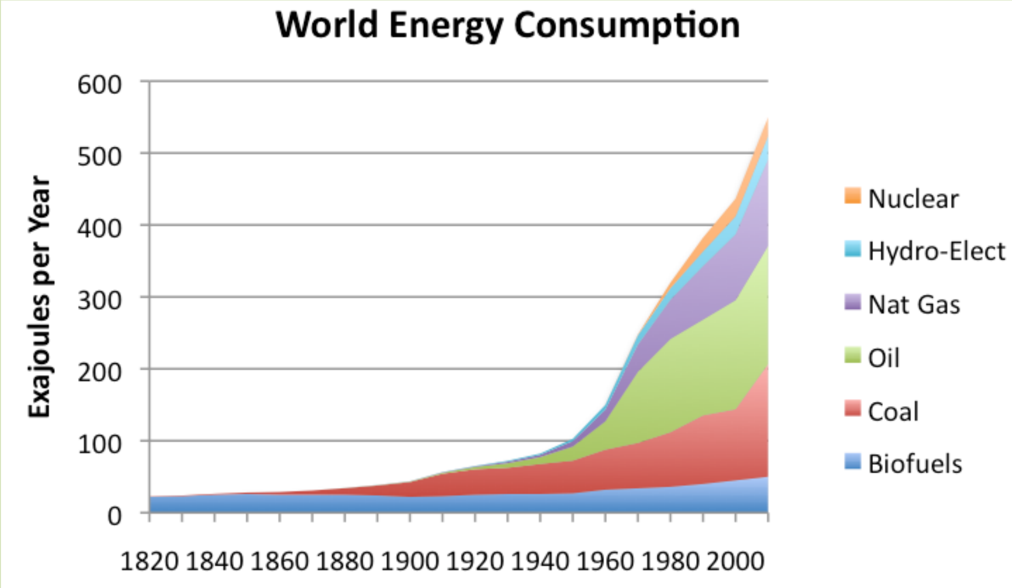
- If we want society to run completely on renewable energy sources we need to know the world energy makeup.
- There are 2 dominant and very similar reports that denote the world energy make-up.
  - International Energy Agency- They have a free annual report called World Energy Outlook. They split it up into US and International. IEA also has a new web-interface for energy that is useful.
  - BP's Annual Energy Report - Also a free annual energy report. Very surprisingly, this is not biased towards the oil industry.
- These sources are excellent at collecting previous year's energy information, but bad at predictions.
- The world bank also has energy data as well as the Energy Information Agency (US Data only).
- Shell is now also producing an Energy Transition Report.

Energy Consumption

- In 2018, we used 18.6 Terrawatts with only 0.75 TW being renewables (2.5 TW if biomass included).
- Figures can be deceiving. On the left it seems we have linear growth, while the right shows exponential growth.
- Oil, coal, and natural gas all are increasing at significant rates.



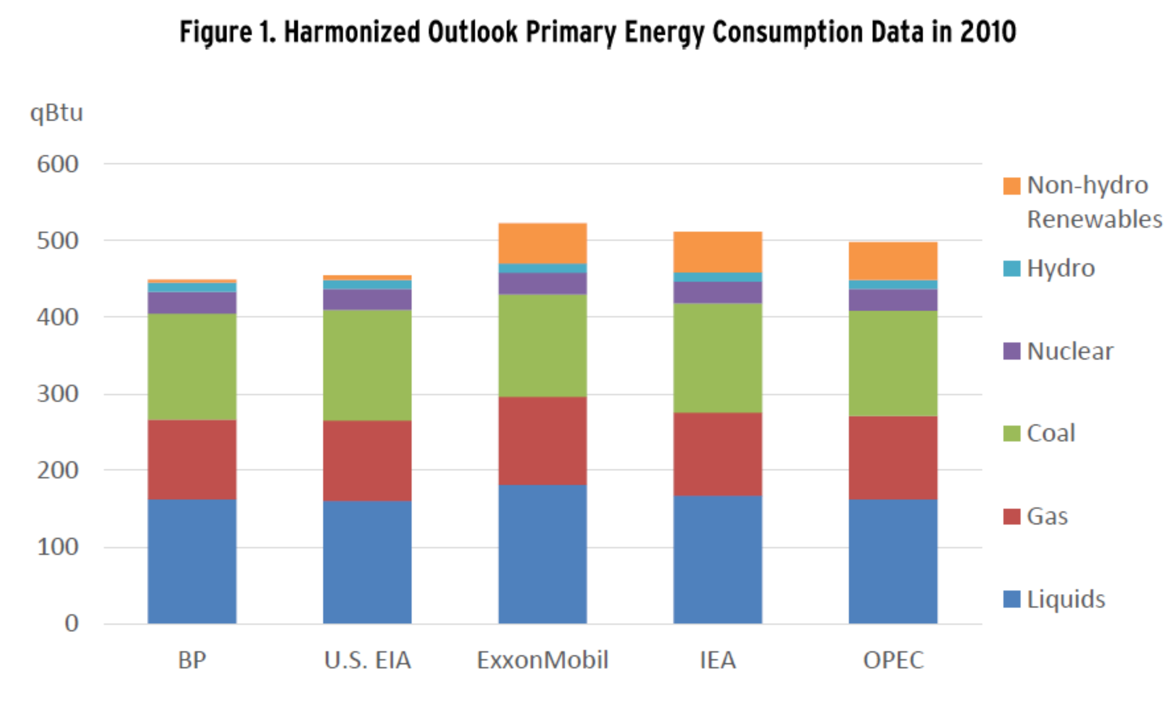
From BP Energy report 2018



From finiteworld.com

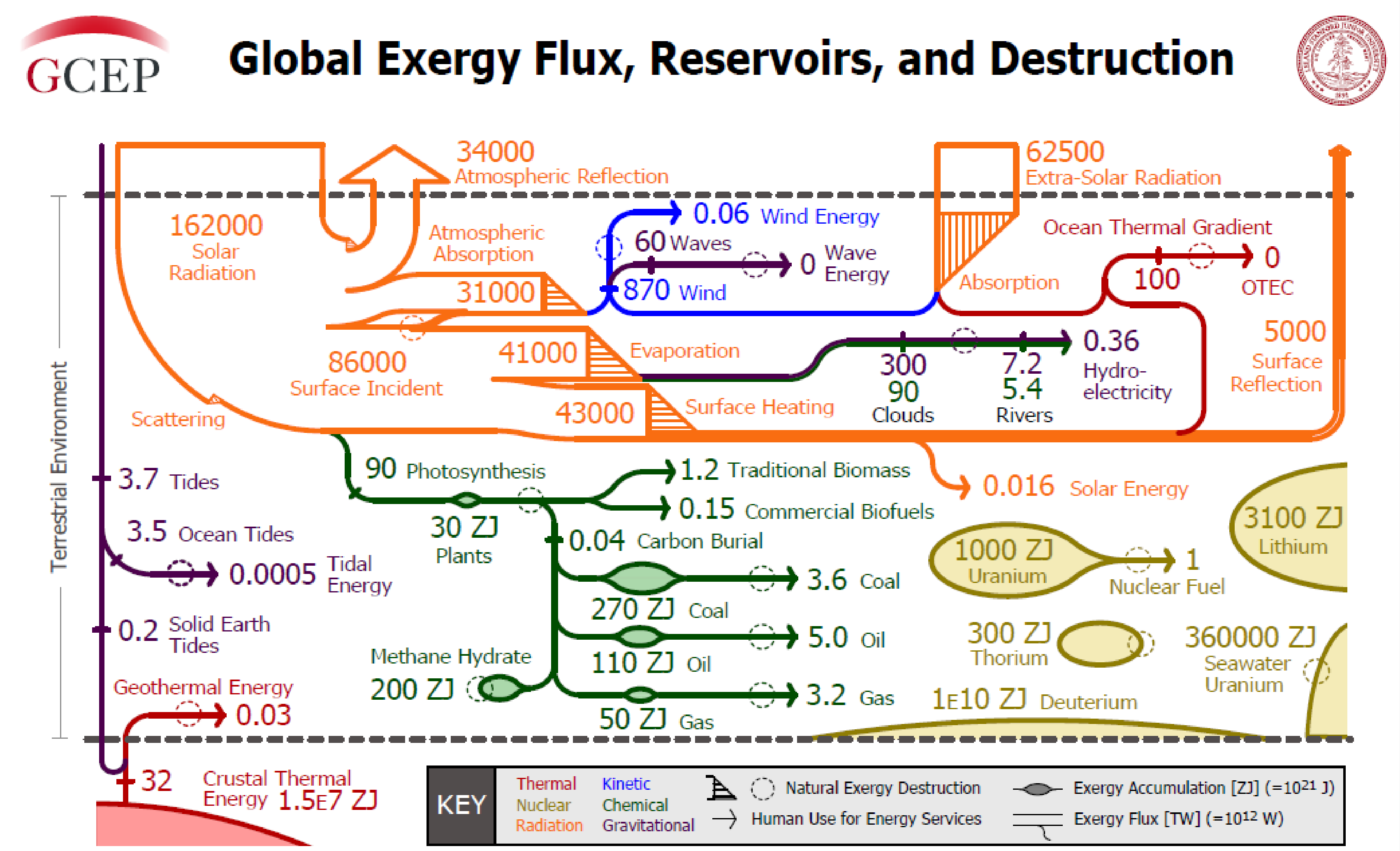
Worldwide Energy Data

- While there are variations on energy data, in general the different sources provide basically the same results.
- The one are of differentiation is non-hydro renewables resources. This includes biomass from 3rd world countries, which is difficult to estimate.



Note: IEA, ExxonMobil and OPEC include non-marketed renewables, whereas BP and the U.S. EIA do not.

This chart says it all



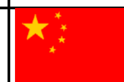
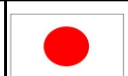
Exergy is the useful portion of energy that allows us to do work and perform energy services. We gather exergy from energy-carrying substances in the natural world we call energy resources. While energy is conserved, the exergetic portion can be destroyed when it undergoes an energy conversion. This diagram summarizes the exergy reservoirs and flows in our sphere of influence including their interconnections, conversions, and eventual natural or anthropogenic destruction. Because the choice of energy resource and the method of resource utilization have environmental consequences, knowing the full range of energy options available to our growing world population and economy may assist in efforts to decouple energy use from environmental damage.

Prepared by Wes Hermann and A.J. Simon
Global Climate and Energy Project at Stanford University (http://gcep.stanford.edu)

Herman, Energy, 2006

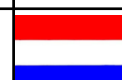
Largest companies in the world (2019)

- 8 of the top 10 biggest companies in the world relate to energy.

Rank	Company	Country	Industry	Revenue (B$)
1	Wal-Mart Stores, Inc		Retail	$500
2	State Grid Corporation of China		Electric utility	$349
3	Sinopec		Oil and gas	$327
4	China National Petroleum Corporation		Oil and gas	$327
5	Royal Dutch Shell		Oil and gas	$312
6	Toyota		Automotive	$265
7	Volkswagon		Automotive	$260
8	BP		Oil and gas	$245
9	Exxon Mobil		Oil and gas	$244
10	Berkshire Hathaway		Investments	$242

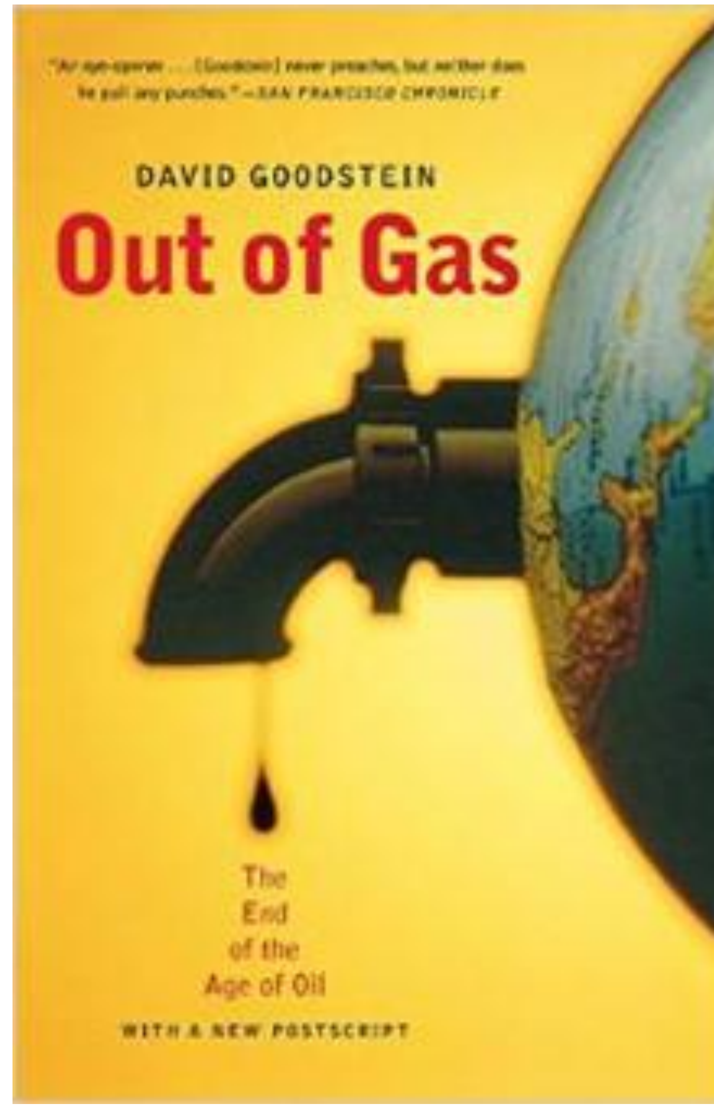
Largest companies in the world (2016)

- There is significant change in the top 10. This means serious money is gained/lost in the energy field.

Rank	Company	Country	Industry	Revenue
1	Wal-Mart Stores, Inc		Retail	$482
2	Sinopec		Oil and gas	$455
3	China National Petroleum Corporation		Oil and gas	$428
4	Saudi Aramco		Oil and gas	$338
5	State Grid Corporation of China		Electric utility	$333
6	Samsung Group		Conglomerate	$305
7	Royal Dutch Shell		Oil and gas	$273
8	ExxonMobil		Oil and gas	$268
9	Vitol		Commodities	$270
10	Kuwait Petroleum Corporation		Oil and Gas	252

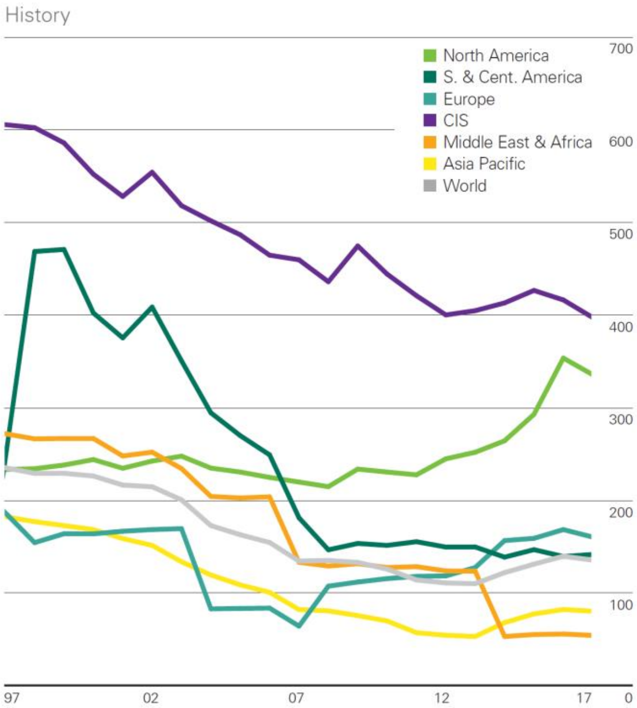
What is Sustaianble Energy ?

- Sustainability in regards to:
  - Replacing fossil fuels
  - Sustainable climate
- How much energy are we using?
  - In total
  - Coal, Oil, Natural Gas, Others
- How much do we have:
  - Remaining (non-renewables)
  - Potential for (renewables)



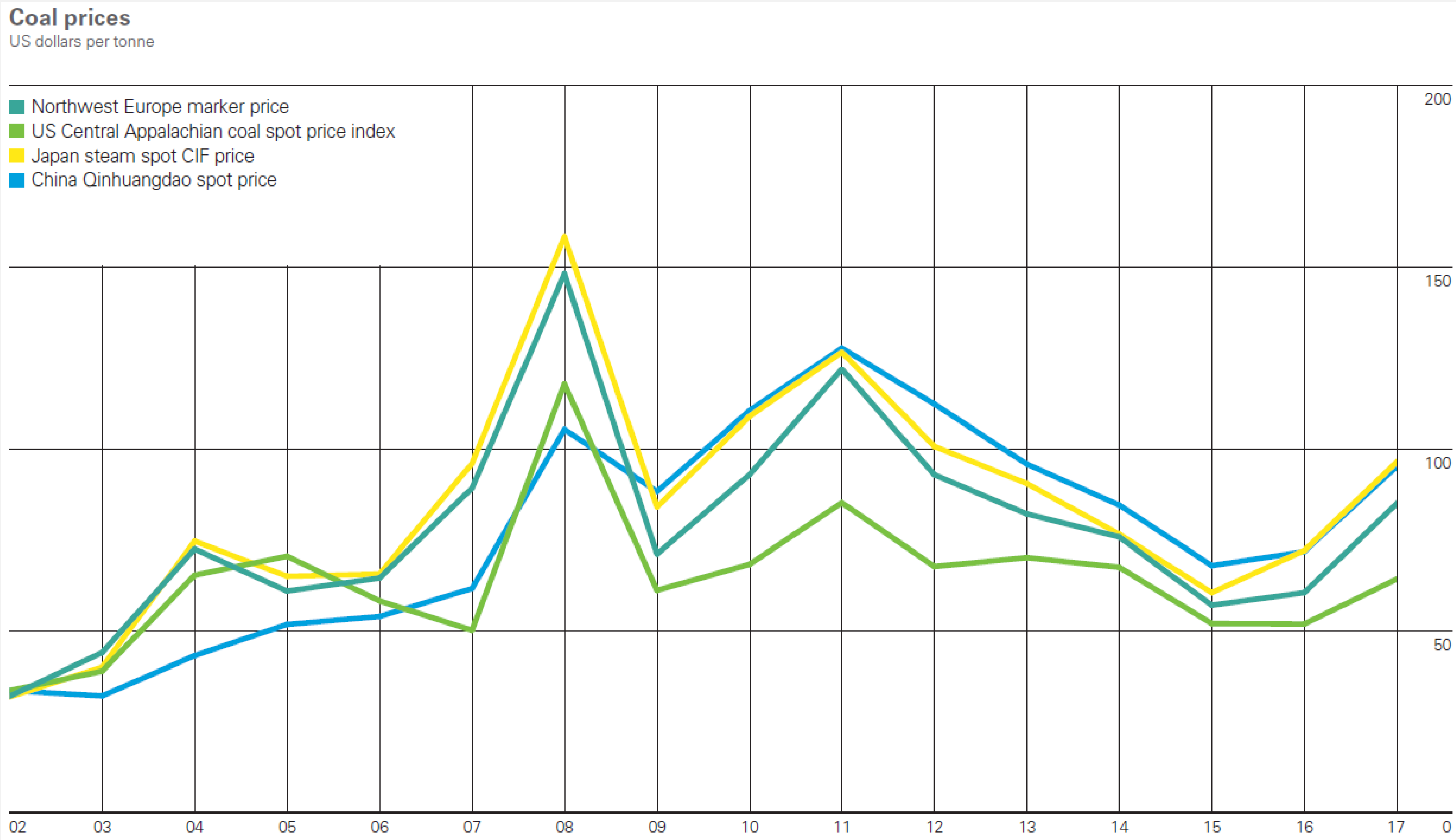
Coal

- Coal has been used since the invention of the steam engine in 1700.
- Coal's main use is for burning for electrical production.
- In theory we have 100 years worth of coal (assuming we don't increase production.)



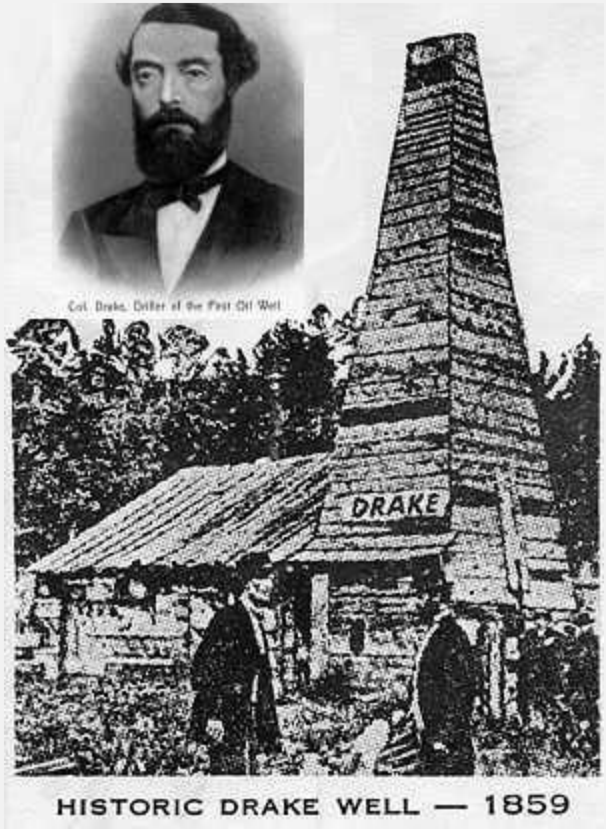
Coal Reserves to Production ratio

Historical Coal Prices



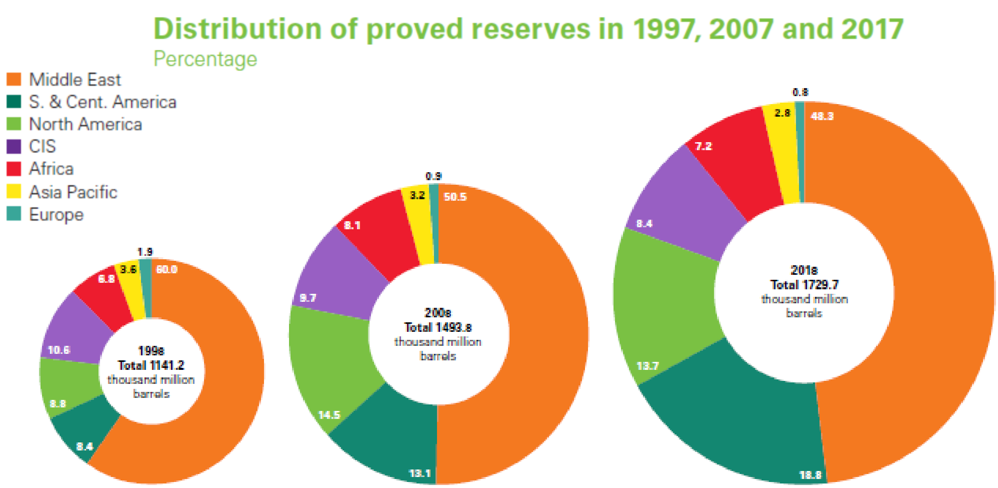
Oil

- Edwin Drake started mass production in 1859.
- Oil is probably the most flexible-useful of all the fossil fuels because it can be used in transport, electricity, and heating.
- Oil also provides the raw precursors for the chemicals industry.

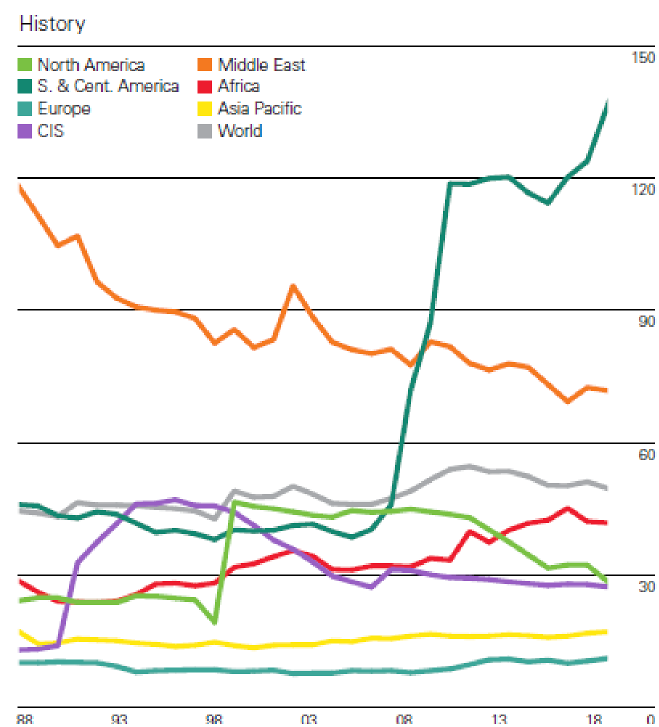


Oil

- Interestingly oil's reserve to production ratio has stayed constant for ~30 years.
- The boost in S. American oil was due to off-shore oil discovered in Brazil.
- Great book by Daniel Yerstin entitled 'The Prize'.



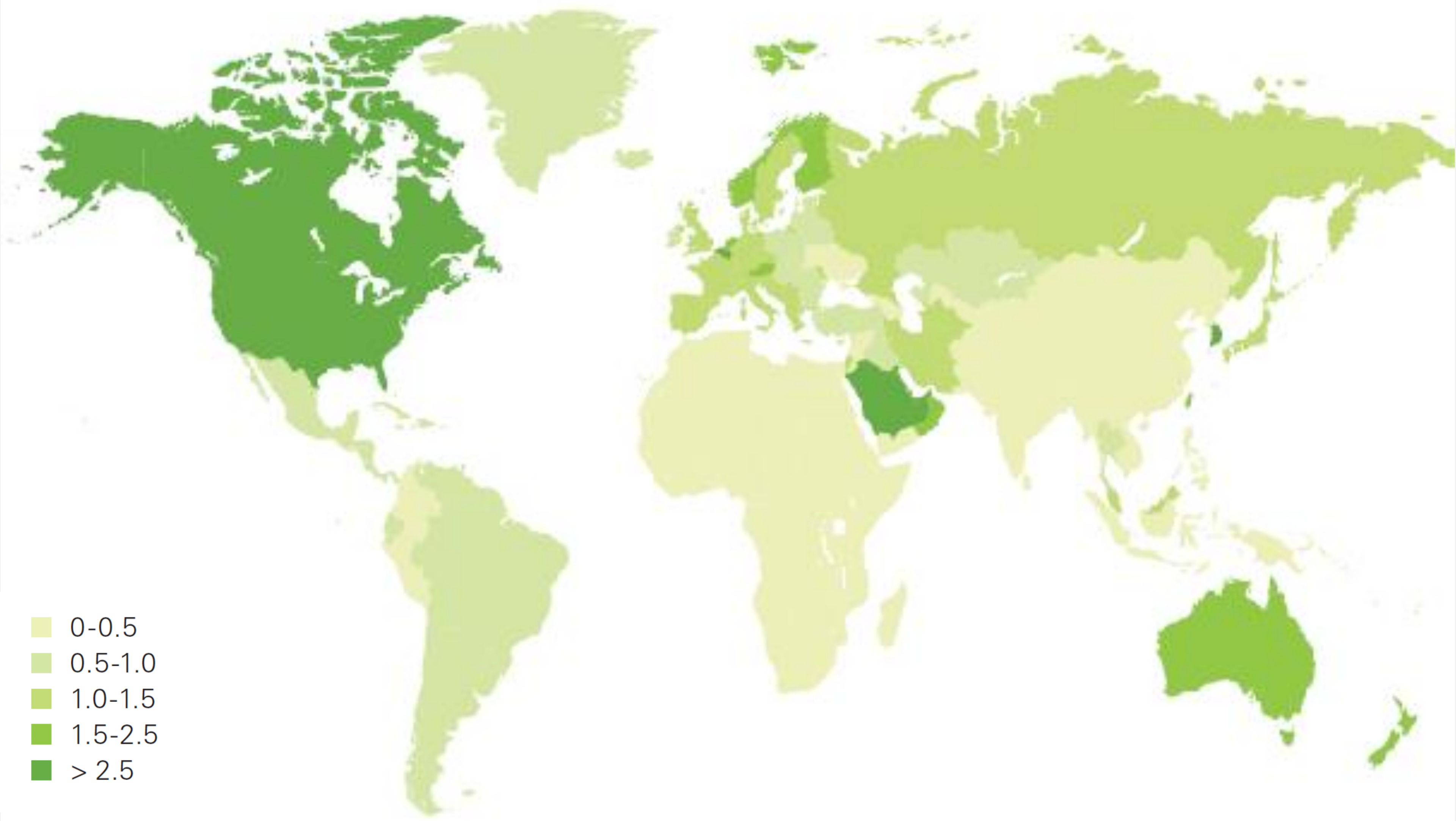
Absolute oil reserves



Oil Reserves to Production ratio

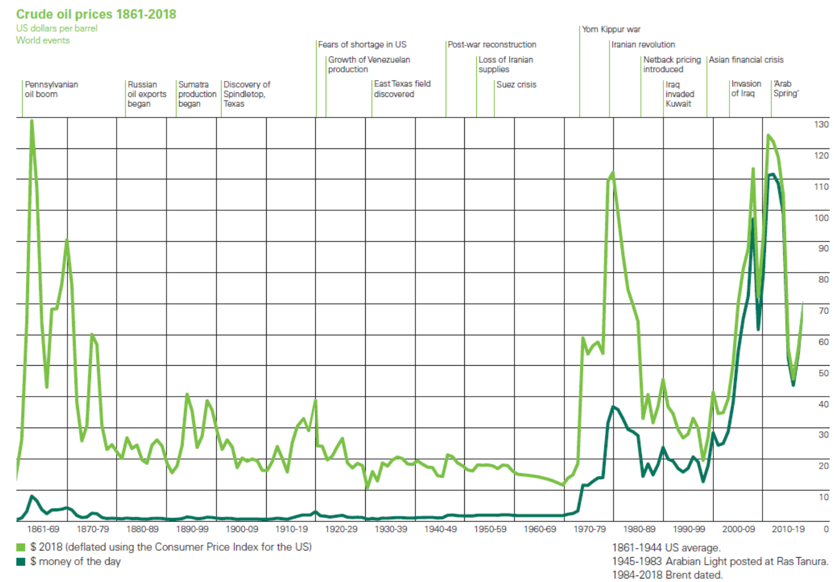
Oil: Consumption per capita 2018

Tonnes



Oil

- While oil consumption is fairly consistent, oil prices are extremely erratic.

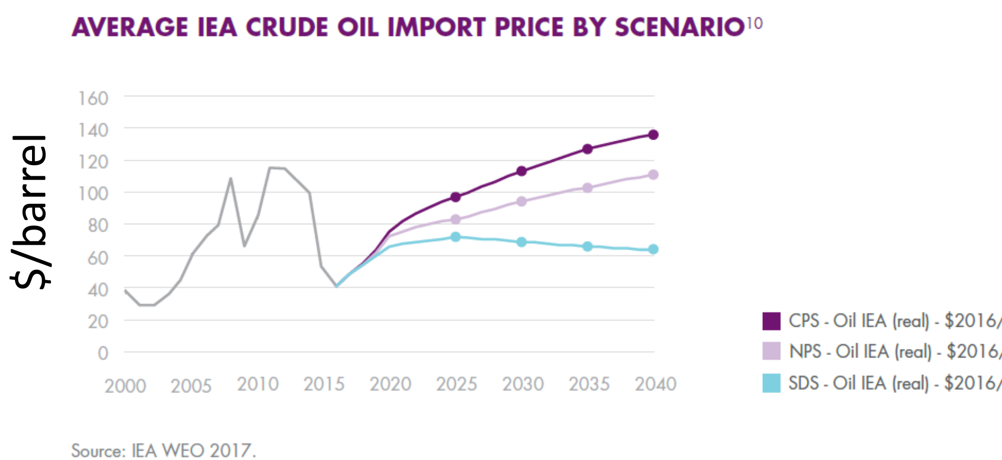


2019 BP Statistical Review of World

- Much of this has to do with inconsistent supply (or fear of that).

- This is what makes predicting oil prices difficult.

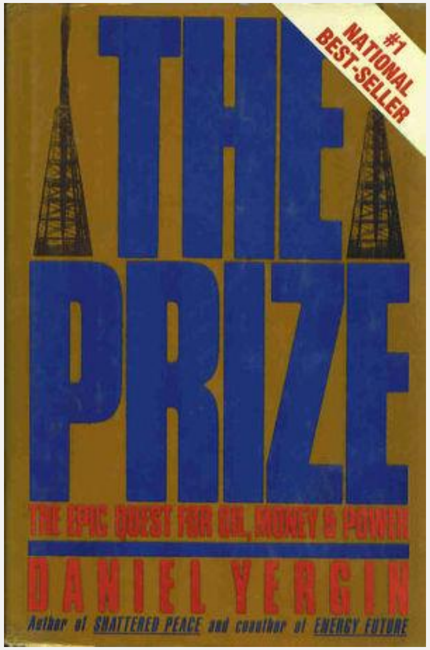
- Nevertheless companies like Shell still try.

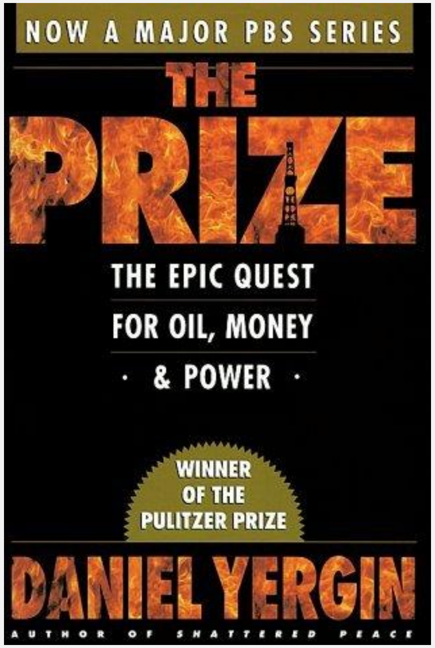


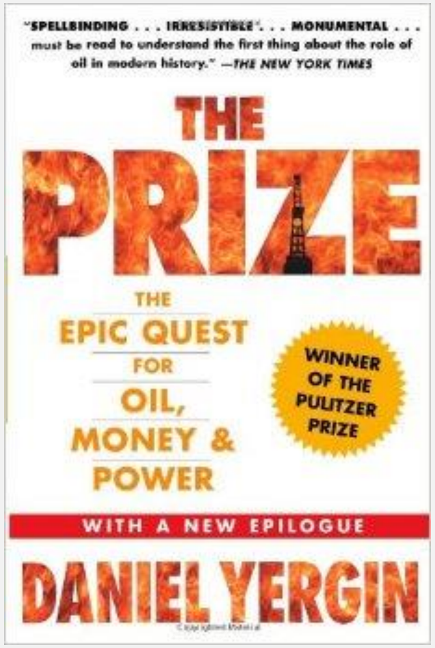
2018 Shell Transition Energy Report

Oil- Further Interest

- Daniel Yerstin basically wrote the history/biography on oil called " The Prize".
- It explains oil in a very straightforward, truthful manner.
- It won a Pulitzer Prize award in 1992.



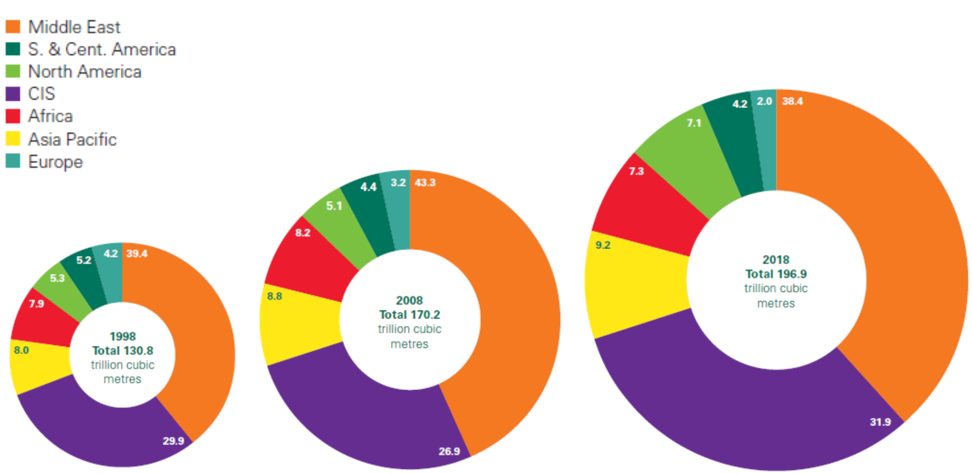


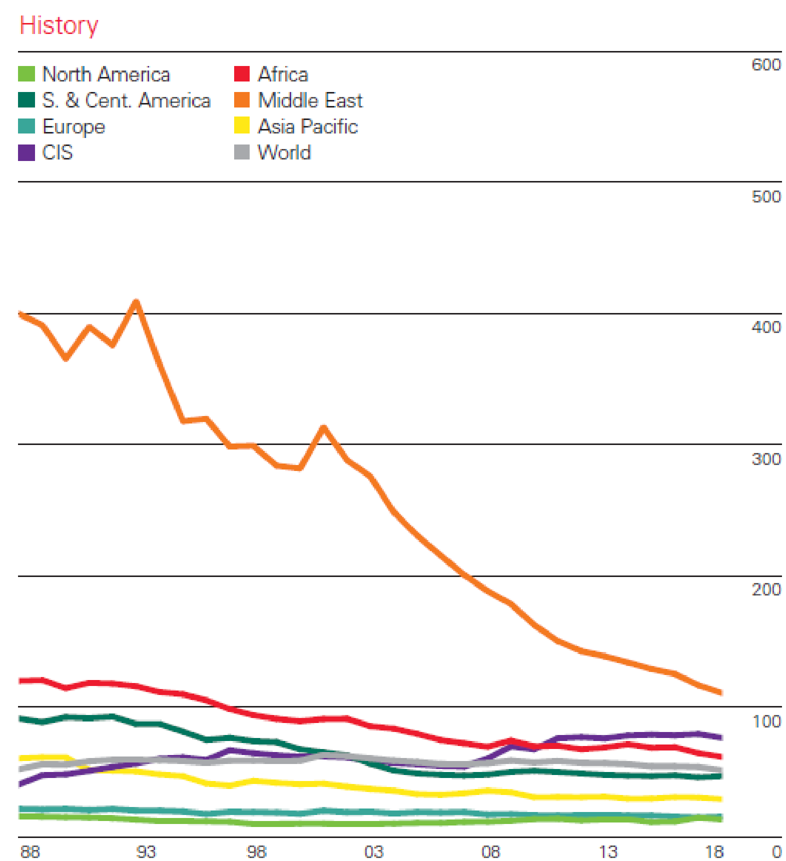


Same book, different covers

Natural Gas

- Natural gas was typically thought of a less-useful byproduct associated with oil drilling and oil wells.
- Recently it has found to be quite useful especially for heating and to a lesser extent in electrical generation.
- Natural gas reserves to production have remained constant for the last 30 years.





Natural Gas Reserves to Production ratio

Oil and Gas Wells

- In a typical oil or gas well the amount extracted due to internal well pressure is only 5-15%.
- By pressuring the well you can get up to 35-45%.
- Nevertheless 55% of most oil is never extracted.
- An initiative by the Mærsk and the North Sea oil producers ise investing 1 Billion kroner at DTU over 10 years (started in 2015) with the hopes of increasing extraction efficiency 1-2%.
- There are some new techniques that are being used to either increase production or find new oil
  - Off-shore drilling
  - Horizontal drilling
  - Fracking

Fracking

- Fracking basically is a technique that puts high pressure in an old well and cracks the rock, and uses sand to keep the cracks open
- This has been done since the 1970’s albeit at low pressures
- When the pressure is released the sand keeps the cracks open allowing more oil to come out.
- In 2010 a movie came out called ‘Gasland’ showing fracking basically led to gas seeping into people’s water supply.
  - This movie was nominated for an Academy Award, and greatly hurt the fracking industry.
  - The fracking industry came out with their own movie called ‘Truthland’ saying how ‘Gasland’ was completely wrong.
  - Some other documentarists didn’t like ‘Gasland’ and also made a rebuttal movie called ‘Fracknation’.
  - ‘Gasland 2’ came out saying ‘Truthland’ was completely wrong.

Fracking- lighting water on fire

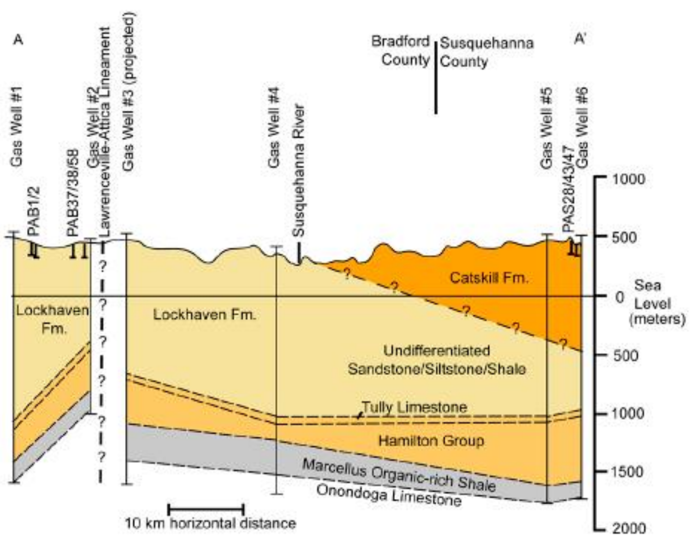
Start video at 1:15 point

https://www.youtube.com/watch?v=4ApZkNsXfJE&t=75s

Fracking

- Scientists came to straighten things out.
- A group led by Robert Jackson published paper explaining the fundamental geophysics behind this.

- They showed that gas could not diffuse through 1000's of meters of soil.
- **This is why you don't let the movie industry try to do science.**



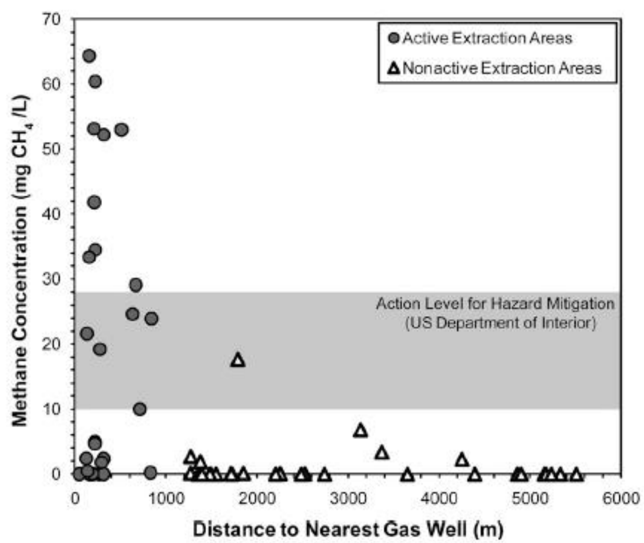
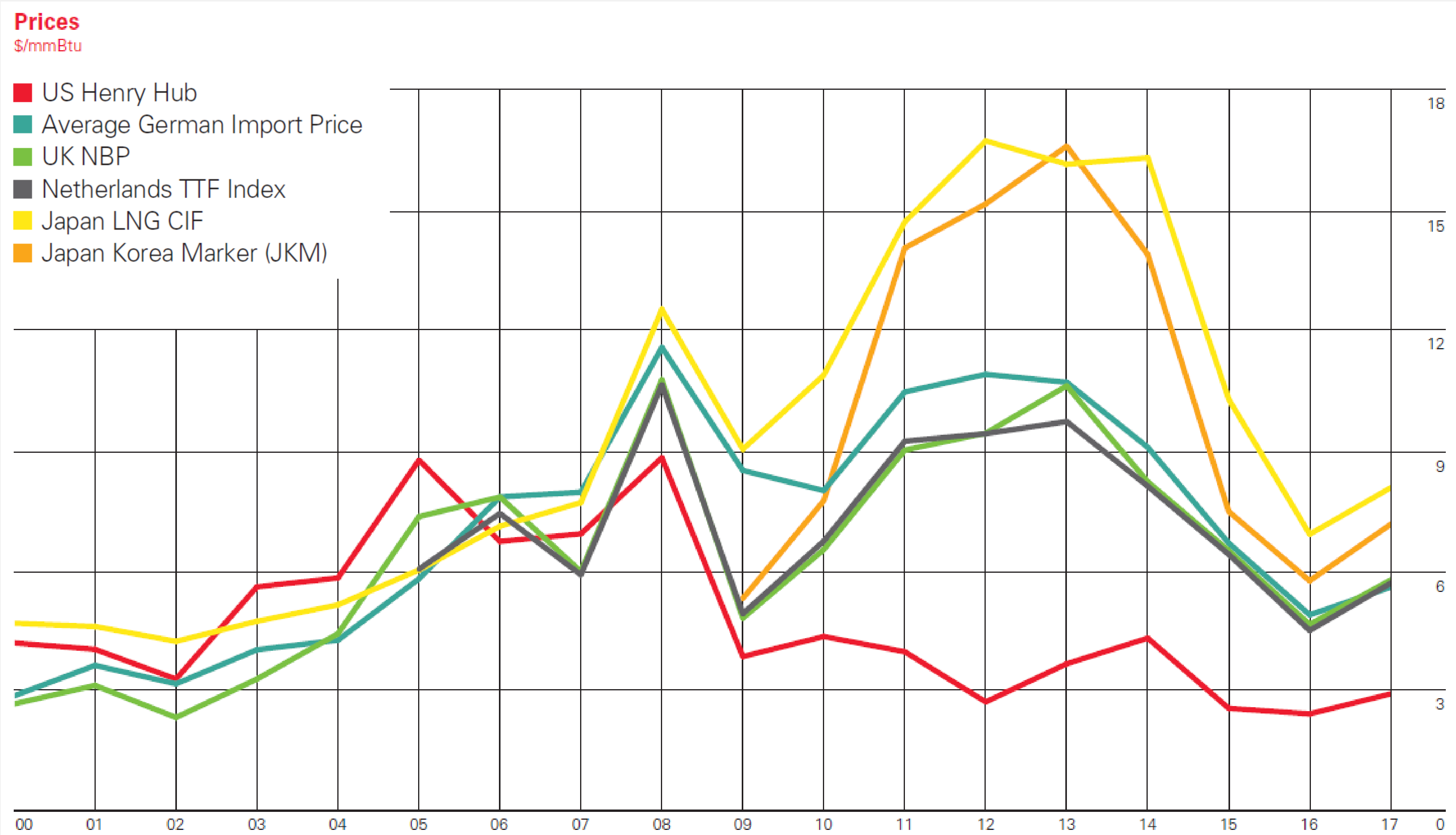


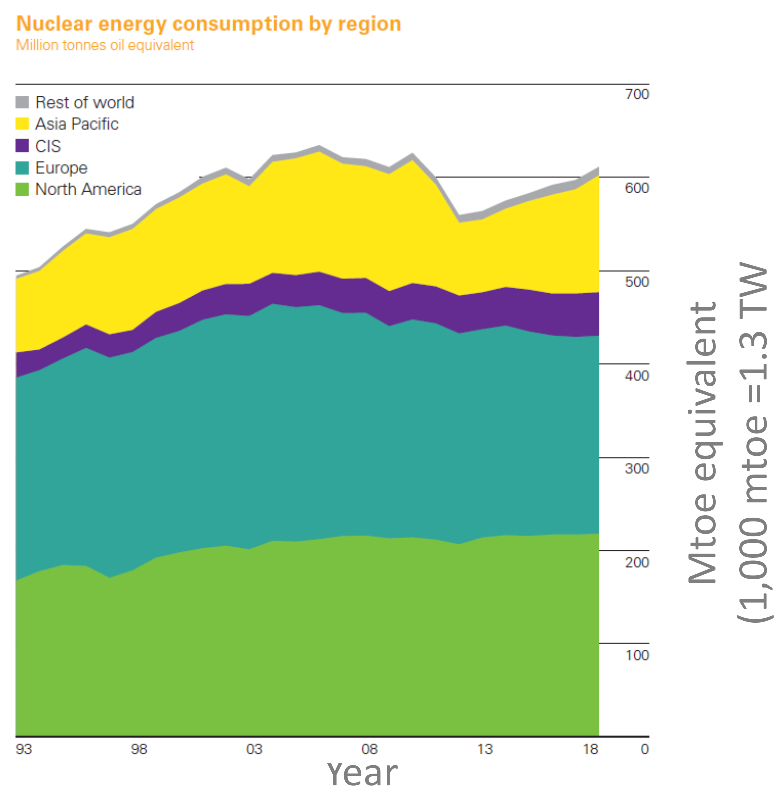
Figure 2 and Figure 3 from Osborn et al., 2011, PNAS

Economic Advantage of Fracking ?



Nuclear

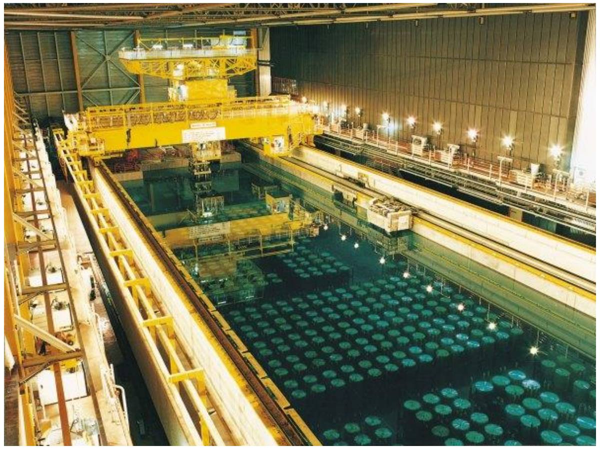
- There are 2 types of nuclear- fusion and fission with only fission giving useful power currently.
- In theory this is non-renewable resource because we use an isotope of Uranium and this is limited.
- We have ~200 TW-years left of Uranium.
- Nuclear waste is still an unresolved issue.
- Breeder reactors have the possibility to extend Uranium lifetime, but are expensive.



World's nuclear power

The Dark Side of Nuclear

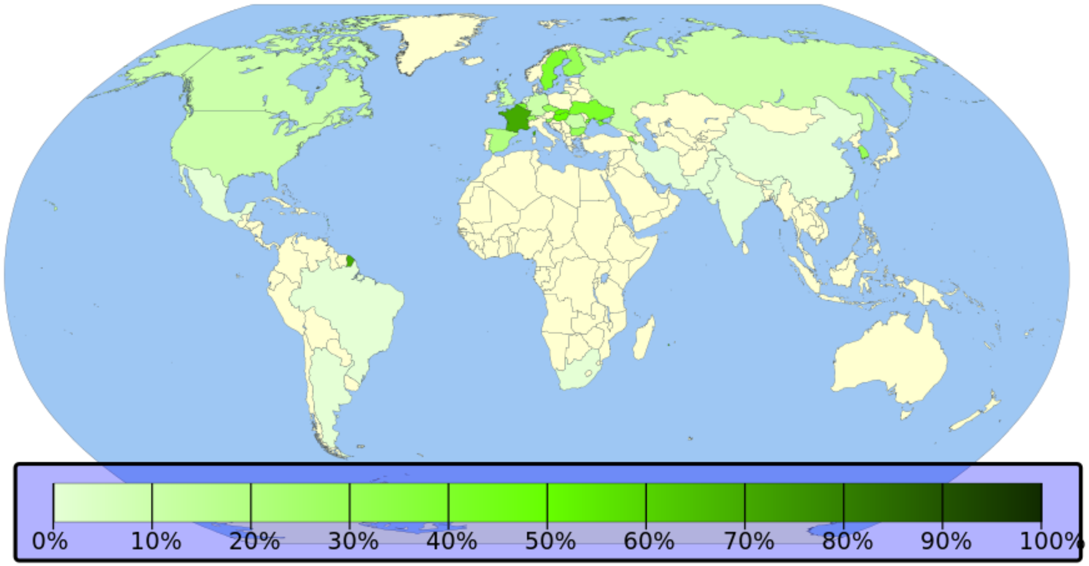
- Nuclear weapons are a constant threat, and advances in knowledge, communication, transport, etc. make this easier to acquire.
- Plutonium is a by product of nuclear fission and is 3 times as energetic as uranium.
- 2 tennis balls of plutonium is enough for an atomic bomb.
- Waste issues are currently unresolved.



Storage pond for used fuel at the Thermal Oxide Reprocessing Plant (Thorp) at the UK's Sellafield site (Sellafield Ltd).

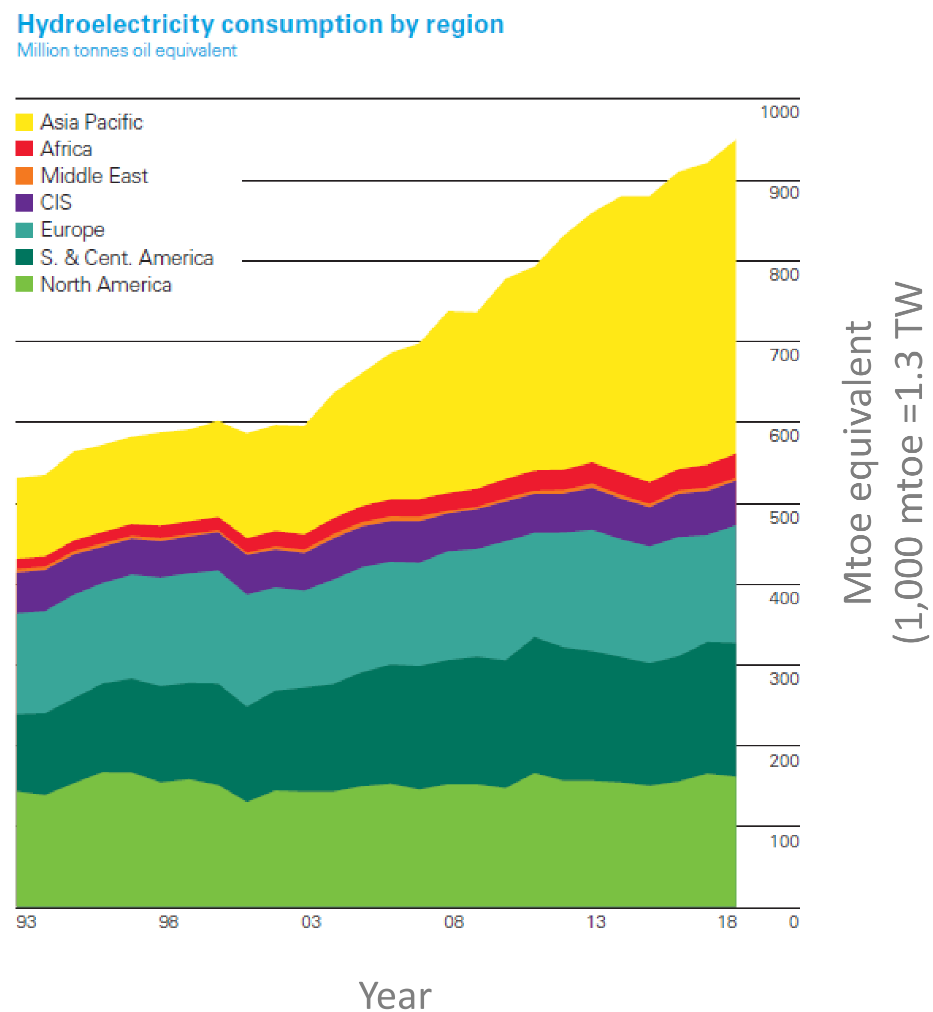
Nuclear

- France is by far the largest country invested in nuclear with 75% of it's electricity coming from nuclear.
- To meet 18 TW we would roughly have to build 440 new plants/year **forever** (assuming plant lifetime of 40 years).
- Currently there are only about 450 nuclear plants online.
- After the Fujishima accident IEA's prediction for new nuclear plants dropped by 50%.
- We will have 1 lecture on nuclear power.



Renewables- Present Day

- Hydropower is by far the largest producer of renewable energy.
- This is really simple, so we have been doing this for a long time.
- This energy source is good at meeting fluctuations in demand.
- 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.

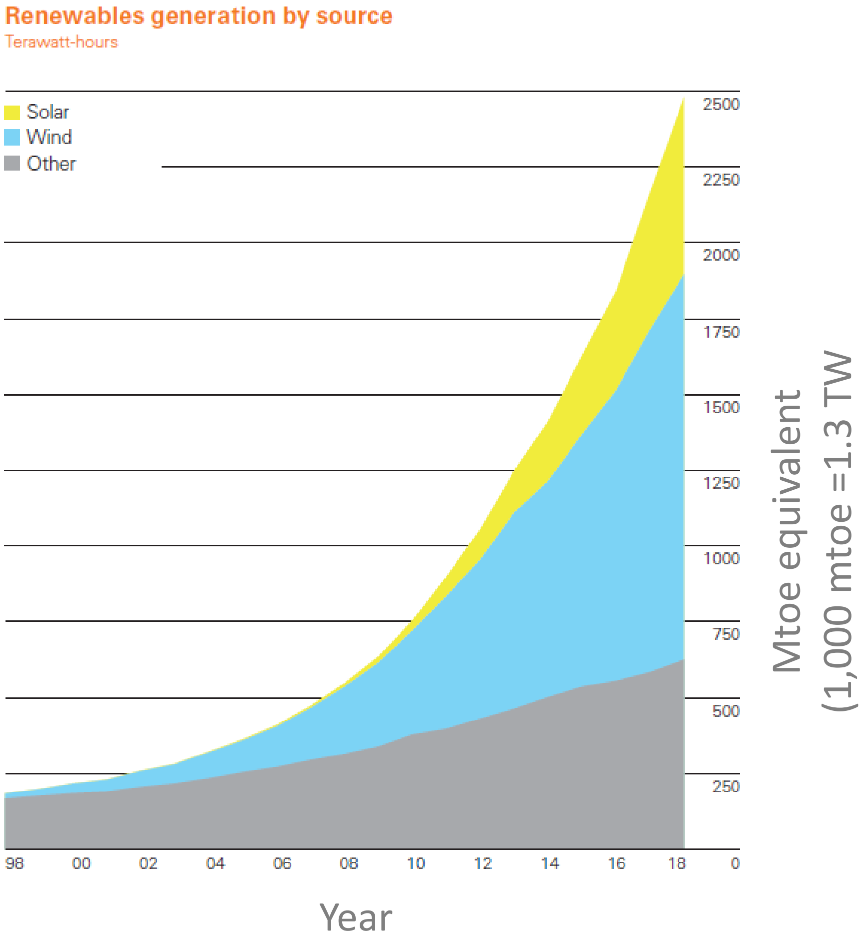


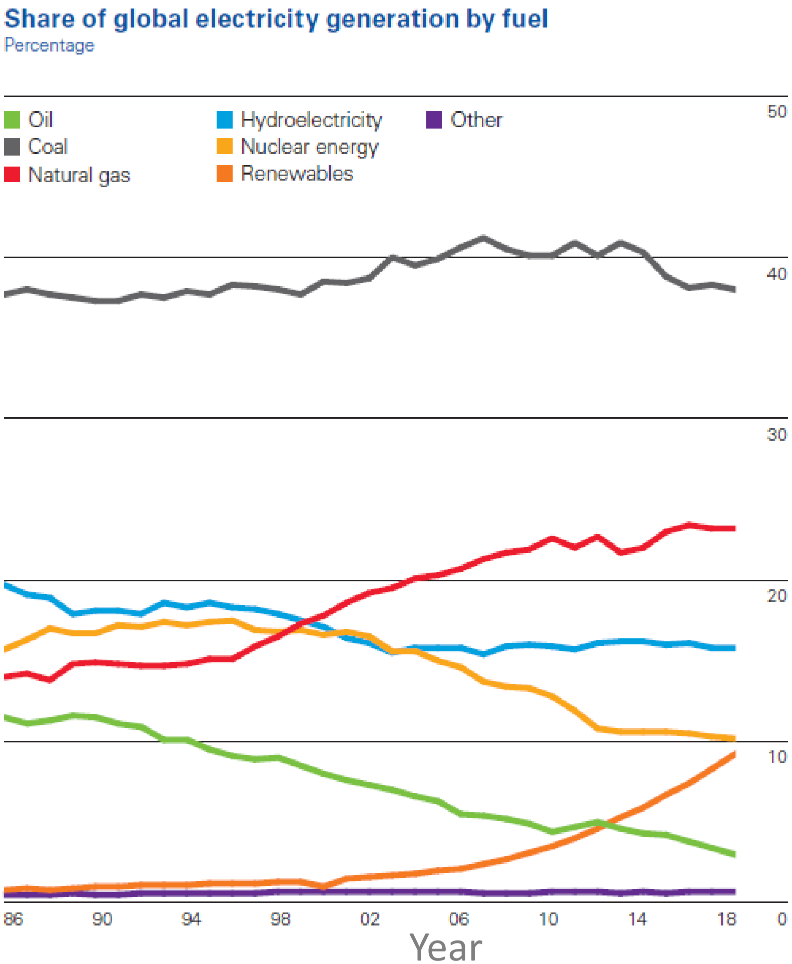
Renewables- Present Day

- Some countries can get almost all their electricity from hydropower.
- 3 Gorges dam in China is the largest in the world.

Country	Annual hydroelectric production (GW)	% of total electrical capacity
China	126	22
Canada	43	61
Brazil	41	85
United States	28	5.7
Russia	19	18
Norway	16	98
India	14	16
Japan	9.8	69
Sweden	8.6	7.2
Venezuela	8.4	44

Renewables- Present Day



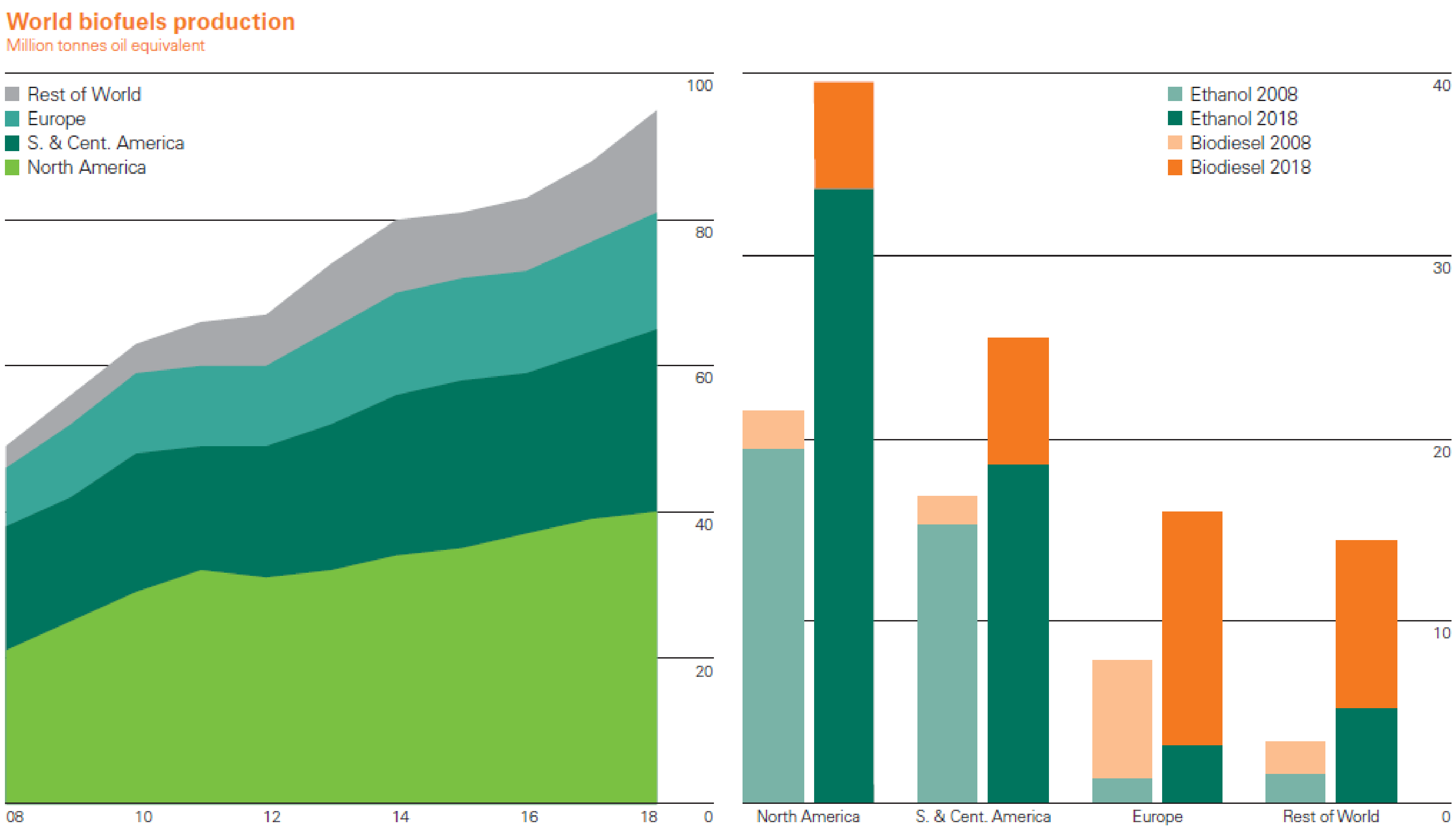


Renewables consumption*

Million tonnes oil equivalent	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	**2018**	Growth rate per annum 2018	Growth rate per annum 2007-17	Share 2018
US	29.7	33.9	39.3	45.7	51.7	60.2	67.2	71.5	83.1	94.5	**103.8**	9.8%	14.3%	18.5%
Total Europe	54.1	61.2	71.0	85.9	101.5	114.7	123.8	141.5	144.5	162.3	**172.2**	6.1%	13.1%	30.7%

Renewables- Present Day

- Corn and Sugarcane are the reasons the Americas have so much Biomass



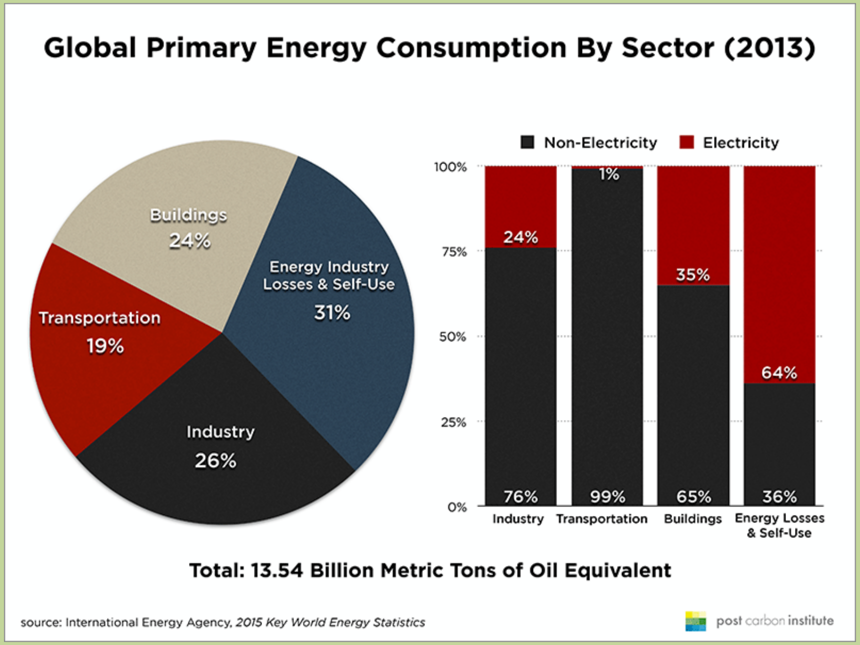
Carbon dioxide emissions

Million tonnes of carbon dioxide	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Growth rate per annum 2018	Growth rate per annum 2007-17	Share 2018
Canada	545.6	502.3	526.7	539.0	523.2	541.9	551.3	544.6	535.9	549.5	**550.3**	0.1%	◆	1.6%
Mexico	431.6	433.0	442.4	465.4	473.7	472.5	459.2	463.0	468.5	476.8	**462.5**	-3.0%	1.1%	1.4%
US	5675.7	5263.9	5465.6	5355.7	5137.0	5260.5	5300.4	5153.7	5053.7	5014.4	**5145.2**	2.6%	-1.5%	15.2%
Total North America	6652.9	6199.2	6434.7	6360.1	6134.0	6274.9	6310.9	6161.2	6058.2	6040.7	**6157.9**	1.9%	-1.2%	18.2%
Argentina	160.2	154.3	166.0	168.8	175.3	182.8	182.8	186.0	185.9	184.1	**180.3**	-2.1%	1.6%	0.5%
Brazil	374.0	351.4	399.4	424.4	443.4	483.4	504.6	487.6	451.0	458.9	**441.8**	-3.7%	2.7%	1.3%
Chile	77.4	74.3	76.1	87.0	89.4	91.1	88.4	88.9	94.1	93.1	**95.8**	2.9%	2.0%	0.3%
Colombia	67.4	65.2	72.6	71.3	79.7	83.5	89.2	89.8	97.9	93.2	**98.1**	5.2%	4.5%	0.3%
Ecuador	27.5	27.9	32.1	32.9	34.3	36.6	38.5	37.6	35.5	34.4	**37.1**	7.9%	2.4%	0.1%
Peru	34.7	34.9	38.6	44.1	43.8	45.1	46.0	49.7	53.2	49.2	**52.3**	6.4%	4.6%	0.2%
Trinidad & Tobago	21.6	20.4	22.5	22.5	21.8	23.2	22.6	22.1	21.6	20.7	**20.7**	-0.1%	-0.4%	0.1%
Venezuela	171.8	172.0	166.4	170.8	181.3	176.0	170.5	163.6	151.4	142.6	**123.7**	-13.2%	-1.4%	0.4%
Other S. & Cent. America	209.7	204.9	208.0	214.0	211.6	209.0	212.7	221.8	230.1	229.4	**236.8**	3.2%	0.7%	0.7%
Total S. & Cent. America	1144.4	1105.3	1181.8	1235.8	1280.7	1330.6	1355.2	1347.3	1320.4	1305.6	**1286.5**	-1.5%	1.7%	3.8%
Austria	69.0	62.9	68.1	62.4	60.4	59.6	56.4	59.4	59.7	62.5	**61.2**	-2.0%	-0.9%	0.2%
Belgium	142.3	129.8	138.4	125.1	120.9	121.8	114.2	121.3	123.2	126.0	**129.6**	2.9%	-1.1%	0.4%
Czech Republic	120.0	113.3	116.3	112.8	109.0	104.8	101.7	102.9	104.9	103.0	**103.2**	0.2%	-1.9%	0.3%
Finland	60.0	57.4	65.5	57.6	51.5	52.9	48.5	44.7	48.2	45.4	**46.6**	2.7%	-3.9%	0.1%
France	371.1	356.3	361.5	334.9	336.3	336.0	302.3	310.5	315.3	321.4	**311.8**	-3.0%	-1.4%	0.9%
Germany	806.5	751.0	780.6	761.0	770.3	794.6	748.4	751.9	766.6	762.6	**725.7**	-4.8%	-0.6%	2.1%
Greece	108.9	104.2	96.0	95.4	89.8	81.3	77.7	75.1	71.9	77.1	**76.2**	-1.2%	-3.9%	0.2%
Hungary	54.4	48.2	48.8	50.3	45.9	43.3	42.3	45.1	45.5	47.9	**47.7**	-0.4%	-1.5%	0.1%
Italy	446.9	404.0	409.8	399.8	386.6	353.6	330.2	343.1	343.6	346.3	**336.3**	-2.9%	-2.8%	1.0%
Netherlands	231.4	222.6	232.4	224.4	217.3	211.7	200.8	209.2	212.7	205.9	**202.7**	-1.6%	-1.3%	0.6%
Norway	35.5	35.5	36.5	36.7	36.5	36.5	35.8	35.8	34.7	35.0	**35.5**	1.4%	-0.3%	0.1%
Poland	319.2	305.0	322.8	322.6	307.2	309.8	292.9	292.9	305.6	315.4	**322.5**	2.3%	-0.1%	1.0%
Portugal	57.7	56.9	51.5	51.4	50.7	49.3	49.3	53.7	53.0	57.8	**54.5**	-5.7%	-0.2%	0.2%
Romania	93.3	79.7	77.5	83.3	80.1	69.2	69.7	70.6	69.3	72.6	**72.0**	-0.9%	-2.7%	0.2%
Spain	352.3	314.4	298.7	308.8	307.2	275.9	273.6	289.2	282.3	299.9	**295.2**	-1.6%	-2.3%	0.9%
Sweden	56.1	53.4	56.7	52.0	49.2	48.0	46.2	46.4	46.7	45.9	**44.8**	-2.4%	-2.5%	0.1%
Switzerland	43.0	43.6	41.3	39.4	40.7	42.8	38.0	38.8	37.4	38.2	**36.6**	-4.0%	-0.5%	0.1%
Turkey	276.9	276.1	278.6	301.5	316.9	305.5	337.5	346.1	366.0	388.5	**389.9**	0.3%	3.6%	1.2%
Ukraine	317.3	271.8	286.9	303.0	296.7	285.7	244.9	192.5	213.7	185.0	**186.5**	0.9%	-5.2%	0.6%
United Kingdom	562.8	516.1	532.6	495.0	511.8	498.4	457.3	438.4	414.7	403.2	**394.1**	-2.3%	-3.4%	1.2%
Other Europe	414.2	387.4	400.1	400.6	377.1	371.4	352.6	362.3	370.8	378.0	**375.7**	-0.6%	-1.0%	1.1%
Total Europe	4939.0	4589.6	4700.6	4618.0	4562.0	4452.3	4220.3	4230.0	4285.9	4317.5	**4248.4**	-1.6%	-1.5%	12.5%
Azerbaijan	29.6	25.9	24.9	28.5	29.6	30.2	31.0	33.8	33.2	32.2	**31.8**	-1.4%	0.7%	0.1%
Belarus	59.4	57.2	60.2	57.1	58.5	58.1	57.3	53.1	53.4	54.0	**56.6**	4.9%	-0.5%	0.2%
Kazakhstan	189.4	170.6	183.9	202.5	209.7	211.0	212.5	207.5	208.5	219.7	**248.1**	12.9%	2.3%	0.7%
Russian Federation	1554.3	1445.3	1492.2	1555.9	1569.1	1527.7	1530.8	1489.5	1501.5	1488.4	**1550.8**	4.2%	-0.3%	4.6%
Turkmenistan	32.3	50.3	54.3	59.9	65.2	58.3	60.5	71.5	68.8	71.8	**78.5**	9.3%	6.4%	0.2%
Uzbekistan	103.3	102.9	100.7	107.1	104.0	103.5	108.1	103.1	103.2	107.2	**104.3**	-2.7%	-0.4%	0.3%
Other CIS	24.7	23.4	22.9	24.2	27.0	25.7	27.3	28.3	28.6	28.0	**30.3**	8.5%	2.0%	0.1%
Total CIS	1993.0	1875.6	1939.0	2035.1	2063.1	2014.6	2027.5	1986.8	1997.3	2001.2	**2100.4**	5.0%	0.2%	6.2%
Iran	503.6	516.5	518.0	538.0	539.7	572.9	588.9	585.7	593.9	622.1	**656.4**	5.5%	2.6%	1.9%
Iraq	82.4	93.2	99.1	104.0	111.1	119.5	115.6	115.6	132.1	133.7	**151.4**	13.3%	5.4%	0.4%
Israel	71.6	68.4	71.6	73.1	78.9	69.4	66.8	69.8	69.1	70.0	**69.6**	-0.6%	-0.1%	0.2%
Kuwait	79.6	81.2	87.0	85.9	96.0	100.5	90.3	98.3	99.3	98.4	**98.2**	-0.2%	3.0%	0.3%
Oman	42.3	42.1	49.0	52.3	57.6	65.6	65.2	68.6	69.4	68.7	**71.4**	3.9%	6.8%	0.2%
Qatar	50.3	51.0	59.8	68.0	76.8	83.7	91.0	100.9	99.9	102.4	**101.2**	-1.2%	8.5%	0.3%
Saudi Arabia	424.4	443.2	485.1	501.5	525.5	534.3	570.4	587.1	597.6	591.1	**571.0**	-3.4%	4.2%	1.7%
United Arab Emirates	211.5	205.5	215.3	222.3	233.5	248.9	245.1	267.1	276.4	269.2	**277.0**	2.9%	3.8%	0.8%
Other Middle East	154.8	155.3	151.4	143.8	134.3	131.5	131.9	126.5	123.7	123.1	**122.7**	-0.3%	-1.9%	0.4%
Total Middle East	1620.5	1656.5	1736.2	1789.0	1853.3	1926.3	1965.2	2019.5	2061.5	2078.7	**2118.8**	1.9%	3.2%	6.3%
Algeria	90.8	95.8	94.2	100.6	108.9	115.4	123.6	129.0	127.7	127.8	**135.5**	6.0%	4.1%	0.4%
Egypt	170.5	177.2	188.8	189.5	200.4	199.0	203.5	208.8	218.3	221.3	**224.2**	1.3%	3.3%	0.7%
Morocco	48.6	45.2	49.1	52.9	53.9	54.3	56.5	56.7	57.0	60.0	**62.8**	4.6%	3.2%	0.2%
South Africa	447.5	446.7	448.9	440.2	434.4	435.1	439.1	425.9	428.5	418.5	**421.1**	0.6%	0.2%	1.2%
Other Africa	270.4	276.8	290.6	289.9	308.6	326.9	343.5	353.3	359.8	378.5	**391.0**	3.3%	3.9%	1.2%
Total Africa	1027.8	1041.6	1071.6	1073.1	1106.4	1130.7	1166.2	1173.7	1191.2	1206.1	**1234.6**	2.4%	2.3%	3.6%
Australia	420.5	414.8	408.7	414.6	406.7	401.8	408.8	413.2	418.3	412.3	**416.6**	1.0%	0.1%	1.2%
Bangladesh	43.0	47.7	50.8	55.0	60.3	61.6	66.0	78.0	79.2	82.7	**90.4**	9.3%	7.6%	0.3%
China	7378.5	7708.8	8135.2	8805.8	8991.5	9237.7	9223.7	9174.6	9119.0	9229.8	**9428.7**	2.2%	2.5%	27.8%
China Hong Kong SAR	79.2	86.5	88.3	92.0	88.7	91.5	89.8	90.5	92.7	98.9	**99.5**	0.6%	1.5%	0.3%
India	1466.9	1595.6	1661.0	1735.7	1849.2	1930.0	2083.3	2147.8	2234.2	2316.9	**2479.1**	7.0%	5.4%	7.3%
Indonesia	376.1	387.9	427.6	479.0	511.8	526.4	480.6	488.6	493.1	516.1	**543.0**	5.2%	2.9%	1.6%
Japan	1274.9	1112.5	1183.8	1194.7	1285.6	1273.6	1239.6	1197.4	1178.5	1171.8	**1148.4**	-2.0%	-0.8%	3.4%
Malaysia	197.8	190.3	213.0	213.5	226.3	232.4	240.2	245.6	240.8	241.6	**250.3**	3.6%	2.4%	0.7%
New Zealand	36.9	33.9	34.0	33.5	35.3	35.0	35.0	35.5	34.7	36.8	**35.9**	-2.7%	0.3%	0.1%
Pakistan	146.4	146.0	145.7	144.1	145.5	145.5	152.3	159.9	175.5	188.5	**195.7**	3.8%	2.9%	0.6%
Philippines	74.0	74.6	80.1	80.8	83.3	92.2	97.6	106.6	116.9	128.9	**133.7**	3.8%	6.0%	0.4%
Singapore	163.4	176.7	185.3	192.7	192.0	192.8	192.6	204.4	219.3	231.3	**230.0**	-0.5%	4.3%	0.7%
South Korea	557.5	559.7	615.7	646.8	643.8	646.1	644.6	656.5	662.5	678.8	**697.6**	2.8%	2.2%	2.1%
Sri Lanka	12.6	13.2	13.1	14.8	16.1	14.0	14.2	17.9	20.2	21.7	**20.6**	-5.1%	4.6%	0.1%
Taiwan	260.4	249.7	263.9	267.1	261.7	262.4	268.5	266.6	275.7	288.4	**286.0**	-0.8%	0.4%	0.8%
Thailand	237.4	236.5	248.7	253.5	270.9	273.9	280.7	289.4	295.5	299.9	**302.4**	0.8%	2.4%	0.9%
Vietnam	103.7	102.4	121.9	135.0	132.6	140.7	157.1	183.0	194.6	195.5	**224.5**	14.8%	9.5%	0.7%
Other Asia Pacific	130.1	114.7	117.1	108.5	116.0	112.8	124.7	130.5	148.3	152.9	**161.7**	5.8%	2.1%	0.5%
Total Asia Pacific	12959.2	13251.5	13994.0	14867.2	15317.4	15670.5	15799.5	15886.0	15998.9	16292.7	**16744.1**	2.8%	2.6%	49.4%
Total World	**30336.7**	**29719.4**	**31057.9**	**31978.3**	**32316.7**	**32799.9**	**32844.8**	**32804.4**	**32913.5**	**33242.5**	**33890.8**	**2.0%**	**1.0%**	**100.0%**
of which: OECD	13405.4	12496.2	12952.7	12821.1	12653.8	12692.0	12512.1	12389.0	12314.4	12352.9	**12405.0**	0.4%	-1.0%	36.6%
Non-OECD	16931.3	17223.1	18105.2	19157.2	19663.0	20107.9	20332.7	20415.5	20599.2	20889.6	**21485.8**	2.9%	2.4%	63.4%
European Union	4149.4	3846.7	3941.0	3812.2	3754.2	3664.7	3458.0	3501.8	3514.3	3549.5	**3479.3**	-2.0%	-1.7%	10.3%

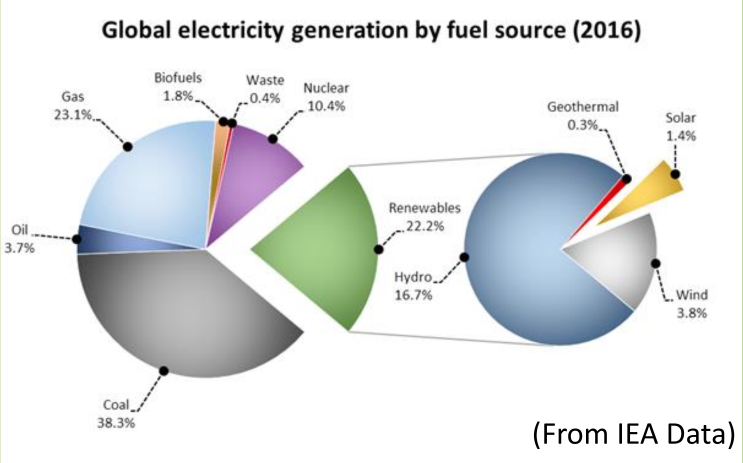
◆Less than 0.05%.

Note: The carbon emissions above reflect only those through consumption of oil, gas and coal for combustion related activities, and are based on 'Default CO_2 Emissions Factors for Combustion' listed by the IPCC in its Guidelines for National Greenhouse Gas Inventories (2006). This does not allow for any carbon that is sequestered, for other sources of carbon emissions, or for emissions of other greenhouse gases. Our data is therefore not comparable to official national emissions data.

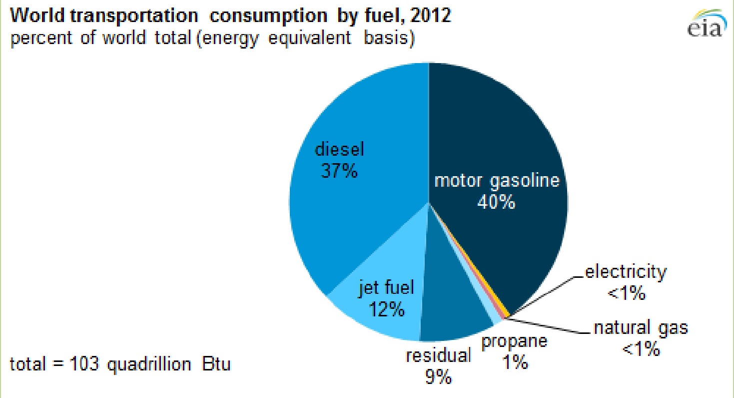
Where the energy is used and what for



Energy by sector

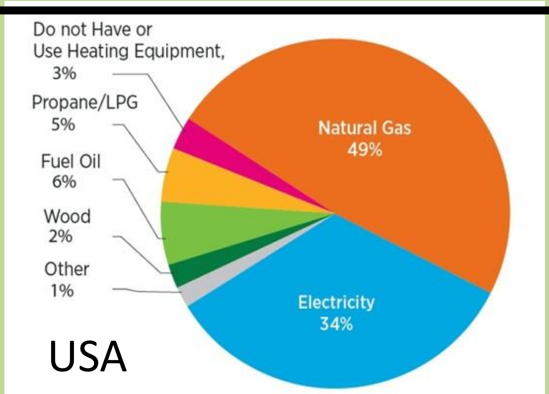


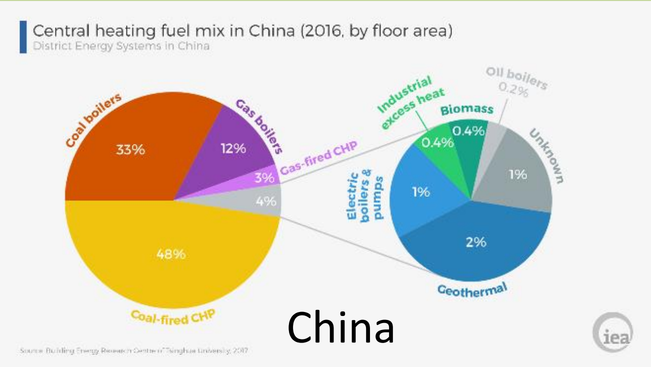
Electricity



Heating

Transportation

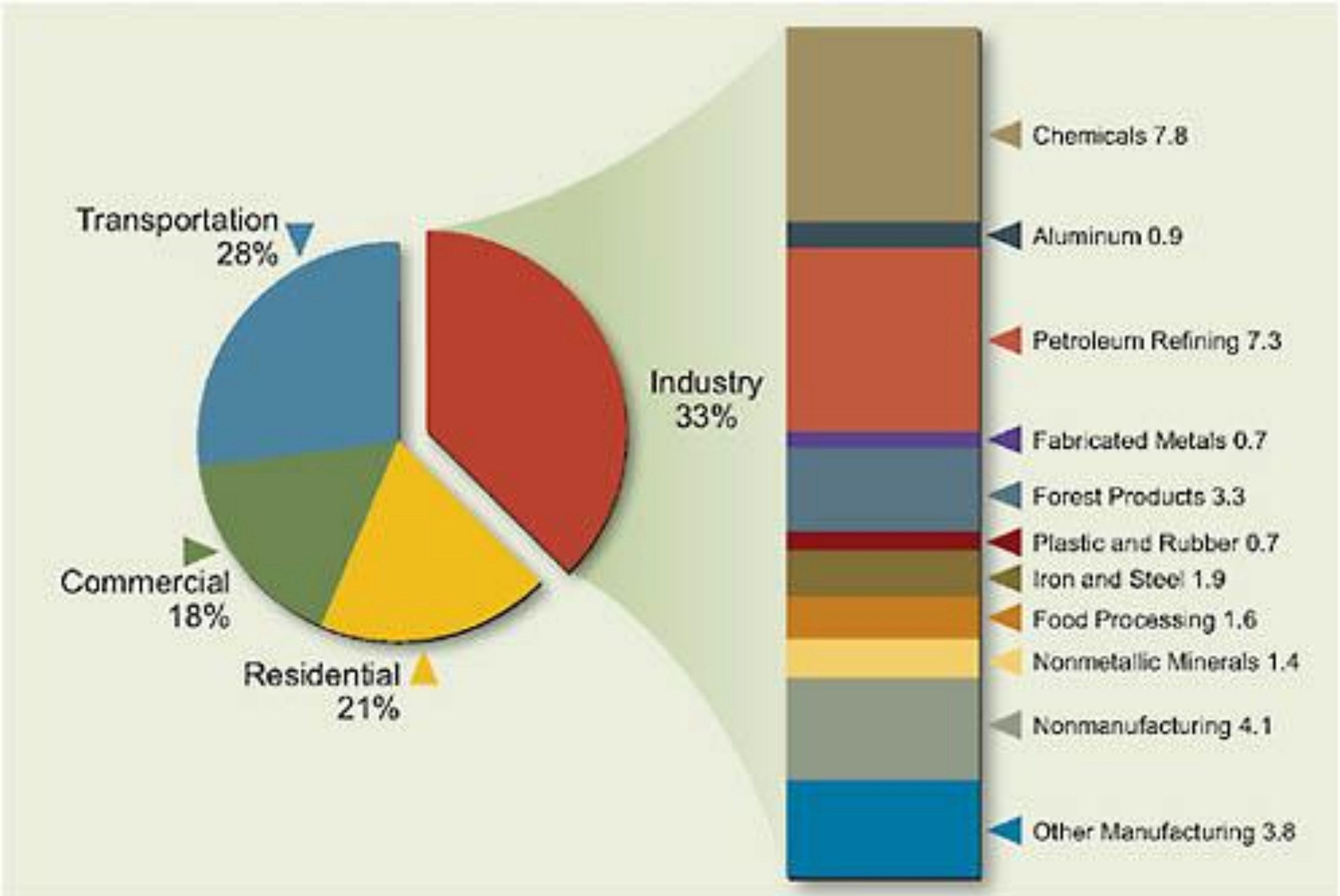




EU (basically same as USA)

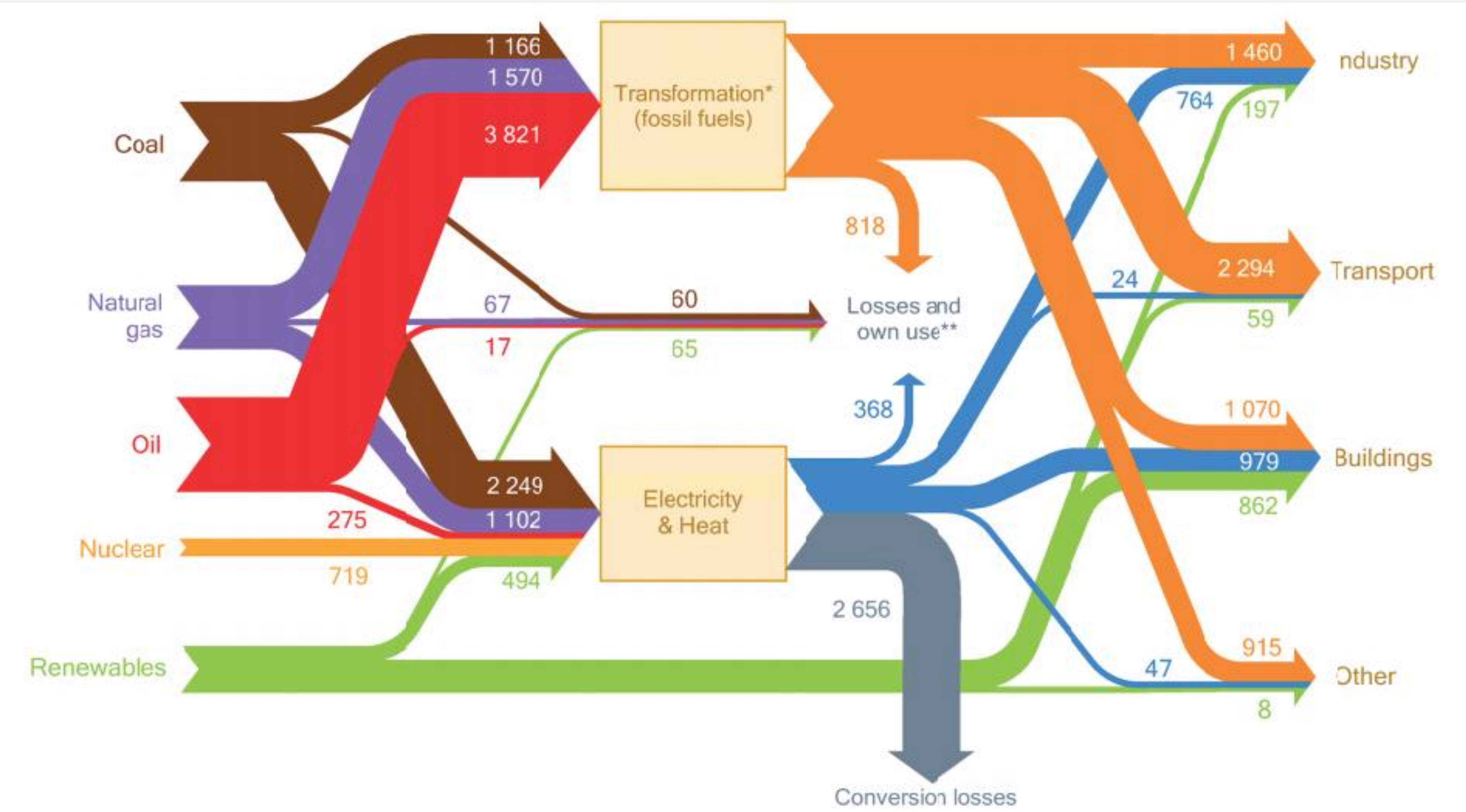
https://doi.org/10.1016/j.enpol.2016.09.016

Where the energy is used and what for



World Energy- Sankey Diagram

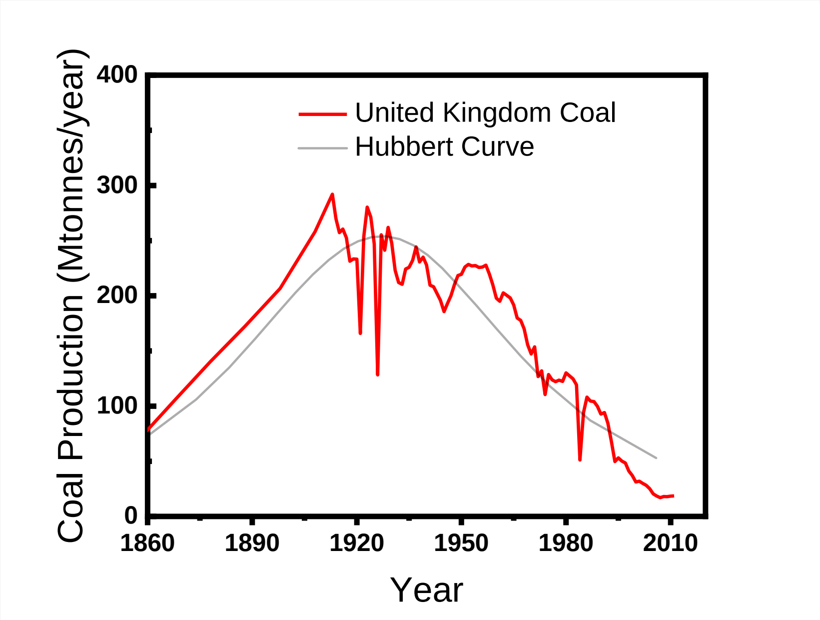
- All data is in million ton of oil equivalent (mtoe)



Hubert’s curve and the quick drop

- In 1956 M. King Hubert went to a conference and said US oil was about to peak in oil production.

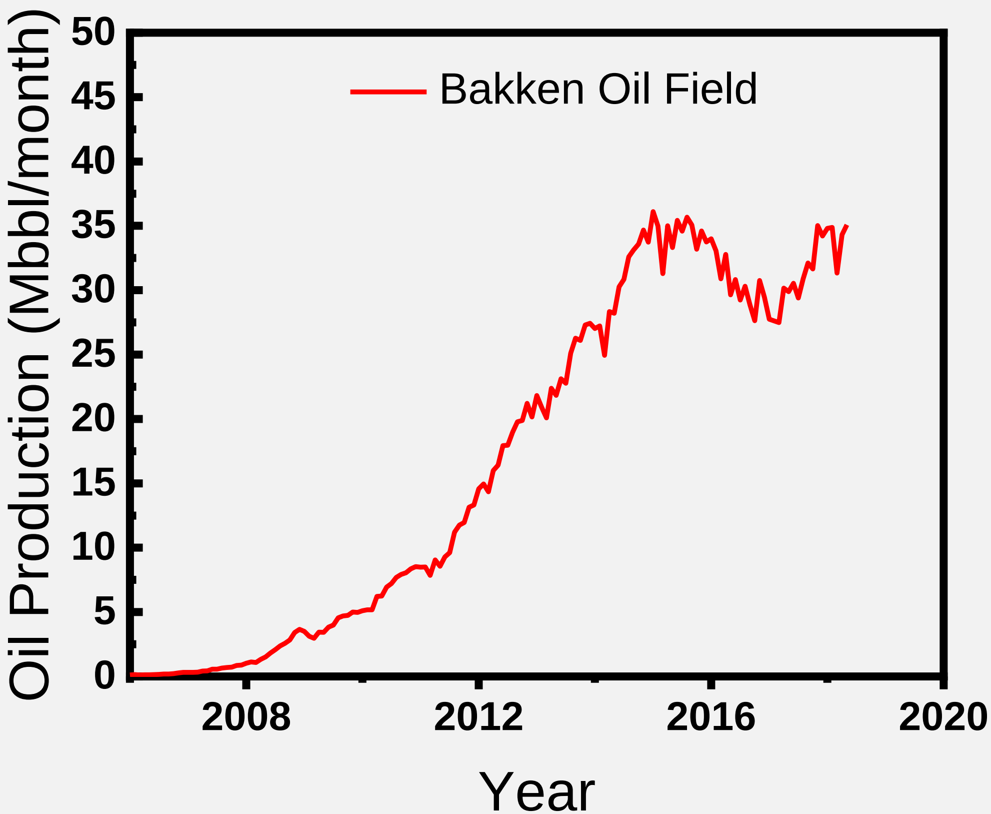
- He was basically laughed at. His basis was simply that production of a finite quantity will have a production rate that mimicks a bell curve.



(Based off M. Hubbert, 1956 & EIA data)

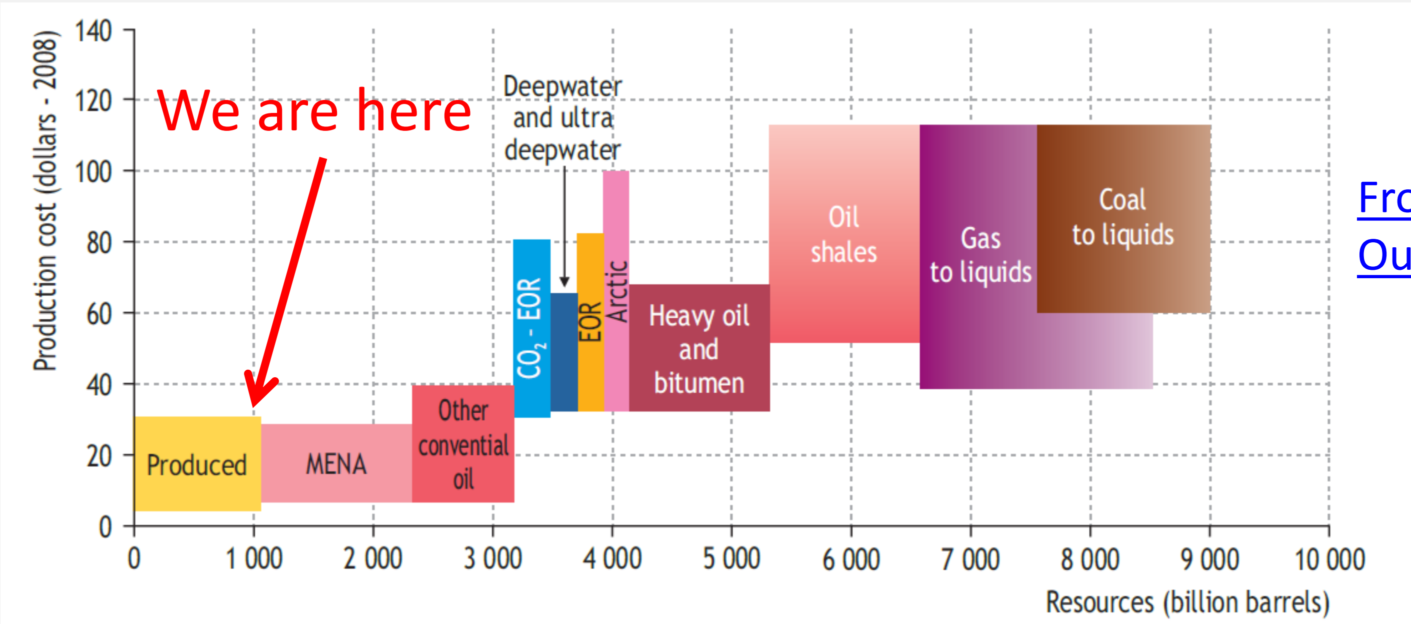
Hubert curve

- Currently a North Dakota (USA) field hit it's peak.
- Technological developments though (Shale oil) has created a secondary ramp up.

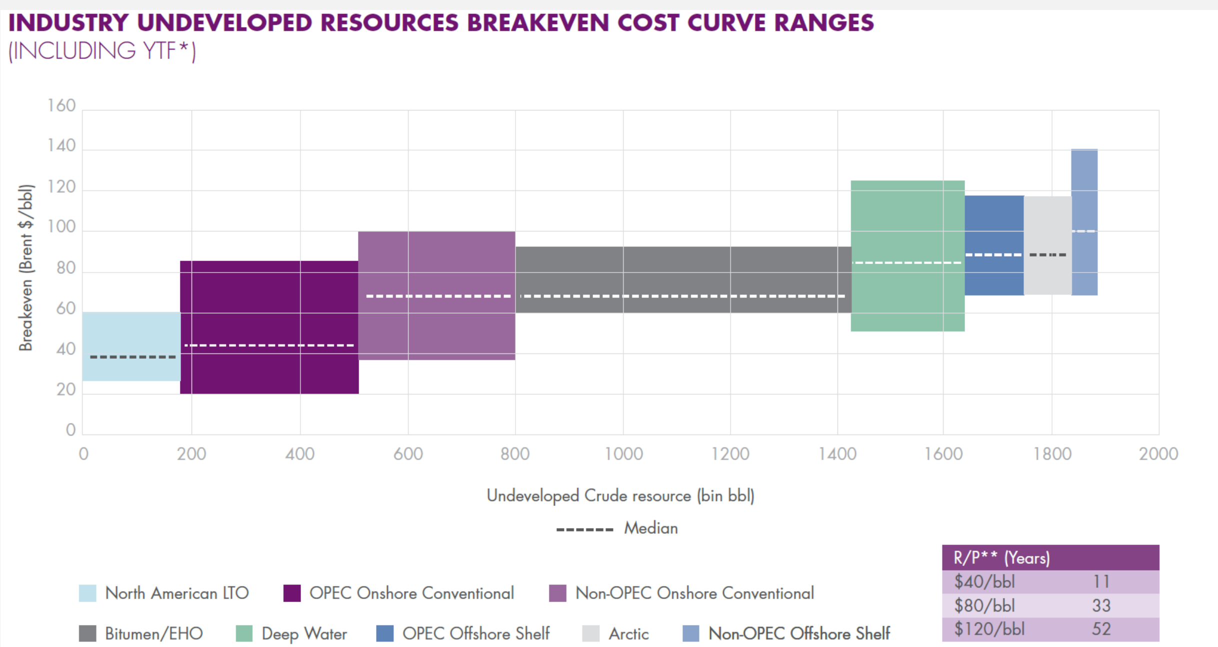


North Dakota Drilling statistics

We still have time to go on oil



[From 2008 IEA World Energy Outlook report (pg. 218)]

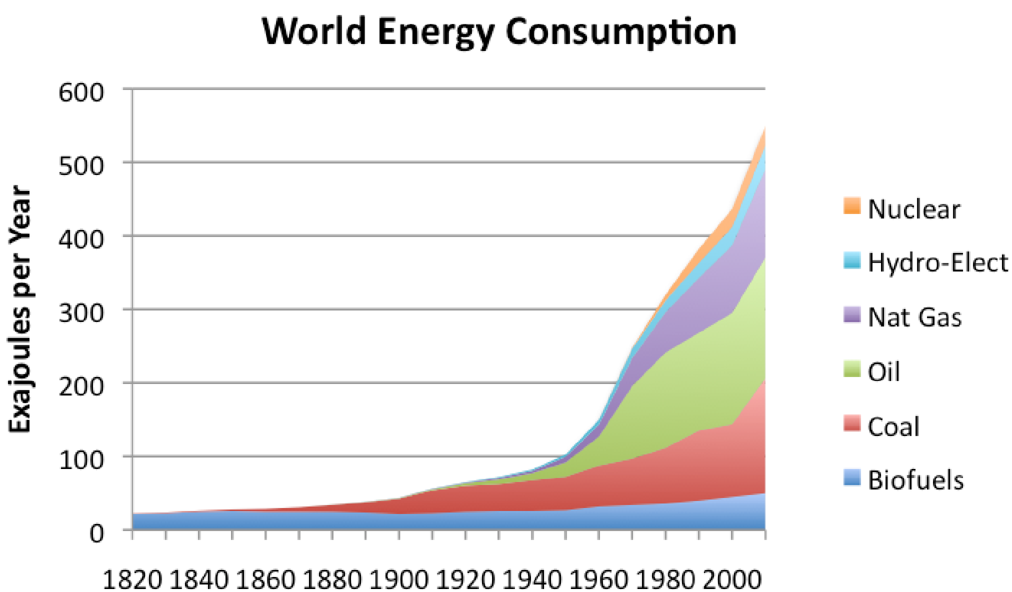


[2018 Shell Energy Transition Report]

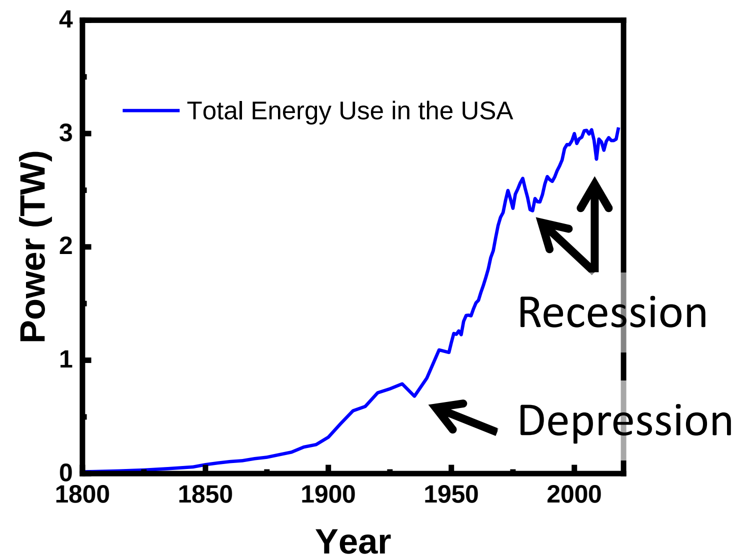
Break

World energy

- Our energy is increasing very fast.
- Why don't we just stop using so much energy.
- Energy production is highly related to economic productivity.

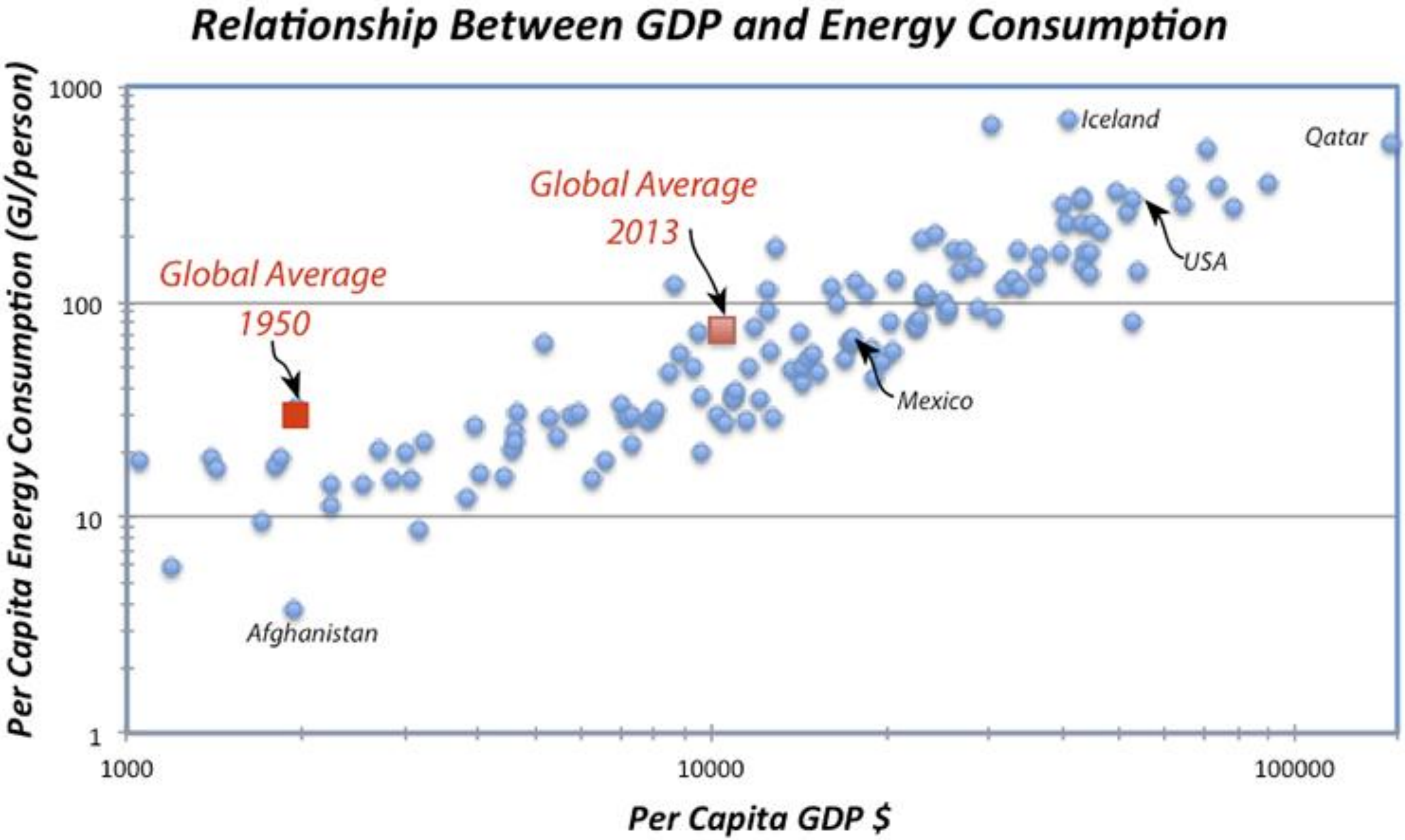


From finiteworld.com



Based off of IEA data

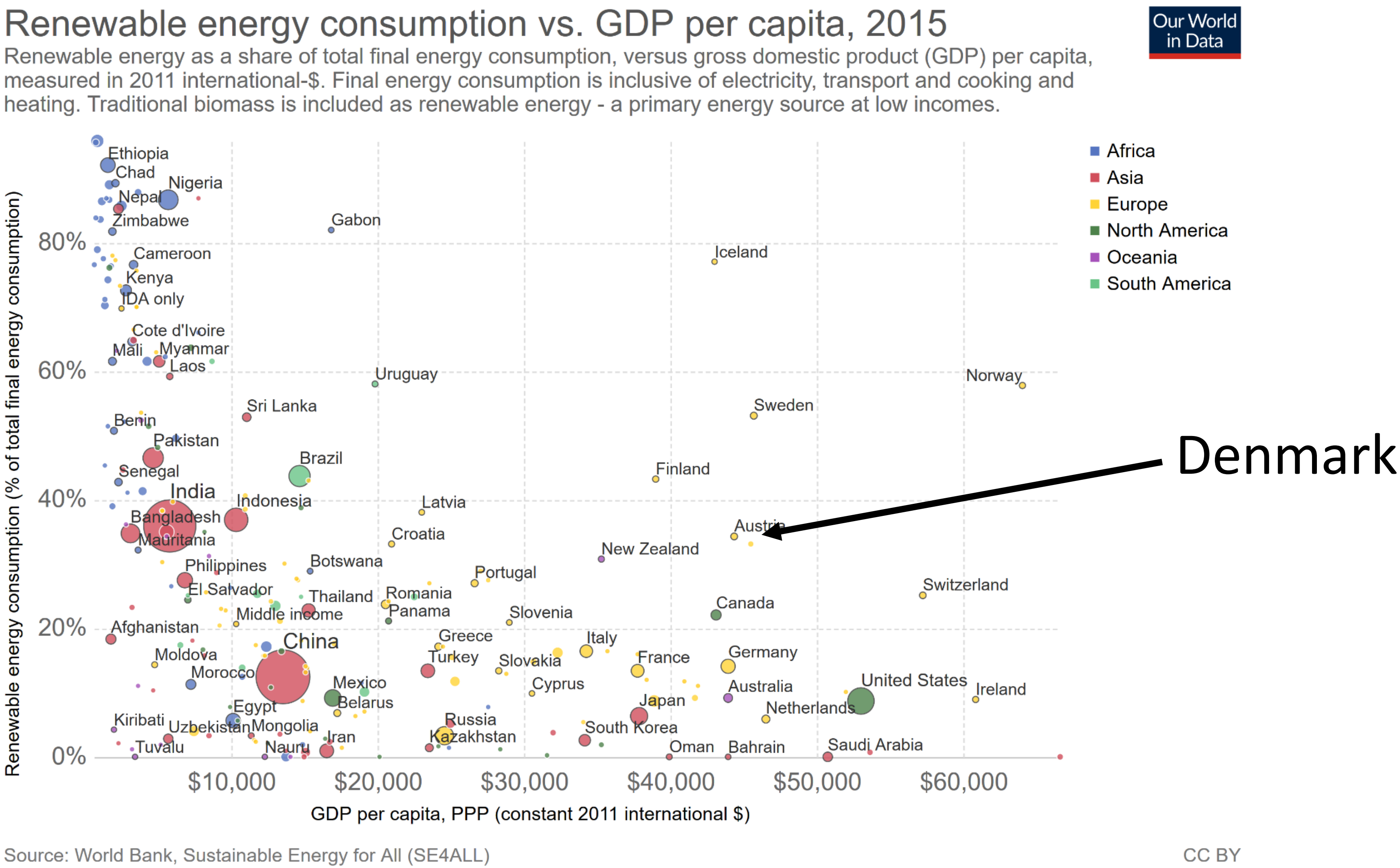
Energy vs. Economic growth



Data from World Bank, figure compiled by David Bice

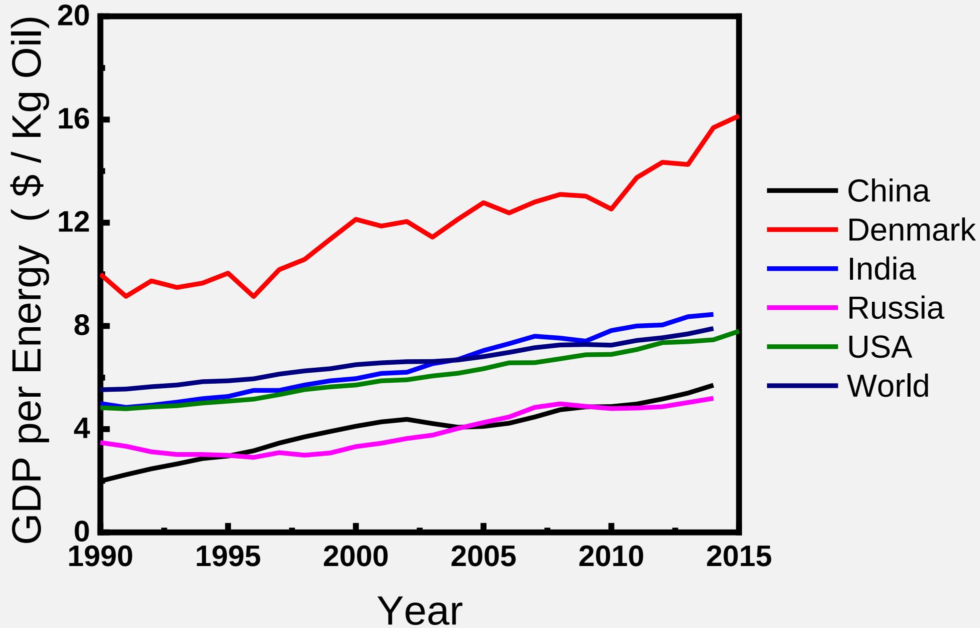
Energy vs. Economic growth

- The rich don't really use renewables though.



Economic Growth

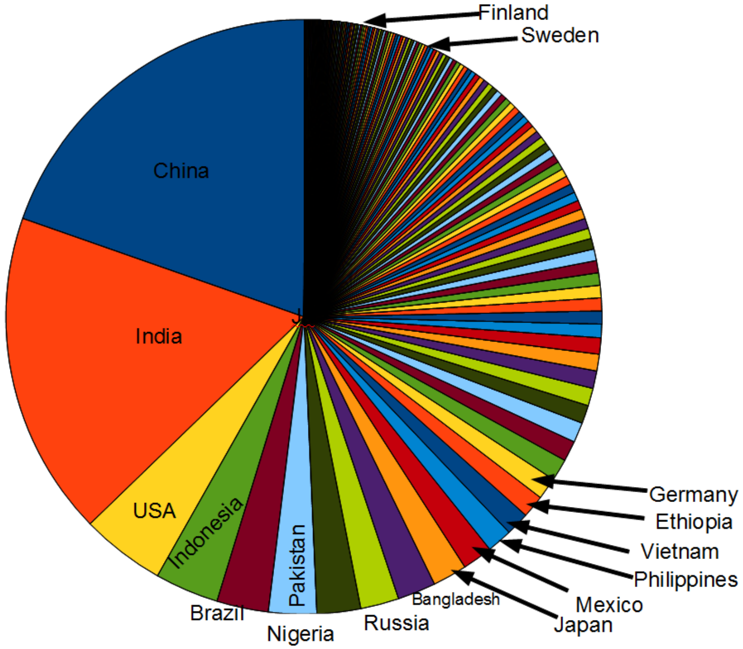
- A glimmer of hope is that our economic growth is becoming less dependent on energy.
- Basically we are creating more services and less things.
- We have increased our GDP/Energy 43% in the last 25 years.
- Our GDP over that time increased 232%.
- The non-energy based increase in GDP was 1.3%/year, whereas the overall GDP was 3.4%/year.



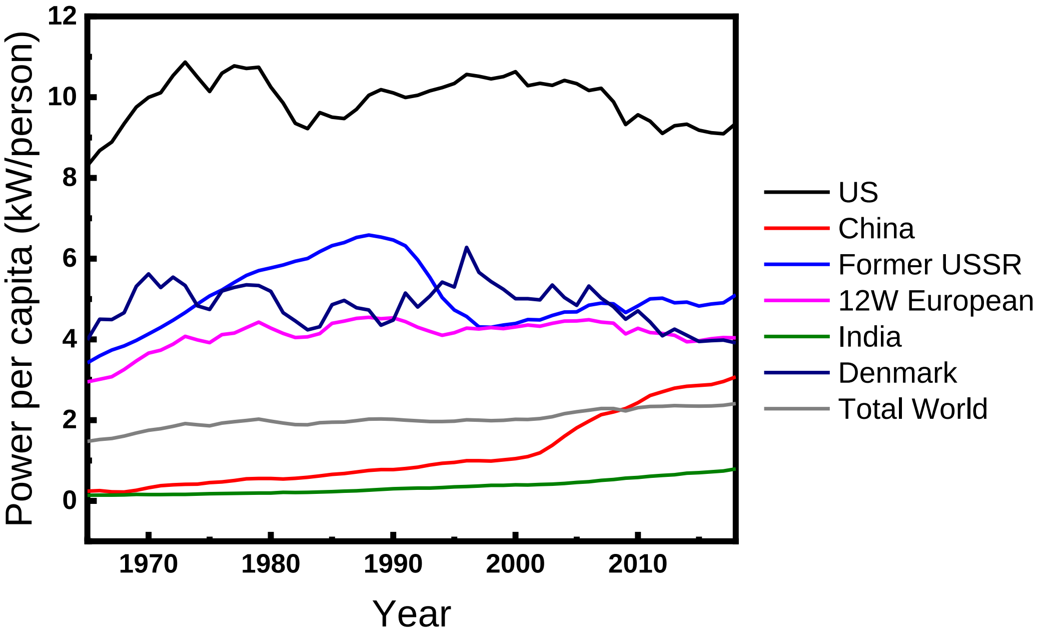
Data from World Bank

Population issues

- Most highly populated countries are still economically underdeveloped.
- As China and India grow so will their energy consumption.

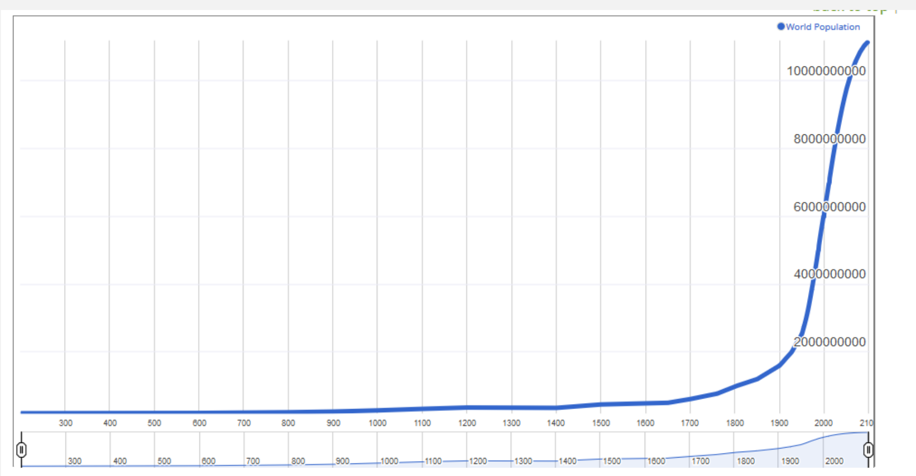


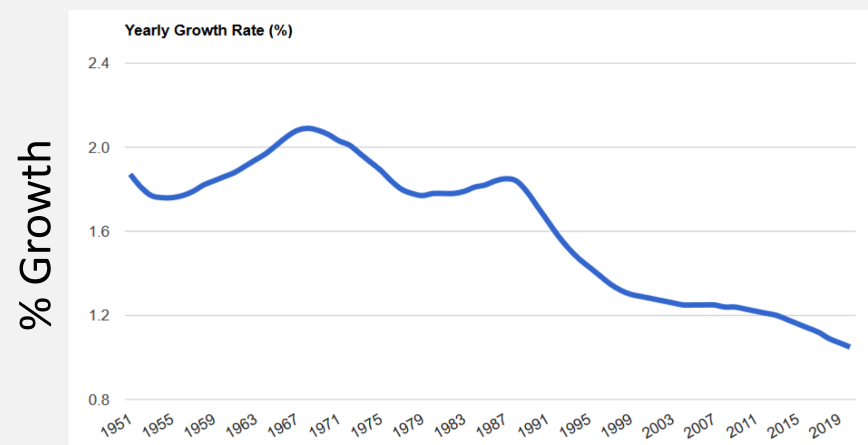
Population Distribution



Population

- The population has absolutely exploded in the last 100 years.
- Unfortunately the earth has stayed the same size.
- One sliver of hope is that the growth rate as a percentage is slowing down.
- With an increased population, and higher energy/person, it is estimated that in 2050 we will need 30 TW.

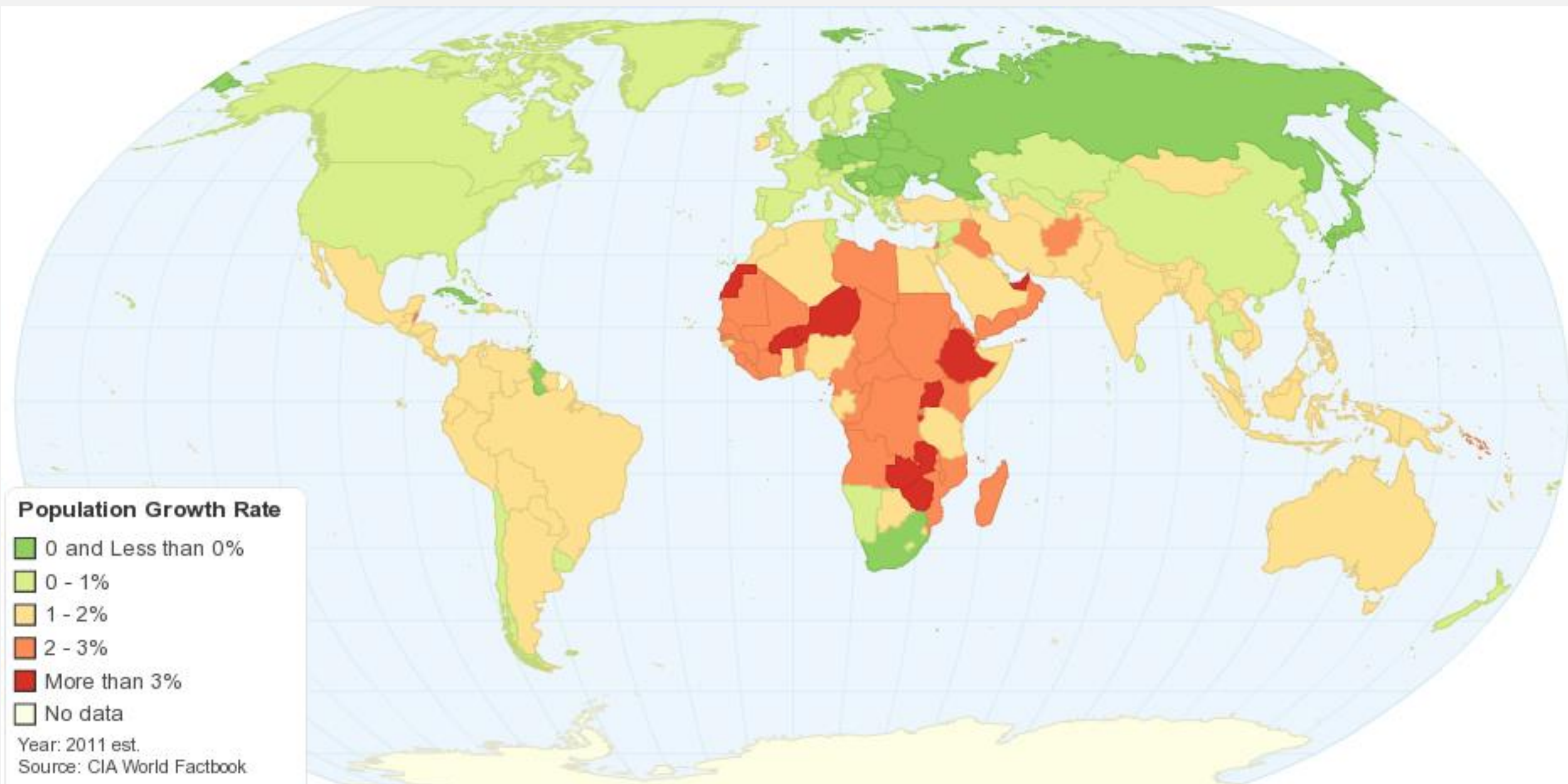




[Population data found here]

Population

- The future population is not where the current population is located.
- Building more hydroelectric dams in Norway is not going to help the people of Kenya.



- Al Gore:
  - Has been elected vice-President twice
  - Claimed to have created the internet
  - Is currently on the Apple's Board of Directors
  - Won a Nobel Prize for his promotion of climate change
- While not perfectly accurate, his documentary on global warming, "Inconvenient Truth" has stood up in court as fundamentally accurate.
- IPCC:
  - Started in 1988
  - UN backed organization
  - Hoesung Lee is current chairman
  - About 500 people are part of this.

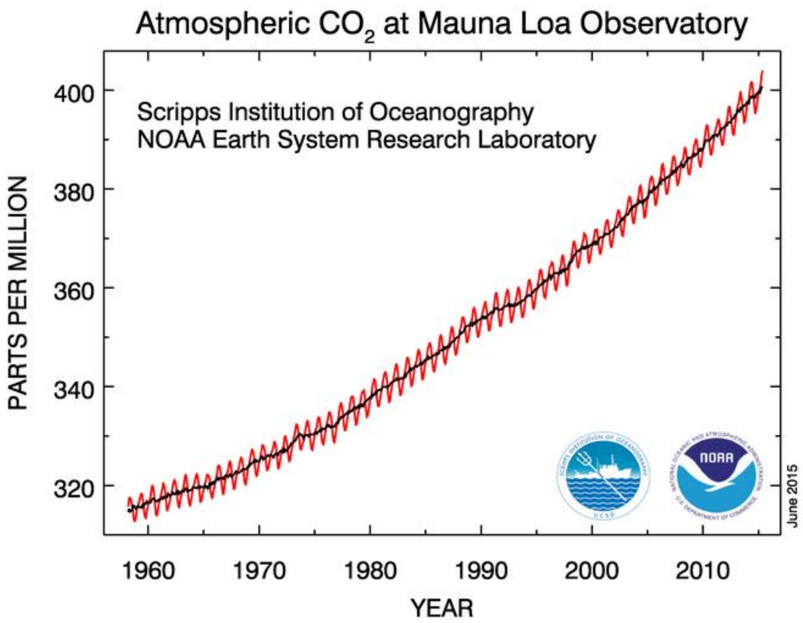
CO_2 Concentrations

- It is pretty clear that burning hydrocarbons (i.e. fossil fuels) will put CO_2 into the atmosphere.

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

Generic hydrocarbon

- A lab in Hawaii ended up being the standard reading of the worldwide average CO_2 in the air.
- The inconsistencies are due to seasonal fluctuations.



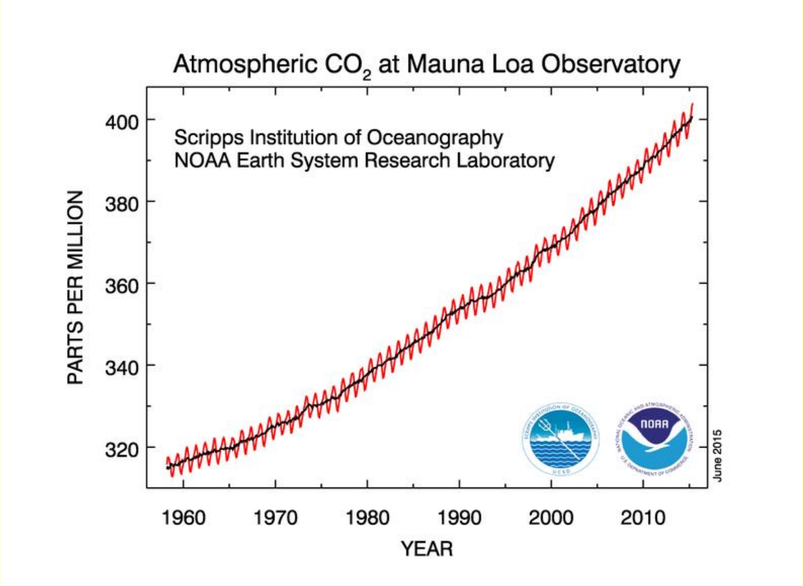
CO_2 Concentrations

- Since we know how much energy we use (18.6 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, the earth's radius is 6,400 km, CO_2's density is 1.98 kg/m^3, and the earth's atmosphere can be approximated to be 7.5km thick (@ average of 1 bar).

- The average CO_2 increase over the last decade is 2.1 ppm/year.

- Could this be due to fossil fuel combustion?



Long term effects

- Once CO_2 gets into the atmosphere it takes a long time to get removed.

- When you do a world mass balance you will realize that most of the world's CO_2 in dissolved in water.

- Most of the water is too deep to act as a short time-frame (less than 1000 years) CO_2 sink.

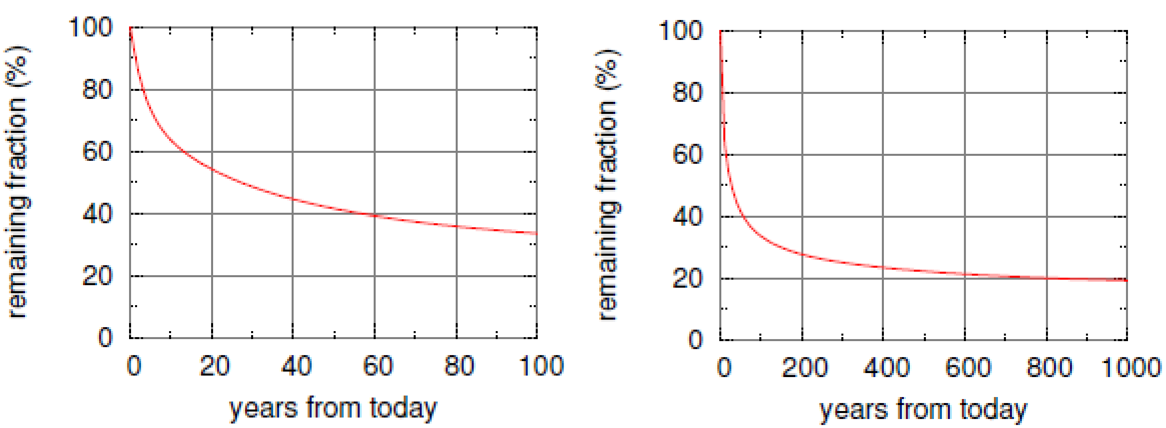
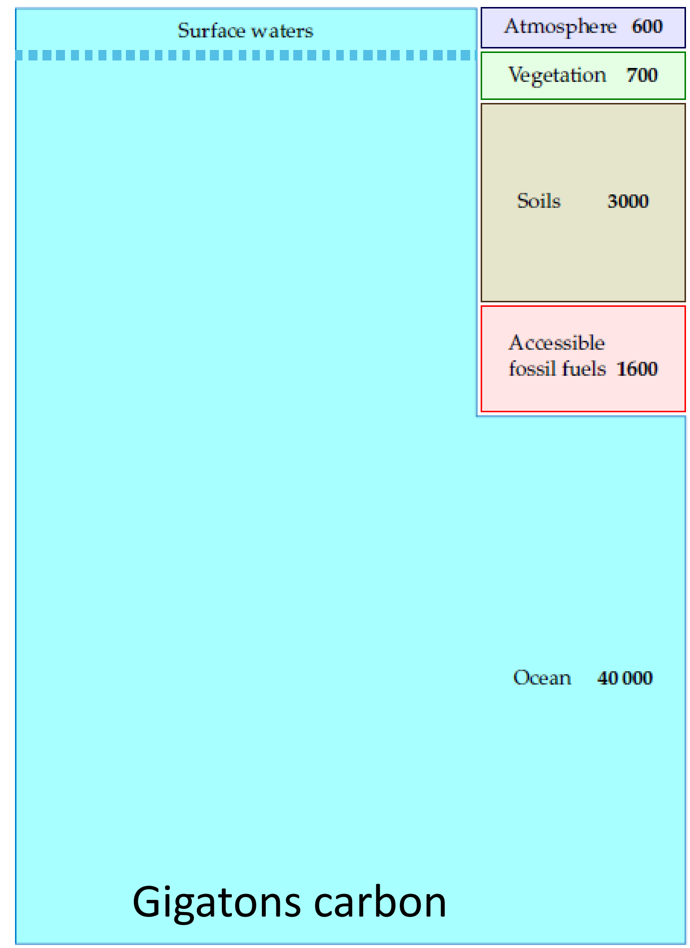
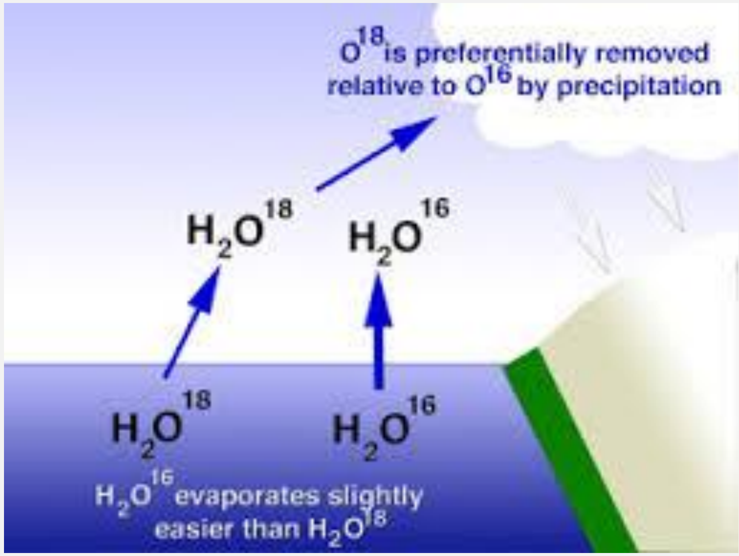


Figure 31.4. Decay of a small pulse of CO_2 added to today's atmosphere, according to the Bern model of the carbon cycle. Source: Hansen et al. (2007).

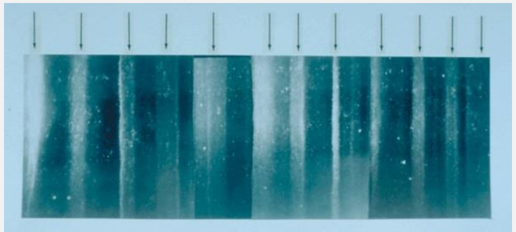


Historical CO_2

- Atmospheric science is very complex and historical data is great for how CO_2 affects the environment.
- It is known that 2 different isotopes of water evaporate at different rates.



- The ratio between isotopes is a function of temperature.
- Comparing the water isotope ratio in ice cores allows to determine temperature for a given year´.
- Air bubbles then allow for researchers to determine the amount of CO_2 in the atmosphere.



Ice Core

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 event happened in 1769?

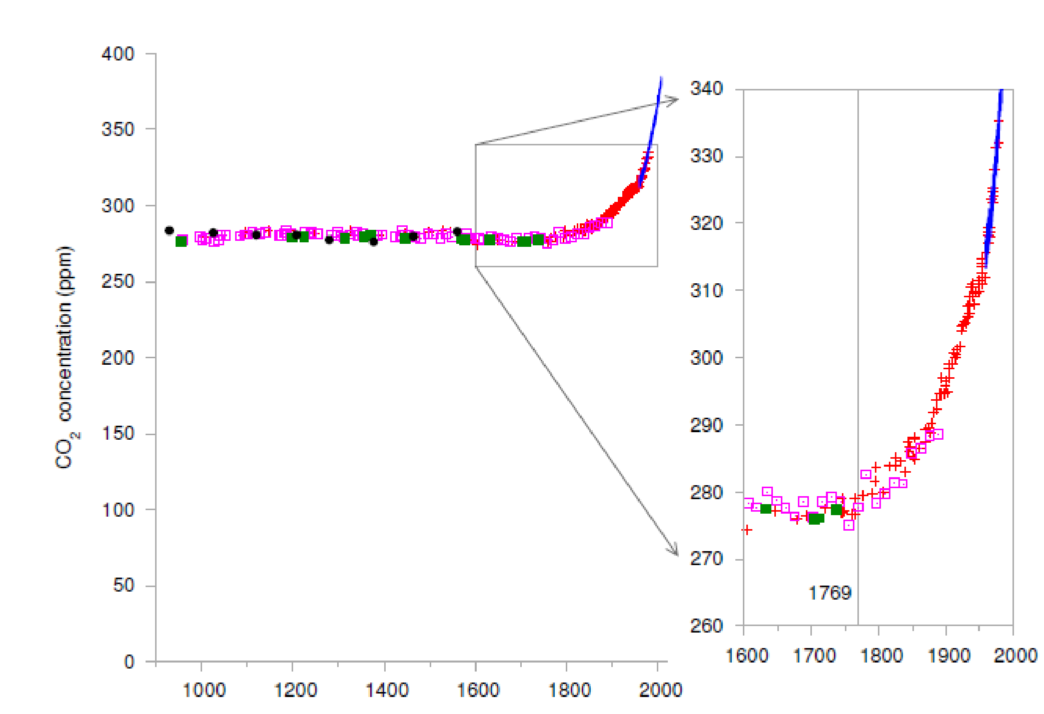
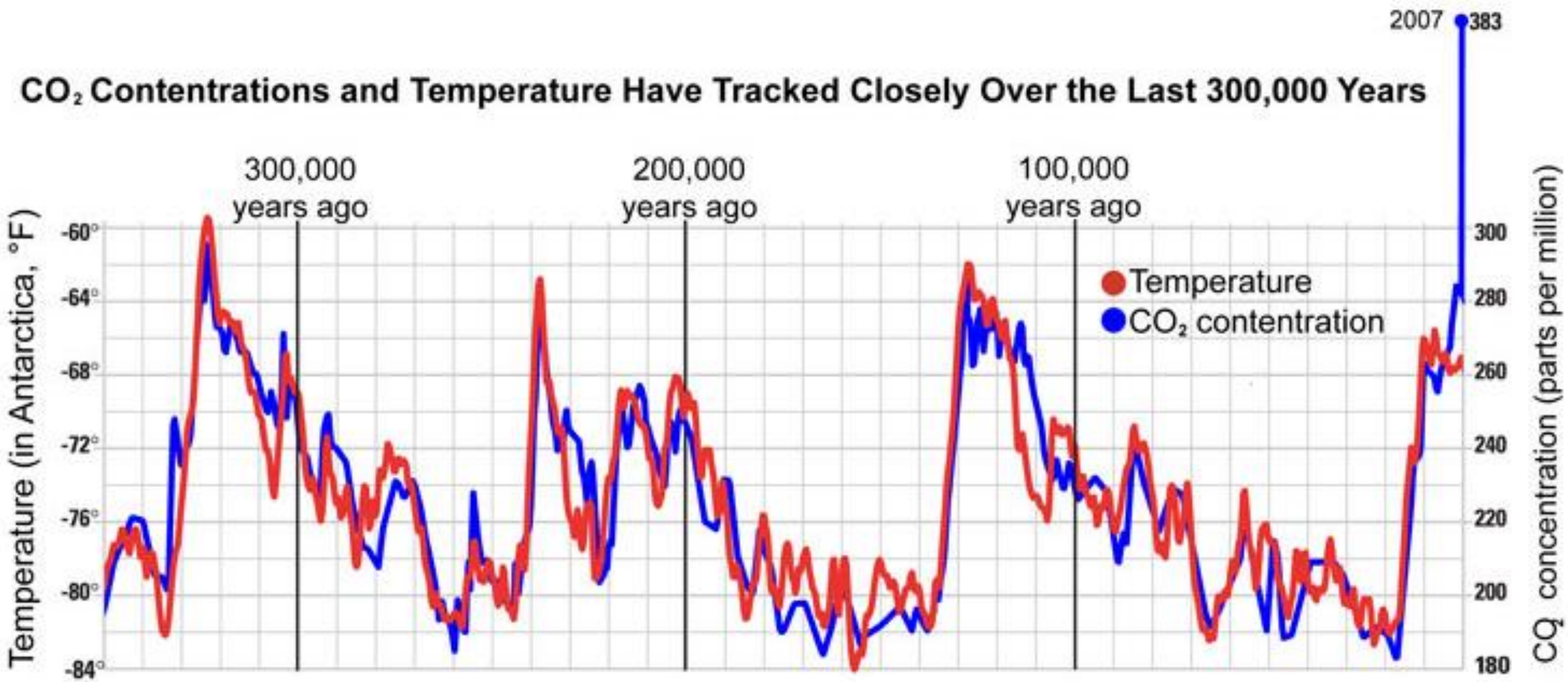


Figure from SE book

CO_2 relationship to temperature

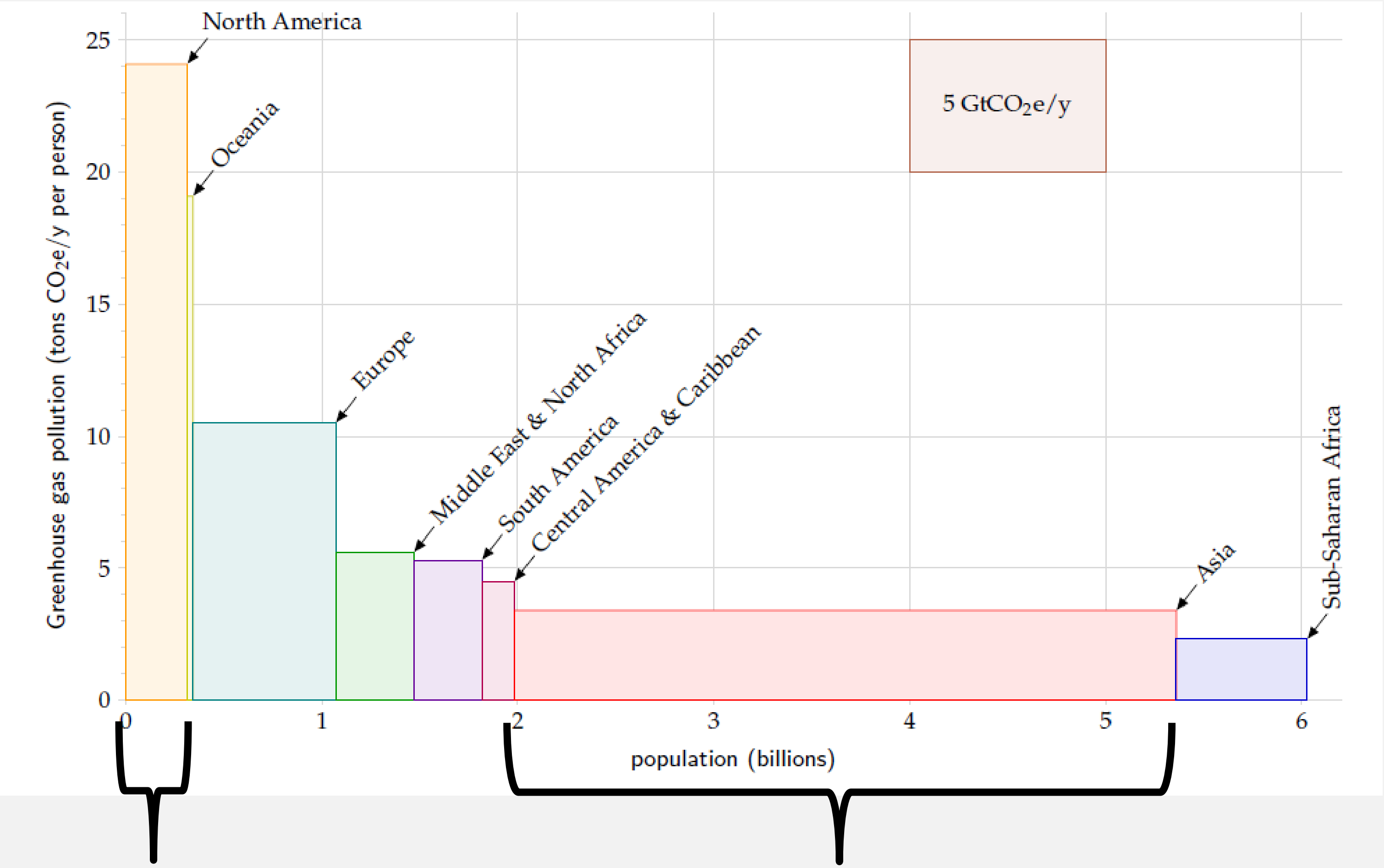
- CO_2 is highly correlated to worldwide temperature.
- Currently we are at a CO_2 concentration (410 ppm) that has never been seen before.
- The fundamentals of why CO_2 scales with temperature will be discussed in a future lecture.



Vostok Ice Core

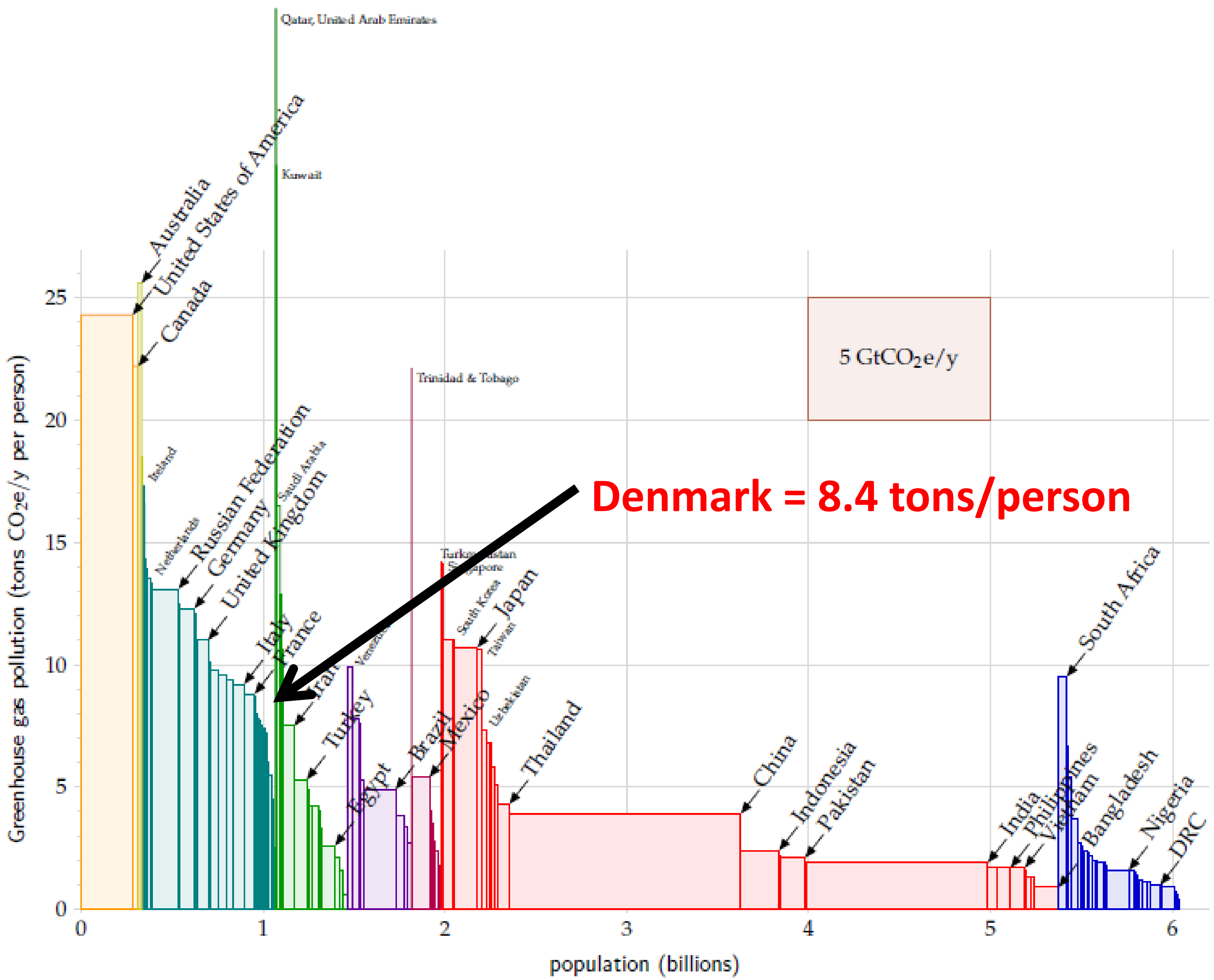
Greenhouse gas emissions

- Breakdown of greenhouse gas by location



Very little people,
a lot of CO_2.

A lot of people, very little CO_2.



Denmark = 8.4 tons/person
5 GtCO2e/y
Qatar, United Arab Emirates
Kuwait
Trinidad & Tobago
Australia
United States of America
Canada
Ireland
Netherlands
Russian Federation
Germany
United Kingdom
Saudi Arabia
Italy
France
Iran
Turkey
Egypt
Brazil
Mexico
Singapore
South Korea
Japan
Taiwan
Uzbekistan
Thailand
China
Indonesia
Pakistan
India
Philippines
Vietnam
South Africa
Bangladesh
Nigeria
DRC
Greenhouse gas pollution (tons CO2e/y per person)
population (billions)

Climate Change Debate

- Science vs Media

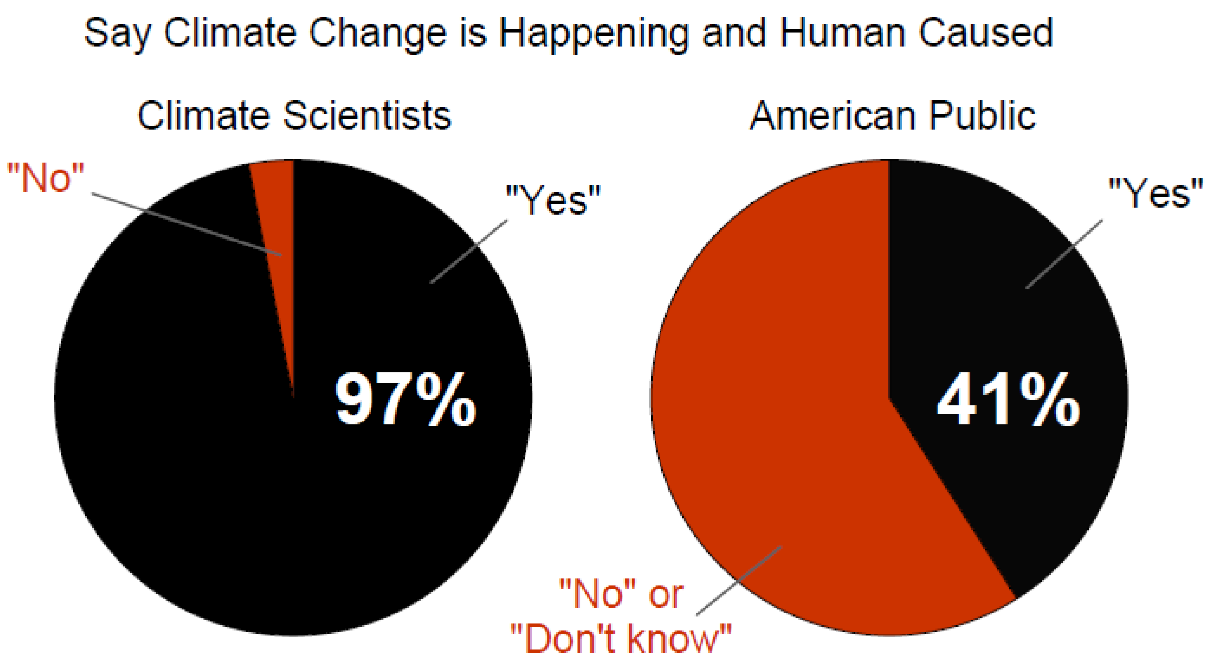


Fig. 1. *Left*: Proportion of peer-reviewed research papers that stated a position on the reality of human-caused global warming and said it is happening and human caused (Cook et al. 2013). *Right*: Proportion of the American public that says climate change is happening and human caused (Leiserowitz et al. 2013).

Complete Sustainability

- There are actually many areas, which need to be sustained.
- Of the UN Sustainbility goals, this course focuses primarily on #7, but also #12 and #13

PLANETARY BOUNDARIES

Earth-system process	Parameters	Proposed boundary	Current status	Pre-industrial value
Climate change	(i) Atmospheric carbon dioxide concentration (parts per million by volume)	350	387	280
	(ii) Change in radiative forcing (watts per metre squared)	1	1.5	0
Rate of biodiversity loss	Extinction rate (number of species per million species per year)	10	>100	0.1–1
Nitrogen cycle (part of a boundary with the phosphorus cycle)	Amount of N_2 removed from the atmosphere for human use (millions of tonnes per year)	35	121	0
Phosphorus cycle (part of a boundary with the nitrogen cycle)	Quantity of P flowing into the oceans (millions of tonnes per year)	11	8.5–9.5	~1
Stratospheric ozone depletion	Concentration of ozone (Dobson unit)	276	283	290
Ocean acidification	Global mean saturation state of aragonite in surface sea water	2.75	2.90	3.44
Global freshwater use	Consumption of freshwater by humans (km^3 per year)	4,000	2,600	415
Change in land use	Percentage of global land cover converted to cropland	15	11.7	Low
Atmospheric aerosol loading	Overall particulate concentration in the atmosphere, on a regional basis	To be determined		
Chemical pollution	For example, amount emitted to, or concentration of persistent organic pollutants, plastics, endocrine disrupters, heavy metals and nuclear waste in, the global environment, or the effects on ecosystem and functioning of Earth system thereof	To be determined		

Nature 461, 472-475 (24 September 2009)

UN Sustainability Goals

Summarizing current situation

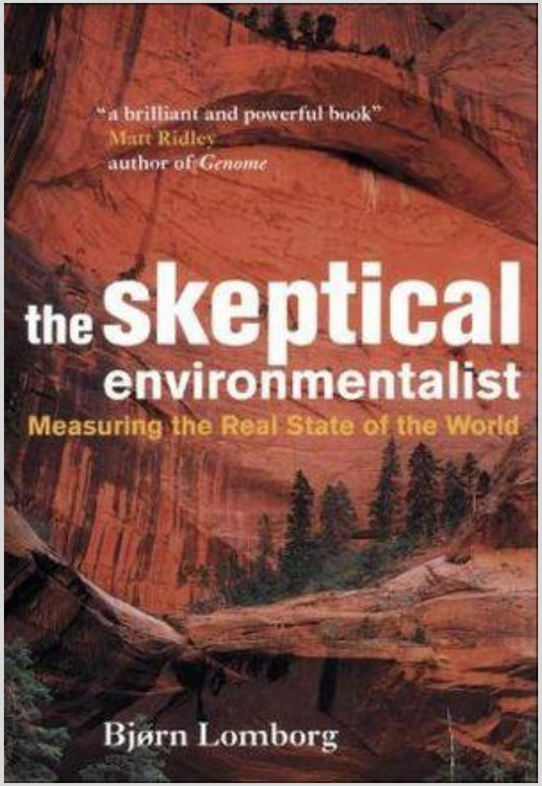
- We appear to have significant amounts of fossil fuels for the next couple of decades.
- While the Hubbert curve appears intimidating, it will be a while before we reach it.
- Energy use = Wealth.
- China and India want to be wealthy, thus energy use will drastically increase.
- The greenhouse gas issue is an absolute disaster.

"Okay – it's agreed; we announce – 'to do nothing is not an option!' then we wait and see how things pan out…"

Figure 1.11. Reproduced by kind permission of PRIVATE EYE / Paul Lowe www.private-eye.co.uk.

Bjørn Lomborg

- Bjørn Lomborg is a prominent Danish economist who wrote a book called ‘Skeptical Environmentalist’ where he stated that while real, global warming is not important.
- There were some inaccuracies in this book and the Danish government looked into it.
- They found his book scientifically inaccurate, but he was not at fault since he was not an expert.
- Bjorn is an economist trying to do environmental science, which leads to some interesting results.



Break

What are the potential renewable energy sources ?

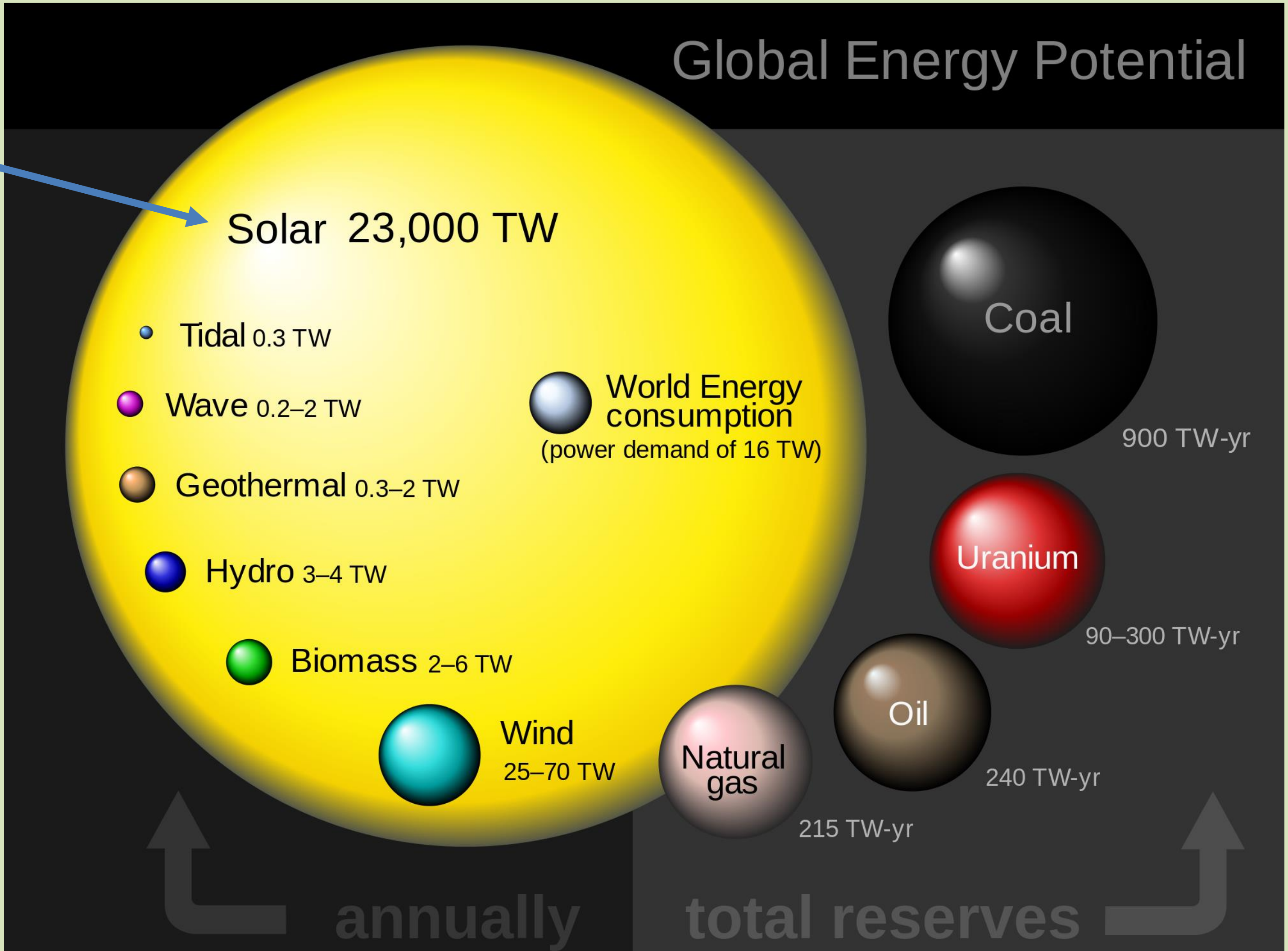
- For a sustainable future we need an energy source that give us ~18 TW of power (28 TW by 2050).
- Below are our choices:
  - Solar Power: 23,000 TW
  - Wind Power: 25-70 TW
  - Hydro Power: 3-4 TW
  - Geothermal: 0.3-2 TW
  - Biomass: 2-6 TW

- There are a bunch of other renewable energy sources, but nothing to support society.

Energy Sources

- This is energy sources graphically.

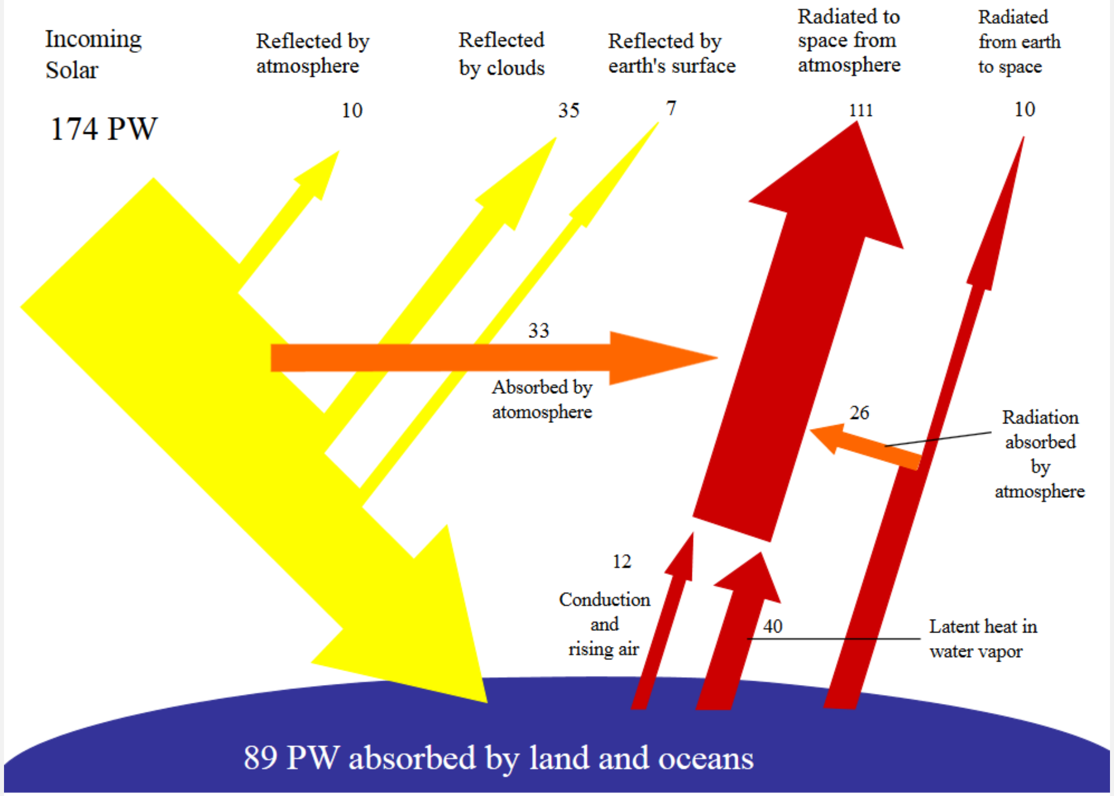
There are ssumptions behind this. It can reasonably range from 14,000 to 177,000.



Solar Irradiation

- In theory it would be possible to gain about 100,000 TW of energy
- That would not allow for any photosynthesis and kill the ecosystem.

1 PW = 1,000 TW



Inequalities in solar irradiation

- Some places get almost triple the light as other places.
- Denmark is very low on the irradiation spectra.

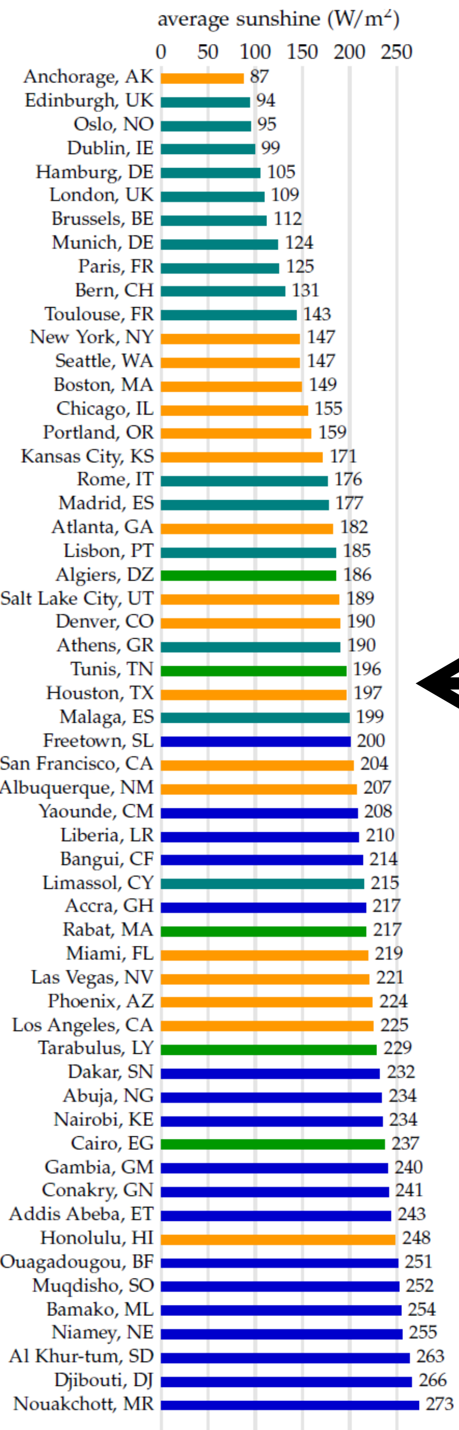
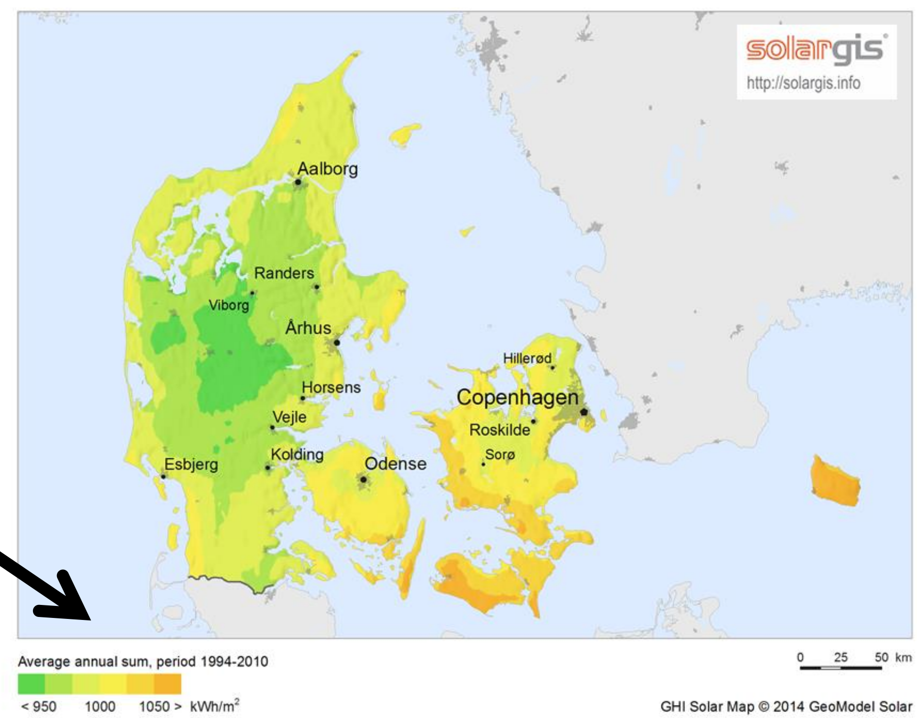


Chart from SE book

1000 kWh/m^2 = 114 W/m^2 (average sunshine)



Uses of Solar Irradiation- 23,000 TW

- There are 3 main uses of solar irradiation.
- ***Solar Heating-*** using mirrors or simply a green house effect to heat water. This is a cheap technique, but useful in some places. Efficiency limited by Carnot efficiency limits.
- **Photosynthesis**- nature converting CO_2 into complex carbon chains. This is a relatively cheap way to use solar irradiation. The efficiency is around 0.1-1%.
- **Solar cells-** using sunlight to provide electricity. These are getting cheap and get ~15-20% efficiency.
- We will spend 1 lecture on solar irradiation and 3 lectures on solar uses

Solar Production- 210 Ewh/year

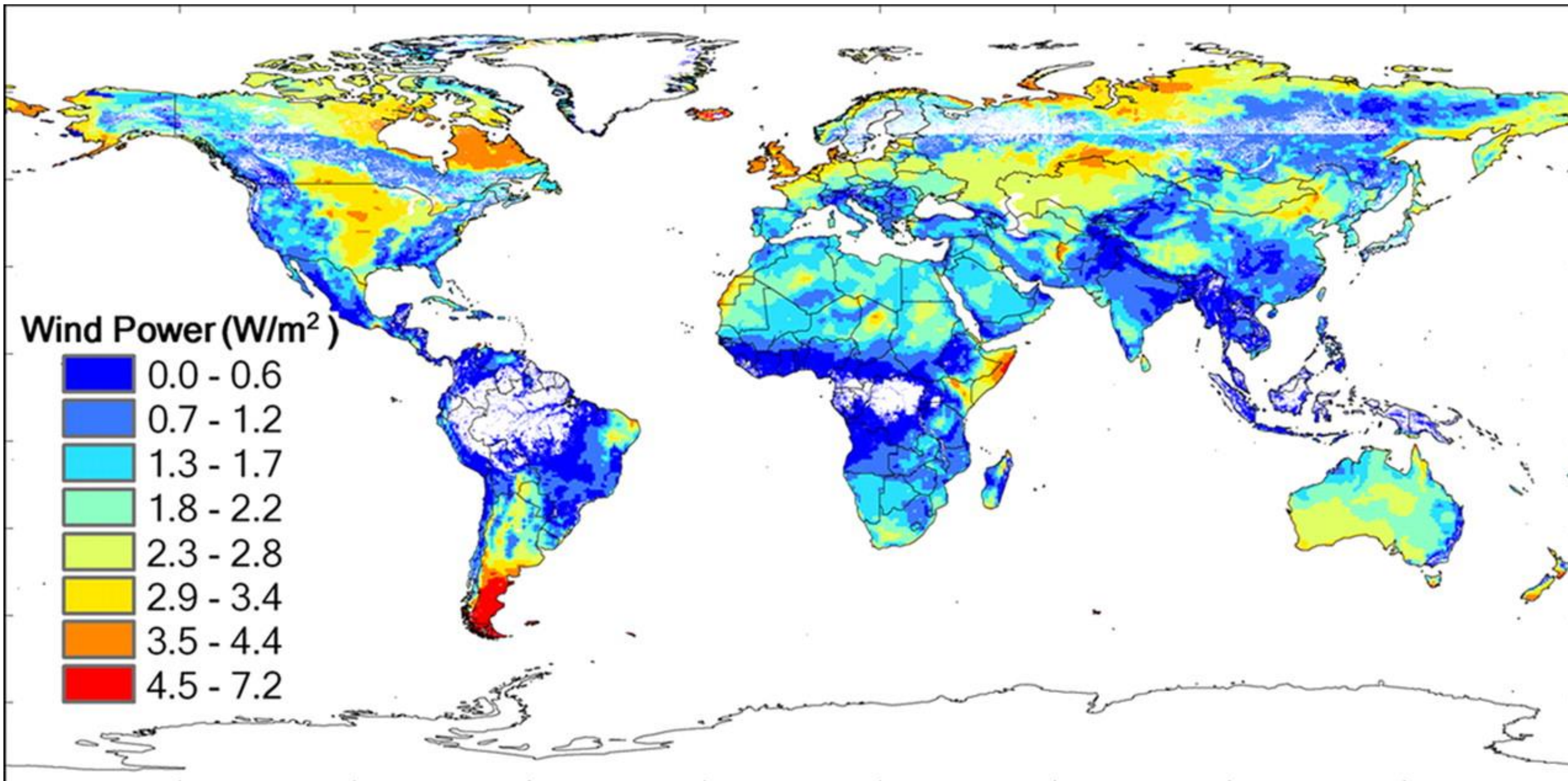
- 1 Exawatt (EW) = 1 million Terrawatts (also note: 8760 hours/year)

Country	Photovoltaic Energy **(TWh)**
China	45.2
USA	39.0
Germany	38.7
Japan	35.9
Italy	22.6
Spain	13.4
UK	7.4
Denmark	0.6
Sweden	0.1
World	10.63

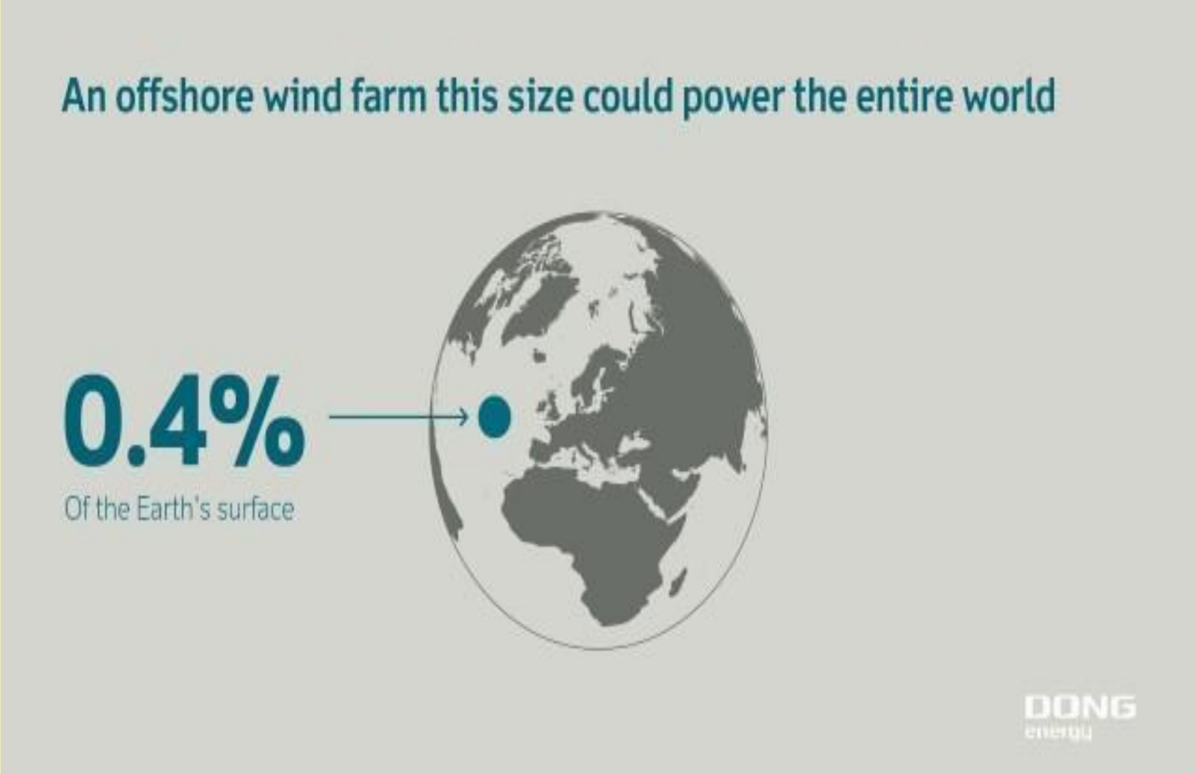
Country	Biofuels **(TWh)**
US	77.7
China	63.7
Germany	57.4
Brazil	48.8
IJapan	41.5
UK	33.0
India	26.5
Italy	21.8
Denmark	5.0
Sweden	12.0
World	81.94

Country	Solar Heating **(GW)**
China	24.91
Turkey	1.61
USA	1.25
Germany	0.81
Brazil	0.73
India	0.60
Australia	0.57
Denmark	0.038
Sweden	0.018
World	30.86

Worldwide Wind Potential



Wind Power: Is this right?



LinkedIn Advertisement, 31/8/2016

Ørsted's newest wind plant

(Borssele in Netherlands)

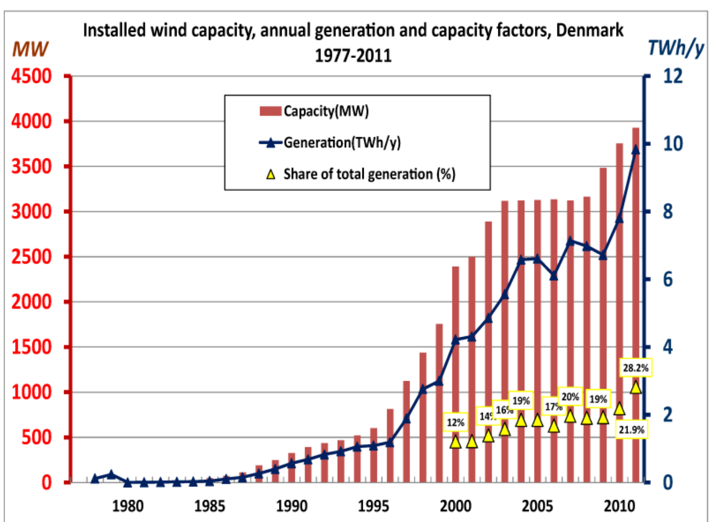
Power = 700 MW
(maximum power)

Area = 128 km^2

The earth's radius is 6,400 km

Wind: 25-70 TW (219-615 PWh)

- In very windy areas, wind power is cheaper than traditional fossil fuel based power for electricity.



- We will have 1 lecture on this topic.

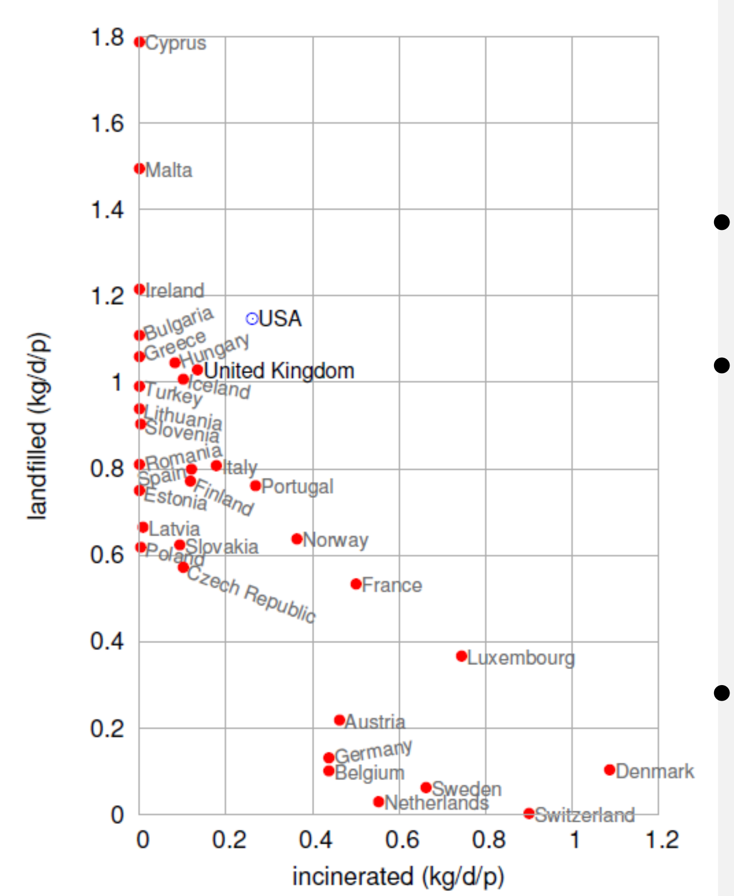
Country	Windpower Production **(TWh)**	% of World Total
United States	191	22.9
China	186	22.3
Spain	79	9.5
Germany	48	5.8
India	43	5.1
United Kingdom	40	4.
Canada	26	3.1
Denmark	14	1.7
World Total	834	100%

Geothermal, Wave and Tide

- Geothermal energy is basically pulling energy from the earth's core.
- Unfortunately this is most effective near tectonic plates, where there are high frequencies of volcanoes.
- Wave power can provide a marginal amount of power.
  - Waves are derived from wind, thus the amount of power derived from wave should always be less than that of wind
- Tide power also provides a marginal amount of power.
  - This power is derived from the gravitational pull between the Earth and the Moon.
- We will have presentations on these topics

Renewable energy sources, small impact

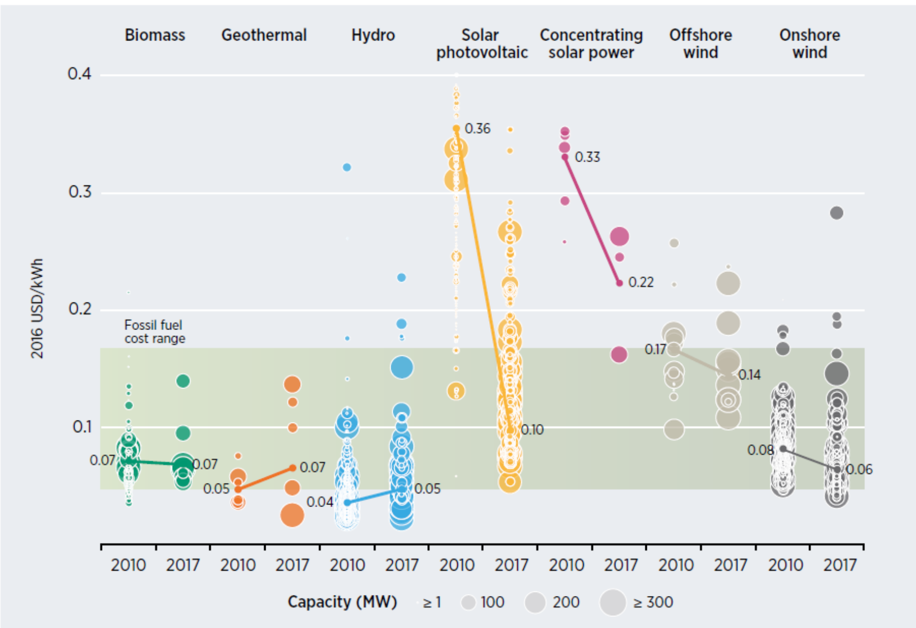
- Burning, rather than burying landfill material can provide a little boost.
- Denmark is one of the world leaders in burning their junk.



- Interestingly, Denmark produces slightly more junk than the USA.
- However this process produces CO_2.
- Furthermore the energy gained by burning only corresponds to 4% of the total Danish energy needs.
- If Danes are environmentally friendly and produce less junk, this number will drop.

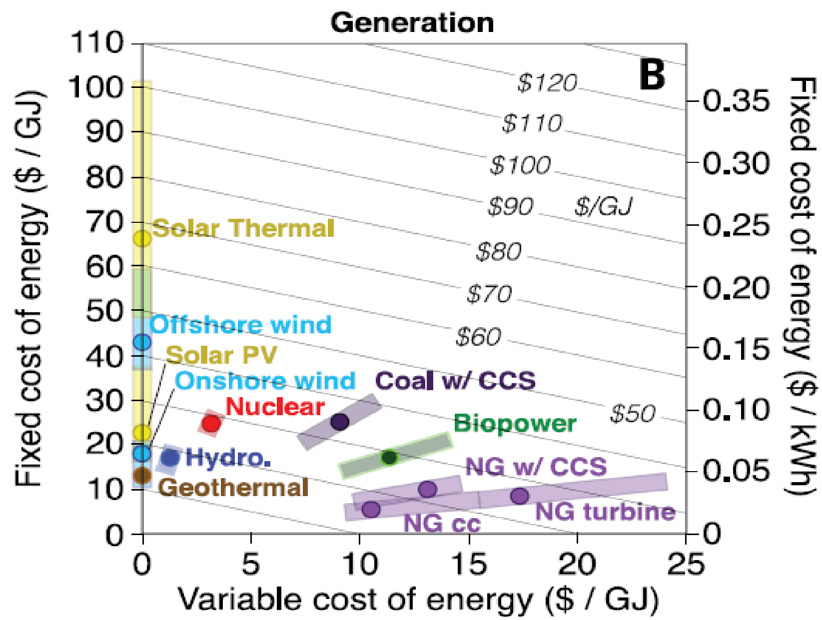
Economic Competitiveness

- Are renewable energy sources economically competitive?



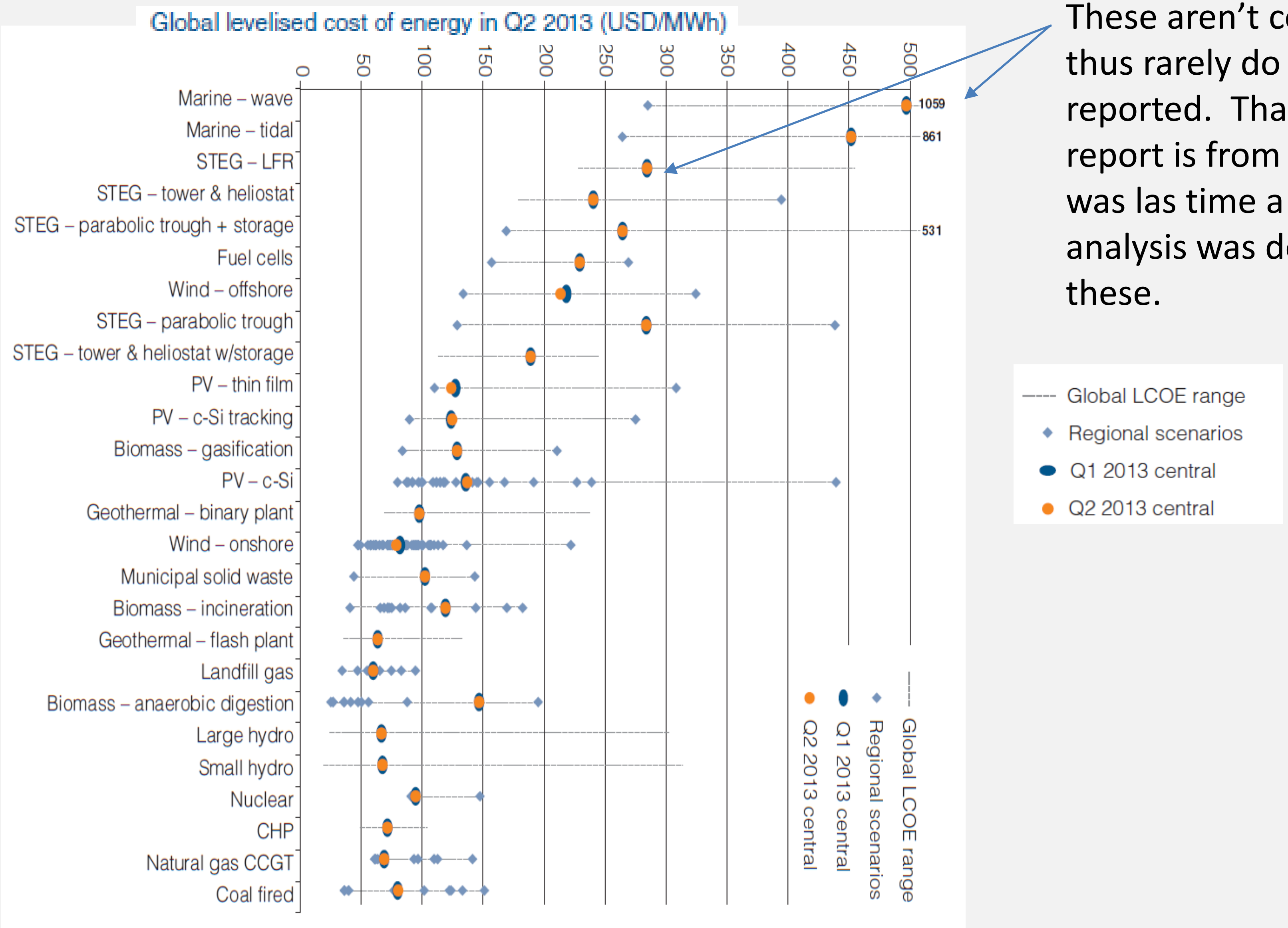
Source: IRENA Renewable Cost Database.

Note: The diameter of the circle represents the size of the project, with its centre the value for the cost of each project on the Y axis. The thick lines are the global weighted average LCOE value for plants commissioned in each year. Real weighted average cost of capital is 7.5% for OECD countries and China and 10% for the rest of the world. The band represents the fossil fuel-fired power generation cost range.



Economic Competitiveness

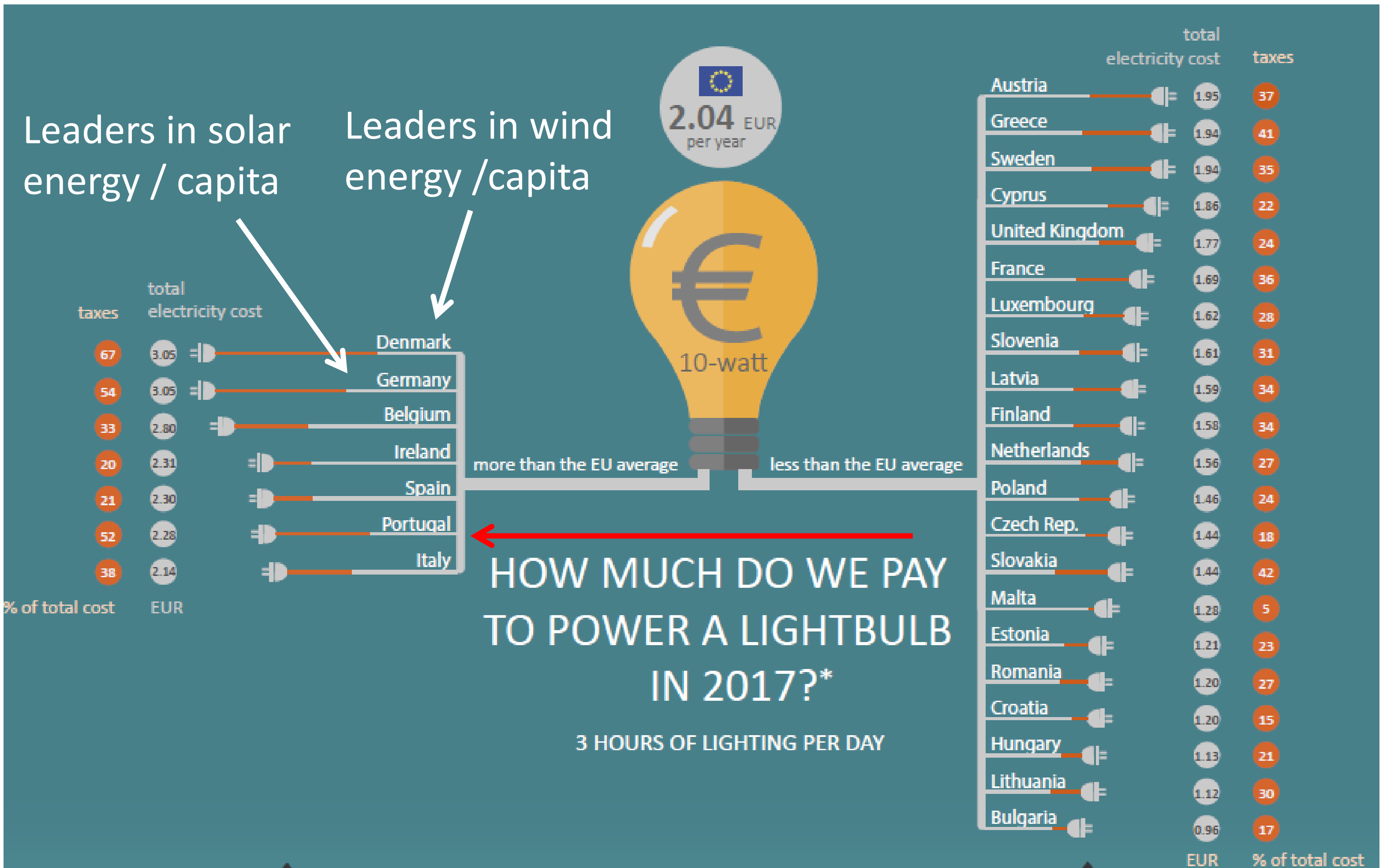
- How about other renewable sources?



These aren't competitive, thus rarely do they get reported. That is why this report is from 2013. This was las time a thorough analysis was done on these.

Electricity Costs

- Divide the number below by ~10 to get Euro/kWh.
- For reference, electricity prices are .09 Euro/kWh in USA and in 0.07 Euro/kWh in China



From Eurostat

Scale Up

Now

Solar Energy
(0.03 TW)

Wind Energy
(0.1 TW)

Hydropower Energy
(1.05 TW)

30 years from now

30 TW

- To reach this we would need either:

  1) 48,000 km^2 of PV deployed every year (Denmark is 43,000 km^2)
     - assuming they last 20 years

  2) 500,000 of 6 MW wind turbines/year
     - assuming they last 40 years
     - currently there are 35,000 6 MW (equivalent) units worldwide

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!

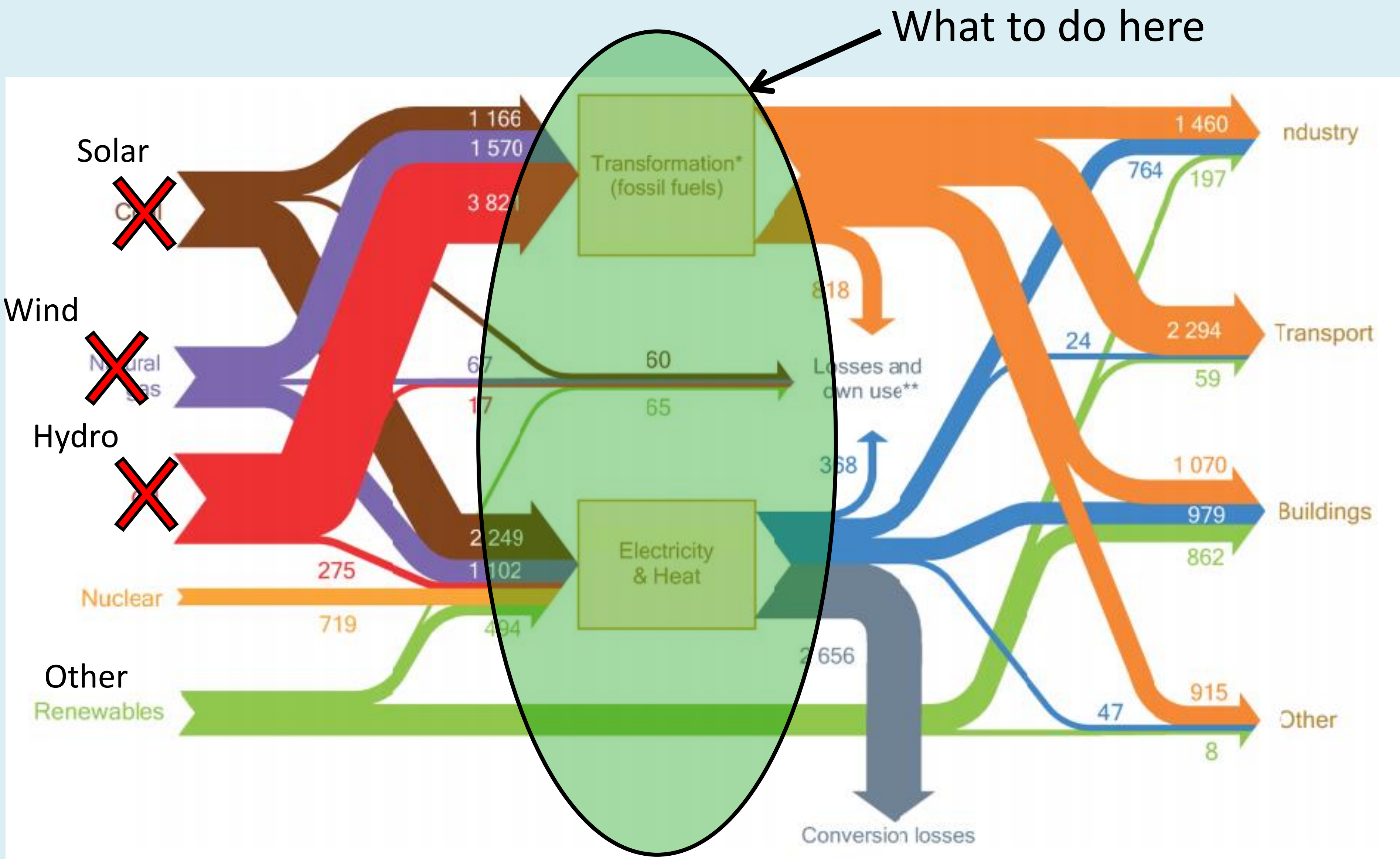
Current Situation

Oil

Future Situation

Sun

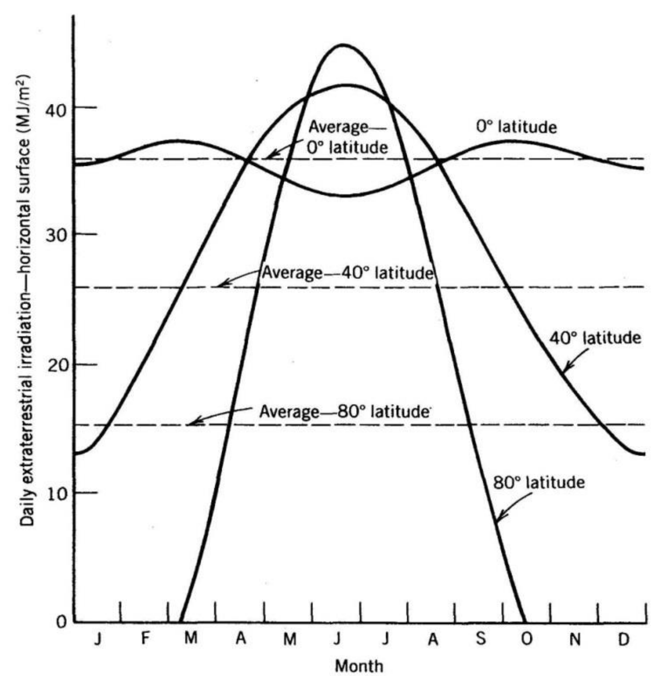
We need the inputs to match the outputs



Energy Fluctuations

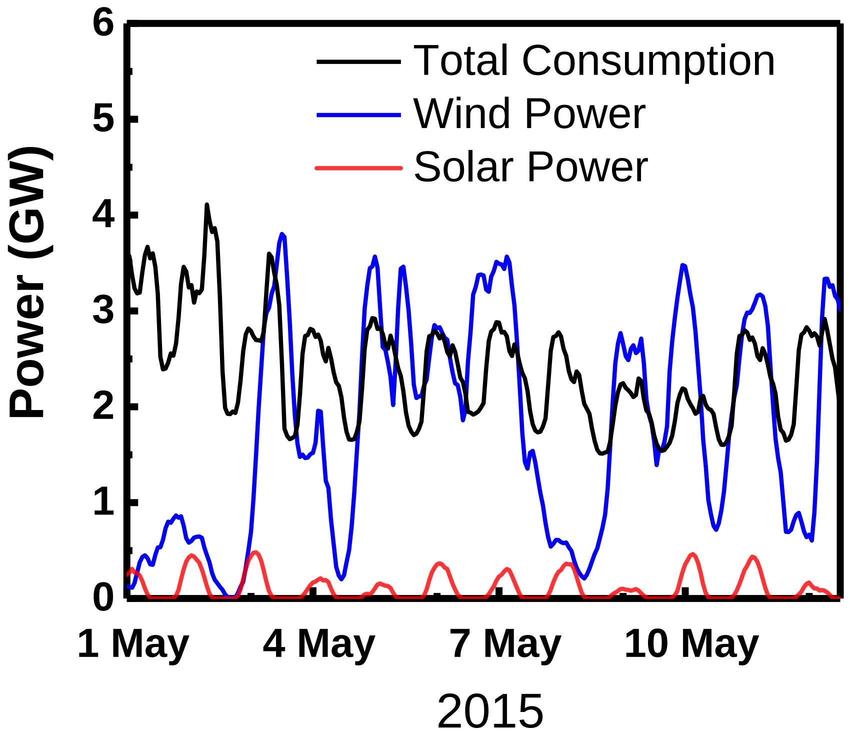
- Unlike fossil fuels that are just sitting there, most renewables have large fluctuations.
- **Solar**- Fluctuates on a seasonal basis with cloud coverage effecting on a daily or even minute time scale.
- **Wind**- Fluctuates on a daily basis with minor fluctuations on a second time scale.
- **Hydropower**- Little fluctuations, some seasonal issues.
- **Geothermal, tide** – Little fluctuations.

Copenhagen latitude – 55.7º



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 8 years, ~50% of its wind power was not used within Denmark.
- Economically this is bad.
- Currently we sell our excess electricity to other countries.



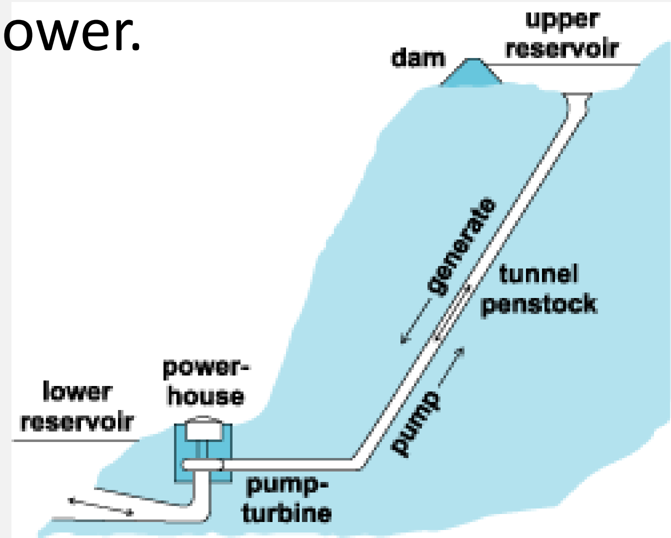
Denmark electricity generation/consumption
(data from Energinet.dk)

Storing Energy

- Rather than make a large excess number of solar cells/wind turbines, its 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, underveloped, great for long times and large amounts.
- There are also a relatively large amount of minor approaches:
  - Pumped storage
  - Flywheels
  - Supercapacitor
  - Compressed air

Pumped Storage

- Pumped storage is basically an inverted hydro-electric plant.
- Pump the water up a hill to store the energy, gain the energy when it comes back down.
- You need mountains to have pumped storage.
- Norway has large pumped storage and is acting as a storage depot for Denmark and Germany's excess wind power.
- Typically the roundtrip efficiency is 70-80%, which is quite good.
- Current worldwide maximum output is 0.132 TW, but most sites empty in less than 24 hours.



Why pumped hydro storage is unscalable:
http://physics.ucsd.edu/do-the-math/2011/11/pump-up-the-storage/

Using Batteries

- Batteries store energy via a chemical redox reaction.
- Roundtrip efficiencies of 80-90%.
- Typically made of Li or Ni and Cd.
- Current battery production is about [170 GWh](#) per year.
- Upscaling batteries is Tesla's approach.
- We will have 1 lecture on this topic.

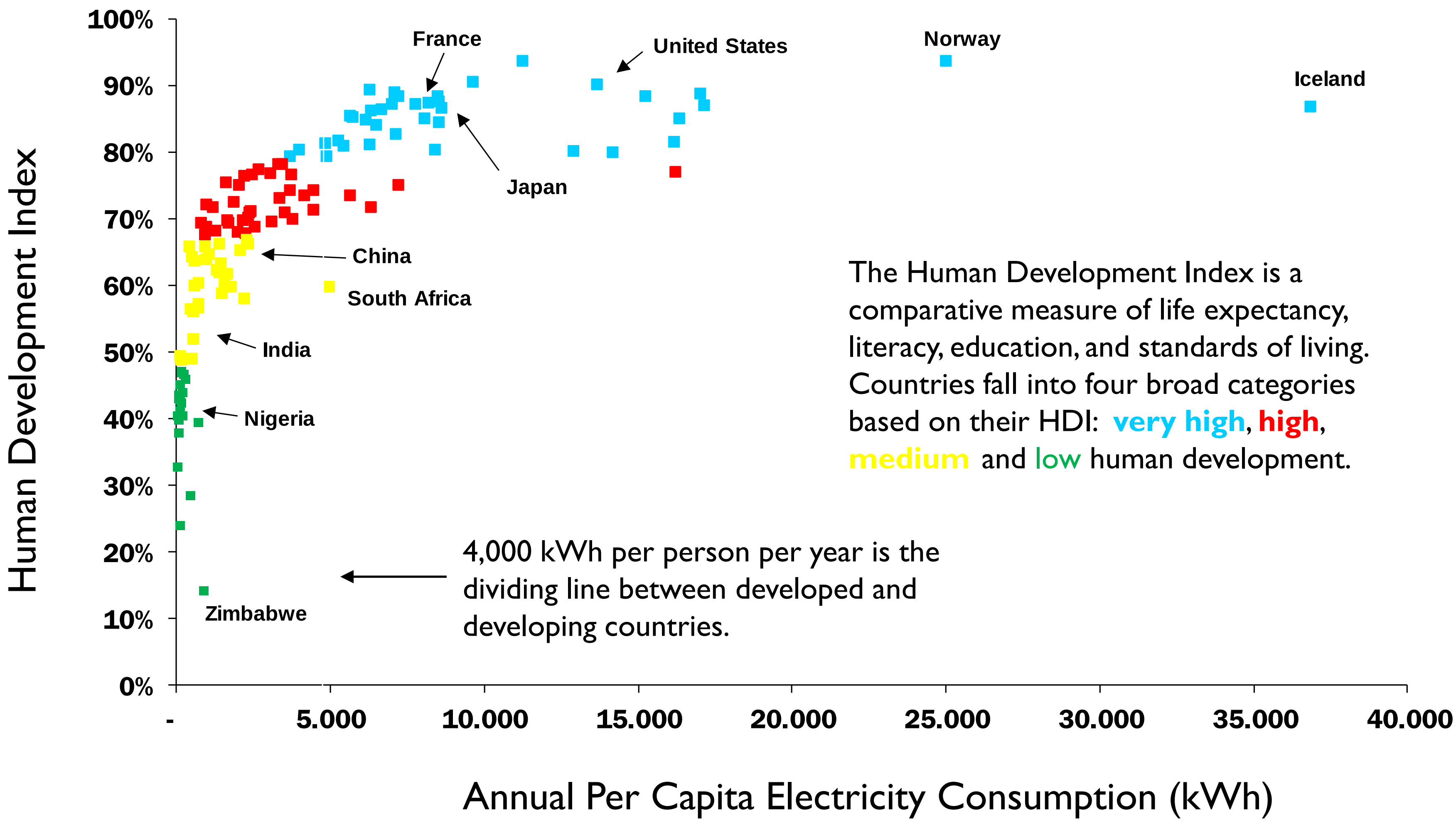
The advantage of electricity

- Coal, oil, and natural gas derive useful power based off of the heat engine.
- This is limited by Carnot efficiency:

$$\eta = \frac{T_h - T_c}{T_h}$$

- Typical fossil fuel power plants are limited to efficiencies of ~30-35%.
- The worldwide 18 TW energy # is a raw energy number.
- Electrical power is not limited by the Carnot Efficiency.
- However there are still entropy effects that can limit the efficiency.

Correlation Between Human Development and Per Capita Electricity Consumption



Source: Human Development Index – 2010 data United Nations; Annual Per Capita Electricity Consumption (kWh) - 2007 data World Bank

Updated: 4/11

Molecular Fuels

- Molecular fuels allows for storage on the year-decade scale.
- There is already an infrastructure for fossil fuels.
- These can be made via biomass conversion or electro-chemical reactions.
- Electrochemical reactions simply take electricity and precursors (like H_2O and CO_2) and create fuels.
- Electrochemically, the simpler the molecule the easier it is to make.
- H_2 production and CO_2 to hydrocarbons are the 2 biggest areas of focus.

H_2 Economy

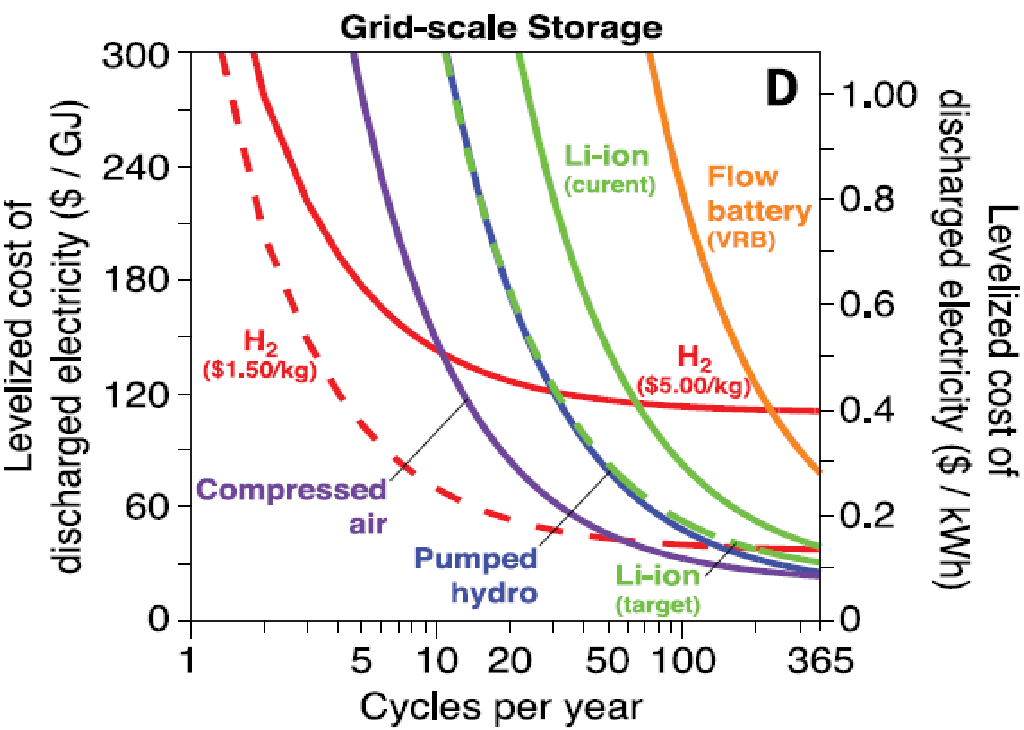
- One grand-scheme approach is to run society on H_2 as a fuel.
- Basically electrolyzers convert unused wind or solar to hydrogen and then fuel cells convert them back to electricity when needed.

$$H_2O \underset{\text{Fuel cell (or combustion)}}{\overset{\text{Electrolysis}}{\leftrightarrow}} H_2 + \frac{1}{2}O_2$$

- Electrolyzer efficiencies are 70-75% efficient and fuel cells are 60-70% efficient. Round trip efficiency of 47%.
- Bad catalysis is preventing higher efficiencies for fuel cells and electrolyzers.
- We will have 1 lecture on this topic.

How does Storage Compare

- The cost is a function of how much 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.



Materials

- Basically we are looking to produce 17-30 TW of energy from nothing.
- Do we produce enough raw materials to make solar cells, wind turbines, batteries, etc?
- It depends- we can't make our solar cells out of Au and Pt, but Fe and Si is not a problem.
- If a rare material is cheap now, will it still be cheap if we need 30 TW of it?
- What are the 'sustainability' limits from a materials stand point?

Energy conservation

- Can we conserve our way out of the energy dilemma?
- Not completely- We need drastic drops to resolve the CO_2 dilemma.
- Drastic drops equals drop in economic activity.
- There are areas where we can make significant savings though.
  - Improved lighting efficiency
  - Improved heating efficiency
  - Improved insulation
  - Switch from heat engines to electrical devices.

Summary

- We use 18 TW of energy, mostly of fossils fuels.
- Population is increasing and the energy/capita is also increasing.
- Energy = wealth.
- The issue with CO_2 and climate change appears to be an absolute disaster.
- There is potentially enough renewable energy to meet our demands with solar irradiation having the largest potential.
- The world produces very little renewable energy now.
- Storing and intermittency issues are almost as big an issue as harvesting renewable energy.

Lecture - Learning objectives

At the end of this lecture you should understand:

- What fuels we currently use, how much of we use, how we use it, and how much is left.
- How population and economics are related to energy.
- How much CO_2 we are contributing to the atmosphere.
- What are the major sustainable energy approaches and storage mediums.

Exercises:

- Assuming we have a 10 year supply of batteries (170 GW-h/year), how long could batteries support the world's energy needs (18 TW)?
- Approximately how much of the world's energy consumption is based off the heat engine/Carnot Efficiency? Do a rough estimation based off the energy data presented here (very little math needed, but just reasonable estimates).

- Energy Vault wants to store energy by picking up concrete and using gravity as a means to store energy. If each block is 1m high 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.

Concept Check

How much energy does the Earth use on average?

a) 800 GW

b) 2 TW

c) 10 TW

d) 18 TW

e) 30 TW

Concept Check

What renewable energy production method has provided the world with the most energy?

a) Geothermal

b) Hydroelectric

c) Photovoltaic

d) Wind Energy

Concept Check

The world's coal reserves will last

a) 10 years

b) 30 years

c) 50 years

d) more than 100 years

Concept Check

The average CO_2 increase per year over the last decade is:

a) 10 ppb / year

b) 2 ppm / year

c) 0.1 % / year

d) 1 % / year

Concept Check

The largest energy source for electricity (in 2012) is:

a) Biomass

b) Coal

c) Nuclear

d) Natural Gas

e)Renewables