ENERGY:
SOURCES, CONVERSION & UTILIZATION

Ahmed Ghoniem

Lecture # 1
Feb 3, 2020

- Subject Themes
- Sources and consumption, now and then
- Environmental Impact, CO_2
- Solutions and Scaling
- Technologies

Ghoniem, A.F., Needs, resources and climate change: Clean and efficient conversion technologies, *Progress Energy Combust Science*, 37, 2011, pp. 15-51. http://dx.doi.org/10.1016/j.pecs.2010.02.006
Ghoniem, A.F., Energy Conversion Engineering, Chapter 1.

FUNDAMENTALS OF ADVANCED ENERGY CONVERSION

2.60 (U), 2.62 (G), 10.390J (U)10.392J (G), 22.40J (G)

Instructor: Ahmed Ghoniem

TA: Omar Labban

Spring 2020, MW 12:30-2:30 PM

Fundamentals of Energy conversion Engineering: processes and systems utilizing fossil and renewable energy (solar, wind biomass, geothermal) and nuclear resources, with emphasis on efficiency and environmental impact especially CO_2.

Prereq.: 2.006/equivalent or permission of instructor.
Grading: Homework and term project
U and G students are graded separately.

Energy conversion engineering: power for electricity production; conventional, renewable and hybrid. Direct conversion & fuel cells, Synthetic and biofuels. Solar, wind and biomass. Storage. "Hydrogen & electric economies". CO_2 capture and reuse. Life Cycle Analysis: efficiency and emissions.

Image courtesy of DOE.

SUBJECT THEMES 1

We cover concepts and tools used to analyze conversion of energy sources into useful forms, primarily electricity and fuels, using different technologies. For instance, the conversion of the chemical energy to carbon free (H_2) fuels for transportation, or biomass to ethanol.

We discuss converting chemical energy to electricity, covering fuel cells and turbines. We compare options, e.g., biomass to electricity for electric cars, or biomass to ethanol for a flex fuel engines. Comparisons are based on overall efficiency and CO_2 emissions (WTW or LCA).

An important theme is "CO_2" and what to do about it: use carbon capture, reuse and storage, nuclear or renewables?

We discuss capturing heat from the sun, geothermal wells or nuclear reactors, and how it is used to produce electricity or fuels.

We discuss hydrogen production using thermolysis of electrolysis.

SUBJECT THEMES 2

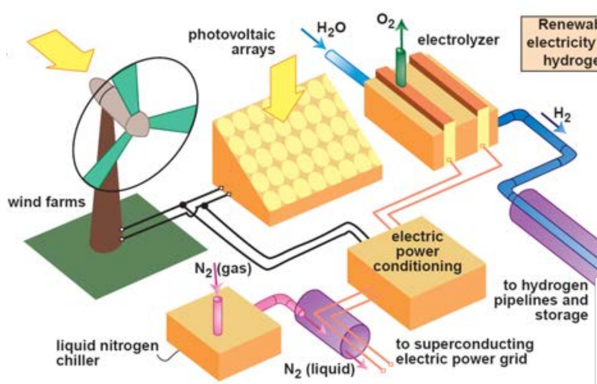
We discuss fundamentals of battery technology for electricity storage.

We discuss the challenges for hydrogen as a transportation fuel and how it can be enabled.

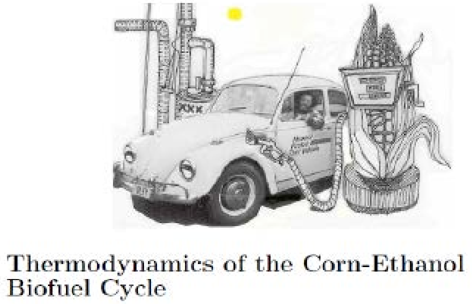
We talk about carbon capture in power and fuel production, the technical advantages using different technology pathways.

We cover integrated and hybrid systems and how combining different conversion technologies can improve efficiency : combined cycles, hybrid solar-NG, etc., also how integrating storage can further improve the system.

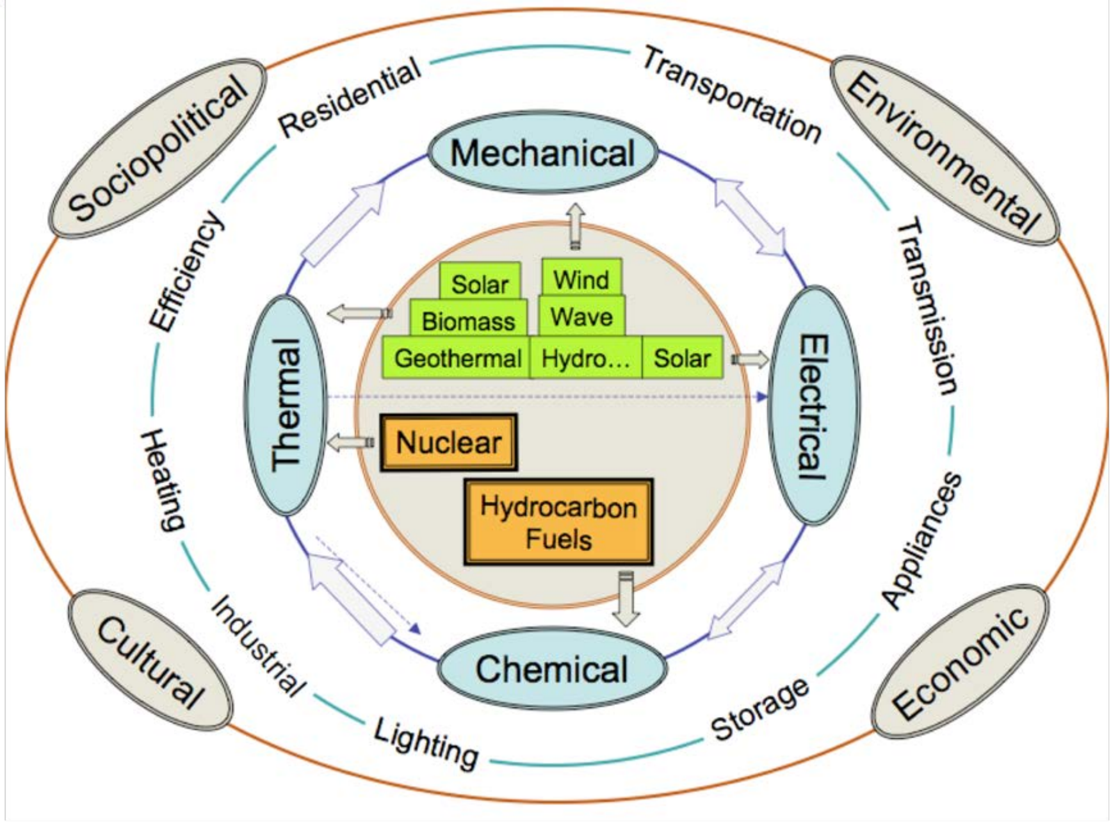
We talk about the difference between concentrated generation and distributed generation,

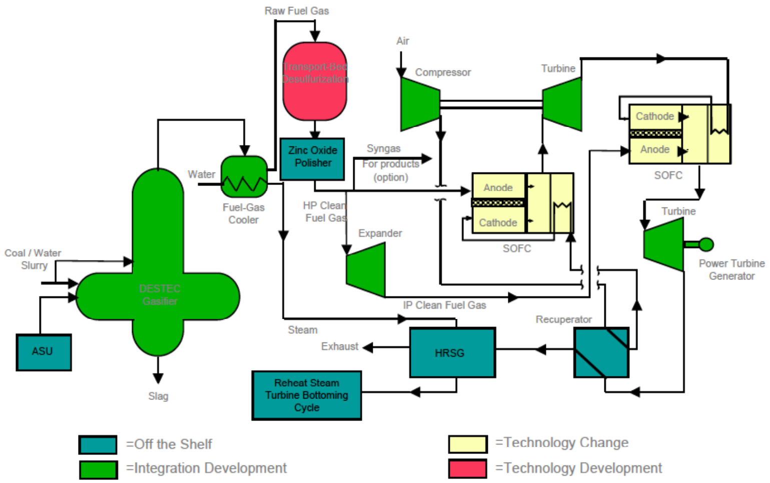


Hoffert et al., Science, 298 (2002)



Tad W. Patzek (2004) "Thermodynamics of the Corn-Ethanol Biofuel Cycle", *Critical Reviews in Plant Sciences*, 23:6, 519-567, DOI: 10.1080/07352680490886905.





Fuel cell handbook. Office of fossil energy.

Image courtesy of DOE.

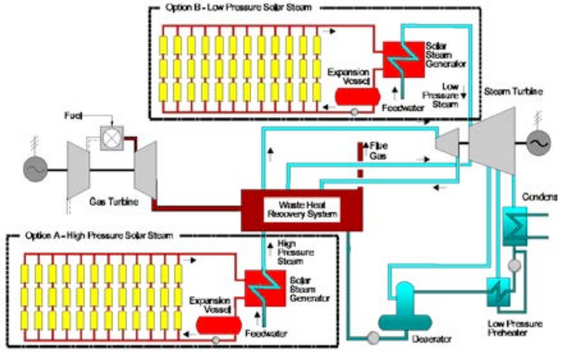


Figure 2. Integrated Solar Combined Cycle System [1].

Mancini TR. An overview of concentrating solar power.

Image courtesy of DOE.

#	Date	Topic	HW	Project
1	M 02/03	Introduction, Energy Challenges		
2	W 02/5	Thermodynamics, Availability		
3	M 02/10	Mixtures and Separation	HW 1, posted	
4	W 02/12	Applications, EES-1		Project posted
5	T 02/18	Chemical Thermodynamics	HW 1, DUE	
6	W 02/19	Conversion and Equilibrium	HW 2, posted	
7	M 02/24	Gasification, Reforming, EES-2		projects selected
8	W 02/26	Electrochemistry	HW 2, DUE	
9	M 03/02	Fuel Cells	HW 3, posted	
10	W 03/04	Electrolysis, H_2 & Storage		
11	M 03/09	Batteries	HW 3, DUE	
12	W 03/11	Photovoltaics	HW 4, posted	
13	M 03/16	Power plants I		
14	W 03/18	Power Plants II	HW 4, DUE	

#	Date	Topic	HW	Project
15	M 03/30	Geothermal/Solar Thermal		Mid Terms Report
16	W 04/01	System Modeling & Aspen	HW 5, posted	
17	M 04/06	Energy & Materials		
18	W 04/08	Gas separation	HW 5, Due	
19	M 04/13	CCS I	HW 6, posted	
20	W 04/15	CCS II		
21	W 04/22	Wind	HW 6, DUE	
22	M 04/27	Biomass I		
23	W 04/29	Biomass II		
24	M 05/04	Storage		
25	W 05/06	Nuclear Energy		Final Report due, 05/08
26	M 05/11	PROJECT PRESENTATIONS		

Please note that, from experience, some small changes in the ordering of the lectures or the topics may be used during the semester according to the pace and coverage, but the HW and project schedule will remain fixed.

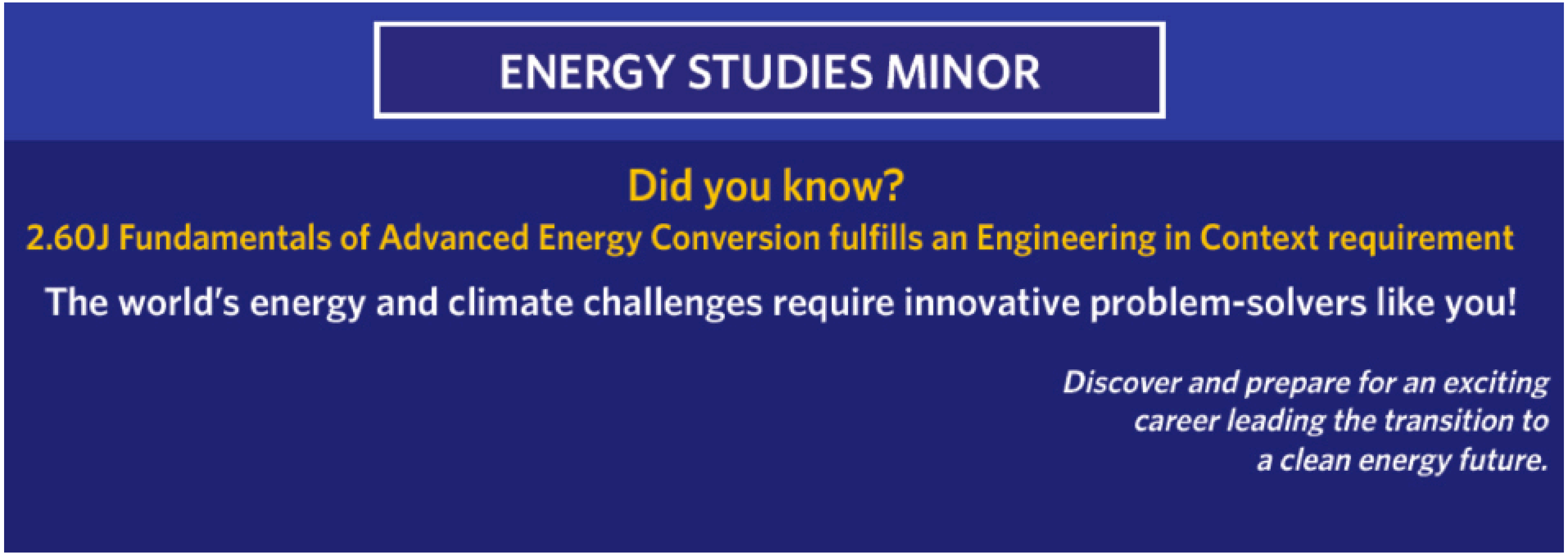
- Lectures are 2x50 min (with a break in between)
- PPTs will be posted lecture by lecture
- HW every other week, last two weeks of the semester dedicated to finishing the project

Grading policy:
U & G are graded separately.
66% Homework (6x11) + 34% Project (total).
Term project: 9% midterm report + 20% final report + 5% presentation

ENERGY CONVERSION ENGINEERING FOR LOW CO_2 POWER & FUELS:

FUNDAMENTALS AND SYSTEMS FOR CCS AND RENEWABLES;
WITH FOCUS ON EFFICENCY AND INTEGRATION

1. Low carbon Energy?
2. Thermodynamics: Availability
3. Chemical Thermodynamics:
4. Electrochemical Thermodynamics,
5. Gas Turbine Cycles
6. Rankine Cycles
7. Fuel Cells, SOFCs
8. Combined and Hybrid Cycles
9. Solar Thermal & Geothermal
10. Gas Separation
11. Low CO_2, NG
12. Coal
13. Low CO_2, Coal
14. Biomass



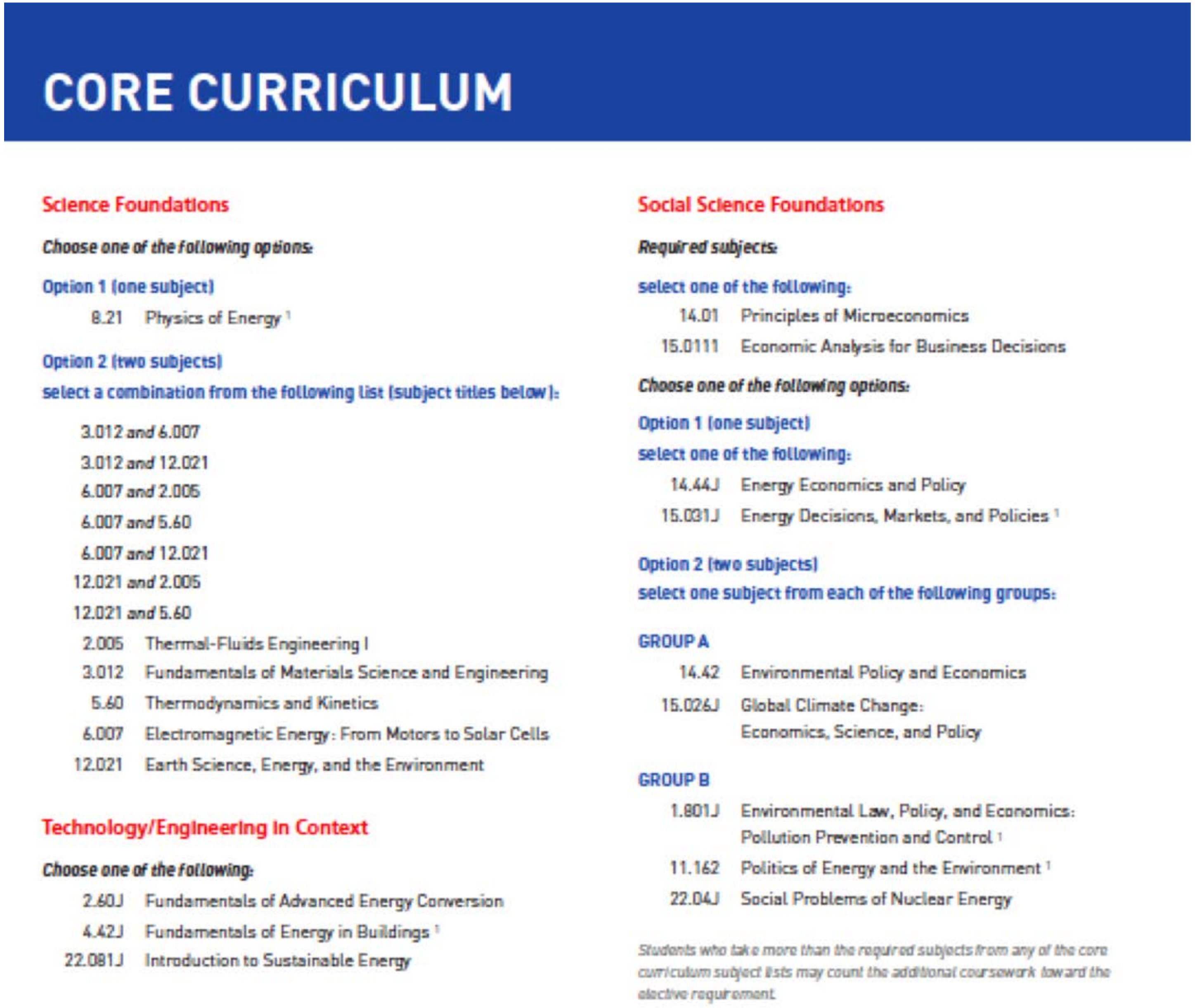
ENERGY STUDIES MINOR

Did you know?

2.60J Fundamentals of Advanced Energy Conversion fulfills an Engineering in Context requirement

The world's energy and climate challenges require innovative problem-solvers like you!

Discover and prepare for an exciting
career leading the transition to
a clean energy future.



CORE CURRICULUM

Science Foundations

Choose one of the following options:

Option 1 (one subject)

8.21	Physics of Energy [1]

Option 2 (two subjects)

select a combination from the following list (subject titles below):

3.012 *and* 6.007
3.012 *and* 12.021
6.007 *and* 2.005
6.007 *and* 5.60
6.007 *and* 12.021
12.021 *and* 2.005
12.021 *and* 5.60

2.005	Thermal-Fluids Engineering I
3.012	Fundamentals of Materials Science and Engineering
5.60	Thermodynamics and Kinetics
6.007	Electromagnetic Energy: From Motors to Solar Cells
12.021	Earth Science, Energy, and the Environment

Technology/Engineering in Context

Choose one of the following:

2.60J	Fundamentals of Advanced Energy Conversion
4.42J	Fundamentals of Energy in Buildings [1]
22.081J	Introduction to Sustainable Energy

Social Science Foundations

Required subjects:

select one of the following:

14.01	Principles of Microeconomics
15.0111	Economic Analysis for Business Decisions

Choose one of the following options:

Option 1 (one subject)

select one of the following:

14.44J	Energy Economics and Policy
15.031J	Energy Decisions, Markets, and Policies [1]

Option 2 (two subjects)

select one subject from each of the following groups:

GROUP A

14.42	Environmental Policy and Economics
15.026J	Global Climate Change: Economics, Science, and Policy

GROUP B

1.801J	Environmental Law, Policy, and Economics: Pollution Prevention and Control [1]
11.162	Politics of Energy and the Environment [1]
22.04J	Social Problems of Nuclear Energy

Students who take more than the required subjects from any of the core curriculum subject lists may count the additional coursework toward the elective requirement.

A Perpetual Concern …..

"Matter and Energy" (1912)
Frederick Soddy,Noble Prize, Chemistry, 1921.

"The laws expressing the relations between energy and matter are not solely of importance in pure science. …………. they control the rise or fall of political systems, the freedom or bondage of nations, the movements of commerce and industry, the origin of wealth and poverty and the physical welfare of the race."

The Terawatt Challenge: R. Smalley, Noble Prize, Chemistry 1997

- **ENERGY**
- WATER
- FOOD
- ENVIRONMENT
- POVERTY
- TERRORISM, WAR
- DISEASE
- EDUCATION
- DEMOCRACY
- POPULATION

Needs: Energy Consumption

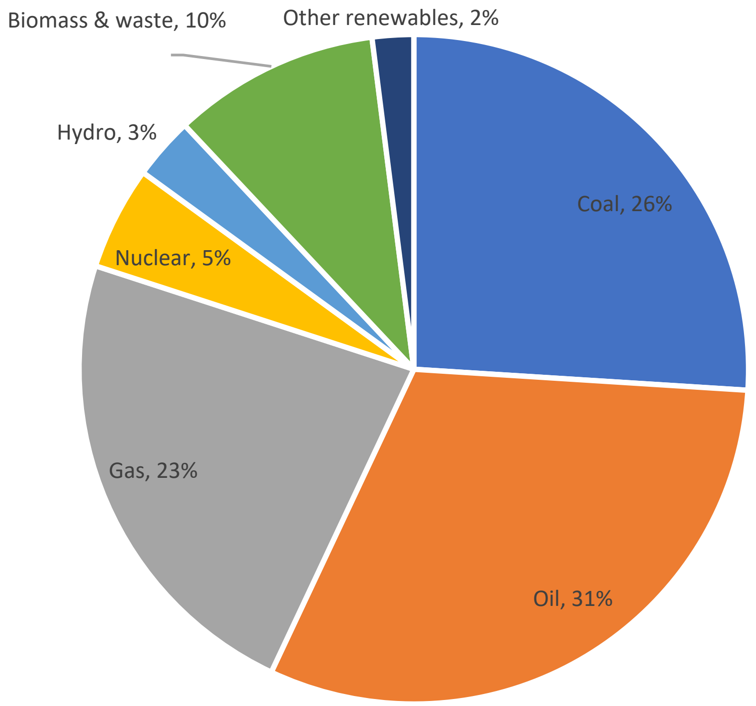
~ 600 EJ (~ 440 EJ in early 2000's) produced by close to 18 TW Power (6.1 TW for electricity generation)

The breakdown of the World primary energy consumption in 2014. The total is 13,558 Mtoe (million tonne oil equivalent) (was 11,059 Mtoe in 2006). Except for hydropower, primary energy measures the thermal energy equivalent in the fuel that was used to produce a useful form of energy, e.g., thermal energy (heat), mechanical energy, electrical energy, etc. When energy is obtained directly in the form of electricity, efficiency is used to convert it to equivalent thermal energy.

1 toe ~ 42 GJ.

IEA World Energy Outlook 2015, p57.

Breakdown in 2018



US resources, consumption and patterns ~100 EJ annually in 2018,

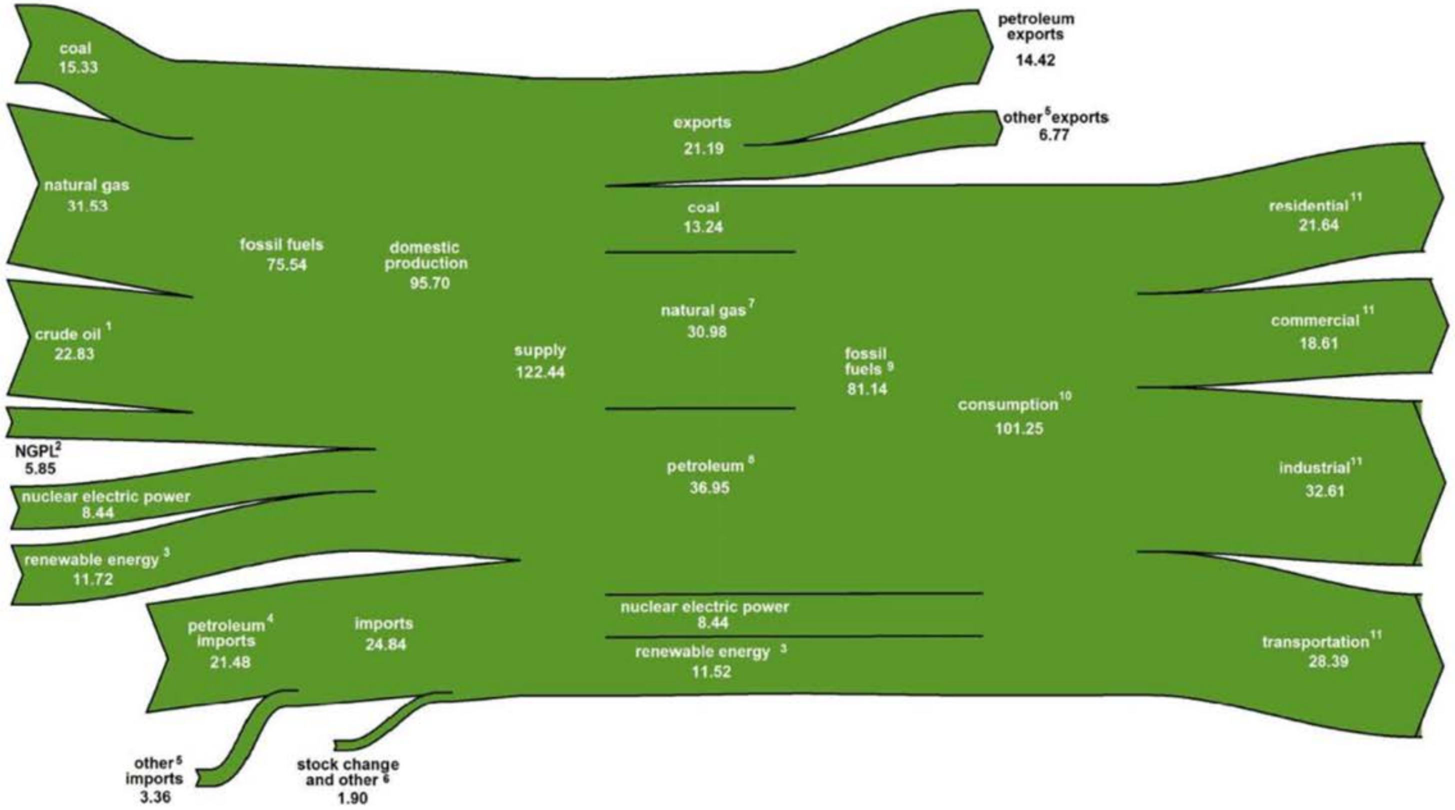
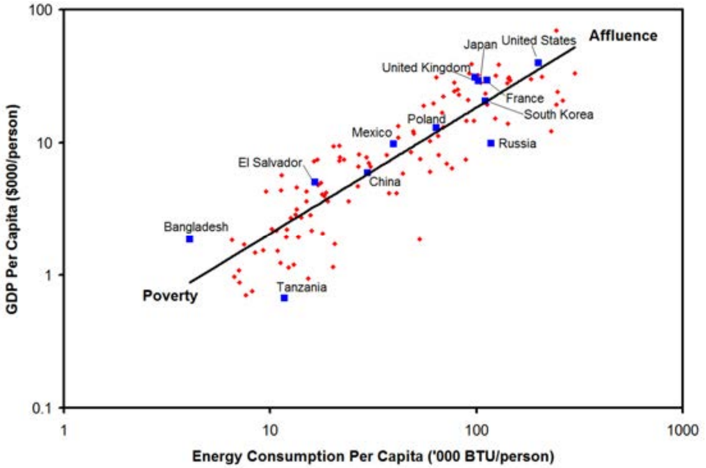


Image courtesy of U.S. Energy Information Administration.
https://www.eia.gov/totalenergy/data/monthly/pdf/flow/total_energy.pdf

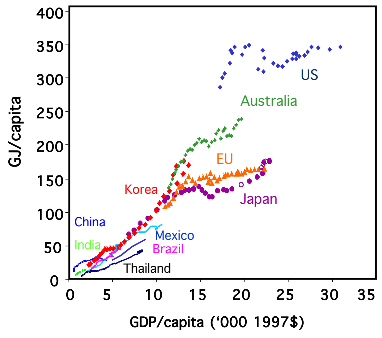
© by Ahmed F. Ghoniem

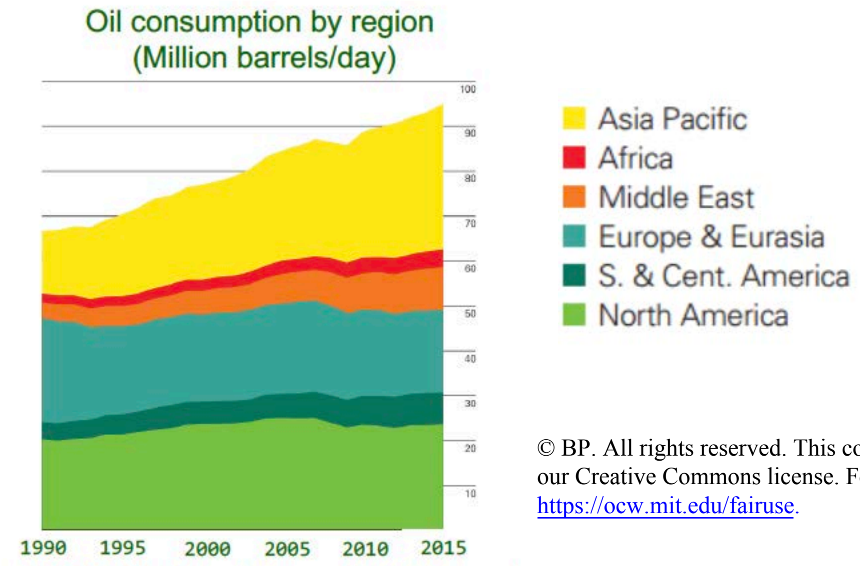
Who uses how much?

Per capita energy consumption and GDP. (Produced from data from the United Nations Development Programme (UNDP) Human Development Report (HDR) 2006.

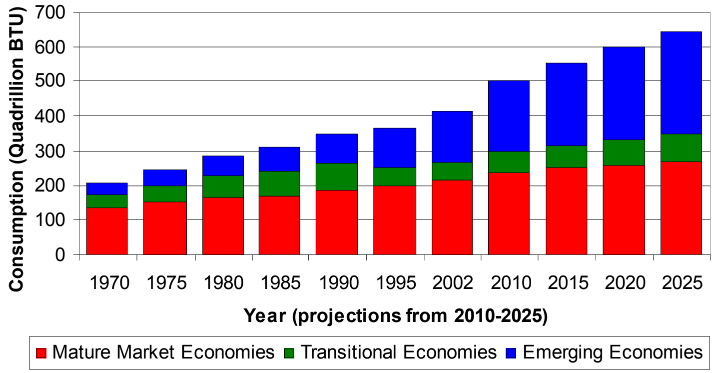


Reference: GDP per capita data for 2004 from Table 1, pages 283-286. Energy consumption per capita found by dividing GDP per capita data for 2004 (Table 1, pages 283-286) by GDP per unit of energy use for 2003 (Table 21, pages 353-356). GDP per unit of energy use for 2003 is expressed in dollars for the year 2000.



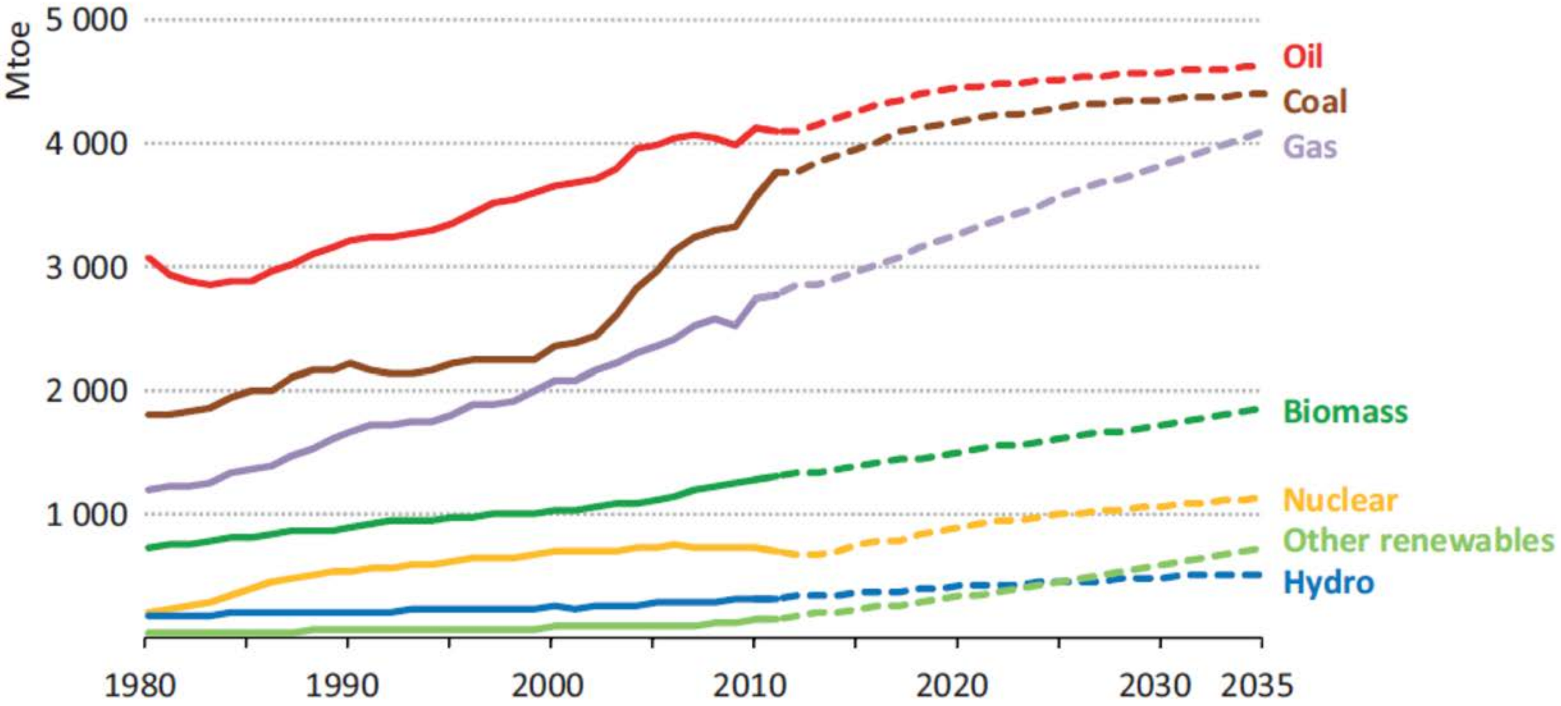


BP 2016 Statistical Review of World Energy



Energy demand by economic status for the past three decades, and projects for the next three on the basis of the current trends (IEA Energy Outlook, 2005)

World primary energy demand by fuel

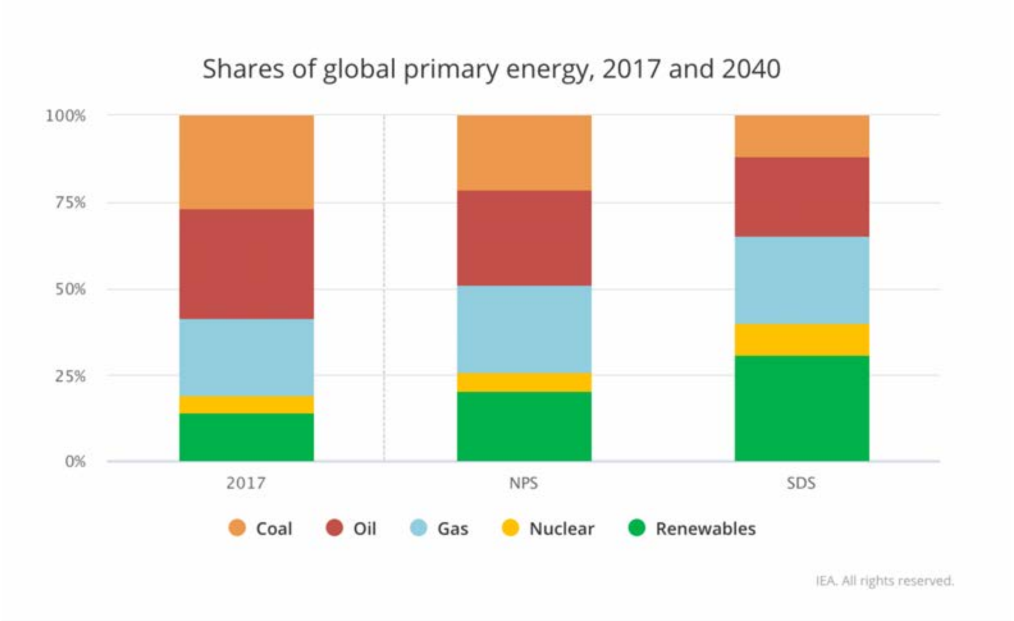


Predicted based on the continuation of existing policies and measures as well as cautious implementation of policies that have been announced by governments but are yet to be given effect (mid-2013).

Source: IEA world energy outlook 2013, P63

Shares of global primary energy, 2017 and 2040

Source: https://www.iea.org/weo2018/fuels/



New Policies Scenario (NPS): Global oil demand growth slows but does not peak before 2040.

Sustainable Development Scenario (SDS): Determined policy interventions to address climate change lead to a peak in global oil demand around 2020 at 97 mb/d.

Global Greenhouse Gas Emissions by Economic Sector (2015)

https://www.epa.gov/sites/production/files/2016-05/global_emissions_sector_2015.png

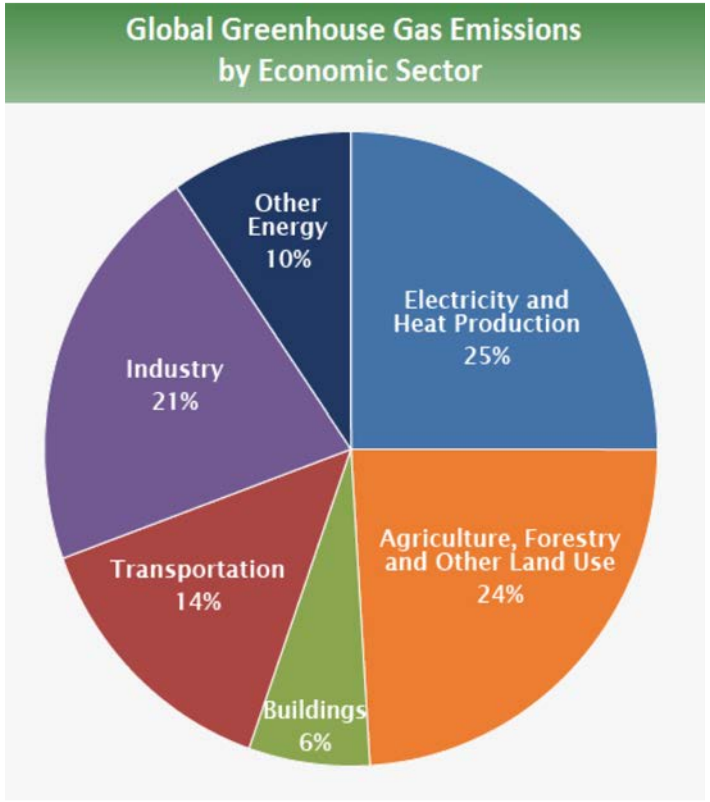
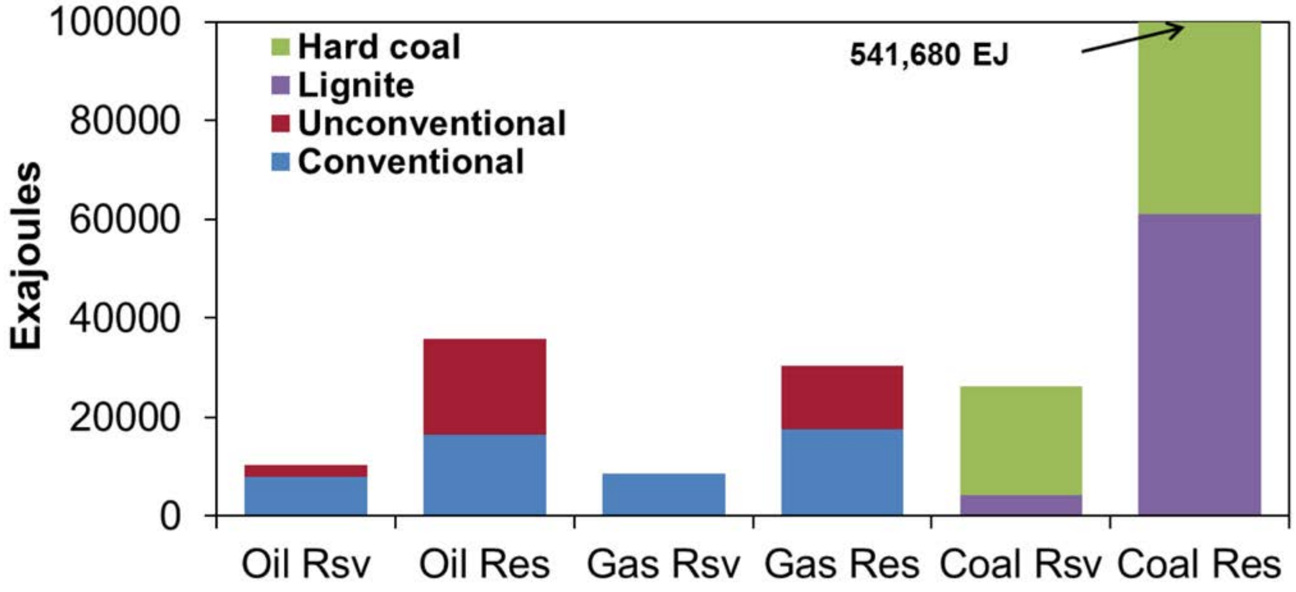


Image courtesy of EPA.

Fuel Reserves and Resources

there is plenty of Hydrocarbons, but ..



	Reserves/(2013 Consumption/yr)	Resource/(2013 Consumption/yr)
Oil	44 – 58	93 – 203
Gas	70	145 – 250
Coal	133 – 158	3282 - 3652

Care should be exercised when projecting?

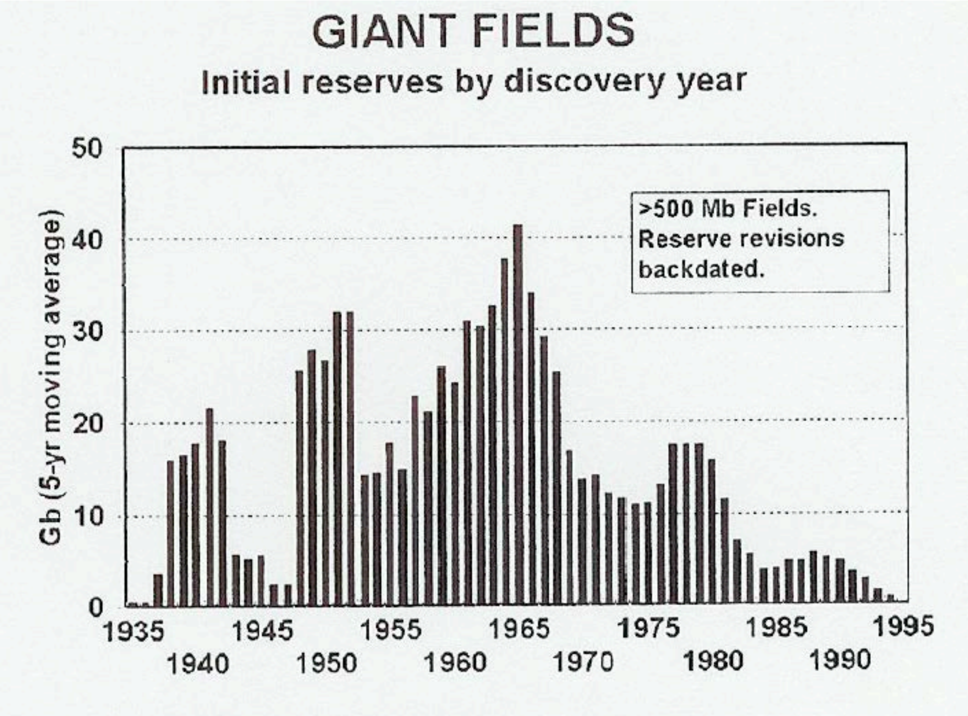
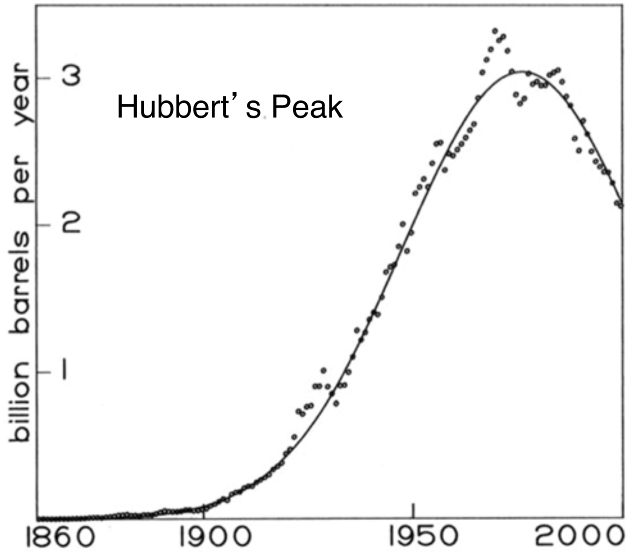


Fig. 15-2. Giant discovery.

US production
Predicted _______
Actual . . . . . .
In 2015, US production was 3.4 BBy



Campbell, the Coming Oil Crisis, 1998

The US is now the largest oil producer (thanks to fracking)

CO_2 emissions and Climate Change!

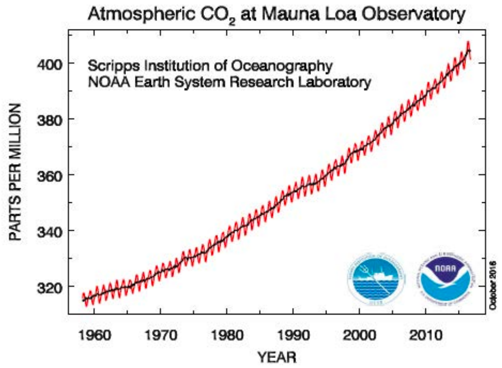
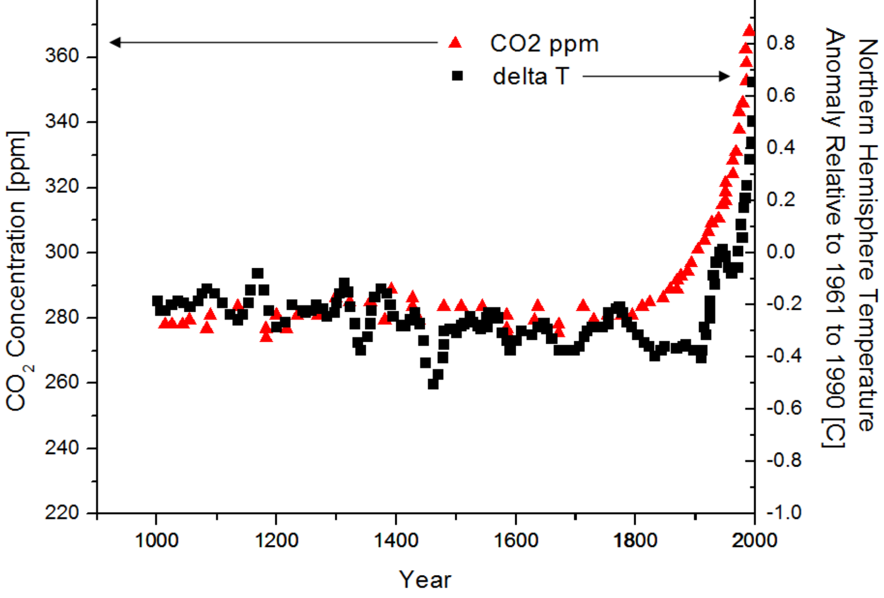


Image courtesy of NOAA.



Courtesy Elsevier, Inc., http://www.sciencedirect.com. Used with permission.

Source: http://dx.doi.org/10.1016/j.pecs.2010.02.006

Greenhouse gases are: CO_2, CH_4 and N_2O and CFCs (H_2O and aerosols are also GH gases)

Arrhenius predicted CO2 impact on global T back in 1896

Intergovernmental Panel on Climate Change record of temperature over Antarctica, atmospheric concentration of CO_2 and methane during the past 420,000 years

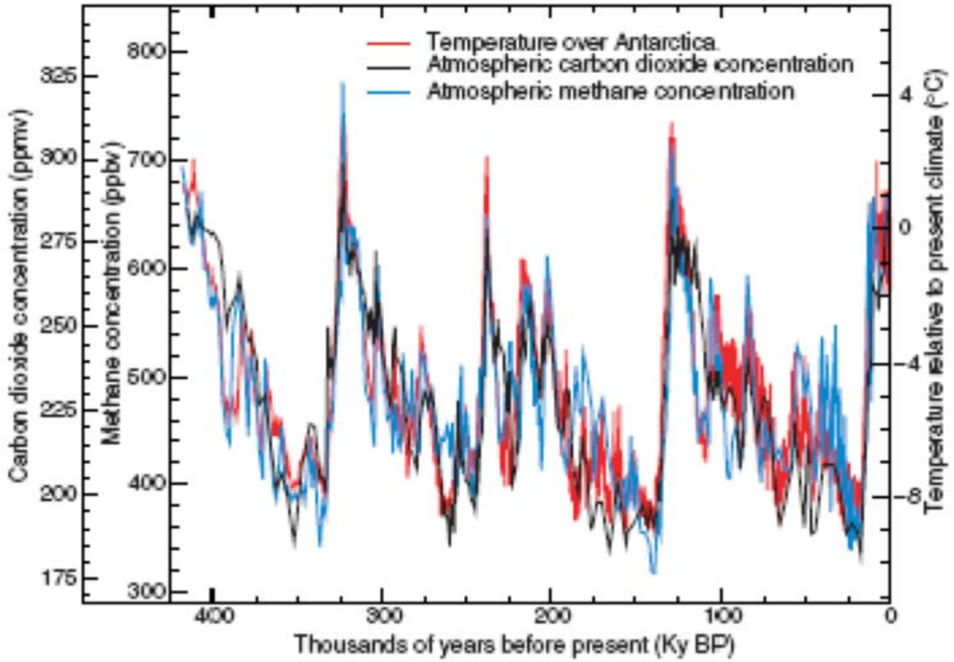


Figure 2.22: Variations of temperature, methane, and atmospheric carbon dioxide concentrations derived from air trapped within ice cores from Antarctica (adapted from Sowers and Bender, 1995; Blunier *et al.*, 1997; Fischer *et al.*, 1999; Petit *et al.*, 1999).

Reference: IPCC Third Assessment Report (2001), Working Group I, Ch. 2, Figure 2.22, page 137. Variations of temperature, methane, and atmospheric carbon dioxide concentrations derived from air trapped within ice cores from Antarctica.

The global energy balance

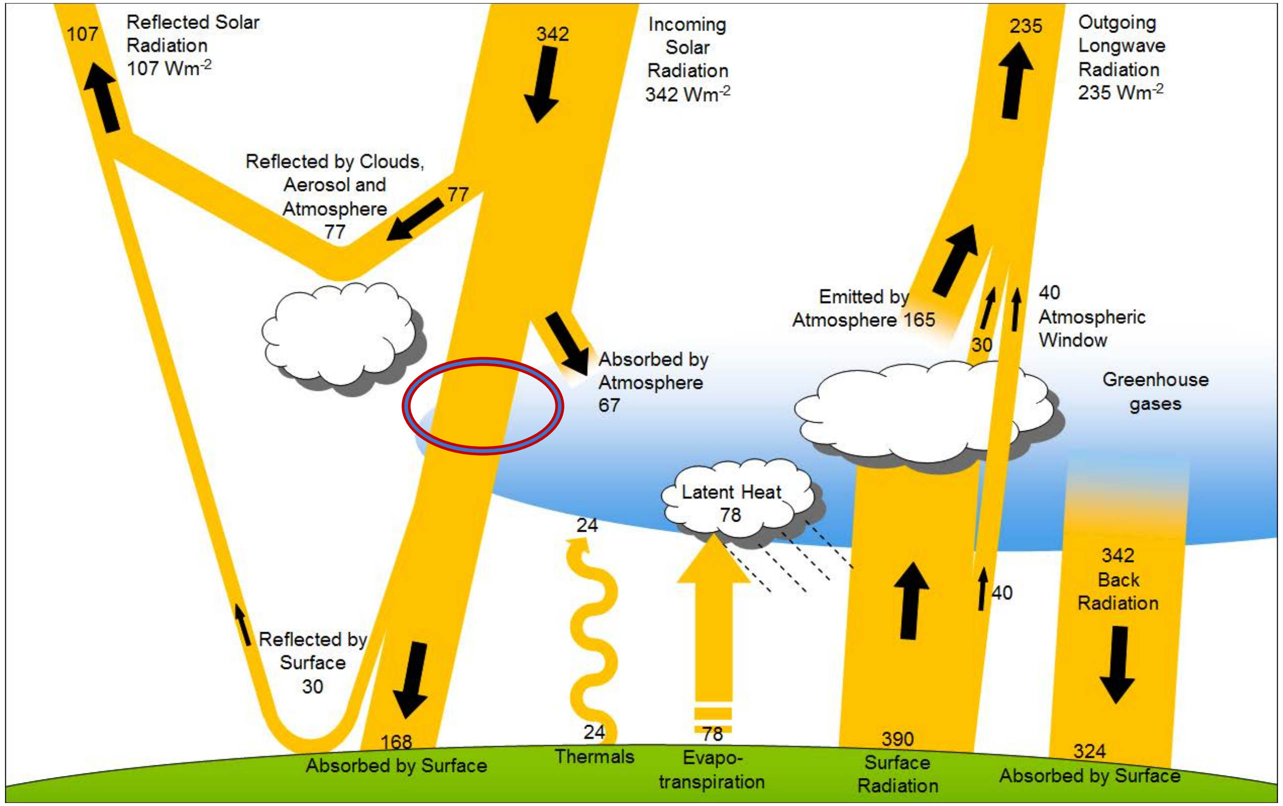
Greenhouse gases absorb part of the outgoing radiation, with water molecules absorbing in the 4-7 and at 15 microns wavelength, and carbon dioxide absorbing in 13-19 micron.

A fraction of this energy is radiated. The change of the energy balance due to this greenhouse gas radiation is known as *the radiation forcing*, and its contribution to the Earth energy balance depends on their concentration.

The net effect of absorption, radiation and re-absorption keep the Earth surface warm, at average temperature ~15 C. Without it the surface temperature could fall to ~ -19 C.

Because of its concentration, carbon dioxide has the strongest radiation forcing, except for that of water. However water concentration is least controlled by human activities.

The Green House Effect



Solar energy flux, how much of it reaches the Earth's surface; the radiation emitted by the ground, and the balance that is re-radiated back to the surface. All numbers are in units of Wm^{-2}. Adapted from Intergovernmental Panel on Climate Change, Working Group 1: The Physical Basis of Climate Change, Chapter 1, Historical Overview of Climate Change Science, page 96, FAQ 1.1, Figure 1 (2007).

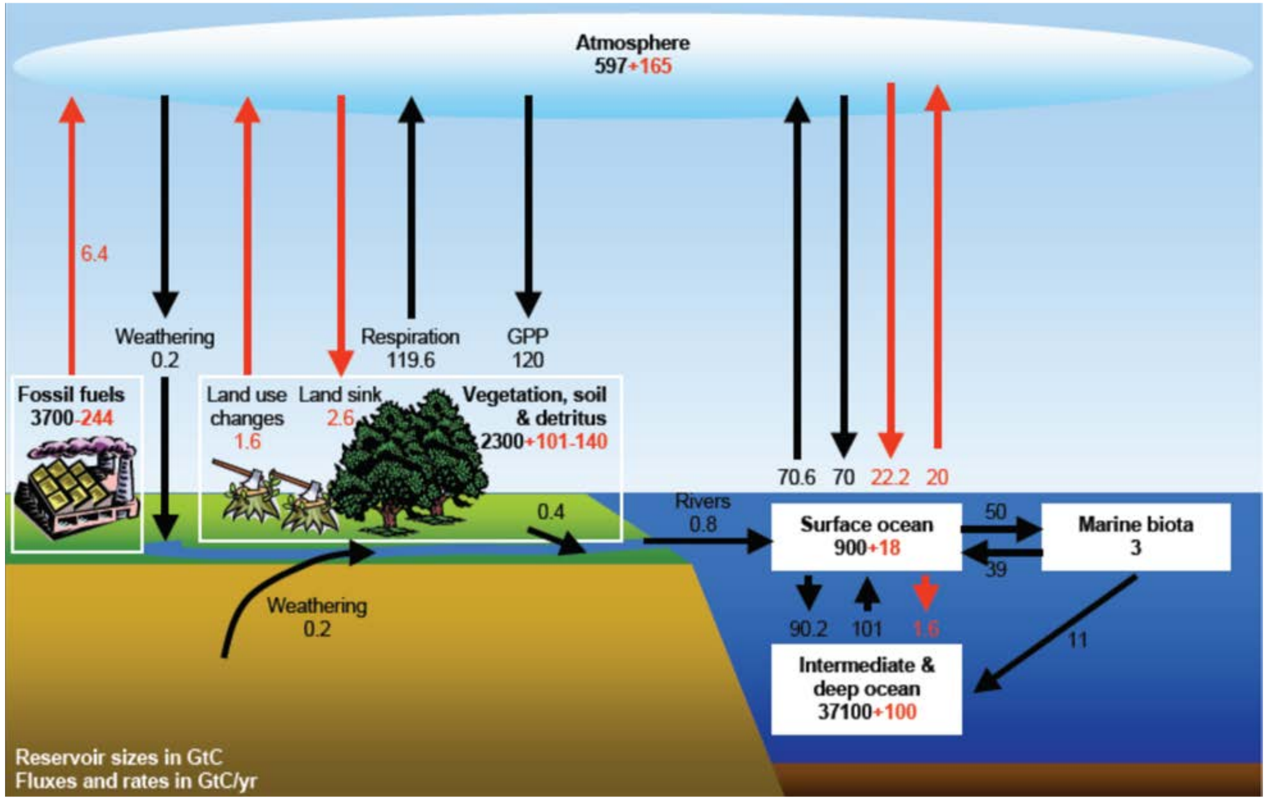
The carbon balance

Fossil fuel:

- 3700 GtC was available at onset of the industrial revolution.
- 244 GtC has been used so far.
- 6.6 GtC is being burnt and emitted each year.

GPP (Gross Primary Production) accounts for photosynthesis (CO_2+H_2O+ Sun photons)

Other activities show a sink of ~ 3.4 GtC/y



Fluxes of CO_2 are shown in terms the equivalent C

Courtesy Elsevier, Inc., http://www.sciencedirect.com. Used with permission.

Source: http://dx.doi.org/10.1016/j.pecs.2010.02.006

Fossil fuel combustion produces ~ 6 GtC/y (1 Gt_C is = 44/12=3.667 $GtCO_2$).

- Carbon dioxide is injected into the atmosphere through *respiration* and the *decomposition of biomatter*, and is removed by *absorption* during photosynthesis and by the phytoplankton living in the oceans.
- Respiration produces ~ 60 Gt_C/y, while photosynthesis removes ~ 61.7 Gt_C/y, with a balance of a sink of 1.7 Gt_C/y.
- The surfaces of the Oceans act as a sink, net uptake of 2.2 Gt_C/y, a source/sink balance between production of 90 and consumption of 92.2 Gt_C/y.
- Changing land use (deforestation) and ecosystem exchange adds/removes 1.4/1.7 Gt_C/y, for a net balance of a sink of 0.3 GtC/y.

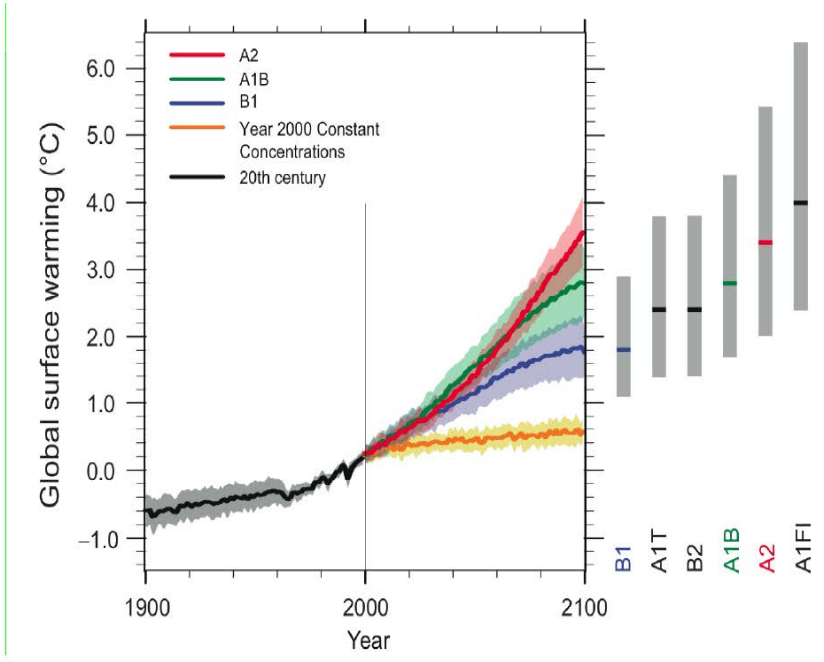
The overall net gain of CO_2 in the atmosphere is estimated to be around 3.5 Gt_C/y.
It is relative these balances that the contribution of fossil fuel combustion (and cement production) appears significant.

These numbers are uncertain and that there is 1-2 Gt_C/y unaccounted for in the overall balance (in ways that are not well understood).

For each 2.1 Gt_C introduced in the atmosphere, CO_2 concentration rises by 1 ppm (the average lifetime of CO_2 in the atmosphere is 100-200 years).

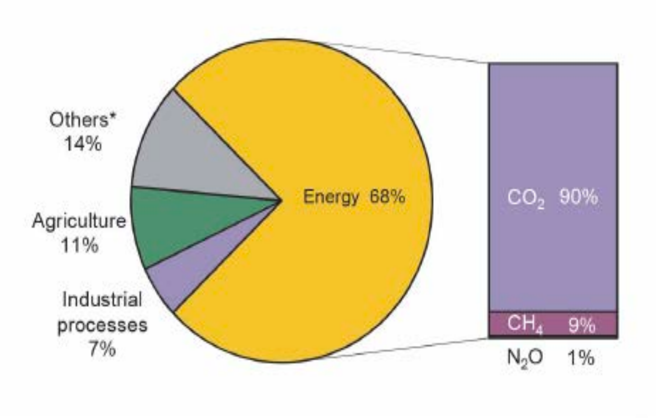
How warm will it get

Climate sensitivity: change in global temperature as CO_2 doubles, estimates: 1.5-4.5 ^oC

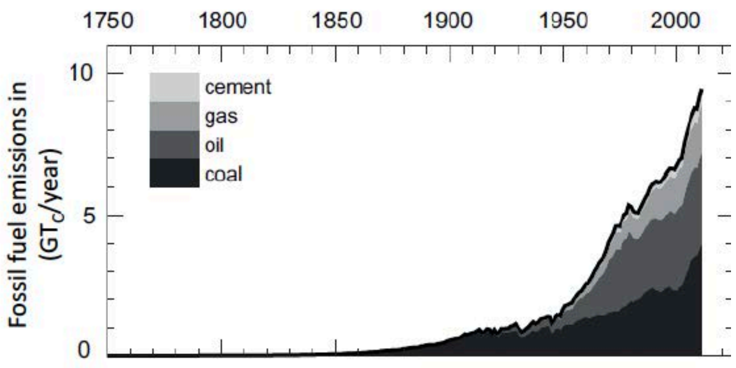


Prediction of the temperature rise during the 21st century, according to different models that account for scenarios for the introduction of CO2 into the atmosphere and its response. Source: IPCC WGI Fourth Assessment Report, Summary for Policymakers, Figure SPM-5, page 14, Multi-model Averages and Assessed Ranges for Surface Warming.

Emissions by Source



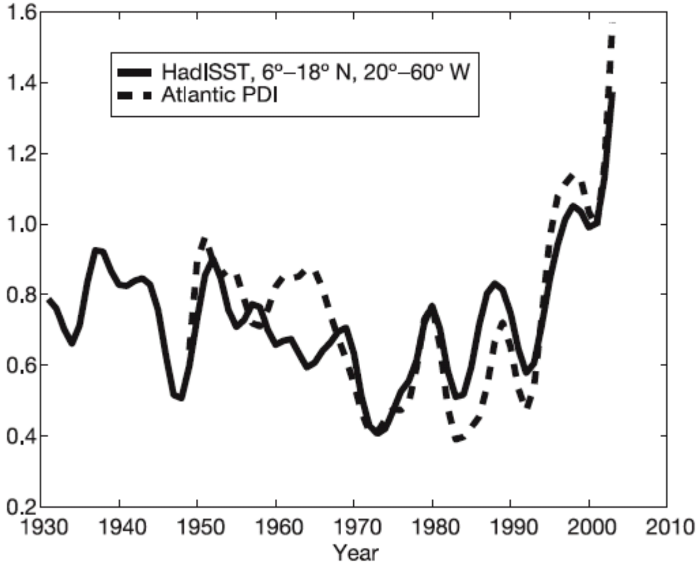
International Energy Agency, CO_2 Emissions from Fuel Combustion, 2016 Highlights



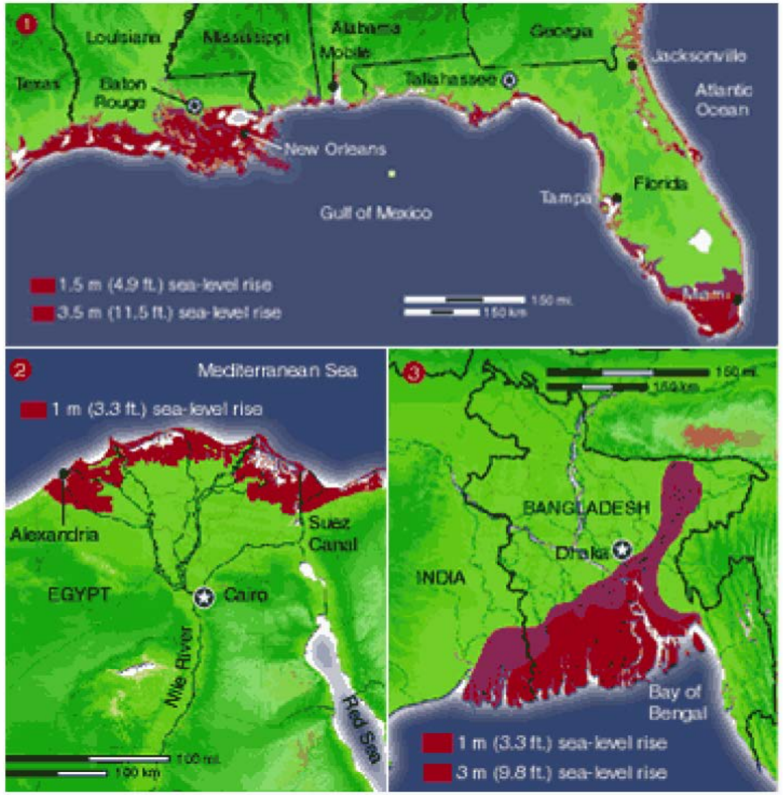
GHG emission by fuel and cement production, reached 9.8 GTC by 2014, 1/3 is transportation (oil based)

IPCC 2014 Technical Summary, IEA, 2015 CO2 emissions form fossil fuels

Global Warming Impacts



A measure of the total power dissipated annually by tropical cyclones in the north Atlantic (the power dissipation index PDI) compared to September sea surface temperature (SST), measured over the past 70 years. The PDI has been multiplied by 2.1x10-12 and the SST, is averaged over 6-18 N latitude and 20-60 W longitude. North Atlantic hurricane power dissipation has more than doubled in the past 30 years. Emanuel, K., Increasing destructiveness of tropical cyclones over the past 30 years, Nature Letters, Vol 436/4, August 2005.



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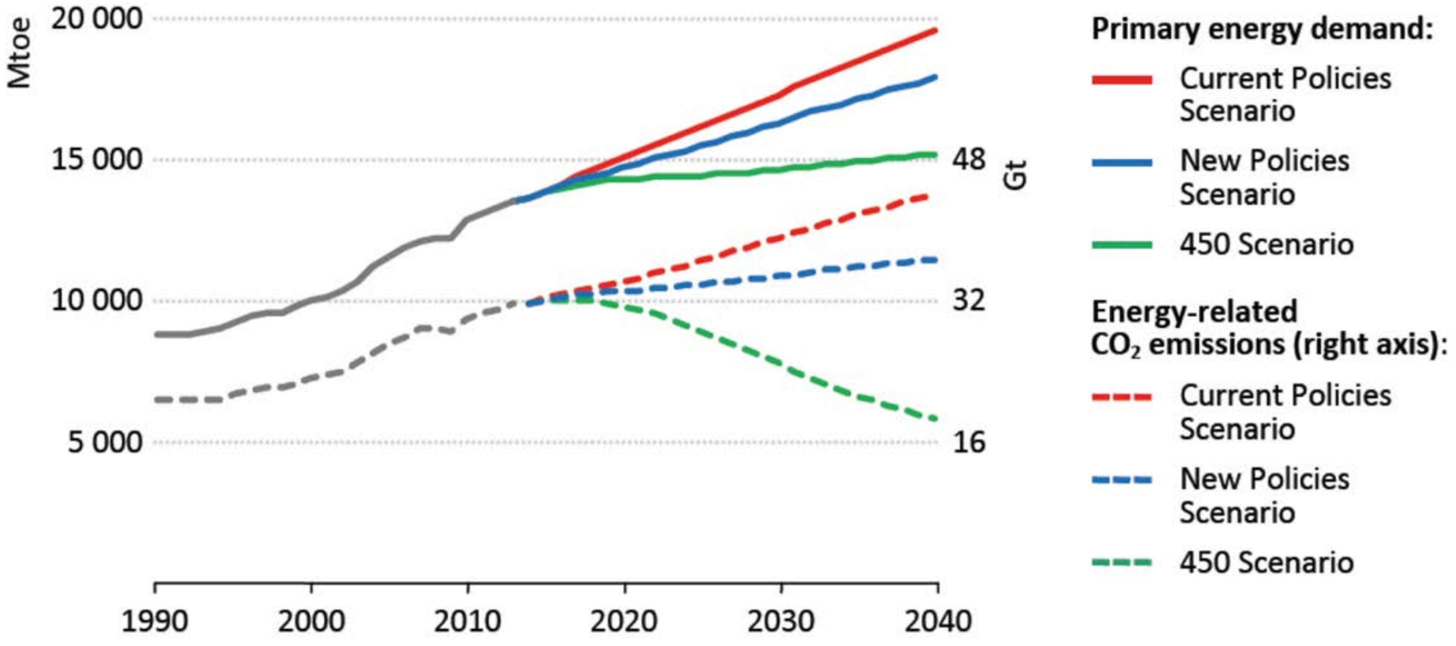
Source: http://dx.doi.org/10.1016/j.pecs.2010.02.006

Rising see levels …..

\>> Rise in ocean acidity

Extrapolation Into the Near Future



New policies scenario: takes into account the policies and implementing measures affecting energy markets that had been adopted as of mid-2015 (as well as the energy-related components of climate pledges in the run-up to COP21, submitted by 1 October)
450 scenario: depicts a pathway to the 2° C climate goal that can be achieved by fostering technologies that are close to becoming available at commercial scale.
Source: IEA world energy outlook 2015, P55

WHILE TIME SCALES ARE UNCERTAIN:

1. Fossil fuel Reserves are limited, 50-300 years.
2. CO_2 and climate change are correlated.

BUT, WE MUST ACT WITHIN CONSTRAINTS:

1. Inertia, big numbers and many stakeholders.
2. Economic, and country dependent scenarios.
3. Social; old habits diehard or do not die at all.
4. Environmental constraints and CO_2 …
5. Political: let us not even get there!

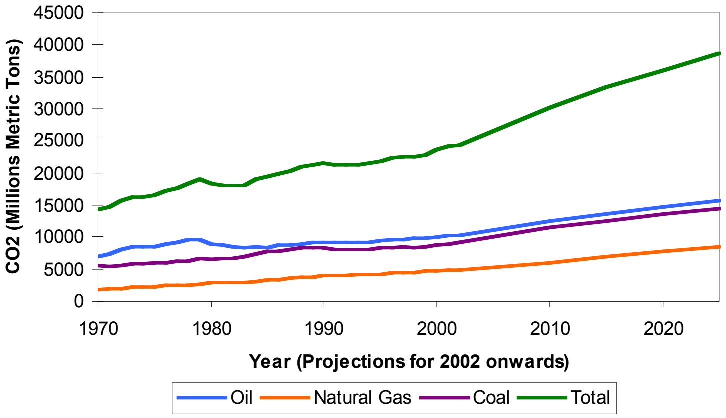
SCALE MATTERS

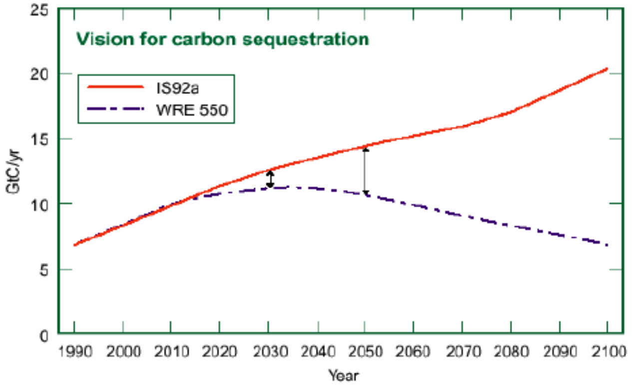
Pacala & Socolow, Stabilizing Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies… Science, Aug 2004,

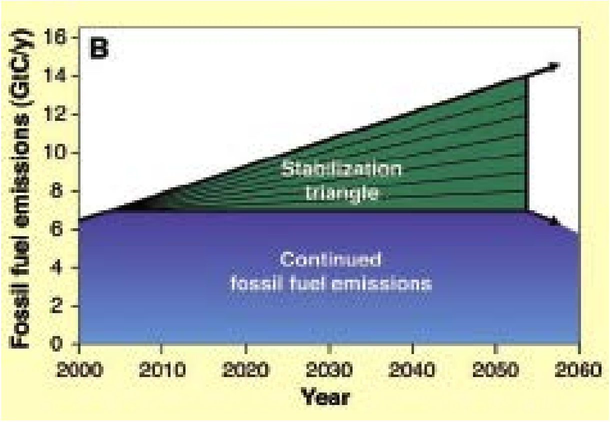
- Goal: Stabilizing CO2 @ ~ 550 ppm by mid century.
- How: hold emission @ 7 GtC/y (1990 level)
- (BAU will double to 14 GtC/y in 50 years growing at the rate of @ 1.5% /y).
- A stabilization "wedge" prevents 1 GtC/y by mid century. Need 7 wedges!

1 GTC/y is produced by:
750 GWe coal at efficiency (32-36%)
1500 GWe NG plants @ efficiency (38-55%)

Many assumptions and some number are confusing but







SCALE MATTERS, NEED A PORTFOLIO
of solutions that offer such wedges, how are they equivalent?

Economy-wide carbon-intensity reduction (CO_2/\$GDP)	Raise global reduction goal by 0.15%/y (in US raise reduction from 1.96% to 2.11%/y)	>>> policy snd challenges
1. Efficient vehicles	Raise fuel economy for 2B cars 30 to 60 mpg	Engine options, size and power, hybrid, electric
2. Less use of vehicles	2B cars @ 30 mpg travel 5000 instead of 10,000 mile/y	Transit options
3. Efficient buildings	1/4th less emissions: efficient lighting, appliances, etc.	Construction cost!
4. Efficient coal plants	Raise thermal efficiency form 32% to 60%	technical

SCALE MATTERS EVEN MORE

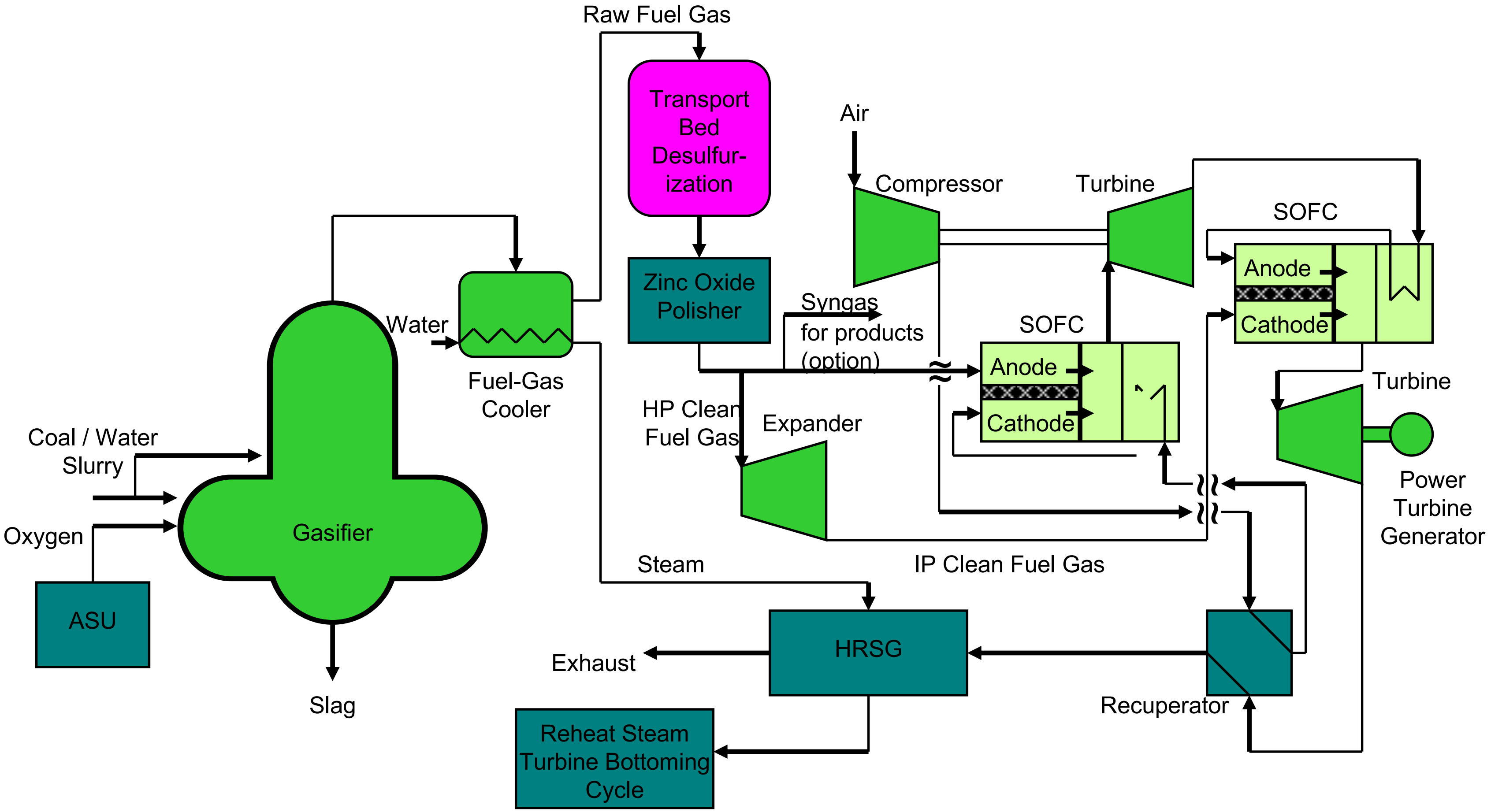
Fuel shift: 5. NG instead of coal for electricity	Replace 1.4 TWe coal with gas (4X of 2004 NG plant capacity	Price of NG
Capture CO_2 (CCS): 6. In power plants	CCS in 0.8 TW coal or 1.6 TW gas	Improved technology
7. In H_2 production for transportation	CCS in coal plants producing 250 MtH_2/y or NG plants producing 500 MtH_2/y	Technology and H_2 issues
8. In coal to Synfuel plants	CCS in plants producing 30 Mbarrel/day (200X current Sasol capacity) from coal	Technology and price

YES SCALES ARE BIG AND MUST BE CONSIDERED

9. **Nuclear** instead of coal for electricity	700 GW fission plants (2X of 2004 capacity)	Security and waste
Renewable Sources: 10. Wind instead of coal for electricity	Add 2 M 1-MW peak turbines ($30\text{x}10^6$ ha, sparse and off shore)	Land use, material, off shore tech.
11. PV instead of coal for electricity	Add 2 TW peak PV ($2\text{x}10^6$ ha)	Cost and material
12. Wind for H_2 (for high efficiency vehicles)	Add 4 M 1-MW peak turbines	H_2 infrastructure
13. Biomass for fuel	Add 100X of 2004 Brazil (sugar cane) or US (corn) ethanol. ($250\text{x}10^6$ ha. 1/6 of total world cropland)	Land use

HIGH EFFICIENCY POWER PLANTS

Layout of an integrated-gasification combined cycle power plant, in which the conventional gas turbine-steam turbine combined cycle is equipped with “topping” high temperature fuel cells



🟦=Off the Shelf

🟩=Integration Development

🟩=Technology Change

🟪=Technology Development

Fuel cell handbook. Office of fossil energy.

Image courtesy of DOE.

Fuel Cells

DOE
Fuel Cell Handbook,2004
Download new version, very useful

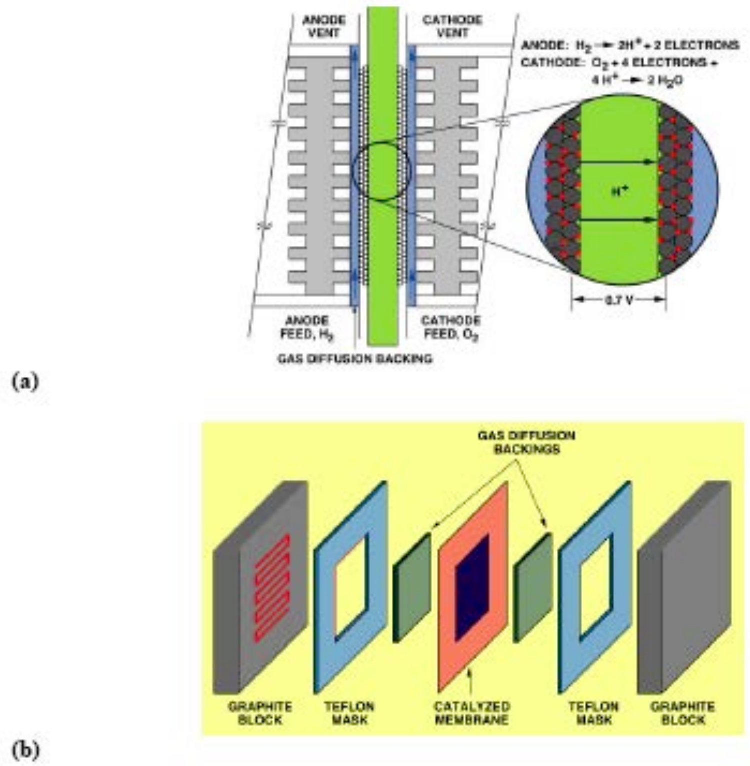
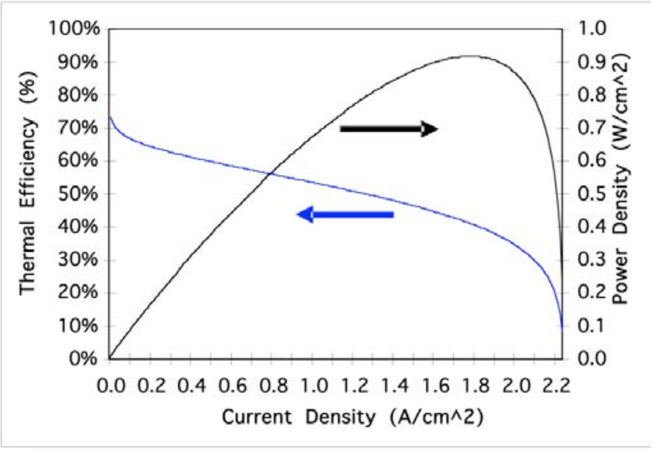


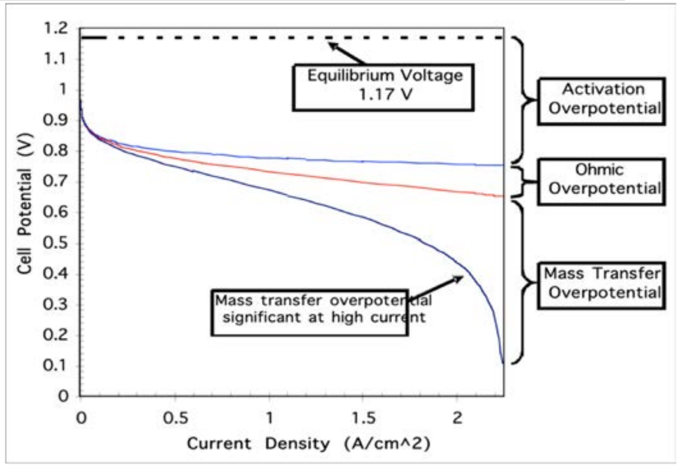
Figure 3-1 (a) Schematic of Representative PEFC (b) Single Cell Structure of Representative PEFC(1)

Image courtesy of DOE.

Also known as membrane-electrode-assembly (MEA), and made of one “physical” plate with anode and electrode material “sprayed” on both side.

The membrane is a polymer (nafion) for low T cells and a ceramic plate for high T cells.





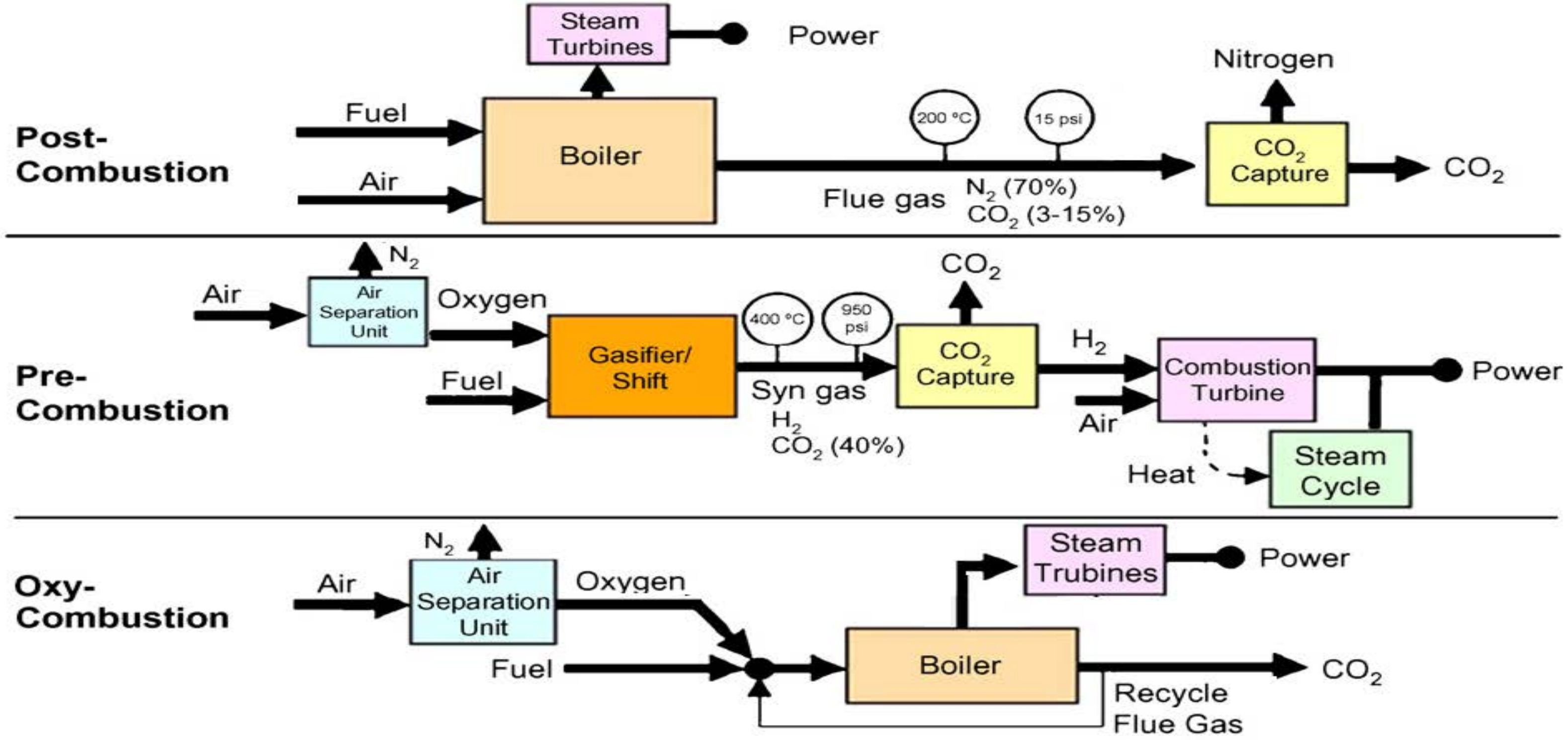
$$\eta_{FU} = \frac{\wp}{\left(\dot{n}_f\right)_{\sup} \Delta\hat{h}_{R,f}} = \frac{IV}{\left(\dot{n}_f\right)_{\sup} \Delta\hat{h}_{R,f}} = \frac{I}{n_e \Im_a \left(\dot{n}_f\right)_{\sup}} \; \frac{V}{V_{OC}} \; \frac{\varsigma V_{OC}}{\Delta\hat{h}_{R,f}}$$

$$= \eta_{far} \; \eta_{rel} \; \eta_{OC}$$

$$\eta_{OC} = \frac{\Delta G_R}{\Delta H_R}$$

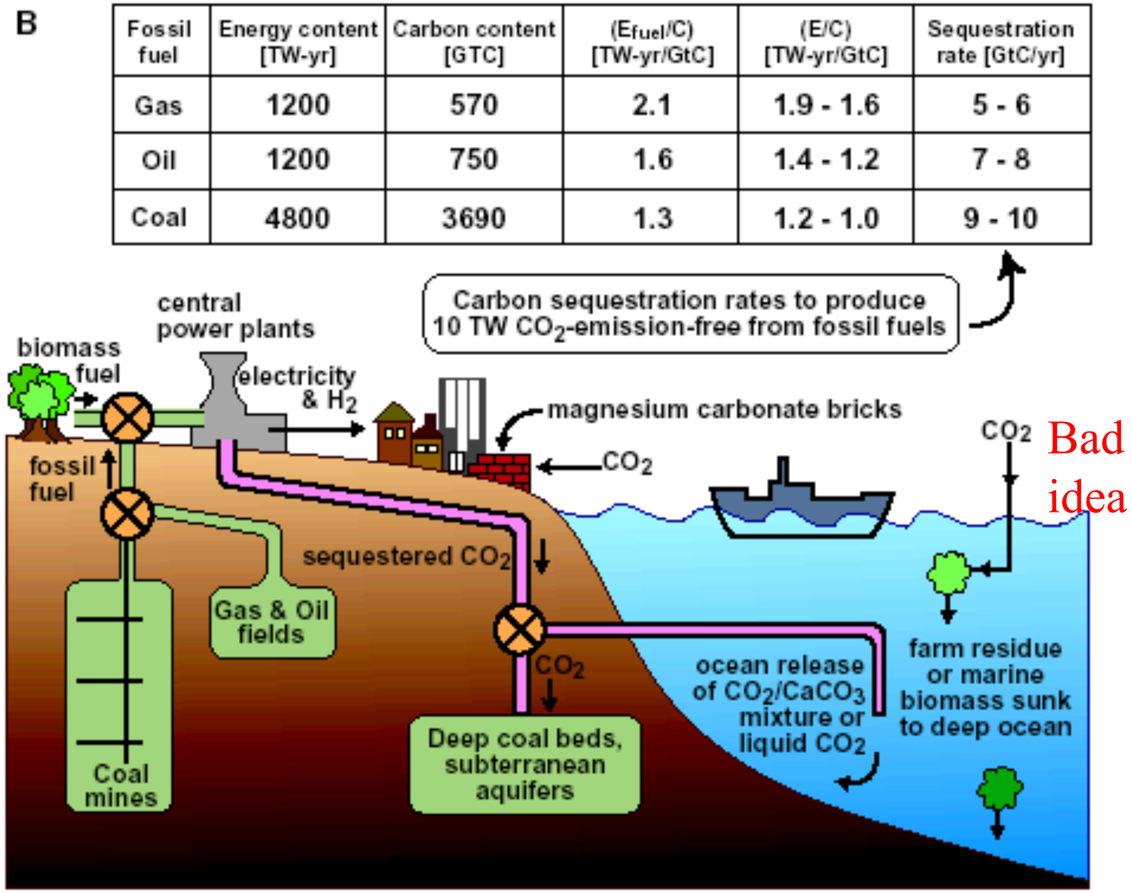
Mome Power Cycle for CO_2 Capture

Penalty in efficiency, minimized with novel technology and system integration….



(1) Post combustion: chemical scrubbing of CO_2 from exhaust.
(2) Oxy-ocmbustion: burning with O_2 first.
(3) Precombustion: IGCC, burn in O_2, separate and then burn H_2.

CO_2 Capture (Reuse!) and Storage



B

Fossil fuel	Energy content [TW-yr]	Carbon content [GTC]	(E_{fuel}/C) [TW-yr/GtC]	(E/C) [TW-yr/GtC]	Sequestration rate [GtC/yr]
Gas	1200	570	2.1	1.9 - 1.6	5 - 6
Oil	1200	750	1.6	1.4 - 1.2	7 - 8
Coal	4800	3690	1.3	1.2 - 1.0	9 - 10

Fig. 1. (A) Fossil fuel electricity from steam turbine cycles. (B) Collecting CO_2 from central plants and air capture, followed by subterranean, ocean, and/or solid carbonate sequestration, could foster emission-free electricity and hydrogen production, but huge processing and sequestration rates are needed (5 to 10 GtC year^{-1} to produce 10 TW emission-free assuming energy penalties of 10 to 25%).

Source: M.I. Hoffert et al., *Science* 298, 981 (2002)

Separation Technology and its impact on efficiency

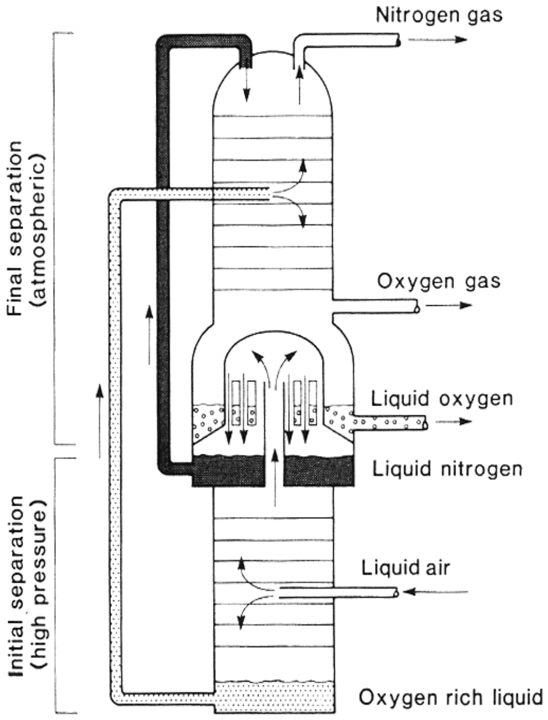


Figure 5.6 Distillation column for fractional separation of liquid air (after Ref. 11).

Probstien, Synthetic Fuels.

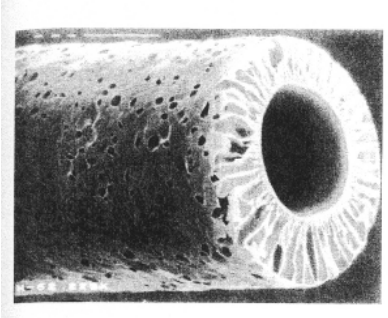
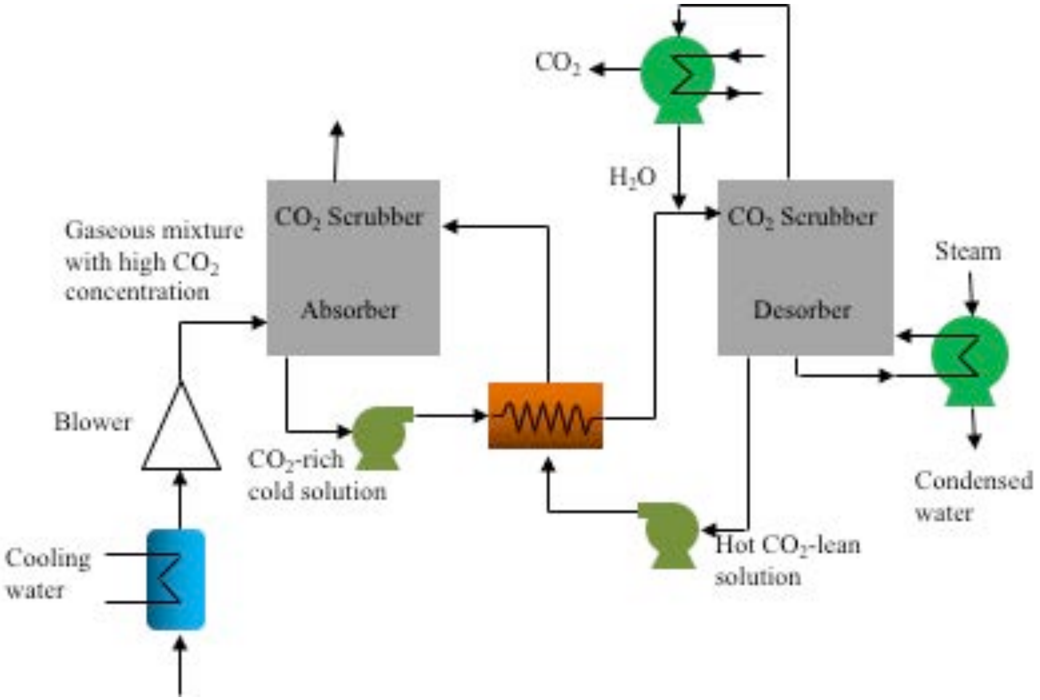
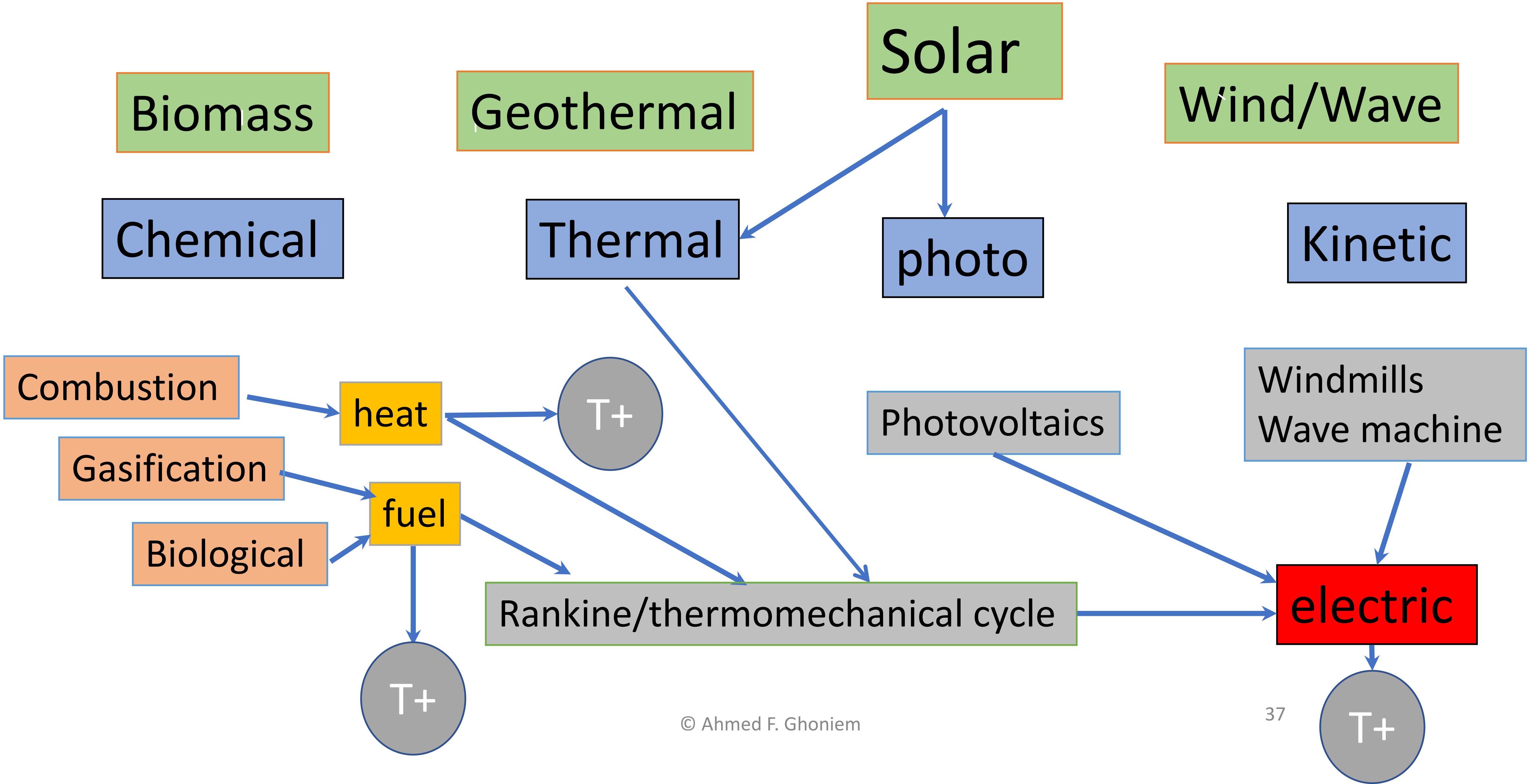


FIGURE 26.3
Capillary ultrafiltration membrane. Electron micrograph (150×) of a DIAFLO™ hollow fiber. (*Courtesy of Millipore Corporation*)

McCabe et al, unit operation of Che. Eng.



Renewable Sources and Their Utilization



Biomass

Geothermal

Solar

Wind/Wave

Chemical

Thermal

photo

Kinetic

Combustion

heat

T+

Gasification

fuel

Biological

T+

Rankine/thermomechanical cycle

Photovoltaics

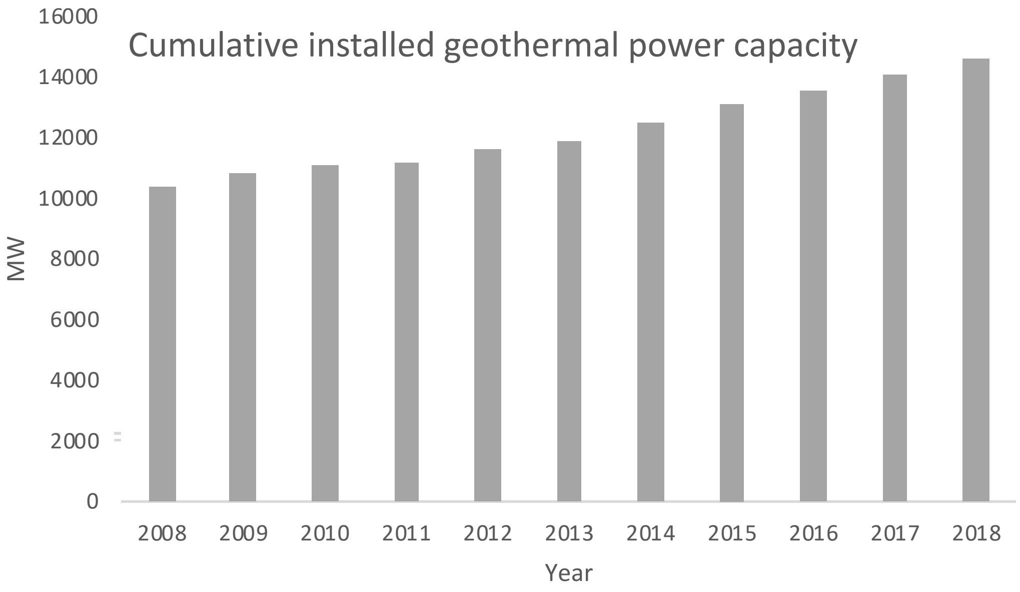
Windmills
Wave machine

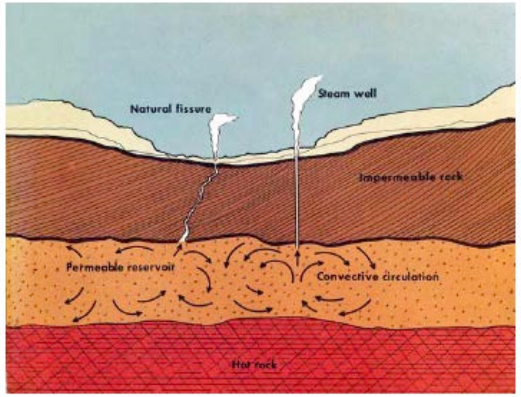
electric

T+

Geothermal Energy

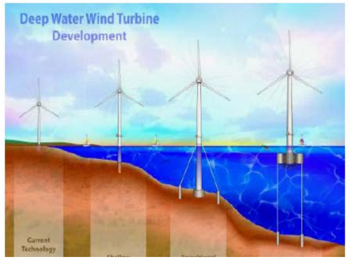
- Nearly emissions free and dispatchable.
- Uses conventional technology (thermal efficiency is low), and prices are closer to fossil electricity.
- Well life is relatively short, resources are localized and distributed.
- Needs alternative drilling technology.
- 2016 capacity worldwide ~ 30 GWe.





Wind Utilization is rising fast ..

Explore technology pathways for installing and operating large wind power facilities in water depths greater than 30 meters.



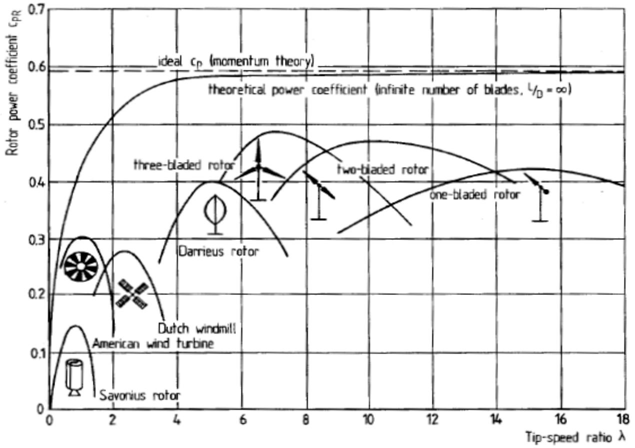
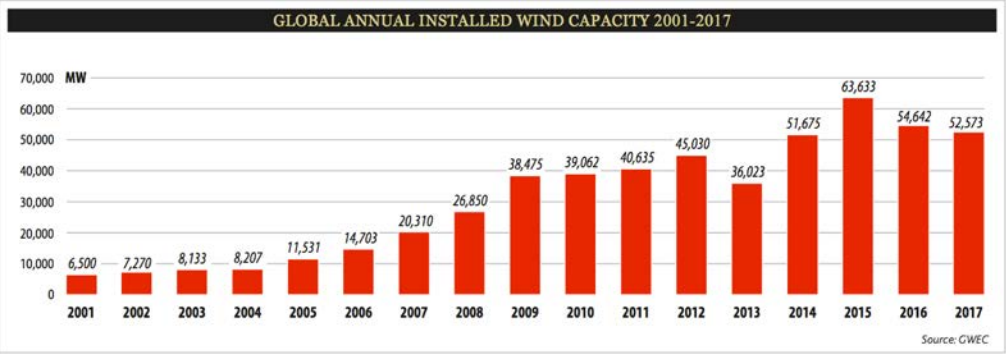


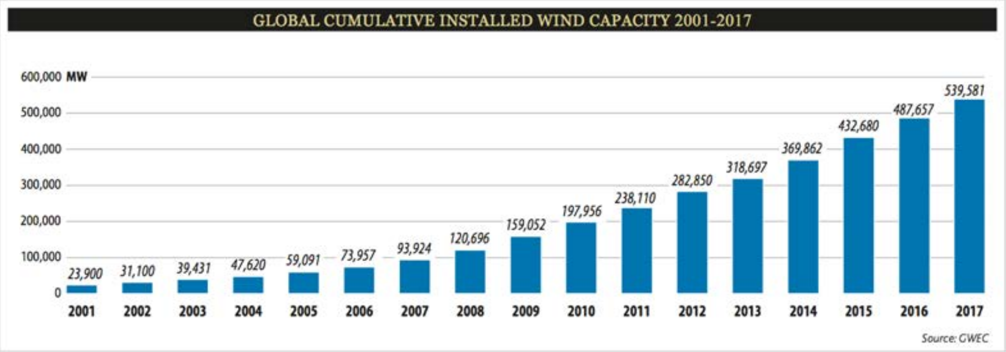
Fig. 5.10. Power coefficients of various of wind rotors [2]

$$F_V = \left(L - \frac{V}{U}D\right)\frac{U}{V_r} = \frac{1}{2}\rho U\left(C_L - \frac{V}{U}C_D\right)V_r A_{bl}$$

$$\wp_{bl} = F_V V = \frac{1}{2}\rho U^3 A_{bl}\left(C_L - \frac{V}{U}C_D\right)\frac{V}{U}\sqrt{1+\left(\frac{V}{U}\right)^2}$$

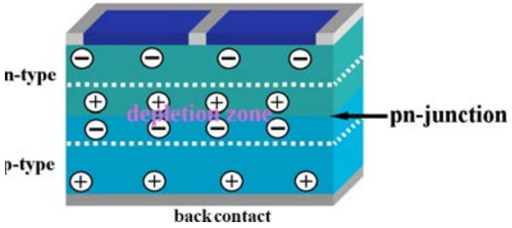
$$C_L \text{ and } C_D \text{ change with } \left(\frac{V}{U}\right)$$

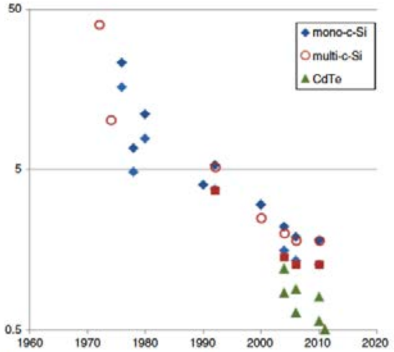




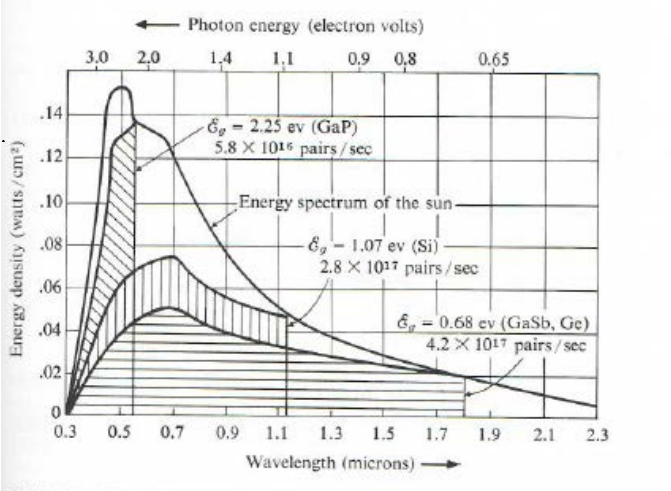
Source: https://gwec.net/wp-content/uploads/vip/GWEC_PRstats2017_EN-003_FINAL.pdf

Solar PVs





Energy payback period for different PV technologies, low numbers are for insolation of 2,400 kWh/m²/y, high are for 1,700 kWh/m²/y



$$j = j_s - j_0\left(\exp\left(\frac{e_0 V}{nkT}\right) - 1\right) \approx j_s - j_0 \exp\left(\frac{\varepsilon_0 V}{nkT}\right)$$

j_s : zero voltage (short circuit) current $V = 0$

j_0 : current in the absence of illumination)

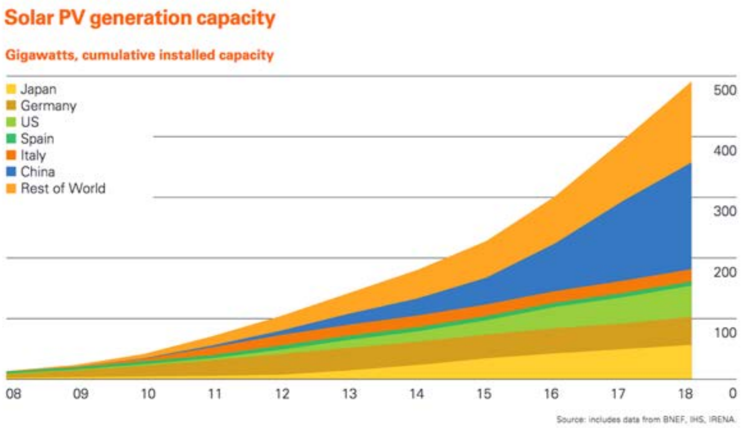
ε_0 : electron charge = $1.602\ 10^{-10}$ Coulombs

V : voltage

n: =1-2 (known as the diode ideality factor)

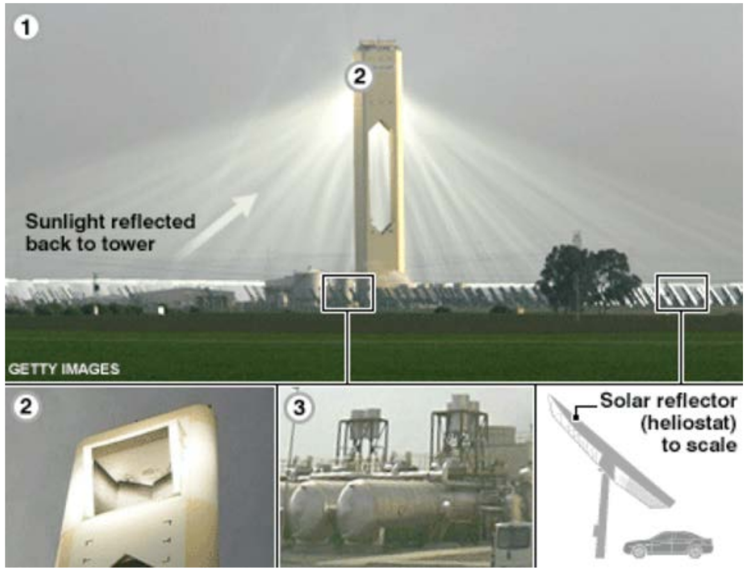
k : Boltzman constant=$1.381\ 10^{-23}$ J/K

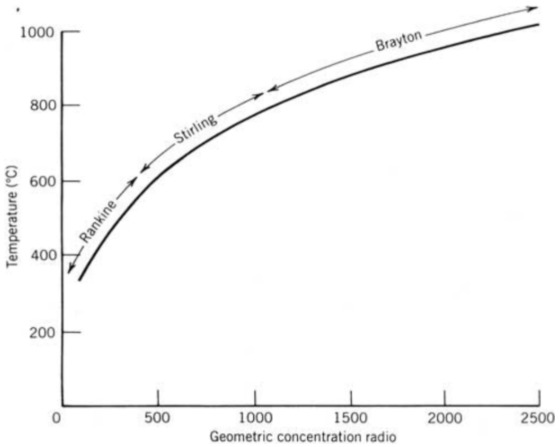
Global PV installed capacity in GW



Source: https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2019-renewable-energy.pdf

Solar Energy Generating System (SEGS) Plant Can Be Used To Satisfy Percentage From Renewable Sources



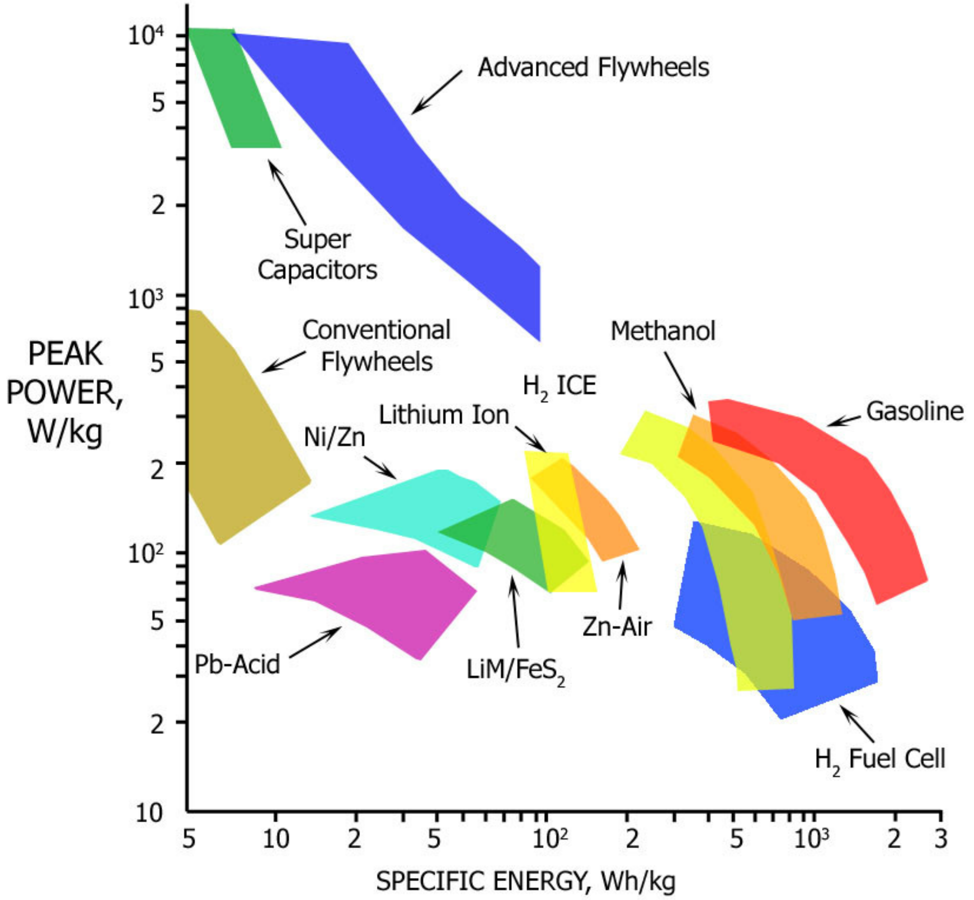


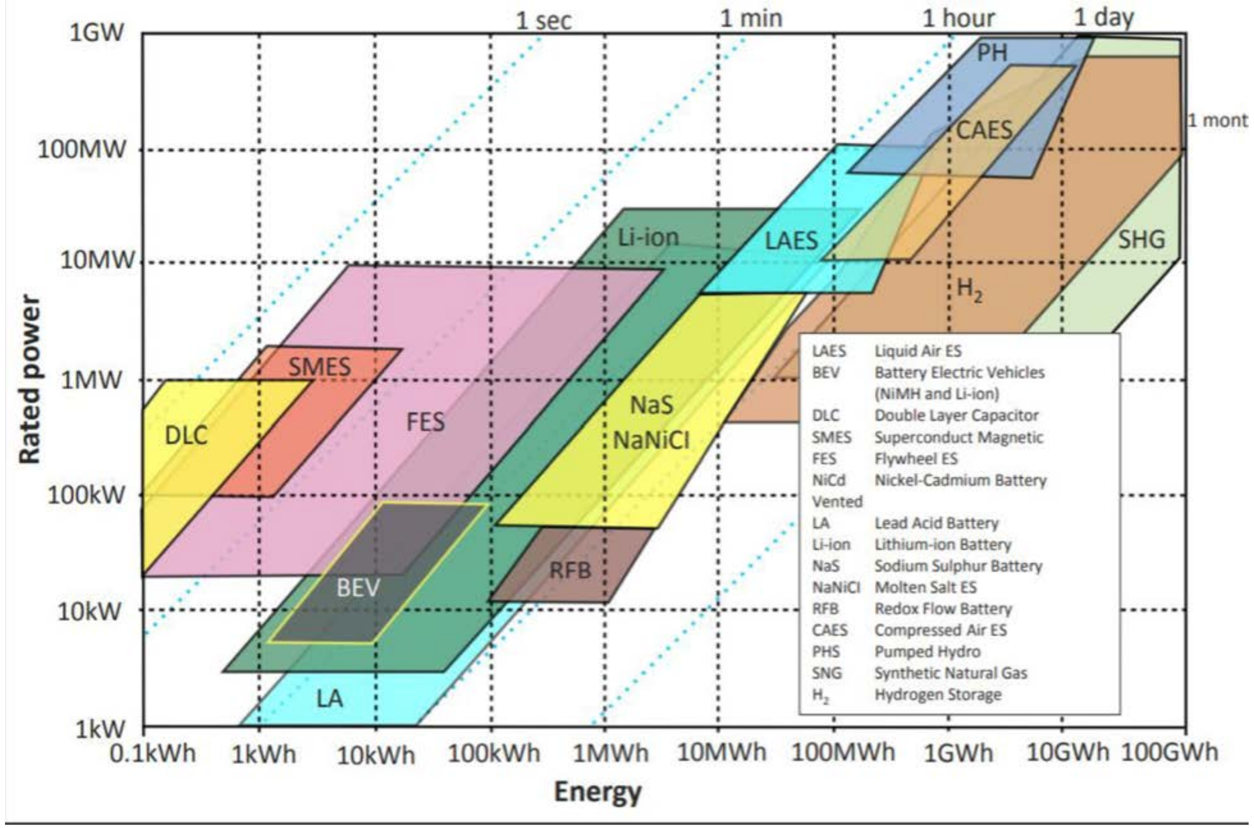
- Thermal Efficiency may reach 54-58%
- Annual average solar-to-electric 10-14%.
- “hybridizable” for dispatchability (25%)
- Storage Ready.

- Total reflective area > 2.3 M. m^2
- More than 117,000 HCEs
- 30 MW increment based on regulated power block size

T. R. Mancini, Concentrating Solar Power ,SNL, Albuquerque, New Mexico, USA

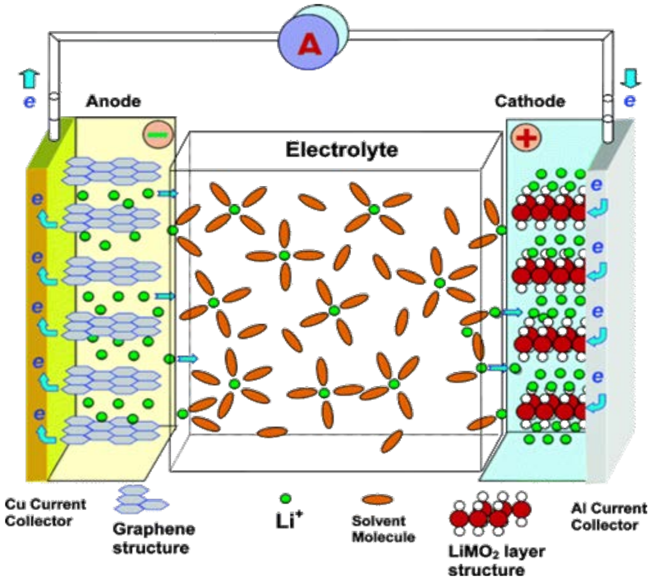
Storage; for all forms of energy





Ragone plot of power density versus energy density

Batteries

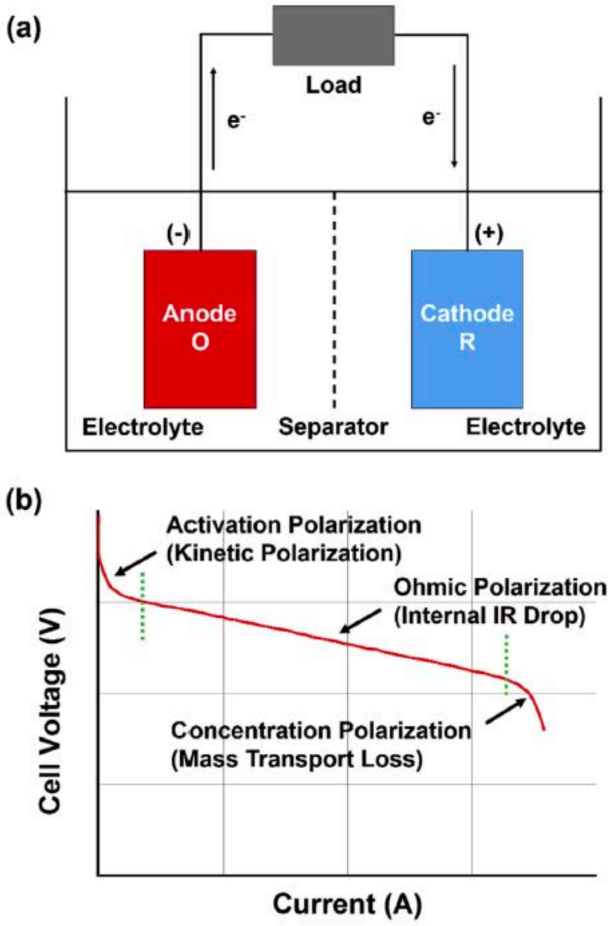


Xu, K. Electrolytes and interphases in Li-ion batteries and beyond. *Chem. Rev.* **114**, 11503–11618 (2014).

- During operation, reversible Li$^+$ intercalation (insertion) into the layered electrode materials

$$Li_xC_6 + Li_{1-x}CoO_2 \leftrightarrow C_6 + LiCoO_2$$

- Forward reaction: discharge ($\Delta G < 0$), Li$^+$ move towards cathode, as shown in figure
- Reverse reaction: charge ($\Delta G > 0$)



Goodenough and Park, *JACS* 135 (2013): 1167

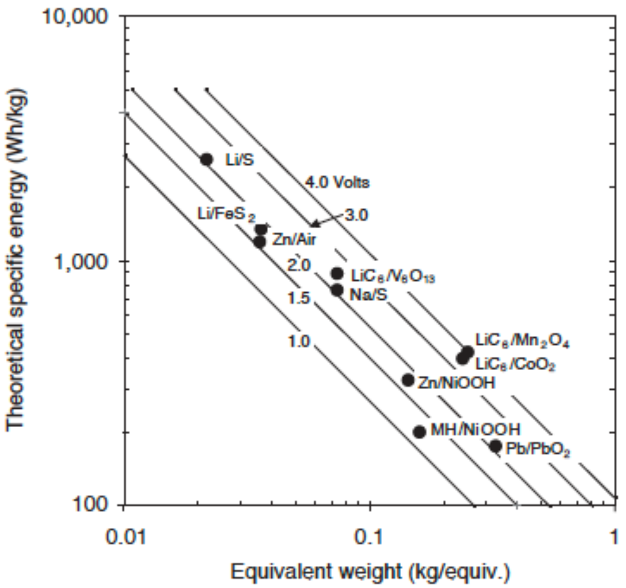
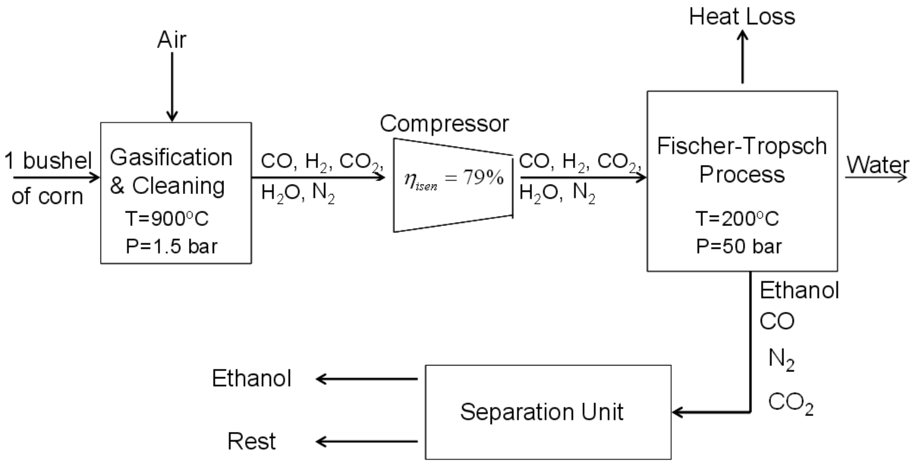


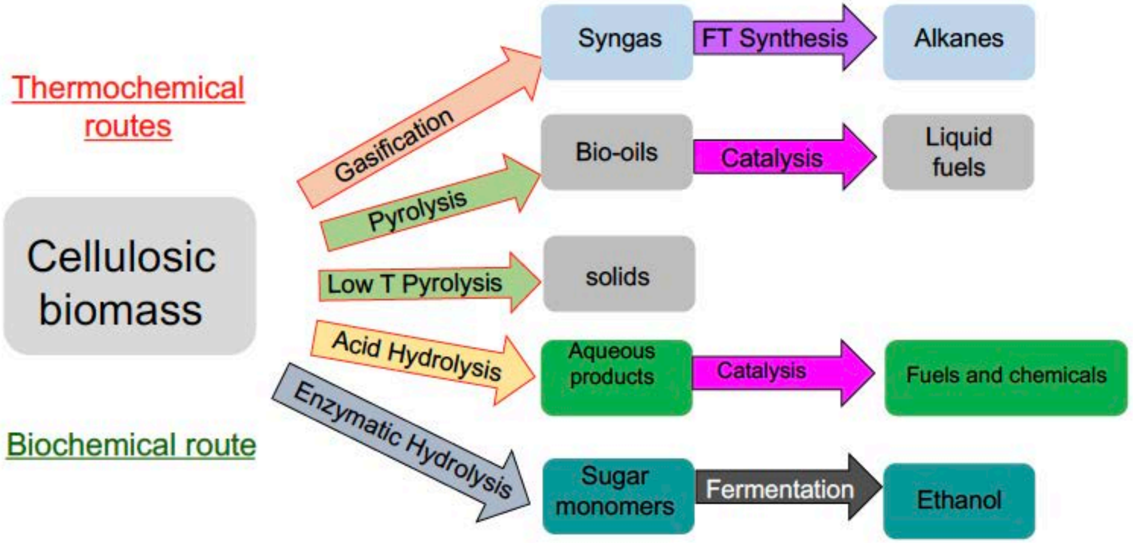
FIGURE 1 Theoretical specific energy for various cells as a function of the equivalent weights of the reactants and the cell voltage.

Biomass & Biofuels

Thermodynamics of the Corn-Ethanol Biofuel Cycle

Tad W. Patzek (2004) "Thermodynamics of the Corn-Ethanol Biofuel Cycle", *Critical Reviews in Plant Sciences*, 23:6, 519-567, DOI: 10.1080/07352680490886905.





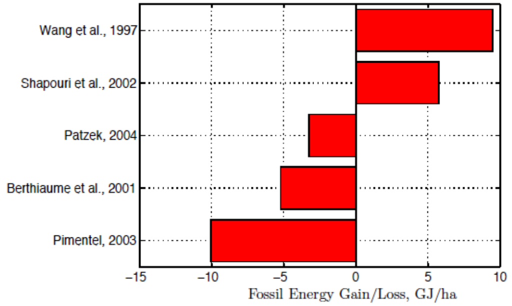
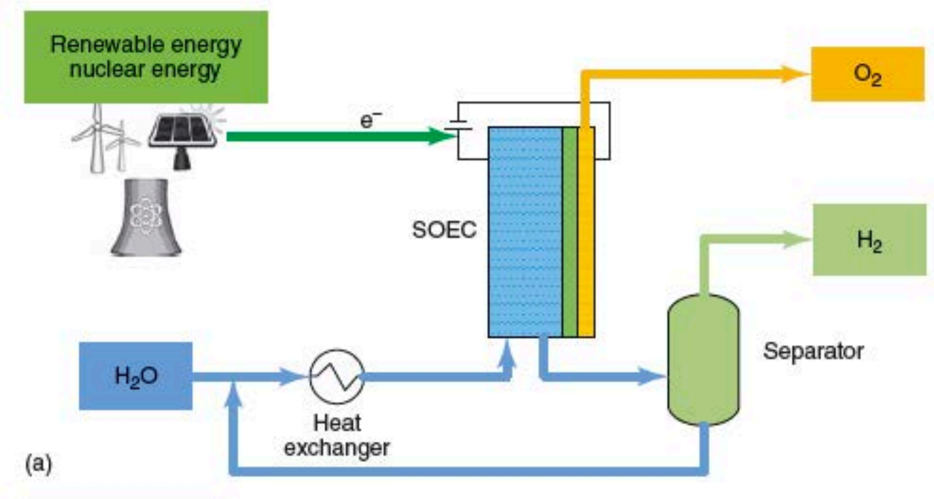


Figure 19: Fossil energy gain/loss in corn ethanol production. Note that the dubious energy credits described in Section 4.4 do not eliminate the use of fossil fuels in the first place, but present alternative useful outcomes of this use.

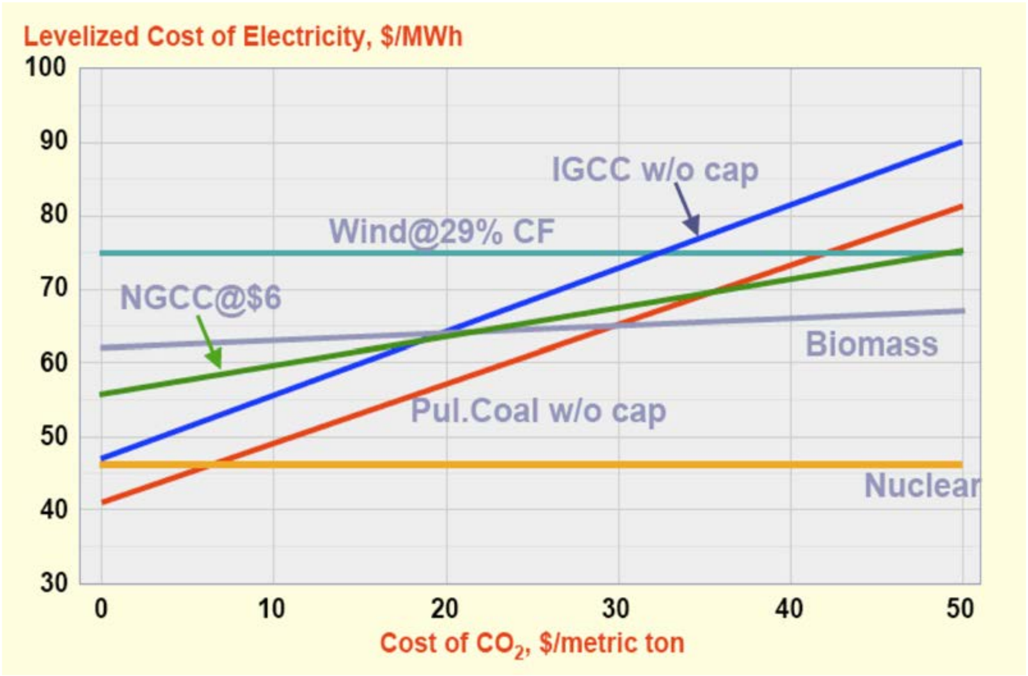
HYDROGEN

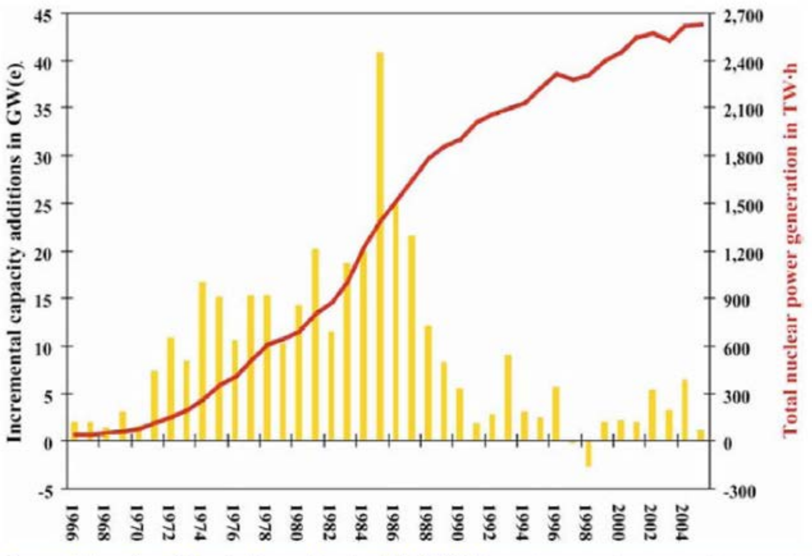
- Like electricity: expensive to produce, not easy to store.
- Produced by:
  - @ Oxygen or steam Reforming of hydrocarbon, or,
  - @ Splitting water electrolytically or thermochemically .
- Has low volumetric by high gravimetric energy density.



- Storage: metal fiber tanks, cryogenic container, in metal hydrides (solids) through physical or chemical sorption.
- It is a “lower grade” of energy than electricity.
- Must be regarded as an energy storage medium.
- Ideal fuel for Low T Fuel Cell: PEMFC

Nuclear Energy;
Potential @ CO2 price





Source: International Atomic Energy Agency (IAEA), 2005

Transition is not new in this business

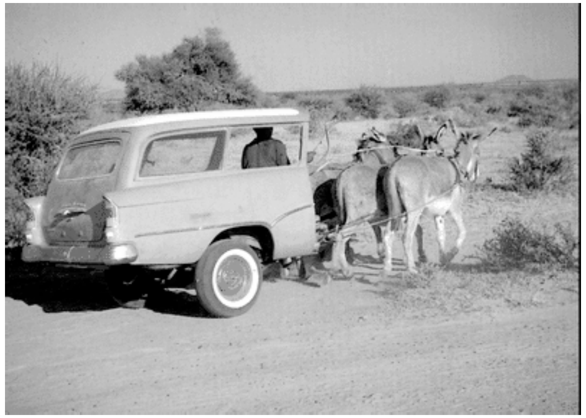
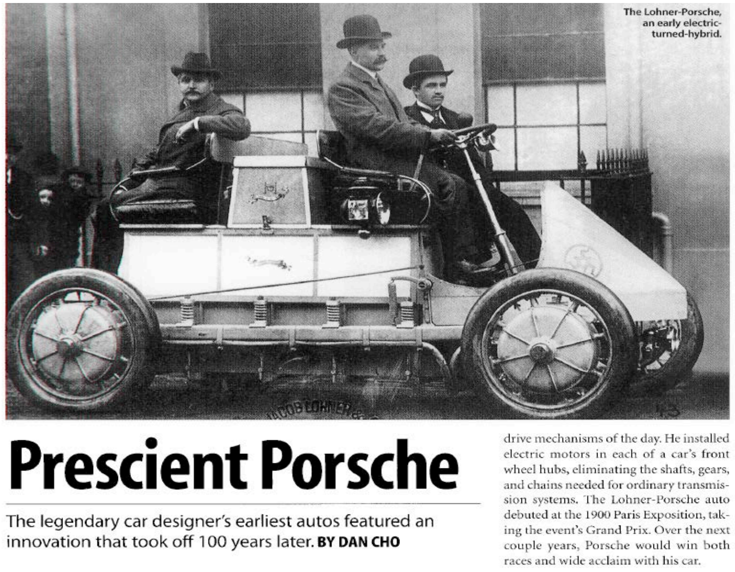


Figure 3-11 BMW's Hydrogen-Powered Internal Combustion Vehicle



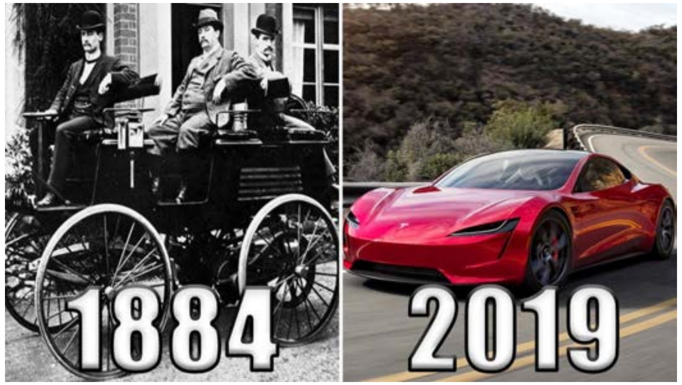
The Lohner-Porsche, an early electric-turned-hybrid.

Prescient Porsche

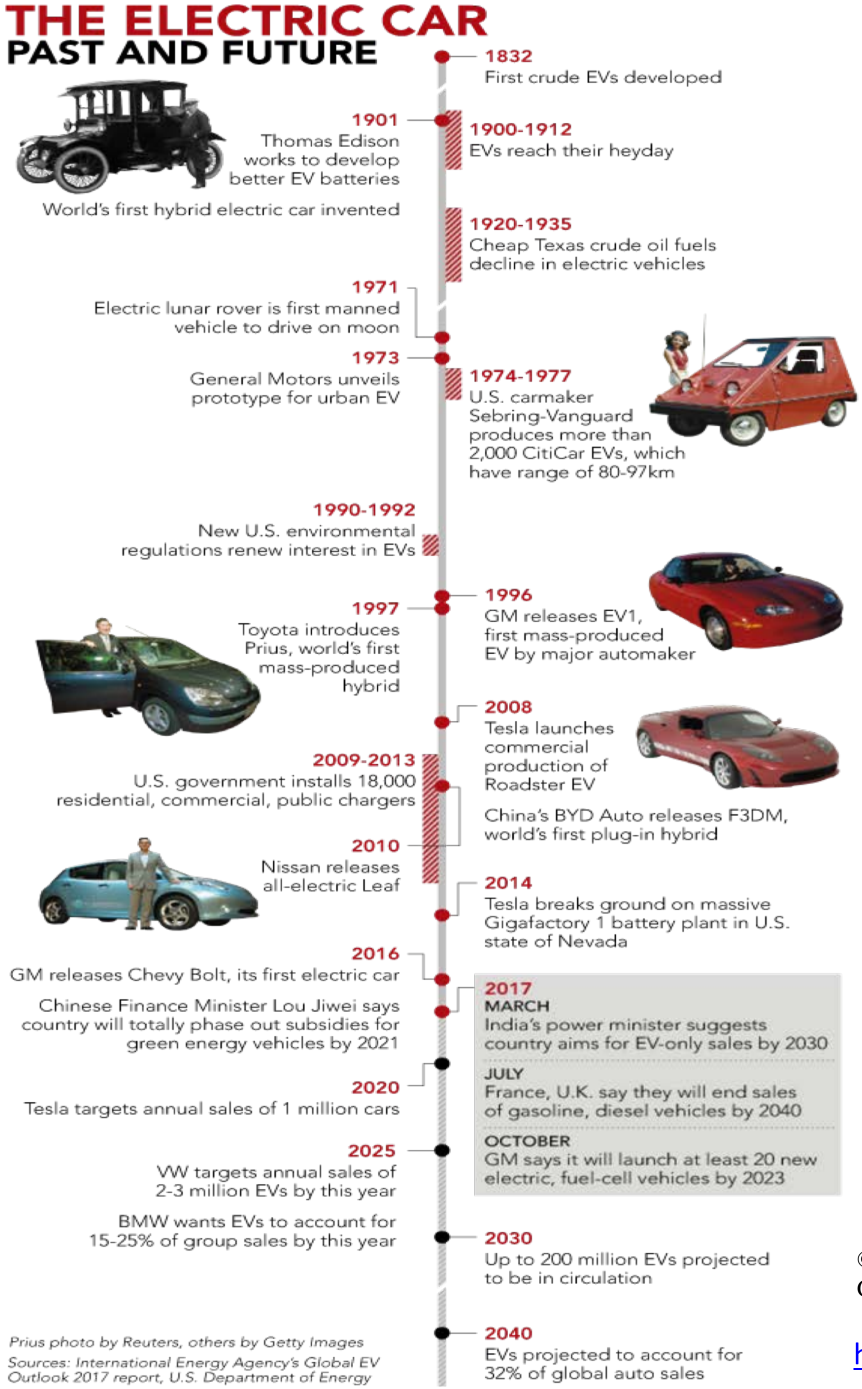
The legendary car designer's earliest autos featured an innovation that took off 100 years later. **BY DAN CHO**

drive mechanisms of the day. He installed electric motors in each of a car's front wheel hubs, eliminating the shafts, gears, and chains needed for ordinary transmission systems. The Lohner-Porsche auto debuted at the 1900 Paris Exposition, taking the event's Grand Prix. Over the next couple years, Porsche would win both races and wide acclaim with his car.

This image is in the public domain.
Source: https://commons.wikimedia.org/wiki/File:Lohner_Porsche.jpg



Prof. Ferdinand Porsche Created the First Functional Hybrid Car



THE ELECTRIC CAR
PAST AND FUTURE

1832
First crude EVs developed

1901
Thomas Edison works to develop better EV batteries

World's first hybrid electric car invented

1900-1912
EVs reach their heyday

1920-1935
Cheap Texas crude oil fuels decline in electric vehicles

1971
Electric lunar rover is first manned vehicle to drive on moon

1973
General Motors unveils prototype for urban EV

1974-1977
U.S. carmaker Sebring-Vanguard produces more than 2,000 CitiCar EVs, which have range of 80-97km

1990-1992
New U.S. environmental regulations renew interest in EVs

1996
GM releases EV1, first mass-produced EV by major automaker

1997
Toyota introduces Prius, world's first mass-produced hybrid

2008
Tesla launches commercial production of Roadster EV

China's BYD Auto releases F3DM, world's first plug-in hybrid

2009-2013
U.S. government installs 18,000 residential, commercial, public chargers

2010
Nissan releases all-electric Leaf

2014
Tesla breaks ground on massive Gigafactory 1 battery plant in U.S. state of Nevada

2016
GM releases Chevy Bolt, its first electric car

Chinese Finance Minister Lou Jiwei says country will totally phase out subsidies for green energy vehicles by 2021

2017
MARCH
India's power minister suggests country aims for EV-only sales by 2030

JULY
France, U.K. say they will end sales of gasoline, diesel vehicles by 2040

OCTOBER
GM says it will launch at least 20 new electric, fuel-cell vehicles by 2023

2020
Tesla targets annual sales of 1 million cars

2025
VW targets annual sales of 2-3 million EVs by this year

BMW wants EVs to account for 15-25% of group sales by this year

2030
Up to 200 million EVs projected to be in circulation

2040
EVs projected to account for 32% of global auto sales

Prius photo by Reuters, others by Getty Images
Sources: International Energy Agency's Global EV Outlook 2017 report, U.S. Department of Energy

https://www.pinterest.com/pin/380272762280612514/

2.60J Fundamentals of Advanced Energy Conversion
Spring 2020