

Global Scalability of Energy Solutions

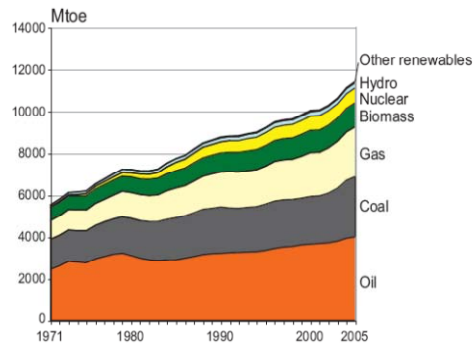
Christopher Polashenski, PhD
30 November 2011

Sizing the Problem - Energy

- Step 1: How much energy, now and in the future is required.
- Step 2: How much carbon can we emit to get it?

Sizing the Problem - Energy

- Current use of all primary energy
 - 402 exajoules/yr (1 exajoule = 10^{18} joules)



Rogner, Hans-Holmér et al, World Energy Assessment, UNDEP, 2004, p. 6, <http://www.undp.org/energy/activities/wea/brief-frame.html>.

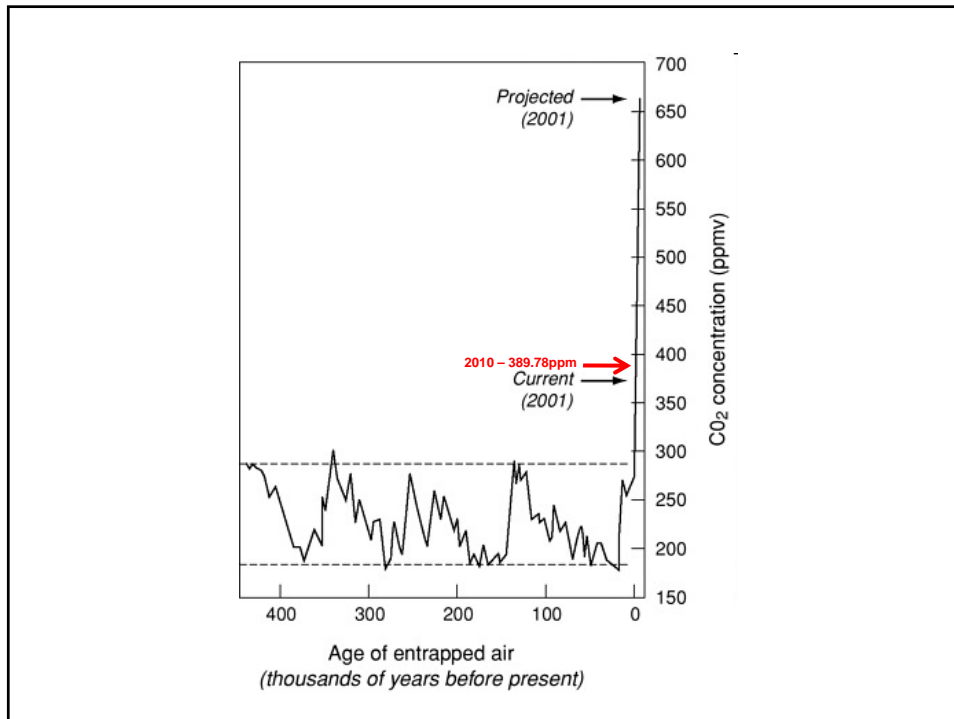
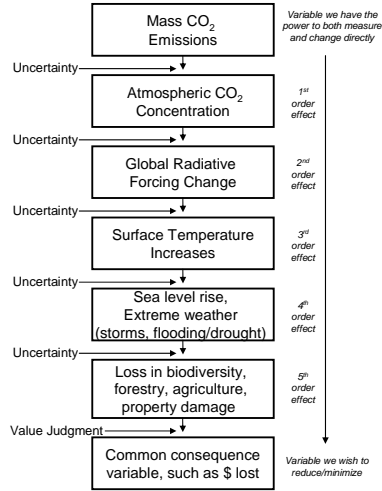
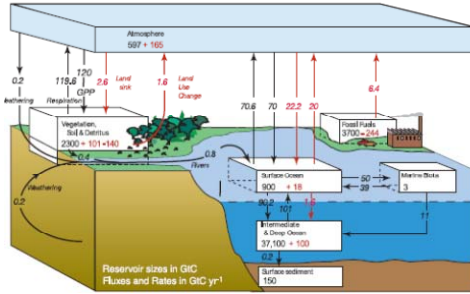
Sizing the Problem - Energy

- Projected energy use
 - 610 to 1040 exajoules/year
 - Some extreme bounds
 - Low Estimate – 380 exajoules/year
 - No increase in affluence
 - Population to 7.6 billion (low UNDEP estimate) (already 6.978 billion)
 - 35% efficiency increase.
 - High Estimate – 3770 exajoules/year
 - Everyone to average U.S. affluence (325 GJ/person/yr)
 - Population to 12 billion (high UNDEP estimate)
 - No efficiency increase

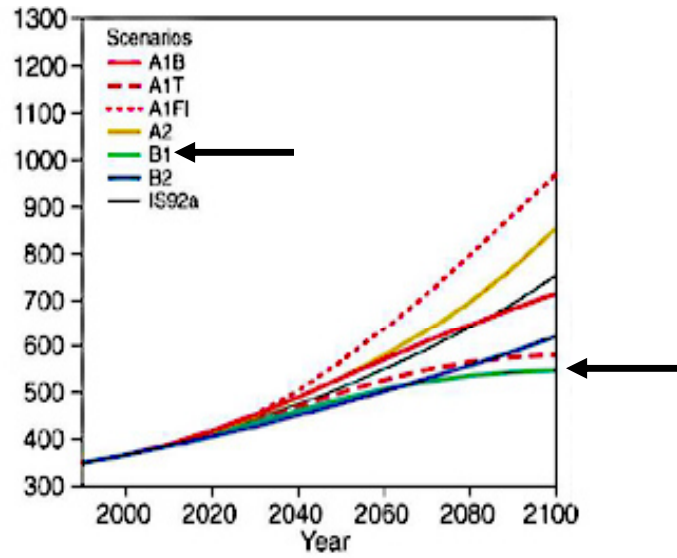
Rogner, Hans-Holmér et al, World Energy Assessment, UNDEP, 2004, p. 6, <http://www.undp.org/energy/activities/wea/brief-frame.html>.

Sizing the Problem – Carbon

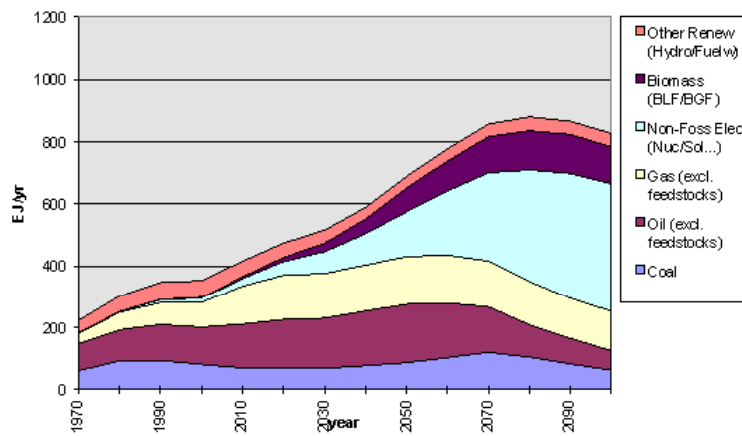
- How much is too much?



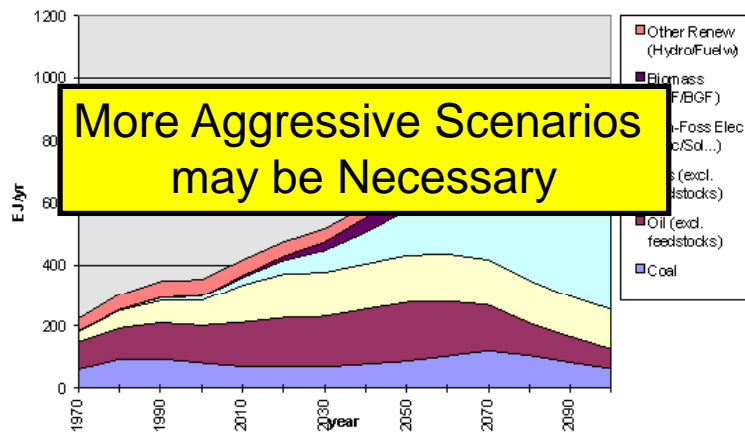
IPCC AR4 Scenarios



IPCC AR4 Scenario B1



IPCC AR4 Scenario B1



Energy Problem Quantified:

- 302 exajoules/year of carbon-free energy needed by 2050

Fossil Fuel Reserves (w/CCS)

Type	Consumption				Reserves		Resources ^a		Resource base ^b		Additional occurrences	
	1860-1998		1998		Exajoules	Gigatonnes of carbon	Exajoules	Gigatonnes of carbon	Exajoules	Gigatonnes of carbon	Exajoules	Gigatonnes of carbon
	Exajoules	Gigatonnes of carbon	Exajoules	Gigatonnes of carbon								
Oil												
Conventional	4,854	97	132.7	2.65	6,004	120	6,071	121	12,074	241		
Unconventional	285	6	9.2	0.18	5,108	102	15,240	305	20,348	407	45,000	914
Natural gas ^c												
Conventional	2,346	36	80.2	1.23	5,454	83	11,113	170	16,567	253		
Unconventional	33	1	4.2	0.06	9,424	144	23,814	364	33,238	509	930,000	14,176
Coal	5,990	155	92.2	2.40	20,666	533	179,000	4,618	199,666	5,151	n.a.	
Total	13,508	294	319.3	6.53	46,655	963	235,238	5,579	281,893	6,562	975,000	15,090

a. Reserves to be discovered or resources to be developed as reserves, b. The sum of reserves and resources, c. Includes natural gas liquids.

	Energy (eJ)	Years of Supply
Reserves	46656	55
Resources	235238	278
Total Resource Base	281503	332

World Energy Assessment (from UNDP)

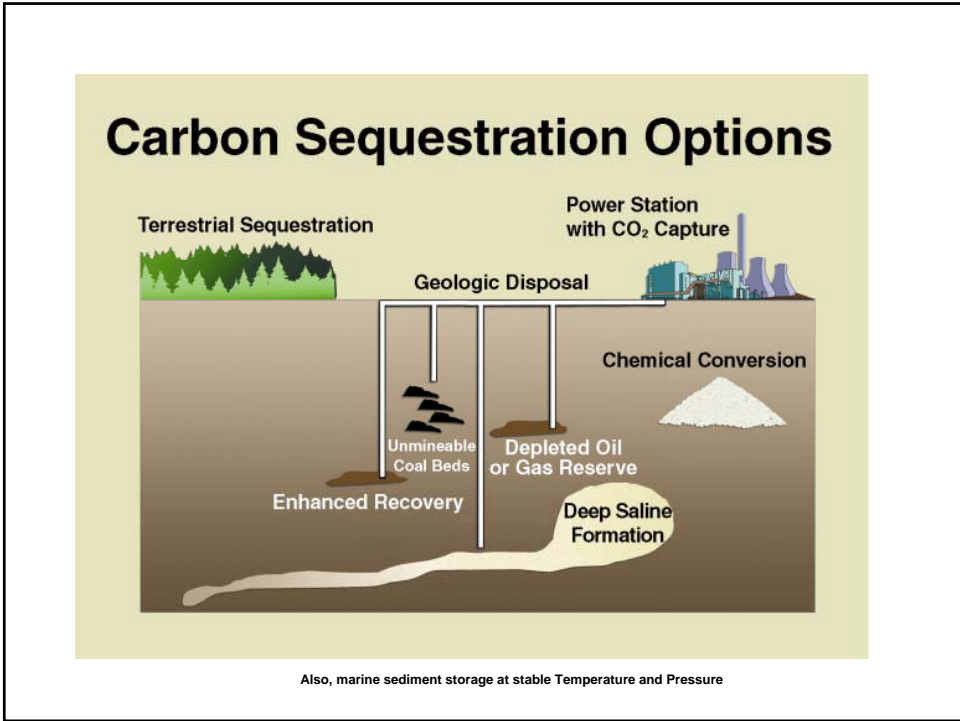
<http://www.undp.org/energy/activities/wea/drafts-frame.html>

Carbon Capture and Storage

- Typically at least a 1/3 parasitic energy load
- Not yet proven on the long term
- Will not be economical without carbon pricing (same technology + new constraints)
- Other, non carbon issues
 - National Security
 - Oilspills
 - Habitat Destruction



http://www.netl.doe.gov/publications/proceedings/07/carbon-seq/data/papers/tue_198.pdf



Nuclear

- Resource limited by readily accessible reserves and how they are utilized**
- Breeder Reactor (600000+ GJ/kg) vs Burner Reactor (600GJ/kg)
 - Tremendous availability in seawater
 - Thorium Reactors?

	Metric Tons U	Energy (eJ)	Years of Supply
Reserves, Burner	2,315,900	1,382	4.3
Reserves, Breeder	2,315,900	138,954	434
Resources, Burner	8,300,500	4,955	15.4
Resources Breeder	8,300,500	498,030	1,556

World Energy Assessment (from UNDP)
<http://www.undp.org/energy/activities/wea/drafts-frame.html>

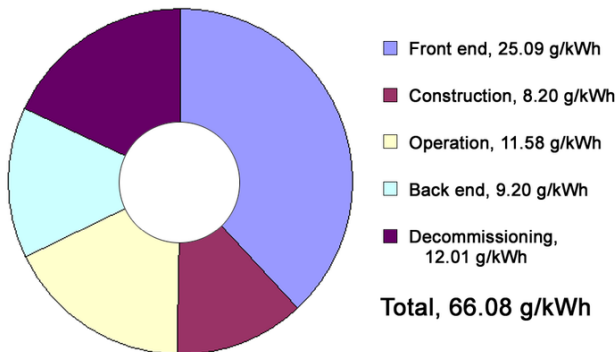
Nuclear

- Proliferation
- Waste Handling and Safety
- Cooling Water Supply
- Mass mobilization – Need to construct 1GW reactor per day until 2050!



Carbon Neutral?

Carbon emissions from nuclear power
Sovacool life cycle study survey, 2008



In comparison:
The life cycle of coal is pegged at 963 g/kWh. (U.S. EIA)

Mean value of carbon dioxide emissions from qualified life cycle studies among 103 surveyed. Includes results of 1997 Vattenfall study.

Benjamin K. Sovacool (2011). *Contesting the Future of Nuclear Power: A Critical Global Assessment of Atomic Energy*, World Scientific, p. 141.

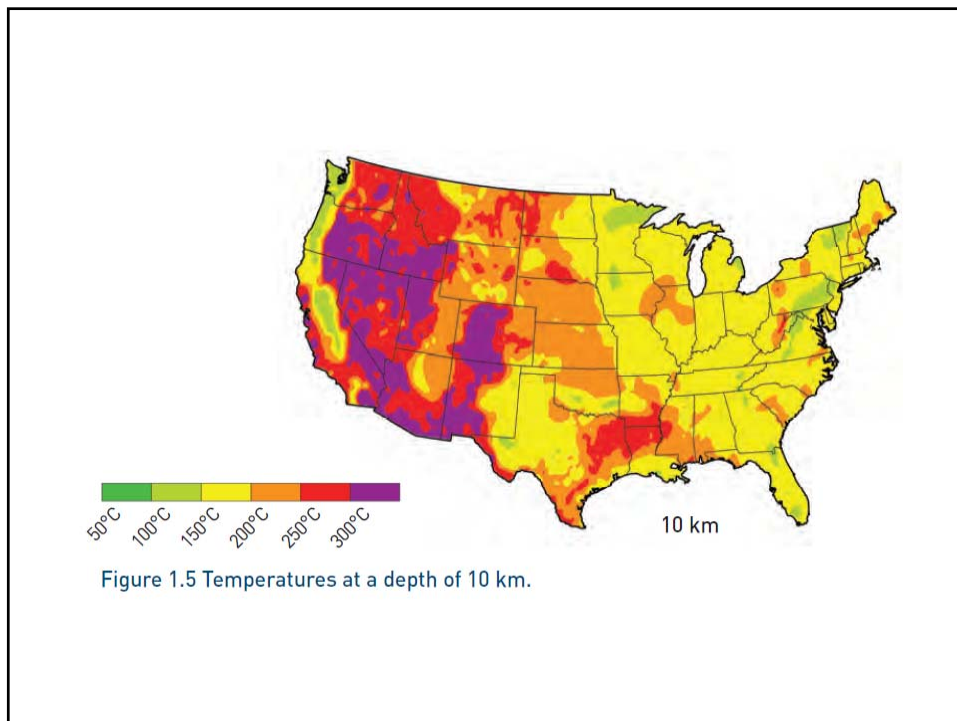
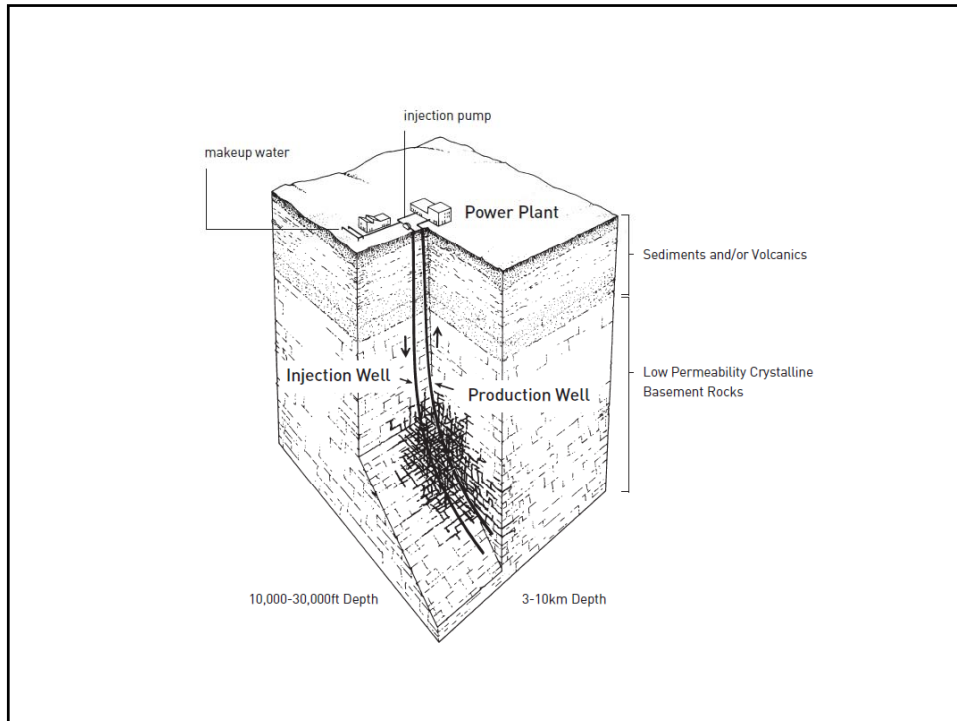
Geothermal

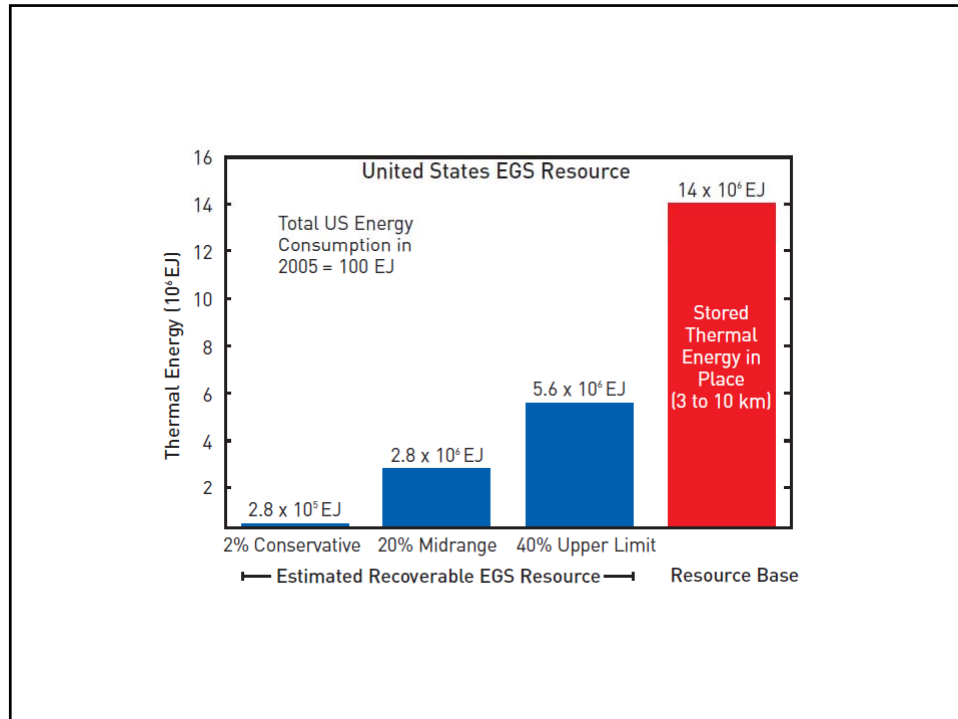
- Runs line of renewable/nonrenewable
- As a renewable:
 - Generation of energy in earth from nuclear decay = 1198 exajoules/yr
 - Not all capture-able (volcanoes, deep ocean ridges)
 - Extractible estimates below 150 exajoules/yr

Geothermal

As a NONrenewable:

- 200,000 exajoules accessible stored in rock formations under U.S. alone.
- Movable resource with centuries of supply...
- Only 3 exajoule/yr estimated to be economical





Wind

- Study:
 - ~2700 exajoules/yr available resource
 - 13% of surface of earth which is where wind >6m/s
- Strong net energy gain (>20-to-1)
- Economical now!!
- Intermittency...
- NIMBY
- Climate effect?
 - Simulations show notable climate change when turbines placed on more than 10% of earth's surface.



Archer, C. L., and M. Z. Jacobson, *Evaluation of global wind power*, *J. Geophys. Res.*, 110, 2005 <http://www.stanford.edu/group/efmh/winds/2004jd005462.pdf>.

Kieth, David, *The influence of large-scale wind power on global climate*, *PNAS*, 2004.

Hydro



- All moving water on Earth
 - 145 exajoules... insufficient to scale
 - Much not recoverable, many good places already taken.
 - May not be greenhouse gas neutral
 - Methane production from submerged rotting biomass
 - Estimates 29 exajoules/yr economical

Francfort, James. [Hydropower's Contribution to Carbon Dioxide Emission Reduction](#), Idaho National Engineering and Environmental Laboratory, 1997.



Biomass*



- Global biomass production = 4500 exajoules/yr
- Leave Ecosystems, produce food, grow high yield biomass, 270-446 exajoules/yr
 - In range with the B1 scenario
- Land use change
- Food security

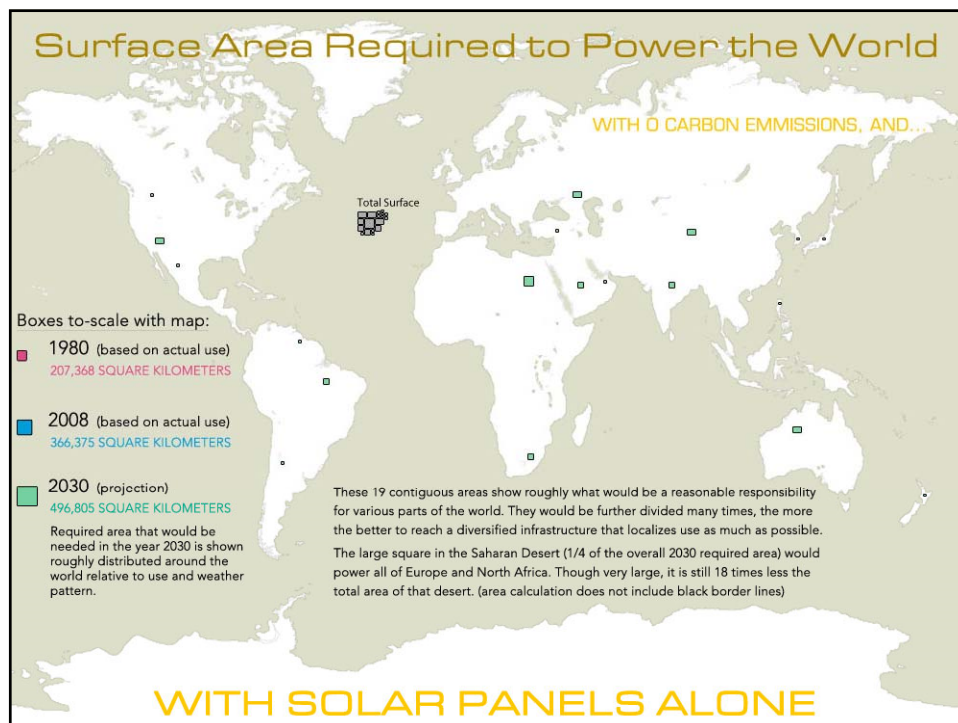


*Includes bio-diesel, vegetable oil, ethanol, wood, manure, combustible organics

Solar



- Theoretical Potential
 - 3,900,000 exajoules/year
- Conversion Efficiency (a few to 20%)
- Land Use (still need to grow crops, have ecosystems)
 - (still between 1,575 and 49,837 exajoules, depending on who's estimate you like)
- Intermittency



Summary

Non-Renewables

	Nuclear w/ breeder (yrs)	Geothermal (yrs)	Fossil w/ CCS (yrs)
Reserves	434	16	55
Resources	1556	1875	278

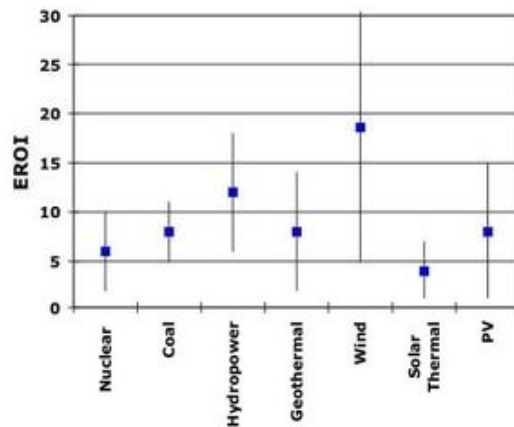
Need 302 exajoules/yr for at least a couple centuries

Renewables

	Wind	Solar	Hydro	Biomass
Theoretical	840 EJ/yr	3900000 EJ/yr	145 EJ/yr	2900 EJ/yr
Technical	280 EJ/yr	1575 EJ/yr	51 EJ/yr	270 EJ/yr
Economic	42 EJ/yr	very little	29 EJ/yr	N/A

Need 302 exajoules/yr to meet 550 ppm stabilization scenario in 2050

Energy Return on Investment



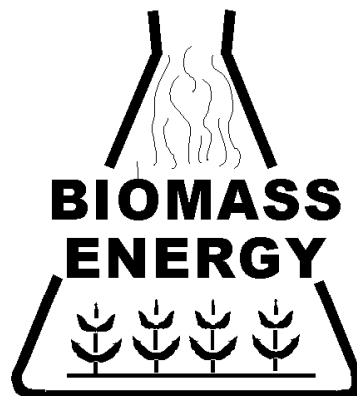
ENGS 37 - 11/28/11

Biomass:

Types, Advantages/Disadvantages,
and (very briefly) energy
conversion technologies

Biomass... Not ethanol conversion

- Types of biomass and advantages/disadvantages of use.
- Is it carbon neutral?
- Growing/Harvesting
- Conversion to final energy use

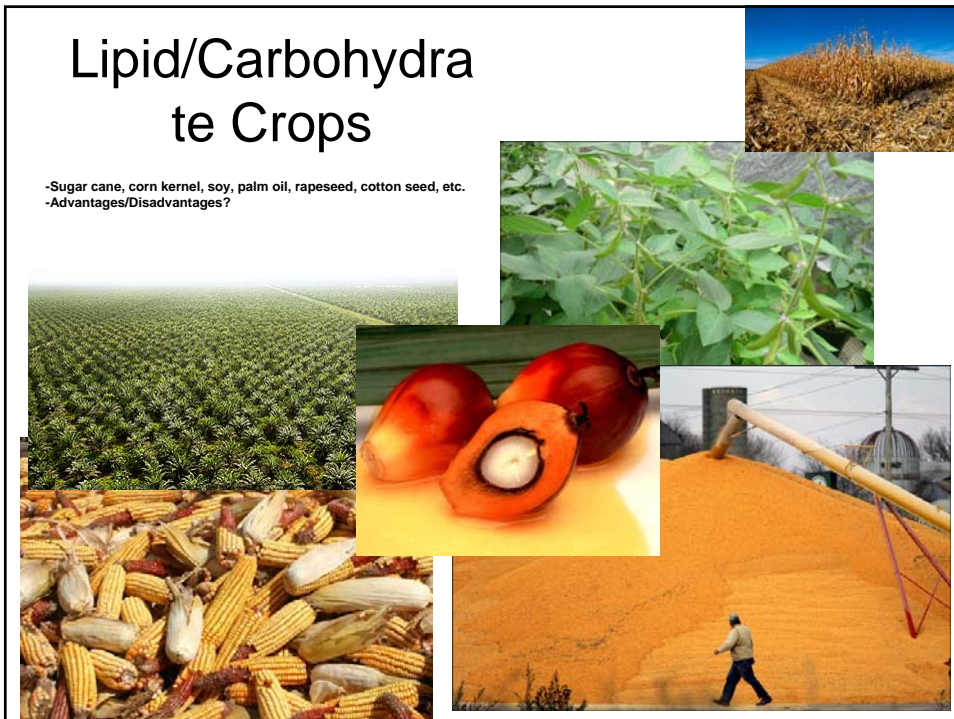


Types of Biomass

- Terrestrial plants
 - Carbohydrate/lipid
 - Cellulosic
 - Woody – Trees, willows
 - Non Woody – switchgrass, corn
- Algae
- Waste Streams
 - Municipal waste
 - Agricultural Process Waste – corn stover, lawn clippings, tree tops, sawdust, hulls
 - Animal dung

Lipid/Carbohydrate Crops

-Sugar cane, corn kernel, soy, palm oil, rapeseed, cotton seed, etc.
-Advantages/Disadvantages?



Cellulosic Crops

- Woody – Trees, willows
- Non Woody – switchgrass, corn (whole plant)
- Process Waste – corn stover, lawn clippings, tree tops, sawdust, hulls
- Advantages/disadvantages?

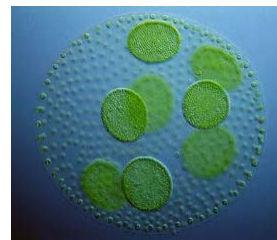
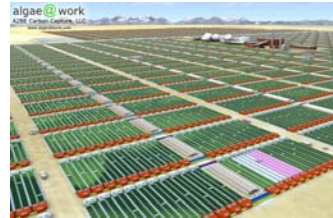


Energy Plantation Challenges

- Land use competition
- Loss of soil carbon
- Fresh water issues
- Availability of cropland
- Fertilizer, genetic engineering,
- Tillage vs perennial crops
- Food prices and famine

Algal crops

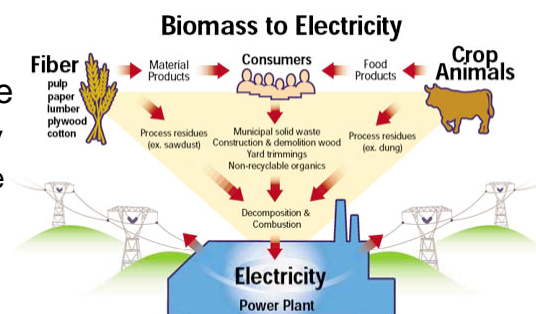
- Water pollution
- Very high lipid production (up to 60% by mass)
- 5000-20,000 gal/yr/acre
- Biosecurity
- Genetic modifications



Waste Streams

Large percentage (7-44% found) of U.S. energy needs is currently thrown away

- Animal dung
- Municipal solid waste
 - 10-20 MJ/person/day
 - Conversion profitable
- Agricultural process waste
 - Corn stover = 1.3 billion dry tons in U.S. 'wasted'



Agricultural Byproducts and wastes

- 30% of global commercial energy use (of which 30% is technically recoverable)
- Not profitable
- Issues with moving wastes around (biosecurity and fertility)

Biomass Advantages

- Can be Carbon neutral over moderate time period, no additional greenhouse effect
- Widely available and globally distributed
- Several ready conversion methods to liquid fuels
- From a U.S. perspective, national security
- Inexpensive, self replicating “equipment” for sunlight harvest

Biomass Disadvantages

- Must be carefully controlled to ensure sustainability
- Competition with crops and food.
- Rather an inefficient way to harvest sunlight
- Ecosystem destruction
- Fertilizer/pesticide use (possible)
- Low conversion efficiency (typical combustion designs similar to coal fired plant)

Are Bio-fuels GHG neutral?

Table 1A – Comparison of GHG Well-to-Wheel Emissions by Stage from Gasoline and Ethanol-Fueled Vehicles – Grams (CO₂ equivalent) Per Kilometer Driven

	Making Feedstock	Refining Fuel	Vehicle Operation (Burning Fuel)	Net Land Use Effects		Total GHG	Change in net GHGs vs. Gasoline
				GREET Feedstock Uptake Credit	Land Use Change		
Gasoline	11	47	220	0		278	
Pure Corn Ethanol	72	121	215	-188		221	-20%
Corn Ethanol with Our Land Use Change Emissions	72	121	215	-188	316	536	93%
Biomass Ethanol	29	26	215	-188		83	-70%
Biomass Ethanol with our carbon charge	29	26	215	-188	336	418	50%

Source: Calculated with GREET 1.7(4) using default assumptions for 2015 scenario. Gasoline is a combination of conventional and reformulated gasoline. Ethanol emissions remove emissions of 15% gasoline from E85 fuels. GREET assumes 7.15 km/liter for ethanol (and rates for gasoline adjusted for higher energy content). The table deletes from Making Feedstock column the GREET 2.5 grams/km estimate of emissions from land conversion for corn ethanol but includes credit for direct soil carbon gain by switching cropland to switchgrass. Land use change emissions are amortized over 30 years. The land use change estimate for biomass assumes switchgrass produced on average-yielding U.S. corn fields, at 18 MT/ha (S33) without feed by-product. Numbers in columns may not sum due to rounding.

Searchinger, 2008, in Science

Sunlight Harvest efficiency

- Sunlight incoming is not all PAR (45% is)
- Theoretical maximum conversion 11%
- Typical 3-6%
- Most not used to create biomass (just used for life processes of plant)
- Typical 0.1-2% efficient, with crops 1-2%

Photovoltaic cells are more efficient!

Conversion technologies

- Combustion... Challenge: Solid fuel (fuels burn as a gas, feed systems work better with fluids)
- Conversion to liquid fuels or hydrogen... challenges in economics and chemical/biological process design.
- Conversion to hydrogen... challenges in storage and transport.

Biomass Summary*

- Global biomass production = 220 billion oven dry tons... 4500 exajoules/yr
- Leave Ecosystems, produce food, grow high yield biomass, 270-446 exajoules/yr
- Total world primary energy use
~ 400 exajoules/year

(*exa* = 10^{18})

*Includes bio-diesel, vegetable oil, ethanol, wood, manure, combustible organics