SEBS Honors Seminar: State of the Earth
A Brief Tour of the Global Energy System – Reference Sheet
Prof. Robert Kopp (www.bobkopp.net)
February 29, 2012

Questions addressed in class

- What is energy?
- What do we (as individuals, as a nation, as a planetary civilization) use energy for?
- What are the proximate sources of the energy we use?
- What are the ultimate sources of the energy we use? How does the human energy system fit into the natural energy system?
- How has human energy use changed over history?
- Is the present energy system sustainable? What are the major risks associated with it?
- What alternatives are there to the present energy system? What are the barriers to energy system transformation?
- What sorts of policies can overcome these barriers?

SI Energy and Power Units
Energy: 1 Joule (J) = 1 kg m/s^2 *(the amount of energy in a 2 kg mass moving 1 m/s)*
Power: 1 Watt (W) = 1 J/s
Energy: 1 Watt•hour (Wh) = 1 W × 1 hour = 1 W × 3600 s = 3600 J
1 W•year = 8,766 Wh

SI Electrical Units
Current: 1 Ampere (A) – *a fundamental unit; practically defined as 1 coulomb/second*
Electrical potential: 1 Volt (V) = 1 W/A = 1 J/C
so 1 A flowing down a 1 V potential gradient will acquire 1 J of energy per second
Resistance: 1 Ohm (Ω) = 1 V/A
Power dissipated into heat is given by voltage x current or by current^2 x resistance

So: on a 120 V circuit (as in the U.S.), a 1,000 W device (e.g., a microwave) will draw a current of 8.3 A.

SI Prefixes
milli (m) = 10^{-3}
kilo (k) = 10^{3}
mega (M) = 10^{6}
giga (G) = 10^{9}
tera (T) = 10^{12}
peta (P) = 10^{15}
exa (E) = 10^{18}
zetta (Z) = 10^{21}

Non-SI Units that appear
1 **calorie** = 4.184 J, *energy required to heat 1 g of water by 1°C*
[note that 1 food Calorie = 1 kcal]
1 **British Thermal Unit (BTU)** = 252 cal = 1.055 kJ
energy required to heat 1 lb (454 g) of water by 1°F (0.56°C)
1 **Quad** = 1 quadrillion BTU = 1.055 EJ (~293 TWh)
1 **tonne oil equivalent (toe)** = 41.9 GJ = 11.6 MWh

Handy Reference Numbers

World annual primary exergy consumption = 474 EJ = 132,000 TWh

Of which, ~35% oil, ~29% coal, ~22% natural gas, ~12% biomass, ~7% nuclear, ~3% renewable

World annual final exergy demand = 325 EJ =91,000 TWh

Civilizational primary power supply = 474 EJ/year = 15 TW

Civilization final power demand = 325 EJ/year = 10 TW

Annual CO_2 emissions = 32 Gt CO_2 = 32 Pg CO_2

Solar cross-sectional energy flux at 1 AU = 1,360 W/m^2

Solar flux distributed over the surface area of the Earth = 340 W/m^2 = 174,000 TW

Solar flux making it to the surface = 184 W/m^2 = 94,000 TW

Geothermal heat flux = 86 mW/m^2 = 44 TW

Per Field et al. (1998)

Net primary productivity (terrestrial + marine) = 105 Pg C/yr

Terrestrial net primary productivity = 56 Pg C/yr

Biomass energy density ~ 2 kWh/kg C

Burial of net primary productivity ~ 0.1%

Transformation of buried organic matter into fossil fuels ~ 0.05%

Human appropriation of net primary productivity ~ 20% (14-26%)

Per Swart & Weaver (2012)

Total conventional oil resource base ~ 23 Gt C

Total unconventional oil resource base ~ 35 Gt C

Total conventional gas resource base ~ 22 Gt C

Total unconventional gas resource bas ~ 190 Gt C

Total coal resource base ~ 980 Gt C

Total fossil fuel resource base ~ 1,250 Gt C

Requried Readings

Cho, Adrian. 2010. "Energy's Tricky Tradeoffs." *Science* 329 (5993) (August 13): 786–787. doi:10.1126/science.329.5993.786.

Cullen, Jonathan M., and Julian M. Allwood. "The Efficient Use of Energy: Tracing the Global Flow of Energy from Fuel to Service." *Energy Policy* 38, no. 1 (January 2010): 75–81.

ExxonMobil, The Outlook for Energy: A View to 2040, 2012, http://www.exxonmobil.com/corporate/files/news_pub_eo2012.pdf.

Hoffert, Martin I, Ken Caldeira, Gregory Benford, David R Criswell, Christopher Green, Howard Herzog, Atul K Jain, et al. "Advanced Technology Paths to Global Climate Stability: Energy for a Greenhouse Planet." *Science* 298, no. 5595 (November 1, 2002): 981–987.

Schiermeier, Quirin, Jeff Tollefson, Tony Scully, Alexandra Witze, and Oliver Morton. "Energy Alternatives: Electricity Without Carbon." *Nature* 454, no. 7206 (August 14, 2008): 816–823.

Smil, V. "Global Energy: The Latest Infatuations." *American Scientist* 99 (2011): 212–219.

Useful web sites

Energy Information Administration: http://www.eia.gov/
International Energy Agency: http://www.iea.gov/
New Jersey State Energy Master Plan: http://nj.gov/emp/
Bloomberg New Energy Finance: http://bnef.com/
Stanford Exergy Flow Charts: http://gcep.stanford.edu/research/exergycharts.html

Other References

Cullen, Jonathan M., and Julian M. Allwood. "Theoretical Efficiency Limits for Energy Conversion Devices." *Energy* 35, no. 5 (May 2010): 2059–2069.

DeLong, J.B. "Estimating World GDP, One Million BC-present." *http://econ161. Berkeley. edu/TCEH/2000/World_GDP/Estimating_World_GDP.htm* (1998).

Field, Christopher B, Michael J Behrenfeld, James T Randerson, and Paul Falkowski. "Primary Production of the Biosphere: Integrating Terrestrial and Oceanic Components." *Science* 281, no. 5374 (July 10, 1998): 237–240.

Imhoff, Marc L., Lahouari Bounoua, Taylor Ricketts, Colby Loucks, Robert Harriss, and William T. Lawrence. "Global Patterns in Human Consumption of Net Primary Production." *Nature* 429, no. 6994 (June 24, 2004): 870–873.

Kempton, Willett, Felipe M Pimenta, Dana E Veron, and Brian A Colle. "Electric Power from Offshore Wind via Synoptic-scale Interconnection." *Proceedings of the National Academy of Sciences* 107, no. 16 (April 20, 2010): 7240–7245.

Kyle, Page, Leon Clarke, Graham Pugh, Marshall Wise, Kate Calvin, James Edmonds, and Son Kim. "The Value of Advanced Technology in Meeting 2050 Greenhouse Gas Emissions Targets in the United States." *Energy Economics* 31, Supplement 2, no. 0 (December 2009): S254–S267.

MacKay, D.J.C. 2008. *Sustainable Energy–without the Hot Air*. Cambridge: UIT Cambridge. http://www.withouthotair.com/.

National Academy of Sciences Committee on America's Energy Future. *America's Energy Future:Technology and Transformation: Summary Edition*. Washington, D.C.: The National Academies Press, 2009.

Trenberth, Kevin E., John T. Fasullo, and Jeffrey Kiehl. "Earth's Global Energy Budget." *Bulletin of the American Meteorological Society* 90, no. 3 (March 2009): 311–323.

Zhu, Xin-Guang, Stephen P Long, and Donald R Ort. "What Is the Maximum Efficiency with Which Photosynthesis Can Convert Solar Energy into Biomass?" *Current Opinion in Biotechnology* 19, no. 2 (April 2008): 153–159.