A Conspectus on US Energy

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Great source of data

- [www.eia.doe.gov](http://www.eia.doe.gov)

- Look up aer2007 (Annual Energy Review, and pick your year)
From Scientific American ca. 1970

2007: 101.5 quads
   = 107 EJ

3.39 TWt (all energy)

US Population 2007
   298 million

11.4 kWt/capita

10^9

10^8

10^7

10^{15} BTU = 1 quad

Updates

Population

US annual energy, BTU
All US Energy 2007
= 107 EJ$_{\text{thermal}}$

US Energy Sources 2007

- Petroleum: 40%
- Coal: 22%
- Gas: 23%
- Nuc: 8%
- Renewable: 7%

85% from coal, oil, & gas
All 2007 Renewables = 7.2 EJ\textsubscript{t}

US Energy From Renewables

- Hydro: 36%
- Wood: 32%
- Bio. Liquids: 15%
- Waste: 6%
- Geothermal: 5%
- Solar/PV etc: 1%

Shown: % of Renewable contribution

6.83% of all energy
All 2007 US Electricity from 44.4 EJ\(_t\)

US Sources of Electricity

- **Coal**: 51%
- **Gas**: 18%
- **Nuclear**: 20%
- **Oil**: 2%
- **Renewable**: 9%

\[4.160 \times 10^{15} \text{ Wh produced}\]
\[3.890 \times 10^{15} \text{ Wh end use}\]
\[440 \text{ GW} = <P>_{\text{end use}}\]

Overall: 31.3% efficient (heat-to-electricity)
Electricity from Renewables

= \(0.35 \times 10^{15}\) Wh

Renewable Electricity Generation

- Hydro: 71%
- Wind: 9%
- Solar/PV etc: 0.17%
- Wood: 11%
- Waste: 5%
- Bio Liquid: 0%
- Geothermal: 4%

Renewables produce 9% of electricity
Mostly by hydro
US Energy Usage

Energy Usage, US 2007

- Residential: 21%
- Commercial: 18%
- Industrial: 32%
- Transportation: 29%
Sources, Dist., & Sinks

- Coal
- Gas
- Oil
- Nuc Ren

≈ equal

Res
Comm
Industrial
Transportation
(Heat loss allocated)

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U.S. ENERGY-CONSUMPTION GROWTH (curve in color) has outpaced the growth in population (black) since 1900, except during the energy cutback of the depression years. Next
U.S. Per-capita energy consumption

Annual US Energy Consumption
EJ per Million Population 1795-2004

Exajoules per Million Population

1750 1800 1850 1900 1950 2000 2050

3.5 ×
History of Renewables: The Decline from 100%
Virtually all solar energy comes from two sources

Hydro

Biomass
Solar Intensity

- Above atmosphere $\Rightarrow 1368 \text{ W/m}^2$
- Surface, noon clear sky, sun overhead $\Rightarrow 950 \text{ W/m}^2$
- Average 24/7/365 $\Rightarrow 200 \text{ W/m}^2 \pm 20\%$ (covers most of US)
- Note: All solar systems should be expressed in W/m$^2$ (save, perhaps, hydro)
Note on hydro & wind.

- EIA / DOE reckons heat in BTU
- EIA / DOE reckons electricity in millions (or billions) of kWh
- 1 kWh = 3413 BTU (direct conversion)
- But steam engines typically require about 10,000 BTU to get 1 kWh.
- For wind & hydro, EIA / DOE multiplies kWh by ≈ 3 for “replacement” purposes
EIA example

Hydro:

- $2.46 \times 10^{15}$ BTU
- 248.3 billion kWh
- $9,910 \text{ BTU} / \text{kWh}$ instead of 3413 (direct)
Solar Math: Find the largest

A. 11,700 calories per square centimeter during one month
B. 254 BTU per square foot per minute
C. 2 MWe generated per 130 acres of solar collector
D. 1/2 cord of white oak per acre per year
E. 397 Langleys per day
Which is largest?

- A: 45 W/m²
- B: 89 W/m²
- C: 800 W/m²
- D: 15 W/m²
- E: 0.05 W/m²

N.B. Use a consistent system of units.
The Fair-haired boys

- Corn $\Rightarrow$ ethanol
  - We’ll ignore this abomination
- Wind (0.3% of U.S. energy)
- Solar-thermal (the largest)
  - + Solar-thermal/electric
  - + Photovoltaics
    $\cong 0.07\%$ of U.S. energy
- Wind $\approx 50 \times$ Solar / PV (electricity)
Power from Wind

- Proportional to $R^2$
- Proportional to $v^3$
- $v_{\text{tip}} \approx 6 \times v_{\text{wind}}$
- Separation of adjacent turbines typically 10 diameters

\[ P(\text{watts}) \approx 0.8 \times [R(\text{meters})]^2 \times [v(\text{meters/sec})]^3 \]

at maximum possible efficiency

Betz limit = 59%
Power from Wind: Output Power *versus* Wind speed

- Precious little power
- Fluctuations troublesome to grid
- Steady power but rare occurrence
- Blades trimmed, thereby lowering efficiency
- Shut off

Precious little power
Steady power but rare occurrence
Blades trimmed, thereby lowering efficiency
Shut off
Designing the Capacity Factor

- Huge generator on a pinwheel
  - 0% annual C.F.
- Huge blades driving 1-watt generator
  - Near 100% annual C.F.
- Choose an engineering compromise
  - Now designed for 35% annual C.F.
    - Most places don’t reach it.
- Wind electricity is not dispatchable
Wind Power (%), 1-hr intervals

6 turbines

104 turbines, 4 locations

Power from Wind: Land requirements

- Power output *per unit land area* of wind farm is independent of \( R \)
  \[ P \propto R^2 \; ; \; D_{\text{separation}} \propto R \; ; \; P/A_{\text{land}} = \text{const} \]

- Actual results of year-round average power production from wind farms
  - About 12.5 kW/ha (5 kW per acre)
    - 770 km\(^2\) (300 mi\(^2\)) for 1000 MW

- Will environmentalists tolerate it?
Solar Electricity

- Solar-thermal electricity
  - 2-angle tracking (Field of mirrors)
  - 1-angle tracking (Parabolic mirrors)

- Photovoltaics
Solar-2
(Field of 2-axis mirrors)

10 MW *peak* on 53 hectares

This expensive experiment is now the Keck Solar Two Observatory.
Solar-II (in Mojave Desert)

10 MW, full-tilt, noon, sunny day
1.6 MW average

Serious power station:
500 MW (?) around the clock
around the year
Solar/thermal-electric
One-axis parabolic mirrors

SEGS at Kramer Junction, CA, in the Mojave Desert
Solar Energy Generating System (SEGS)

- 355 MW *peak* on ~ 725 hectares

Human

$\sim 10 \text{W/m}^2 (100 \text{ kW/ha})$ on 24/7/365 basis
Solar/ thermal-electric

This California system produces almost all solar electricity in the US --- 616 GWh 2006

PV is so insignificant that the US Energy Information Agency ([www.eia.doe.gov](http://www.eia.doe.gov)) doesn’t bother keeping track of it separately from solar/thermal-electric.
Photovoltaics

Main Problem #1:
- Asking a broad spectrum to do a quantum job

Main Problem #2
- Sunlight is dilute

Main Problem #3
- You can collect solar energy only where you put collectors
Solar PV Replaces Nuclear?

Rancho Seco 900 MW nuclear power station

Removed from Service June 1989

2 MW peak PV farm

Rancho Seco nuclear power plant

Solar PV array to replace Rancho Seco
Biomass

- Open-field growth
  - Plant small seeds, get big plants

- Closed-environment growth
  - Must build structure
  - Better control

Chlorophyll absorbs 6.6% of the solar spectrum.

\[
\frac{P_{\text{thermal}}}{A} \approx \text{wind}_{\text{elec}}, \text{ at best} \text{ (with good water, fertilizer, weed control, insect control...)}
\]

- Always competes with food production
  - ‘Nuff said
Q&A

It’s your turn