Energy, Science and Society

A physicist’s perspective…

(Some charts taken from R. Muller, Physics and Technology for Future Presidents (Princeton, 2010))
Energy vs. GDP (per capita)
Your (N. America) Energy Use

- Rate of about 10 kW, or 10,000 Watts
- ≈ 100 times your body’s energy output
# Table of Power Examples

<table>
<thead>
<tr>
<th>value</th>
<th>equivalent</th>
<th>example of that much power use</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 watt</td>
<td>1 joule per second</td>
<td>flashlight</td>
</tr>
<tr>
<td>100 watts</td>
<td></td>
<td>bright light bulb; heat from a sitting human</td>
</tr>
<tr>
<td>1 horsepower (1 hp)</td>
<td>≈ 1 kilowatt^A</td>
<td>typical horse (for extended time) human running fast up flight of stairs</td>
</tr>
<tr>
<td>1 kilowatt (1 kW)</td>
<td>≈ 1 hp^B</td>
<td>small house (not including heat); power in 1 square meter of sunlight</td>
</tr>
<tr>
<td>100 horsepower</td>
<td>≈ 100 kW^C</td>
<td>small automobile</td>
</tr>
<tr>
<td>1 megawatt (MW)</td>
<td>1 million (10^6) watts</td>
<td>electric power for a small town</td>
</tr>
<tr>
<td>45 megawatts</td>
<td></td>
<td>747 airplane; small power plant</td>
</tr>
<tr>
<td>1 gigawatt = 1 GW</td>
<td>1 billion (10^9) watts</td>
<td>large coal, gas, or nuclear power plant</td>
</tr>
<tr>
<td>400 gigawatt</td>
<td></td>
<td>average electric power use US</td>
</tr>
<tr>
<td>= 0.4 terawatts</td>
<td></td>
<td>average electric power for World</td>
</tr>
<tr>
<td>2 terawatts</td>
<td>= 2 x10^{12} watts</td>
<td></td>
</tr>
</tbody>
</table>

^A more precise value: 1 hp = 746 watts

^B more precise value: 1 kW = 1.3 hp

^C more precise value: 100 hp = 74.6 kW
## Energy per Gram

<table>
<thead>
<tr>
<th>Object/Material</th>
<th>Calories</th>
<th>Compared to TNT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bullet (moving at sound speed, 1000 ft/sec)</td>
<td>0.01</td>
<td>0.015</td>
</tr>
<tr>
<td>Battery (car)</td>
<td>0.03</td>
<td>0.05</td>
</tr>
<tr>
<td>Battery (rechargeable computer)</td>
<td>0.1</td>
<td>0.15</td>
</tr>
<tr>
<td>Battery (alkaline flashlight)</td>
<td>0.15</td>
<td>0.23</td>
</tr>
<tr>
<td>TNT</td>
<td>0.65</td>
<td>1</td>
</tr>
<tr>
<td>Modern high explosive (PETN)</td>
<td>1</td>
<td>1.6</td>
</tr>
<tr>
<td>Chocolate chip cookies</td>
<td>5</td>
<td>8</td>
</tr>
<tr>
<td>Coal</td>
<td>6</td>
<td>10</td>
</tr>
<tr>
<td>Butter</td>
<td>7</td>
<td>11</td>
</tr>
<tr>
<td>Alcohol (ethanol)</td>
<td>6</td>
<td>10</td>
</tr>
<tr>
<td>Gasoline</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>Natural gas (methane, CH4)</td>
<td>13</td>
<td>20</td>
</tr>
<tr>
<td>Hydrogen (H2)</td>
<td>26</td>
<td>40</td>
</tr>
<tr>
<td>Asteroid or meteor (moving at 30 km/sec)</td>
<td>100</td>
<td>165</td>
</tr>
<tr>
<td>Uranium 235</td>
<td>20 million</td>
<td>30 million</td>
</tr>
</tbody>
</table>
Our love affair with gasoline

- Cheap!
  
  Well, it used to be.

- Clean!

  Unlike coal, no ash residue.

  Emits mostly carbon dioxide! Hey – that’s the same stuff we breathe out. It’s good for plants!

- Safe!

  No horrific dangers (c.f. meltdown ‘China syndrome’). Unless, of course, you consider war in the Mideast to be related to oil

It’s more like an unhappy marriage
## Cost of energy

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Plug-in Hybrid: more expensive than $15/gallon gasoline! (but less carbon dioxide)
World primary energy consumption grew more slowly in 2006 but growth remained just above the 10-year average. Oil was the slowest-growing fuel, while coal was the fastest-growing. Although oil remains the world's leading energy source, it has lost market share to coal and natural gas in the past decade.
Climate Change
aka “Global Warming”

• Excessively politicized topic; exaggerators on all sides
• A very complex scientific problem
  – Involves tracking slow changes over long periods of time
  – Could (always!) use more data
  – Sources of heating and cooling are temperature dependent, hence there are feedback cycles
• Also a complex political problem
  – Solutions will be expensive
  – Developed/un-developed conflict
Global Average Temperature

The graph shows the global average temperature from 1850 to 2000, with the temperature in °F on the vertical axis and the year on the horizontal axis. The graph indicates a general increase in temperature over time, with notable fluctuations. The 1998 peak is marked, as well as the 5-year and 1-year average temperatures. The scale on the right side of the graph represents the temperature relative to the 1961-1990 period.
What’s not in dispute...

- The Earth is getting warmer
  - Average global temperatures have risen by close to 2 °F over the last century
  - May not sound like much, but during the last ice age average temperatures were only about 10 °F colder than now
  - Averaged over the last 10 years, Earth is warmer than it has been in 400 years
  - In the past century global sea levels have risen at a rate 10 times faster than during any time over the last 3000 years
The real question…

- Is the warming just natural variation, or is it the result of human activity?
  - Humans have been burning fossil fuels (coal, oil, natural gas) in increasing quantities since the Industrial Revolution (late 1800s)
  - Result is that large quantities of carbon dioxide (and other “greenhouse gases”) have been released into the atmosphere
  - Worries about an enhanced greenhouse effect

- **If it is human caused, then it will get worse!**
  - Best estimates are a further 3 °F to 10 °F over the next 50 years
  - A 10 °F rise would likely cause massive economic dislocation
The Greenhouse Effect

- With no atmosphere, Earth’s surface temperature would be about 26 °F
- Trapped heat from atmosphere raises this to about 57 °F – comfy!
- Just like a greenhouse, or a car parked in the sun
CO$_2$ in the Atmosphere

- Data from a variety of sources; all in essential agreement
- Increase of about 36% since late 1800s
- Agrees with known fossil fuel usage
- The CO$_2$ level is now higher than at any time in the past 12 million years (!)
Carbon Dioxide and Temperature Records

Present CO₂ level

Atmospheric CO₂ (ppm)

Thousands of Years Ago

-320
-340
-360
-380
-400
-420
-440

-300
-350
-400

0
50
100
150
200
250
300
350
400

Atmospheric CO₂ (ppm)
Surface and Satellite Temperatures

Direct Surface Measurements
Satellite Measurements
UAH / RSS
Arctic Ice Mass 1979-2003
Positive proof of global warming.
A possible “feedback cycle”?

• More CO$_2$ results in warmer temperatures
• The warmer temperatures release CO$_2$ from the oceans, leading to still warmer temperatures
  – Also more H$_2$O vapor, another heat trapping gas
• And so on…
• Point of no return sometimes called the “tipping point”
• It’s very unlikely that we are close to triggering a “runaway” greenhouse effect like this
  – Probably what happened on Venus, though
A *Negative* Feedback Mechanism?

- Warming leads to more H$_2$O vapor in atmosphere
- This *might* lead to more cloud cover
- Clouds reflect sunlight, so more clouds could lead to cooling
- Not yet well understood!
- Increase of 2% in cloud cover would overwhelm human CO$_2$
The Scientific Consensus

- *Intergovernmental Panel on Climate Change (IPCC)*
  - Convened by the United Nations and the World Meteorological Organization
  - Shared 2007 Nobel Peace Prize with Al Gore
  - Issues major summary reports every few years; smaller, more specialized reports more or less continually
  - Attempts to synthesize a consensus of thousands of experts
  - Results are often heavily qualified, but statements they do make should be regarded as things almost all experts agree on
"The observed widespread warming of the atmosphere and ocean, together with ice mass loss, support the conclusion that it is extremely unlikely that global climate change of the past fifty years can be explained without external forcing, and very likely that it is not due to known natural causes alone."

- "External forcing" means an outside agency, i.e., greenhouse gases
- They define "very likely" as 90% confidence
  - Thus a 10% chance that the change is natural, not caused by humans
Possible Effects

- Rising sea levels and inundation of coastal areas
- More extreme weather, e.g. droughts followed by periods of heavy rainfall and flooding, hurricanes, monsoons, etc.
- Disruption of agriculture
- Increases in malaria and other insect-borne diseases
- ...
Fig. 1. Track maps of the Atlantic hurricane seasons of 2005 and 1933, the two busiest hurricane years on record for tropical cyclone frequency. The circles highlight large differences in activity that occurred over the open Atlantic Ocean.
Hurricane Frequency

• No statistically significant evidence that frequency or strength are increasing \textit{or} decreasing
• The IPCC make no claim either way
• We just don’t know (yet) what the effect of warming will be on major storms
• BUT this is not evidence against global warming!
  – The temperature data are very strong
Severe Storms

- Also sometimes claimed to be on the rise
- May also reflect an observational bias
  - We detect more of them nowadays using radar
- Storms that do damage appear to be less common
- Could be an effect of global warming!

Strong to violent tornadoes in the US (1950-2005)
Permafrost Melting in Alaska
What about the critics?

• The science is (very) complicated
• Some things are known with high certainty, others are fairly uncertain – and everything in between
• Often very hard for the non-expert to tell where a particular fact/prediction falls in this spectrum
• Technical points are often the subject of lively debate; this may be mistaken for disagreement about well-established facts
  – Sometimes this confusion is intentional!
• “He said, she said” tendency in press exaggerates the status of non-consensus views
Can it be stopped?

• Consensus: 90% chance that global warming is at least partly human-caused
  – At least 1 °F of the rise in the past 50 years is attributable to human activity (according to the IPCC)
• If so, *we can expect it to get worse*
  – CO₂ stays in the atmosphere for perhaps 1000+ years
• Stopping it will not be easy: fossil fuels are the most readily available cheap source of energy
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<table>
<thead>
<tr>
<th>Country</th>
<th>Oil</th>
<th>Coal</th>
<th>Natural Gas</th>
<th>Total</th>
<th>Oil Shale</th>
<th>Total with Shale</th>
</tr>
</thead>
<tbody>
<tr>
<td>US</td>
<td>21</td>
<td>1184</td>
<td>32</td>
<td>1237</td>
<td>2500</td>
<td>3737</td>
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<tr>
<td>Russia</td>
<td>60</td>
<td>754</td>
<td>280</td>
<td>1094</td>
<td>250</td>
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<td>Australia</td>
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<td>377</td>
<td>821</td>
<td>1328</td>
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<tr>
<td>India</td>
<td>5</td>
<td>444</td>
<td>853</td>
<td>1302</td>
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<td>China</td>
<td>48</td>
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<td>Iran</td>
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<td>Saudi Arabia</td>
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<td>Canada</td>
<td>179</td>
<td>32</td>
<td>220</td>
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<td>Qatar</td>
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<td>Brazil</td>
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<td>Venezuela</td>
<td>80</td>
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<td>Mexico</td>
<td>12</td>
<td>17</td>
<td>5</td>
<td>34</td>
<td>100</td>
<td>234</td>
</tr>
</tbody>
</table>
The Kyoto Protocol

• An amendment to the *UN Framework Convention on Climate Change*, signed in Kyoto, Japan (1998)
• Would have required reducing CO₂ emissions to 7% below the 1990 level – not cheap
• Ratified by 164 countries, but not the US (and a few others)
• Main objection: no limits on developing nations like China, India
• Our reduction would be swamped by their expected gains
Pollution per GDP

Greenhouse Gas Emission Intensity

Metric tons CO2 per $1000 GDP

United States: 0.55
EU-15: 0.48
France: 0.29
Germany: 0.46
Spain: 0.57
Sweden: 0.23
United Kingdom: 0.36
Italy: 0.44
Japan: 0.26
China: 3.14
Brazil: 0.51
India: 1.88

(Source: EIA, Emissions of Greenhouse Gases in the U.S. 2005)
CO₂ Emissions Grow Following Copenhagen "Success"

Assumptions:
USA: 80% cut by 2050
Kyoto developed states (Annex I): 60% cut by 2050
China: 4% per year cut in carbon intensity until 2040
(amounts to a 70% cut by 2040)
Chinese economy grows at 10%
Other emerging economies grow at 6%
Emerging economies begin 80% cut in 2040

Data 1990 to 2007: IEA  
Muller & Associates
Solutions?

- Conservation
- “Clean coal”
  - Main issue is whether sequestered CO$_2$ will stay that way
- Biofuels
  - “Carbon neutral” in principle, not always in practice
  - Some good, some bad (e.g., corn ethanol)
- Nuclear power
- Wind
- Solar
Truly Clean Coal?

Sequestration of the carbon dioxide (CSS)

Cost: 4¢ per kWh

We can't just suck it out of the air.
Efficient and Clean Coal: IGCC (Integrated Gas Combined Cycle)
Wind turbines
In 2002 the world’s largest offshore wind farm was constructed off the Danish west coast. The Horns Rev wind farm is sited 14-20 km into the North Sea, west of Blåvands Huk, and represents the first phase in the Danish Government’s ambitious plan - to have wind turbines with a total capacity of 4000 MW in Danish waters before 2030.
Annual average wind power density at 50m altitude
Solar Cells

At 15% efficiency, 1 GW peak power requires 2.7 square miles
Surface Area Required to Power the World

With 0 carbon emissions, and...

Boxes to-scale with map:

1980 (based on actual use)
207,368 square kilometers

2008 (based on actual use)
366,375 square kilometers

2030 (projection)
496,805 square kilometers

Required area that would be needed in the year 2030 is shown roughly distributed around the world relative to use and weather pattern.

These 19 contiguous areas show roughly what would be a reasonable responsibility for various parts of the world. They would be further divided many times, the more the better to reach a diversified infrastructure that localizes use as much as possible.

The large square in the Saharan Desert (1/4 of the overall 2030 required area) would power all of Europe and North Africa. Though very large, it is still 18 times less the total area of that desert. (area calculation does not include black border lines)

With solar panels alone
"Worst Case" Solar Insolation (kWh/m²/day)
Carbon Credits

• An attempt to include environmental costs in the price of fossil fuels, then let the market work
• Idea: Carbon producing plants must buy “credits” for the CO$_2$ they produce
• Clean power plants get credits they can sell
• Set up so that market forces drive towards lower overall CO$_2$ production
• Kyoto had such a system called “cap and trade” – countries were capped but could trade credits
Copenhagen

• Follow-on to Kyoto, took place in December 2009
• No legally binding result; endorsed the continuation of Kyoto
• No emissions targets
• Lots of accusations about who was to blame for the lack of an agreement…
The Future

- Climate change will be driven by the developing world.

- It’s not good enough to set an example if developing nations cannot afford to follow that example.

- Subsidized clean will not be sustainable unless it inspires the development of profitable clean.

The Future

- The problem is serious and complicated
- Solutions are possible, but will need to involve many different approaches
  - Conservation
  - Alternative energy sources
  - CO$_2$ sequestration
  - Carbon trading schemes
  - ...
- Neither the most optimistic nor the most pessimistic scenario is likely to actually occur!
Physics is non-partisan and non-denominational

“…reality must take precedence over public relations, for nature cannot be fooled.”

– Richard Feynman