SLIDES: The Real Biofuel Cycles and The Earth, Biofuels, and Reality

Tad W. Patzek

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This short example of astronomical scale-up problems with biofuel systems builds on the similar calculations described at http://zfacts.com/p/60.html, see Table 1 for details. My conference presentation will cover a broad range of physical, biological, and ecological problems with the real corn-ethanol, switchgrass-ethanol, and sugarcane-ethanol systems.

Suppose that one accepted the unrealistically high ethanol yield used by the USDA and their nonphysical coproduct energy credits, and one claimed that the net energy ratio of corn ethanol production were as high as 1.34. Consistently with this claim, for each 1 unit of input fossil energy, one would get 1.34 units of output fossil energy as ethanol, or for 3 units of input energy, one would get 4 units of output energy. This means that one would have to use the amount of fossil energy equivalent to 3 gallons of ethanol to produce one extra gallon of automotive fuel ethanol. Therefore, it would take the energy in 4/(0.95 × 0.64 + 0.05) = 6.1 gallons of denatured ethanol to eliminate 1 gallon of gasoline. The current cost of these 6.1 gallons EtOH is 6.1 × $3.73 = $22.67, but one would save one gallon of premium high-octane gasoline retailing at $3.24 as of 05/06/06. So the net cost of displacing one gallon of premium gasoline with corn ethanol would be $22.67 − $3.24 = $19.43.

In 2005, the U.S. burned ∼140 billion gallons of gasoline. If one wanted to run a “sustainable” corn-ethanol transportation system, one would have to produce 6.1 × 140 = 851 billion gallons of denatured ethanol, with 5% gasoline by volume, or 808 billion gallons of pure ethanol. The unrealistically low cost of producing this ethanol would be $15.71 trillions, more than the 2005 U.S. GDP of $12.4 trillions.

At 2.48 gallons EtOH/bushel, one would have to produce 327 billion bushels of corn per year (34 times the mean annual U.S. corn production over the last decade) to replace gasoline currently used in the U.S. Let’s suppose that this corn were produced every year at the all-time record yield of 180 bushels/acre in Iowa. One would have to grow corn on 1.8 billion acres, year-after-year, for decades. There are about 400 million acres of arable land now in cultivation in the U.S. Therefore, one would

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1This yield of 2.682 gal EtOH/bushel counts 5% of gasoline denaturant, fusel alcohol, and Brazilian imports of ethanol as parts of the true yield of ethanol produced in the U.S.
2To separate starch from the remainder of corn kernels (coproducts), one does not have to spend the enormous amount of fossil energy necessary to distill ethanol beer.
3Without the coproduct energy credits the USDA net energy ratio hovers at about 1.0.
4A system in which corn ethanol would serve as the main fossil energy source to drive corn agriculture and ethanol refineries. Physics makes such a system clearly impossible.
5One would have to spend additional $ trillions to expand industrial farming (35-fold if all corn went to ethanol) and ethanol refining (200-fold), and protect the entire national water and food supplies, public health, and the environment. Water shortage and pollution, and soil destruction would become extreme across the U.S.
6Such consistently high yields are absolutely impossible if one cultivated only corn on all arable land, including marginal fields, and expanding agriculture to non-agricultural land. Also the hybrid corn seed production would take an enormous additional land area and fossil energy.
have to use the land area equal to 4.5 times the current arable land area just to satisfy the automotive gasoline use in the U.S. There would never be enough water and soil, and other environmental services to support this madness.

Alternatively, one may claim that the U.S. car drivers receive a subsidy of $15.71 trillion - $0.45/0.83 trillion for premium gasoline = $15.1 trillion per year from ancient solar energy and the world. This amount of wealth would disappear every year, once the latter subsidy stops. Since continuous disappearance of wealth at this rate is impossible, the U.S. economy will have to shrink dramatically and reconnect with its natural resource foundation. Enter energy efficiency and lifestyle modifications.

I have not discussed here the 45 billion gallons per year of diesel fuel and 25 billion gallons per year of jet fuel used in the U.S. Oh, and then there are naphtha for heating and natural gas for cooking.

<table>
<thead>
<tr>
<th>Line</th>
<th>Fact</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2005 EtOH production capacity&lt;sup&gt;a&lt;/sup&gt;</td>
<td>4486</td>
<td>10&lt;sup&gt;6&lt;/sup&gt; gallons denatured per year</td>
</tr>
<tr>
<td>2</td>
<td>“Small producers”&lt;sup&gt;b&lt;/sup&gt; EtOH capacity</td>
<td>2597</td>
<td>10&lt;sup&gt;6&lt;/sup&gt; gallons denatured per year</td>
</tr>
<tr>
<td>3</td>
<td>Mean ethanol tax credit&lt;sup&gt;c&lt;/sup&gt; for “small producers”</td>
<td>0.0579</td>
<td>$/gallon denatured</td>
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<tr>
<td>4</td>
<td>VEETC tax credit&lt;sup&gt;d&lt;/sup&gt;</td>
<td>0.5100</td>
<td>$/gallon denatured</td>
</tr>
<tr>
<td>5</td>
<td>Mean ethanol tax credits</td>
<td>0.5679</td>
<td>$/gallon denatured</td>
</tr>
<tr>
<td>6</td>
<td>Cumulative corn subsidies&lt;sup&gt;e&lt;/sup&gt; in US from 1995 to 2004</td>
<td>41.90</td>
<td>$ Billion</td>
</tr>
<tr>
<td>7</td>
<td>Cumulative corn produced&lt;sup&gt;f&lt;/sup&gt; in US from 1995 to 2004</td>
<td>95.309</td>
<td>Billion Bushels</td>
</tr>
<tr>
<td>8</td>
<td>Average&lt;sup&gt;g&lt;/sup&gt; corn subsidies from 1995 to 2004</td>
<td>0.4396</td>
<td>$/bushel</td>
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<tr>
<td>9</td>
<td>Mean rack price&lt;sup&gt;h&lt;/sup&gt; of EtOH (05/05/06)</td>
<td>2.8303</td>
<td>$/gallon denatured</td>
</tr>
<tr>
<td>10</td>
<td>Mean EtOH yield&lt;sup&gt;i&lt;/sup&gt; from 2000 to 2004</td>
<td>2.4776</td>
<td>gallons EtOH/bushel</td>
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<tr>
<td>11</td>
<td>Mean subsidy&lt;sup&gt;j&lt;/sup&gt; of EtOH from corn subsidies</td>
<td>0.1774</td>
<td>$/gallon EtOH</td>
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<tr>
<td>12</td>
<td>Mean state subsidies&lt;sup&gt;k&lt;/sup&gt; for EtOH</td>
<td>0.1535</td>
<td>$/gallon EtOH denatured</td>
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<tr>
<td>13</td>
<td>Total mean subsidy&lt;sup&gt;l&lt;/sup&gt; of EtOH</td>
<td>0.8988</td>
<td>$/gallon EtOH denatured</td>
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<tr>
<td>14</td>
<td><strong>Mean cost</strong>&lt;sup&gt;m&lt;/sup&gt; of EtOH to taxpayer</td>
<td>3.7292</td>
<td>$/gallon EtOH denatured</td>
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<tr>
<td>15</td>
<td>Mean tax bias&lt;sup&gt;n&lt;/sup&gt; against ethanol</td>
<td>-0.1347</td>
<td>$/gallon EtOH denatured</td>
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<tr>
<td>16</td>
<td><strong>Energy equivalent</strong>&lt;sup&gt;o&lt;/sup&gt; cost of EtOH to taxpayer</td>
<td>5.4626</td>
<td>$/gallon GGE</td>
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</tbody>
</table>

<sup>a</sup> http://www.ethanolrfa.org/industry/locations/, updated 04/12/06
<sup>b</sup> As in a. A “small-producers” tax credit of $0.10/gallon for the producers of up to 60 million gallons EtOH per year
<sup>c</sup> Line 2/1 × 0.10
<sup>e</sup> http://www.ewg.org/farm/region.php?fips=00000, accessed 4/14/06
<sup>f</sup> http://www.ers.usda.gov/Briefing/Corn/, accessed 04/14/06
<sup>g</sup> Line 6/7
<sup>h</sup> http://www.axxispetro.com/ace.shtml, accessed 05/06/06. The mean rack price in the largest ethanol producing states in the Midwest. The rack price of ethanol delivered to both coasts will be at least $0.15 higher because of transportation costs
<sup>i</sup> The mean of (Industry-reported yields - Brazilian imports), multiplied by 0.95 to remove gasoline denaturant
<sup>j</sup> Line 8/10
<sup>k</sup> Source: http://www.opisnet.com/headlines.asp, Sunny Forecast for Summer Ethanol Blending, accessed 02/21/05
<sup>l</sup> Lines 5 + 11 + 12
<sup>m</sup> Lines 9 + 13
<sup>n</sup> Ethanol has less energy per unit volume than gasoline, but taxes collected on both are equal. Federal excise tax on gasoline is 18.4 cents, and mean state excise tax is 21 cents (DOE EIA). The energy-equivalent tax bias against ethanol is 39.4 × (1 – 0.95 × 0.64 – 0.05)
<sup>o</sup> Direct cost, excluding environment subsidies. Lines (14 + 15)/(0.95 × 0.64 + 0.05). GGE = Gallon Gasoline Equivalent
The Earth, Biofuels, and Reality

Tad Patzek, Civil & Environmental Engineering, U.C. Berkeley
June 7, 2006, Boulder, CO
This is What We Do...

In addition to extracting ancient plants (oil, gas, and coal) from the earth and burning them, we now burn the earth surface in real time:

- Corn, soybeans, sugarcane, wheat, sorghum, rapeseed, beets, potatoes, switchgrass, rice, ...  
- Tropical forests, palm oil, pines, acacias, eucalypts, poplars, ...  
- Wood chips, bagasse, rice straw, corn stover, hay, ...  
- Leftovers of animal carcasses, fish oil, human fat, ...  

Is there anything else left we might burn to further our lifestyles?
“I perceived it to be possible to arrive at knowledge highly useful in life . . . and thus render ourselves the lords and possessors of Nature.”

“I am come in very truth leading you to Nature with all her children to bind her to your service and make her your slave. . . . The mechanical inventions of recent years do not merely exert a gentle guidance over Nature’s course, they have the power to conquer her and subdue her, to shake her to her foundations.”
They Spoke So Well For Us...

“I perceived it to be possible to arrive at knowledge highly useful in life . . . and thus render ourselves the lords and possessors of Nature.”

René Descartes, 1596-1650, Discourse on Method (1637)

“I am come in very truth leading you to Nature with all her children to bind her to your service and make her your slave. . . . The mechanical inventions of recent years do not merely exert a gentle guidance over Nature’s course, they have the power to conquer her and subdue her, to shake her to her foundations.”

Sir Francis Bacon, 1561-1626, Cogitata et Visa (1607)
They Also Speak For Us...

- **Aggressive** action to develop advanced biofuels
  ...could virtually eliminate our demand for gasoline

- Farmers will plant **energy crops** on a large scale

- Fast-growing, cost-efficient trees such as poplar and eucalyptus, and grasses such as alfalfa and switchgrass, [are] to be **harvested as biofuels**

- More power plants will **burn** biomass along with coal to produce electricity
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Natural Resources Defense Council, 2006
The Fundamental Incompatibility...

- The rate at which we use fossil energy, makes replacing it by biomass impossible.
- Colonizing all available land on the earth will be insufficient.
- If we really want to switch to solar cells, biofuels, wind, etc., we will have to shrink our energy use by a factor of 10.
- US will have to look and act more like China or India.
Talk Outline...

- The new and old agriculture
- The new and old machines
- The developing and developed countries
- Energy use in US: Homo Colossus Americanus
- Energy flows in US agriculture
- Endo- and exosomatic energy use
- Conclusions
Old and New Agriculture

Old Agriculture = Many People, Small Energy Inputs, Small Harvests, No Pollution
New Agriculture = Few People, Huge Energy Inputs, Large Harvests, High Pollution

Old Agriculture = Diverse, almost sustainable ecosystems powered by the sun
New Agriculture = Unsustainable deserts paved with single plants running on fossil fuels
Old and New Machines

Old Machines = Small and Few, Powered by Animals, Water or Wind, No Pollution
New Machines = Gigantic and Many, Powered by Fossil Fuels, High Pollution
Developing and Developed Countries

Developing = Huge Poor Farming Populations, Low Agricultural Productivity
Developed = Tiny Farming Populations, High Agricultural Productivity

Agricultural workers in China = 40% of population can barely feed China
Agricultural workers in US = 0.17% of population can feed US, China, and Bangladesh
Developing and Developed Countries

Developing = Tiny Chemical Waste Fluxes, Low Environmental Impact, Sustainable
Developed = Large Chemical Waste Fluxes, High Environmental Impact, Unsustainable

CO₂ emissions in Kenya = 0.2 tonnes/person
CO₂ emissions in US = 20.2 tonnes/person
Units in My Presentation...

The fundamental unit of energy is 1 exa Joule (EJ)

\[ 1 \text{EJ} = 1,000,000,000,000,000,000,000,000 \text{ J} \]

is the amount of metabolized energy in food sufficient to sustain the entire U.S. population for one year

Currently the U.S. uses 105 EJ/year; one hundred and five times more than we need to live

If we were to metabolize this amount of energy, we would be 15 m long sperm whales, each weighing 40 tonnes. There are \(~1.9\) million of sperm whales worldwide and 300 million Americans
Homo Colossus Americanus...

1 Statistical American = 1 Sperm Whale

Eugene Odum, Ecological Vignettes, 1998
We Burn More Than Plants Produce

Primary Energy Use 105 EJ/yr

Biomass Energy Production 94 EJ/yr

- Crude Oil
- Coal
- Natural Gas
- Nuclear

Biomass for energy
- Food & Feed
- Industrial Wood
- Roots, etc.
- Sparse vegetation

Sources: Good & Bell, 1980; Patzek, 2005
We Burn More Than Plants Produce

Primary Energy Use
105 EJ/yr

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- Industrial Wood
- Roots, etc.
- Sparse vegetation
- Biomass for energy

Sources: Good & Bell, 1980; Patzek, 2005
Energy Use in Agriculture

Primary Energy Use
105 EJ/yr

Food Production
22 EJ/yr

Sources: USDA; Miller, Environmental Science, 1995, p. 377
US Agriculture: Crop Areas

Crop areas, $10^6$ hectares

Source: USDA NASS. Total crop area 120 Mha (300 million acres)
US Agriculture: Crop Energy

Crop energy, EJ ($10^{18}$ J)

- Corn
- Soybean
- Wheat
- Hay
- Corn Silage
- Sorghum
- Rice
- Barley
- Cotton
- Potatoes
- Oats
- Beans
- Canola

Sources: USDA NASS, Patzek (2004). Total crop energy 9.14 EJ (9 quads)
US Agriculture: Fertilizer Energy

Sources: USDA NASS, Patzek (2004)
Oilfields are: South Belridge, Cymric, Kern River, Midway Sunset, and Elk Hills
US Agriculture: Power Flux

Solar power sequestered in crops, W/m²

Sources: USDA NASS, Patzek (2004). Mean crop power flux 0.53 W/m²
Each person in US uses 11,250 W of primary energy + Imported goods
US Petroleum: Power Flux

Sources: US DOE EIA, Patzek (2004)
## Endo- and Exosomatic Energy Use

### Human Metabolism vs. Societal Metabolism

<table>
<thead>
<tr>
<th></th>
<th>Human Metabolism</th>
<th>Societal Metabolism</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy Use</strong></td>
<td>0.0001 MW/average person</td>
<td>0.012 MW/average person</td>
</tr>
<tr>
<td><strong>Land Usage</strong></td>
<td>0.02 ha/avg. person to live</td>
<td>2 ha/avg. person to function</td>
</tr>
<tr>
<td><strong>Very Productive Land</strong></td>
<td>$6 \times 10^6$ very productive ha to live</td>
<td>$6 \times 10^6$ km$^2$ to function</td>
</tr>
<tr>
<td><strong>Oil&amp;Gas Worker Inputs</strong></td>
<td>Ag worker inputs 0.8 MW</td>
<td></td>
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<tr>
<td></td>
<td>Ag worker outputs 3 MW</td>
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<td></td>
<td></td>
<td>Oil&amp;Gas worker outputs 14.5 MW</td>
</tr>
</tbody>
</table>
US Fuel Use: Energy Flux

Sources: US DOE EIA, Patzek (2004)
Ghawar and Burgan are two most productive oilfields on the earth
Resource Classification...

**RESOURCES**

**STOCKS**

**DEPOSITS** (dead stocks)
Petroleum, minerals, metals, etc.
A deposit can only give a flow while diminishing

**FUNDS** (living stocks)
Forests, fields, etc.
The “yield” of a fund is a flow, e.g., forest crops and agricultural crops

**NATURAL FLOWS**
Sunlight, winds, rivers, floods, ocean currents
## True Cost of Ethanol

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<td>4.3060</td>
<td>$/gallon EtOH denatured</td>
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<tr>
<td><strong>Energy equivalent cost of EtOH to taxpayer</strong></td>
<td>6.5440</td>
<td>$/gallon GGE</td>
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### Current Gasoline Prices

<table>
<thead>
<tr>
<th>Country</th>
<th>Unleaded gasoline price in US$/gallon on 05/26/06</th>
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<tbody>
<tr>
<td>US Ethanol Equiv.</td>
<td>6.1</td>
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<tr>
<td>Norway</td>
<td>7.1</td>
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<tr>
<td>Netherlands</td>
<td>6.0</td>
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<tr>
<td>Denmark</td>
<td>6.3</td>
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<tr>
<td>Belgium</td>
<td>6.7</td>
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<tr>
<td>GB</td>
<td>6.4</td>
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<tr>
<td>Northern Ireland</td>
<td>6.4</td>
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<tr>
<td>Portugal</td>
<td>6.4</td>
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<tr>
<td>Italy</td>
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<tr>
<td>Finland</td>
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<tr>
<td>Germany</td>
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<td>France</td>
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<tr>
<td>Sweden</td>
<td>6.2</td>
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<td>Ireland</td>
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<td>Austria</td>
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<td>Luxembourg</td>
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<td>Hungary</td>
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<td>Czech Republic</td>
<td>5.8</td>
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<td>Greece</td>
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<td>Slovakia</td>
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<td>Latvia</td>
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<td>USA</td>
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</tbody>
</table>

Data sources: www.aaroadwatch.ie/eupetrolprices/ and tonto.eia.doe.gov/oog/info/gdu/gasdiesel.asp
Ethanol Yield

Source: petroleum.berkeley.edu/patzek/BiofuelQA/Materials/RealFuelCycles-Web.pdf
One needs 35% more ethanol to drive the same distance!