The GIGATON Problem

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Increasing Material and Energy Uses Depletes Resources and Impacts the Environment

Engineering alone is not the answer. How many hybrids can the earth sustain? We need to think about reducing demand at the systems level.
Nature’s Scream
—A Call for the Sustainable Movement

"I was walking along a path with two friends - the sun was setting - suddenly the sky turned blood red - I paused, feeling exhausted, and leaned on the fence - there was blood and tongues of fire above the blue-black fjord and the city.

"My friends walked on, and I stood there trembling with anxiety - and I sensed an infinite scream passing through nature."

Nature’s infinite scream: I cannot provide the resources you need in a sustainable way

Who can hear it?

- The scream could only be heard by the golden billion (those who have reached the self actualization point on Maslow’s pyramid).
- One would not care if one does not have access to clean water, sanitation, food, and housing.
- It would be important for the golden billion to hear the scream and do something to reduce childhood mortality and poverty, to provide the means for people to lead useful and productive lives, and to develop technologies for a more sustainability world.

Skrik(The Scream), Edvard Munch. Pastel version auctioned for a record $119.9 million at Sotheby’s on May 2, 2012.
We need to recreate the anthroposphere to exist within the means of nature. That is, use resources that nature provides and generate waste nature can assimilate without overwhelming natural cycles. This will require us to examine the interactions between the natural, engineered, social and economic systems.
Sustainable Urban Systems

- Generate waste that nature can assimilate without overwhelming natural cycles.
- Need to look at fate of toxics, Nitrogen, Phosphorus, Water, Carbon, etc. cycles.
- Let's look at the **Carbon cycle**.
In 2010, CO$_2$ emissions rose 5.9% which is the greatest increase we have seen since 1969. The GDP only rose 5%.
IEA BLUE Map Scenario for 2050
Key technologies to reduce Global CO$_2$ emissions

Source: Energy Technology Perspectives 2010, Key Graphs, IEA 2010
Additional investment needs, BLUE Map vs. Baseline ($48 Trillion)

Source: Energy Technology Perspectives 2010, Key Graphs, IEA 2010
<table>
<thead>
<tr>
<th>Resource</th>
<th>Solar PV/CSP</th>
<th>Wind</th>
<th>Geothermal</th>
<th>Water Power</th>
<th>Biopower</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theoretical Potential</td>
<td>206,000 GW (PV)</td>
<td>8,000 GW (onshore)</td>
<td>39 GW (conventional)</td>
<td>140 GW</td>
<td>78 GW</td>
</tr>
<tr>
<td></td>
<td>11,100 GW (CSP)</td>
<td>2,200 GW (offshore to 50 nm)</td>
<td>520 GW (EGS)</td>
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<td></td>
<td></td>
<td></td>
<td>4 GW (co-produced)</td>
<td></td>
<td></td>
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</tbody>
</table>

U.S. Renewable Resources

Credit: Paul Denholm
2010
WWIII - The Plan

• To power the world with 11.5 TW WWS energy
  – 51% by wind (5.8 TW)
    • 3.8 million large wind turbines (5 MW each), 0.8% in place
  – 40% by solar (4.6 TW)
    • 1.7 billion rooftop PV systems (0.003 MW each), <1% in place
    • 89,000 PV and concentrated solar power plants (300 MW each)
  – 9% by water (1.1 TW)
    • 900 hydroelectric plants (1,300 MW each), 70% in place

Jacobson and Delucchi, 2009
## Energy Source Comparison

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>Photovoltaic</th>
<th>Coal</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy Output</strong></td>
<td>9.0</td>
<td>5.0</td>
</tr>
<tr>
<td><strong>Energy Invested</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Water Use</strong></td>
<td>0.001 Gal/kWh</td>
<td>0.49 Gal/kWh</td>
</tr>
<tr>
<td><strong>Land Use</strong></td>
<td>0.51 kWh/acre</td>
<td>690 kWh/acre</td>
</tr>
<tr>
<td>(RET Screen Simulation)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Overnight Cost</strong></td>
<td>$4.75/kWh</td>
<td>$2.84/kWh</td>
</tr>
<tr>
<td><strong>Total job-years/GWh (avg)</strong></td>
<td>0.87</td>
<td>0.11</td>
</tr>
</tbody>
</table>

### REFERENCES


Global GHG abatement cost curve beyond business-as-usual – 2030

Abatement cost
€ per tCO₂e

-100
-80
-60
-40
-20
0
10
20
30
40
50
60

Residential electronics
Residential appliances
Retrofit residential HVAC
Tillage and residue mgmt
Insulation retrofit (residential)
Cars full hybrid
Waste recycling

Gas plant CCS retrofit
Coal CCS retrofit
Iron and steel CCS new build
Coal CCS new build
Power plant biomass co-firing
Reduced intensive agriculture conversion
High penetration wind
Solar PV
Solar CSP

Abatement potential
GtCO₂e per year

15
20
25
30
35
38

Low penetration wind
Cars plug-in hybrid
Degraded forest reforestation
Nuclear
Pastureland afforestation
Degraded land restoration
2nd generation biofuels
Building efficiency new build

Small hydro
1st generation biofuels
Rice management
Efficiency improvements other industry

Electricity from landfill gas
Clinker substitution by fly ash
Cropland nutrient management
Motor systems efficiency
Insulation retrofit (commercial)

Lighting – switch incandescent to LED (residential)

Note: The curve presents an estimate of the maximum potential of all technical GHG abatement measures below €60 per tCO₂e if each lever was pursued aggressively. It is not a forecast of what role different abatement measures and technologies will play.
Source: Global GHG Abatement Cost Curve v2.0
Sustainable Urban Systems

• Use renewable resources that nature provides.
• Of the 14 gigatons/year of material is used in world economy and only 5% is renewable
Resource Consumption for Material Production

Credit: Mike Ashby

• Ratio based on mix design for 30 MPa compressive strength at 28 days (http://www.ctre.iastate.edu/pubs/sustainable/strublesustainable.pdf)
*Michael F. Ashby, Materials and the Environment
**Figure 6.8** A bar chart of the embodied energies of materials per unit mass.

*Michael F. Ashby, *Materials and the Environment*
FIGURE 6.13  Recycle fraction bar chart.

*Michael F. Ashby, Materials and the Environment*
# Iron Intensity for Transportation Options

(180 persons)

<table>
<thead>
<tr>
<th>Bicycle</th>
<th>Walking</th>
<th>Bus</th>
<th>Personal Car</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Bicycle Image" /></td>
<td><img src="image2" alt="Walking Image" /></td>
<td><img src="image3" alt="Bus Image" /></td>
<td><img src="image4" alt="Personal Car Image" /></td>
</tr>
</tbody>
</table>

- **Bicycle**: 15 kg Fe/cap
- **Walking**: 10 Mg Fe/bus, 170 kg Fe/cap
- **Bus**: 1 Mg Fe/car, 670 kg Fe/cap

**Credit**: Tom Graedel
Gigaton Problems Need Gigaton Solutions -
Let a Million Flowers Bloom

- With *1 billion people* using *14 Gt of materials, 12 Gtoe of energy, 2*10^6 billion Gal of water* and emitting *8 Gt of Carbon* per year globally, a shift of scale and paradigm is needed to address the issues of global sustainability.
- From an egalitarian point of view, we should expect this to increase by a factor of 9 for 9 billion people in 2050, if every one has the same life style and uses today's technologies.
- With more than half of the population being urban dwellers, *urban infrastructure* plays a crucial role in the approach toward sustainability.

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</thead>
<tbody>
<tr>
<td><strong>Population (Total)</strong></td>
<td>5%</td>
<td>20%</td>
<td>54%</td>
<td>0%</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Material Use (Gt/yr)</strong></td>
<td>20%</td>
<td>54%</td>
<td>0%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Energy Use (ton of oil equivalent)</strong></td>
<td>5%</td>
<td>20%</td>
<td>54%</td>
<td>0%</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Carbon from fossil fuels (Gt/yr)</strong></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td><strong>Water Use (10Km^3/yr)</strong>*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>54%</td>
<td></td>
</tr>
<tr>
<td><strong>Passenger Cars (Total number of units)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5%</td>
</tr>
</tbody>
</table>

*Graph showing the distribution of resources and their sources.*
Childhood Mortality and Population Growth

Source: Hans Rosling - Gapminder.org
Thoughts on Solving the Gigaton Problem

• High performance buildings
• Efficient power generation
• Electrification of transportation
• Enhancing ecosystem services or avoiding their destruction
• Mandates for product performance and take back
• Market drivers for energy efficiency (SEAR 16 versus 13 etc.)
• Smart grid
• Distributed power and water generation
• Biomass reforming to create fuels, commodity chemicals, specialty chemicals
• Integrated resource recovery (metals, nutrients, energy etc from waste or shall I say byproducts)
• Policy issues that relate to the above
• Econometrics and economic flows that favor the above
• Devise a market or stipulate mandates that gets gigatinventors, gigainvestors and gigaentrepreneurs on task.
Photovoltaic (PV): Experience Curve

- Currently, the energy payback period for PV modules is ~2 years.

**Source: Energy policy 2002, p.1276**

The Rebound Effect Associated with Increased Energy Efficiency: The Solid-state Lighting (SSL) Example

Direct

Solid-state Lighting (SSL) Higher Efficiency

Lower Cost of Light

Higher Demand for Light

Indirect

Increased Human Productivity

Increased Energy Consumption

Historical and Contemporary Consumption Patterns of Light and Energy

\[ \varphi = \beta \cdot \frac{gdp}{CoL} \]
\[ \dot{e} = \frac{\varphi}{\eta_\varphi} \]
\[ \dot{e} = \frac{\beta}{(1 + \kappa_\varphi)} \cdot \frac{gdp}{CoE_\varphi} \]

\( \varphi \): per-capita consumption of light

\( e \): per-capita rate of consumption of associated energy to produce the light

Manufacturing in America
——Current State

America is now the world’s second largest maker of manufactured goods
- Production just under $1 trillion in 2010 (only next to China, which produced just over $1 trillion in 2010)

America still far surpasses China in productivity
- 8.7 times the productivity per worker compared with China (HIS Global Insight)

America offers decent wages to blue-collar workers
- The average American manufacturing worker earned $74,447 in 2009, including benefits (National Association of Manufacturers)

Source: T. Friedman, <That used to be us>. Published by Farrar, Straus and Giroux, 2011.
Manufacturing in America —— Problems and Solutions

The Problem
How do we expand manufacturing in America while keeping the drive for greater productivity?

The size of typical new businesses in America

<table>
<thead>
<tr>
<th>Year</th>
<th>Number of employees</th>
</tr>
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<tbody>
<tr>
<td>2000</td>
<td>8</td>
</tr>
<tr>
<td>2010</td>
<td>4</td>
</tr>
</tbody>
</table>

The Solution
We need a comprehensive twenty-first century job-creation strategy

- Addressing the growing mismatch between the needs of employers and the skills workers get in school
- Finding ways to make globalization a better source of job creation in the United States
- Creating Manufacturing Jobs
- Stimulating innovation and new company start-ups
- Simplifying regulatory procedures that create obstacles to job creation

Source: T. Friedman, <That used to be us>. Published by Farrar, Straus and Giroux, 2011.
Thank You!

Any Questions?