Meeting the Energy and Climate Change Challenge

German Physical Society
Berlin, Germany
17 March, 2014
Innovations in energy transformed the world
The sailing warship H.M.S. Temeraire, towed to be broken up for scrap.

J.M.W. Turner (1839)
Innovations in agriculture
In 1898, Sir William Crookes (inventor of the “Crookes tube”) delivers his inaugural lecture as President of the British Association for the Advancement of Science.

“England and all civilized countries are in deadly peril”

“It is the chemist who must come to the rescue...before we are in the actual grip of actual death, the chemist will step in and postpone the day of famine...”
At the beginning of the industrial revolution there were 700 M people.

The Haber-Bosch process enabled us to feed a world that doubled in population.
“The battle to feed all of humanity is over ... In the 1970s and 1980s hundreds of millions of people will starve to death in spite of any crash programs embarked upon now.”

What happened?

Prof. Paul Ehrlich
Stanford Biologist
The Population Bomb
(1968)
Norman Borlaug is awarded the Nobel Prize in 1970

Borlaug bred disease-resistant, dwarf strains of wheat with thick stems that could support heavier kernels and growth spurts due to artificial fertilizer used in the poor soils.
World Production of Grain (1961 – 2004)

1960:
Population = 3 B

2005:
Population = 6.5 B

Source: Food and Agriculture Organization (FAO), United Nations

We need a 2nd Green Revolution
• Perennial crops
• No tillage
• Drought resistant
• Nitrogen fixation
Incumbent industries have an understandable internal conflict in seeing the potential of a new potentially technology.
Incumbent industries usually do not embrace new technologies

Reaction to Alexander Graham Bell’s patent for the telephone by the Chief Engineer of the British Post Office:

“The Americans have need of the telephone, but we do not. We have plenty of messenger boys.”

What use could this company make of an electrical toy?

- Western Union president William Orton, responding to an offer from Alexander Graham Bell to sell his telephone company to Western Union for $100,000.
“Our ability to find and extract fossil fuels continues to improve, and economically recoverable reservoirs around the world are likely to keep pace with the rising demand for decades.”

Steven Chu and Arun Majumdar, Nature (2012)
U.S. Oil Production (1945 – 2012)
U.S. is the biggest producer of oil + nat. gas liquids + ethanol

2013 ~ 7.5 M bbls/day
2014 ~ 8.5 M bbls/day
Groppe, Long & Littell: “During the past 30 years, the firm has earned a reputation for accurate forecasts of major changes in oil and natural gas prices.”
Potential shale gas and tight oil reservoirs can change the energy landscape of the Americas, Asia and Europe.

Figure 1. Map of basins with assessed shale oil and shale gas formations, as of May 2013

Source: United States basins from U.S. Energy Information Administration and United States Geological Survey; other basins from ARI based on data from various published studies.
Technically recoverable shale oil and shale gas (Proved and unproved) may reshape natural gas supplies

Unproved shale oil and gas world reserves may increase 48% overall reserves

<table>
<thead>
<tr>
<th></th>
<th>Crude oil (billion barrels)</th>
<th>Wet natural gas (trillion cubic feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Outside the United States</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shale oil and shale gas unproved resources</td>
<td>287</td>
<td>6,634 tcf</td>
</tr>
<tr>
<td>Other proved reserves</td>
<td>1,617</td>
<td>6,521</td>
</tr>
<tr>
<td>Other unproved resources</td>
<td>1,230</td>
<td>7,296</td>
</tr>
<tr>
<td>Total</td>
<td>3,134</td>
<td>20,451</td>
</tr>
<tr>
<td>Increase in total reserves</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shale as a percent of total</td>
<td>9%</td>
<td>32%</td>
</tr>
<tr>
<td><strong>United States</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EIA shale / tight oil and shale gas proved reserves</td>
<td>n/a</td>
<td>97</td>
</tr>
<tr>
<td>EIA shale / tight oil and shale gas unproved resources</td>
<td>58</td>
<td></td>
</tr>
<tr>
<td>EIA other proved reserves</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>EIA other unproved resources</td>
<td>139</td>
<td>1,546</td>
</tr>
<tr>
<td>Total</td>
<td>223</td>
<td>2,431</td>
</tr>
<tr>
<td>Increase in total resources due to inclusion of shale oil and shale gas</td>
<td>35%</td>
<td>38%</td>
</tr>
<tr>
<td>Shale as a percent of total</td>
<td>26%</td>
<td>27%</td>
</tr>
<tr>
<td><strong>Total World</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
From 1880 - 2012 the average land temperature increased by ~ 0.85 °C.*
Most of that increase was from 1980 – 2013

* IPCC AR-5
Selected IPCC summary points (2014)

• Temperature increase: (1880 – 2012) = 0.85 °C
• Temperature of ocean: (upper 75m) = 0.11° C
• Extreme weather changes: 90% due to human activity.

• Ice sheet loss
  Greenland Antarctic
  1992 – 2001: 34Gt 30 Gt
  2002 – 2011: 215 Gt 147 Gt
Natural Disasters in the United States, 1980 – 2013
Number of Events (Annual Totals 1980 – 2012 vs. First Six Months 2013)

Meteorological events (Storm)

Hydrological events (Flood, mass movement)

Climatological events (Extreme temperature, drought, forest fire)

Geophysical events (Earthquake, tsunami, volcanic eruption)

First Six Months 2013
68 Events

Source: MR NatCatSERVICE

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Overall losses totaled US$ 45bn; Insured losses totaled US$ 13bn

Source: MR NatCatSERVICE
### Costliest Natural Catastrophes Since 1950

**Rank by Insured Losses**

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
<th>Region</th>
<th>Insured Loss (US$m) (in original values)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>Hurricane Katrina</td>
<td>USA</td>
<td>62,200</td>
</tr>
<tr>
<td>2011</td>
<td>EQ, tsunami</td>
<td>Japan</td>
<td>40,000</td>
</tr>
<tr>
<td>2012</td>
<td>Hurricane Sandy</td>
<td>USA, Caribbean</td>
<td>30,150</td>
</tr>
<tr>
<td>2008</td>
<td>Hurricane Ike</td>
<td>USA, Caribbean</td>
<td>18,500</td>
</tr>
<tr>
<td>1992</td>
<td>Hurricane Andrew</td>
<td>USA</td>
<td>17,000</td>
</tr>
<tr>
<td>2011</td>
<td>Floods</td>
<td>Thailand</td>
<td>16,000</td>
</tr>
<tr>
<td>2012</td>
<td>Drought</td>
<td>USA</td>
<td>16,000</td>
</tr>
<tr>
<td>1994</td>
<td>EQ Northridge</td>
<td>USA</td>
<td>15,300</td>
</tr>
<tr>
<td>2004</td>
<td>Hurricane Ivan</td>
<td>USA, Caribbean</td>
<td>13,800</td>
</tr>
<tr>
<td>2011</td>
<td>EQ Christchurch</td>
<td>New Zealand</td>
<td>13,000</td>
</tr>
</tbody>
</table>

**Since 1950 (63 years), 7 of the costliest natural disasters were due to weather. 6 out of 7 of those weather events occurred in the past 8 years**

Source: MR NatCatSERVICE
Statistically, adult smokers have ~ 25 year delay before dying from lung cancer.

20% of all deaths in the U.S. is attributed to smoking.

Smoking increases the risk of

• Lung cancer: 25x
• Coronary heart disease: 2x - 4x
• Stroke: 2x - 4x

More than 10 times as many U.S. citizens have died prematurely from cigarette smoking than have died in all the wars fought by the United States during its history.

Smoking causes about 90% of all lung cancer deaths in men and women. More women die from lung cancer each year than from breast cancer.
“If we don’t change direction, we’ll end up where we are heading.”
<table>
<thead>
<tr>
<th>Consumer Discretionary</th>
<th>Exxon Mobil</th>
<th>$60 by 2030</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Royal Dutch Shell</td>
<td>$40</td>
</tr>
<tr>
<td></td>
<td>BP</td>
<td>$40</td>
</tr>
<tr>
<td></td>
<td>Conoco Phillips</td>
<td>$8 – 46</td>
</tr>
<tr>
<td></td>
<td>Devon Energy</td>
<td>$15</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>$40</td>
</tr>
<tr>
<td></td>
<td>Chevron</td>
<td>$?</td>
</tr>
<tr>
<td></td>
<td>Hess</td>
<td>$?</td>
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<table>
<thead>
<tr>
<th>Financials</th>
<th>Wells Fargo &amp; Company</th>
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<table>
<thead>
<tr>
<th>Industrials</th>
<th>Cummins Inc.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Delta Air Lines</td>
</tr>
<tr>
<td></td>
<td>General Electric Company</td>
</tr>
</tbody>
</table>
~ 70% of the total world oil reserves is heavy, extra-heavy, oil sands and bitumen
Steam-assisted gravity drainage (SAGD)
Estimated recovery 50% - 60%

Can a mixture of steam and CO₂ allow lower temperatures to decrease energy use and increase oil production?
Is it possible to use oil and natural gas in a highly carbon-constrained world? (A 20 - 40 year view)

- **CCUS (carbon capture, utilization and sequestration)** will help demonstrate new capture technologies.

- Advances in mid-IR spectroscopy will allow inexpensive, sensitive, and quasi-remote sensing of CO$_2$ and methane. If we can detect CO$_2$ leakage, we can assign credit for carbon sequestration for non-recovered/non-leaked CO$_2$.

- *Non-biodegradable* materials (e.g. plastics, building materials) is a form of carbon sequestration. At what carbon price will it be more economical to use composite materials, rather than steel and cement in construction?
“The Stone Age came to an end not for a lack of stones and the oil age will end, but not for a lack of oil.”

- Sheik Ahmed Zaki Yamani, former Saudi Oil Minister

We transitioned to better solutions.
Science and technology must help change the current path we are on.

Energy efficiency

Clean energy sources
Data centers (world-wide) consume > 30 GW. The majority of energy consumed in most data centers is used to keep idling servers at full-power in case of a surge in activity.

McKinsey estimates that the centers use 6 – 12% of their electricity to actually perform computations. Typically, 30 -50% more power is used for cooling.
DOING NOTHING IS NOT AN OPTION

THE NETWORK ENERGY GAP

Internet Traffic X 15
2010-2020

Mobile Data X 186
2010-2020

Internet Backbone X 12.8
2010-2020

Networks Energy Use +27%
2012-2016

GROWING GAP!

Mobile Efficiency

Wireline Efficiency

Energy Efficiency is a Necessity for the ICT Industry
# Tegra K1

**Console in the Palm of Your Hand**

<table>
<thead>
<tr>
<th></th>
<th>Xbox 360</th>
<th>PS3</th>
<th>Tegra K1</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>GPU Features</strong></td>
<td>DX9</td>
<td>DX9</td>
<td>DX11</td>
</tr>
<tr>
<td><strong>GPU Horsepower</strong></td>
<td>240</td>
<td>192</td>
<td>365</td>
</tr>
<tr>
<td><strong>CPU Horsepower</strong></td>
<td>3600</td>
<td>1200</td>
<td>5600</td>
</tr>
<tr>
<td><strong>Power</strong></td>
<td>100W</td>
<td>100W</td>
<td>5W</td>
</tr>
</tbody>
</table>
Google’s Power usage effectiveness (PUE) is 1.13. (1.06 if one does not include the sub-station, transformer and generator losses)

Global average PUE: 1.8 – 1.89
How science and technology may change the world.

Energy efficiency

Clean energy sources
Wind turbines are more reliable, efficient and bigger

L.C.O.E. of land wind: Class 3, 4 sites (6.5– 7.5 m/s) = $0.075/kWh ➔ $0.06/MWh. Prediction: 20% -30% decline in price in 10 -15 years.

100 meter wind tower

2.3 MW turbine: 93 meter diameter blades, 115 meters high.
Solar energy
Cost of PV modules are dropping below the power law experience curve. **SunShot goal $1/watt = L.C.O.E. 6.5¢/kWh**

Solar module production costs are currently ~ $0.50/watt for 20 – 21% efficient mono-silicon.
“Unlike physics, where we can fundamentally figure out the upper limit for the efficiency of solar cells, there is no such limit to bureaucracy.”

Minh Le
Program Manager SunShot
Why can’t the installation of a PV system on your roof be handled like the installation of a gas water heater?

Residential PV in Germany costs ~$2.50/W
Residential PV in the US costs ~$5/W
California ISO Data (01/13/2014)

Available Resources

Actual Demand

Hour-Ahead Demand Forecast

Day-Ahead Demand Forecast

08:00 22:00

Solar

Wind

Geothermal

Biomass

Biogas

Small Hydro
Advanced Research Projects Agency – Energy (ARPA-E)
(Short term, *high risk - high reward* research projects)
The first round of investments

Energy Innovation Hubs
(Multi-disciplinary, highly *collaborative teams* ideally working under one roof)
**Miniature (Fast) Magnetics Needs Fast Switches**

- Bandgap (energy to ‘free electron’) increases
  - Reduces transit time
- Breakdown voltage increases
  - Increases frequency
- Drift region can be decreased
  - Reduces on-resistance

---

Wide Bandgap Materials: SiC, GaN, etc.

**Power (VA)**
- 100M
- 10M
- 1M
- 100K
- 10K
- 1K
- 100
- 10

**Operation Frequency (Hz)**
- 100K
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- 100K
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- 1K
- 100
Power Conversion & Energy Storage

Today

70,000 lbs

$100/kWh

Future

100 lbs

$100/kWh

And Smart!

Anywhere In the world
Progress in Batteries
DOE's “EV Everywhere set goals for battery cost, energy density, durability.

Battery Cost vs Year

- $1,000/kWh in 2008
- $500/kWh in 2011
- $1,000/kWh for autos
- $160/kWh for utility-scale storage?
- $100/kWh for utility-scale storage?
Figure 4: Total lithium-ion battery pack cost and traction battery production, 2010-30

Total pack cost ($/kWh)

1,200

1,000

800

600

400

200

0


Annual production (GWh)

240

200

160

120

80

40

0

Electric Vehicle Battery
Price Index H1 2012 result: $689/kWh
H2 2012: $642/kWh
H1 2013: $599/kWh
H1 2014: $568/kWh

Source: Bloomberg New Energy Finance. Note: Some of the data points we have collected represent prices for contracts that might last 1-2 years, refer to Methodology for details. The battery pack price line in the chart is projected cost based on the learning curve of EV lithium-ion batteries.
Tesla projecting 100,000 cars/year by 2016
Figure 2: Comparison of existing EV LiB plants’ capex and Tesla’s proposed Gigafactory ($/Wh)

Source: Bloomberg New Energy Finance based on information disclosed by each company. Note: Investment capital is calculated based on the exchange rate on the date of investment announcement.
Long-lasting batteries can operate over a wide temperature range.

Technologies Beyond Li-Ion

Specific Energy (Wh/kg) vs. Specific Power (W/kg)

- Li-Oxygen
- Li-Sulfur
- Advanced Li-ion
- Li-ion
Eos Aurora 1000 | 6000

Targeted applications define technology characteristics required for profitability

<table>
<thead>
<tr>
<th>Technology Attributes</th>
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</thead>
<tbody>
<tr>
<td>Low-Cost</td>
<td>$1,000/kW and $160/kWh</td>
</tr>
<tr>
<td>Long Life</td>
<td>10,000 cycles (30 years)</td>
</tr>
<tr>
<td>Ample Storage</td>
<td>1 MW for 6 hours = 6MWh in a 40’ ISO shipping container</td>
</tr>
<tr>
<td>Efficient</td>
<td>75% round-trip efficiency</td>
</tr>
<tr>
<td>100% Safe</td>
<td>Non-toxic, non-combustible, no risk of catastrophic failure</td>
</tr>
</tbody>
</table>

10 modules per side
(4) 250 kW inverters

Balance of plant system
Texas Medical Center district cooling: 48 MW combined heat and power with 32,000 ton chiller capacity and 8.8 M gal thermal energy storage tank
Load smoothing options
“The greater danger for most of us lies not in setting our aim too high and falling short; but in setting our aim too low, and achieving our mark.”

Michelangelo
Today, there are ~7 billion people. By ~2025 we will grow to 8 billion. Are technological “fixes” merely postponing the population disaster?


- Constant fertility variant
- High-fertility variant, 2.5 children
- Medium-fertility variant, 2.0
- Low-fertility variant, 1.6

*Total fertility rate: the average number of children women would bear in their lifetime if the birth rate of a particular year were to remain unchanged.
Correlation Between Human Development and Per Capita Electricity Consumption

The Human Development Index is a comparative measure of life expectancy, literacy, education, and standards of living. Countries fall into four broad categories based on their HDI: very high, high, medium, and low human development.

4,000 kWh per person per year is the dividing line between developed and developing countries.

Source: Human Development Index – 2010 data United Nations; Annual Per Capita Electricity Consumption (kWh) - 2007 data World Bank
Updated: 4/11
- The limits of standard of living vs. resource consumption are not known.
- The limits of Earth’s sustainable capacity are not known.
"We came all this way to explore the moon and the most important thing is that we discovered the Earth."

Bill Anders, Apollo 8 Astronaut