Innovations in Materials Technology for a Sustainable World

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Innovation for Sustainable Production 2008
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“Limits of Growth” Meadows et al., (1974)

- Systems analysis study at MIT
- Commissioned by the Club of Rome
- Conclusions were doomsday-ish
  - Study sees disaster by 2100
  - Scientists warn of global catastrophe

- Humanity has the ability to make development sustainable – to ensure that it meets the needs of the present without compromising the ability of the future generations to meet their own needs”
- Must not damage or destroy basic life support system; air, water, soil and biological systems
- Must be economically sustainable to provide continuous flow of goods and services
- Requires sustainable social systems at international, national, local and family levels
Sustainable Development Is:

A globally accepted approach to sustaining economic growth without harming our planet or exhausting its resources while improving the quality of life for its current and future inhabitants.

- Economic Responsibility
- Environmental/Ecological Performance
- Social Responsibilities
What’s driving the ‘Sustainability’ movement?

- Society and growing public concern in U.S.
- Rapidly emerging state regulatory plans
- Recent U.S. elections
- Equity markets considering sustainability in valuations
The scale of the problem grows

- Global warming is real
- Stratospheric ozone depletion
- Forest, wetland and habitat destruction
- Loss of biodiversity
- Encroaching desertification
- Contamination of ground and surface water resources
- Growing population, and subsequent energy and resource use
Indicators of the human influence on the atmosphere during the Industrial era

From the Intergovernmental Panel on Climate Change (IPCC); Climate Change 2001 Synthesis Report
Leaf unfolding dates in Europe

- *Betula pendula* (silver birch) date of leaf unfolding
- *Aesculus hippocastanum* (common horse chestnut) date of leaf unfolding
- Temperature for March April May from 35 meteorological stations in Germany
Global mean temperatures are rising faster with time.

<table>
<thead>
<tr>
<th>Period</th>
<th>Rate</th>
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<tbody>
<tr>
<td>100</td>
<td>0.074±0.018</td>
</tr>
<tr>
<td>50</td>
<td>0.128±0.026</td>
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The diagram shows the change in global mean temperature from 1861-90 to recent years, with linear trends and smoothed series indicating increasing temperatures.
Over the longer term drought is increasing most places.

Change in Palmer Drought Severity Index, 1900 - 2002
Ocean temperatures are rising

Ocean temperatures have increased to depths of at least 3000 m.

Estimates of total heat content from independent analyses show inter-annual variability but a positive trend since 1961.
Recent coral bleaching events
Powering the Planet

Nathan S. Lewis, California Institute of Technology

*MRS Bulletin, 32* 808-820, October 2007
Population Growth to 10 - 11 Billion People in 2050

Per Capita GDP Growth at 1.6% yr\(^{-1}\)

Energy consumption per Unit of GDP declines at 1.0% yr\(^{-1}\)
Energy Consumption vs GDP

GJ/capita-yr

GDP/capita (000's 1997 $ PPP)
Global Energy Consumption, 2001

Total: 13.2 TW
U.S.: 3.2 TW (96 Quads)
Today: Production Cost of Electricity

(in the U.S. in 2002)

Cost, ¢/kW-hr

Coal: 1-4¢
Gas: 2.3-5.0¢
Oil: 6-8¢
Wind: 5-7¢
Nuclear: 6-7¢
Solar: 25-50¢
What we can do now: The Wedge Concept

From Socolow & Pacala, Science (2004), 305 (5686), 968-972;
Data from Climate Mitigation Institute @ Princeton University
Green Engineering & Climate Change

Billion of Tons of Carbon Emitted per Year

Historical emissions

Currently projected path

Flat path

1955  2005  2055  2105
Where are we headed?
The wedge concept

The Challenge

Historical emissions

Currently projected path

14 GtC/y

Seven “wedges”

Flat path

7 GtC/y

1955  2005  2055  2105

Billion of Tons of Carbon Emitted per Year
Carbon Emissions by Sector

Need 7 wedges...

... not all cuts can come from one sector!
A Challenge: Cut Greenhouse Emissions using Current Technology

- CO₂ Capture and Storage
- Coal to Gas
- Energy Efficiency & Conservation
- Natural Sinks
- Renewable Electricity and Fuels
- Nuclear Energy
Efficiency

Double the fuel efficiency of the world’s cars or halve miles traveled

There are about 600 million cars today, with 2 billion projected for 2055

Produce today’s electric capacity with double today’s efficiency

Average coal plant efficiency is 32% today

Use best efficiency practices in all residential and commercial buildings

Replacing all the world’s incandescent bulbs with CFL’s would provide 1/4 of one wedge
Carbon Capture & Storage

Implement CCS at

- 800 GW coal electric plants or
- 1600 GW natural gas electric plants or
- 180 coal synfuels plants or
- 10 times today’s capacity of hydrogen plants

A wedge will require injecting an volume of CO₂ equal to the amount of oil extracted every year

E, T, H / $$ / !-!!
Nuclear Electricity & Hydrogen

Triple the world’s nuclear electricity capacity by 2055
OR
Build 600 high-temperature plants to produce hydrogen (none now)

The rate of installation required for a wedge from electricity is equal to the global rate of nuclear expansion from 1975-1990.

E, T, H / $$$-$$$ / !!!

Phasing out of nuclear electric power would create the need for another half wedge of emissions cuts
Wind Electricity

Install 2 million windmills to replace coal-based electricity,

OR

Use 4 million windmills to produce hydrogen fuel

A wedge worth of wind electricity will require increasing current capacity by a factor of 50

An electricity wedge would require land area equal to about 3% of U.S. land area
Solar Electricity

Install 20,000 square kilometers for dedicated use by 2054

Photos courtesy of DOE Photovoltaics Program

A wedge of solar electricity would mean increasing current capacity 700 times

A wedge would require an array of photovoltaic panels with an area approximately the size of New Jersey
Where can the materials community and industry make a difference?

- Innovation
- Manufacturing and production processes
- Product design
- Alternative materials
- Recycleable (see W Lee et al in Roadmap from ICC-1 (ACerS)) (Plastic bottles)
- Lifetime analysis (think how to reuse every component in an automobile, computers, after useful life)
Materials technology is key to sustainable production

- Sustainable growth
- Reduce emissions (catalysis, membranes, porous materials)
- Advanced surface treatments (less material, more function, wear reduction)
- Smaller, more efficient products
- Quality of life (biomaterials, drug release substrates)
Materials design

- Less mass for improved energy efficiency (lightweighting – Al, foams, porous materials)
- Less energy using
- Mediate the influence of pollution
  - TiO$_2$ coated glass
  - Catalyze the detoxification of gaseous discharges
    - NOx, VOCs
- We must innovate – e.g. how do we replace reliance on precious metals like Pt?
Make ceramic processes more sustainable

- Replace high temperature solid state synthesis processes with room temperature chemistries for synthesis of powders.
- Learn how to lower calcination processes
- Learn how to process with water-based instead of using organic solvents
- Develop processes for total recycle of non-aqueous media
- Invent organic free forming techniques that do not require organic binders
- Learn to sinter at <1000C
- Develop high efficiency sintering furnaces – why do we heat the entire furnace when only the part needs to be heated? Is microwave sintering really more energy efficient?
Better energy storage - e.g. better battery materials (LiFePO$_4$?) to replace Li battery, peak load leveling (Beta alumina for Na-S battery (NGK))

- Thermoelectrics for heat recovery
- Fuel Cells
- Photovoltaics!
- Lighting
Batteries need to get smaller and more efficient
Lighting and Energy Consumption

Adapted from M. Kendall and M. Scholand, "Energy Savings Potential of SSL in General Lighting Applications" (U.S. DOE-OBT study by AD Little, 2001), and EIA Statistics.

US Energy Equivalent Primary Energy Consumption (Quads/yr)

US Electricity Consumption (TWh/yr)

~5x
~3x
~1.5%/yr

US Lighting with SSL

1980 2000 2020

1,000 10,000

Year

Courtesy of NASA
Solid-State Lighting = Semiconductor Light from Crystals and Organic Materials

**Standard Light Sources**

- **Incandescent**: 1879
- **Halogen**: 1959
- **Mercury**: 1904
- **Fluorescent**: 1938
- **Metal halide**: 1961
- **CFL**: 1981

**Light source efficiency**

- **Lumen/Watt**
  - 1950
  - 1990
  - 2000
  - 2010

**White Power LED & OLED**

Potential:
- LED: 2002
- OLED: 2006
- White power LED & OLED: 2010

**Opto Semiconductors**

OSRAM

- Photonics21-Strasb
- 04.04.2005 Seite: 11
Inorganic LEDs Boosting Efficiency and High Flux

There are less then 10 years between the first white LEDs in 1996 and todays LED powermodules.

<table>
<thead>
<tr>
<th></th>
<th>1996</th>
<th>2023</th>
<th>Improvement factor</th>
</tr>
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<tbody>
<tr>
<td>Internal Q.E.</td>
<td>10 %</td>
<td>60 %</td>
<td>6</td>
</tr>
<tr>
<td>Light extraction E.</td>
<td>25 %</td>
<td>75 %</td>
<td>3</td>
</tr>
<tr>
<td>Flux per device</td>
<td>0.5 lm</td>
<td>400 lm</td>
<td>400</td>
</tr>
<tr>
<td>Costs per Lumen</td>
<td>~ 3 €</td>
<td>~ 0.1 €</td>
<td>30</td>
</tr>
</tbody>
</table>

LEDs the enabler for LED based

- Projection
- LCD Backlight
- Headlamp

Hybrid Lamps the best of both flux and color tunability

- CFL combined with LED

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Photonics21-Strasb
04.04.2006 Belle: 12

OSRAM
Organic LEDs the Next Wave in SSL

- 2008
  - Lifetime, brightness, size, cost reduction

- 2012
  - Maturity
  - "Any shape" OLED lighting
  - Active color and brightness tunable OLED
  - White OLED signage and light tiles on glass

- 2016
  - Flexible OLED
  - Transparent OLED sources

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04.04.2006 Seite: 15
All I’m saying is now is the time to develop the technology to deflect an asteroid.
The challenges and potential outcomes imposed by global warming on a sustainable world requires urgent coordination by the world powers of an international research program and set of energy policies like we have never seen before.