Pursuing Sustainable Energy Options

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Humanity’s Top Challenges for the next 50 - 100 years

- Climate
- Disease
- Energy
- Education
- Environment
- Food
- Poverty and Inequality
- Water

Social and Political Instability

1900: 1.6 Billion People
2008: 6.6 Billion People
2050: 8 to 11 Billion People
Energy use inherently linked to our consumptive life style

- Energy is needed to produce most things we use (buildings, highways, electricity, food, etc.) and to operate our cars, heat and cool our living and working spaces, transport of raw materials and goods, info services, etc.
- Transportation fuels for mobility
- Water use for energy conversion
- Our economic health and development are very dependent on availability of affordable and plentiful energy
- Many of the major environmental impacts we have are linked directly to increased energy use

Energy impacts = population x use/person
Global Water Resources and Consumption

Role of Surface Water

<table>
<thead>
<tr>
<th>Surface water available</th>
<th>8600 km³/a</th>
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</thead>
<tbody>
<tr>
<td>2080 km³/a not used</td>
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<tr>
<td>2350 km³/a utilized</td>
<td>= 4430 km³/a withdrawn</td>
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</table>

Agriculture 70%  Industry 25%  Domestic Use 5%

Number of countries (inhabitants) with water stress

- 2000: 28 (335 million)
- 2025: 50 (3,000 million)

Role of Groundwater

<table>
<thead>
<tr>
<th>Water available</th>
<th>3000 km³/a</th>
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<tr>
<td>Renewable use:</td>
<td>1000 km³/a</td>
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<tr>
<td>Depletive use:</td>
<td>200 km³/a</td>
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Despite smaller quantity -- ground water plays a special role due to long term storage and usually high quality.
There are many indicators that suggest a need to transition from the age of hydrocarbons to a new more sustainable energy destination.

For example:

1. Impact of carbon emissions from fossil fuels on global climate
2. Growth in population and energy demand in general
3. Energy and material uses (with embedded energy) pervade all parts of our society – current approaches are based on low cost, abundant fossil fuels
4. Long term availability and location of fossil fuel supplies of conventional oil, gas, and coal
5. Growth in electricity generating capacity
6. Growth in transportation vehicles of all types using liquid fuels
Exploring options for a Sustainable Energy System
1. **Retirements of old coal and nuclear units**
   - In the next 15 to 20 years 40 GWe of “old” coal-fired capacity will need to be retired or updated because of a failure to meet emissions standards.
   - In the next 25 years, over 40 GWe of existing nuclear capacity will be beyond even generous re-licensing procedures.

2. **Projected availability limitations and increasing prices for natural gas** are not favorable for large increases in electric generation capacity for the foreseeable future.

3. **Public resistance to expanding nuclear power** is not likely to change in the foreseeable future due to concerns about waste and proliferation. Other environmental concerns will limit hydropower growth as well.

4. **High costs of new clean coal plants** as they have to meet tightening emission standards and may have to deal with carbon sequestration.

5. **Infrastructure improvements needed** for both base load and interruptible renewables including storage, inter-connections, and new T&D are large.

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A key motivation -- US electricity capacity is now at 1 TWe (1,000,000 MWe) and threatened
The energy landscape is multidimensional, multiscale and multinational

- **Multiple dimensions**
  - 5D’s from discovery, definition, development, demonstration to deployment

- **Multiple scales**
  - Power for villages versus megacities
  - Fuels for cars versus industrial processes

- **Multiple impacts**
  - Natural resource consumption (land, water, etc.)
  - Local and regional environmental and health impacts
  - Global environmental impacts

- **Economic well being is important**
- **Social justice and equity are important**
- **National and international policies should reflect individual goals and values**

*It’s not just about finding a technology solution*
Ideal Sustainable Energy Characteristics

- **Non-depletable** on a short time scale
- **Low impacts on natural resources** -- land, water, etc., across process life cycle
- **Accessible and well distributed resource** – available close to demand
- **Emissions free** – no NO\(_x\), SO\(_x\), CO\(_2\), particulates, etc.
- **Scalable** – from 1 kW to 1000 MW (t or e)
- **Dispatchable** - for base load, peaking, and distributed needs
- **Robust** - simple, reliable, durable and safe to operate
- **Flexible** - applications for electricity, heat, and cogen
- **Competitive economically**
## 21st Century US Energy Supply Options
### Quality Assessment Matrix

<table>
<thead>
<tr>
<th>Attribute (scale of -10 to +10)</th>
<th>Oil</th>
<th>Gas</th>
<th>Coal</th>
<th>Oil Shale</th>
<th>Fission</th>
<th>Fusion</th>
<th>Solar</th>
<th>Wind</th>
<th>Hydro</th>
<th>Biomass</th>
<th>HDR</th>
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<td>1. Resource Size</td>
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<td>11. Adaptable to 1-100 MW Sizes</td>
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<td>12. System Complexity</td>
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<td>16. Economic Projections</td>
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**Total Quality Index**

\[ \Sigma (1-18) \]
New performance paradigms have emerged

- zero emissions power plant
- zero emissions chemical plant
- zero (net) energy building
- zero emissions vehicle (ZEV)

Practical implementation of new performance standards requires full life cycle accounting (LCA)
Energy chains – a connected path of steps from “cradle to grave”

1. Locating a source – solar, fossil, geothermal, nuclear
2. Recovery and/or capture
3. Storage of a depletable resource, or storage due to the intermittency of a renewable energy supply
4. Conversion, upgrading, refining, etc.
5. Storage as a refined product
6. Transmission and distribution
7. Use and reuse
8. Dissipation as degraded energy an/or wastes

Overall efficiency is the product of the efficiency of each step
But we must play by the rules

- The 1\textsuperscript{st} and 2\textsuperscript{nd} Laws of thermodynamics are relevant
- Heat and electric power are not the same
- Conversion efficiency does not have a single definition
- All parts of the system must work – fuel supply, fuel and energy converters, control and monitoring sub systems, transmission and distribution and an interconnection if required
- Scalability of deployment to GJ/GW levels will require using multiple modules or larger plants

And without a sufficiently robust infrastructure to transmit, store and distribute energy -- nothing happens!
US electric grid deals with 1,000,000 MWe of capacity
-- A supreme example of engineering complexity with massive committed infrastructure that will be difficult to change

Lovins refers to it as an “old, fragile, brittle” system that is prone to systemic failure.
Fossil and Nuclear Options

- **Fossil** – both conventional and unconventional oil and gas resources are depletable and maldistributed worldwide; and although coal is more abundant, the adoption of carbon capture and sequestration will be costly and not a permanent solution

- **Fission** – no carbon emissions but wastes, proliferation and safety remain as dominant public acceptance issues

- **Fusion** – technology not ready with uncertain costs and performance
Where do we go from here?
Renewable energy technologies have high sustainability index scores

- Solar
- Wind
- Wave
- Biomass
- Hydro
- Geothermal

But the quality and availability of renewables vary widely, land use and siting issues exist, they often require conversion to other forms, and their costs relative to fossil fuels remain high.
Let’s take a closer look at two options

1. Universal heat mining
   – geothermal energy for everyone!
2. Biomass to transportation fuels
   – re-engineering our approach to agriculture and treating wastes

Examples of Directed Sustainable Energy Research for Achieving Deployment having National Impacts

- Advanced drilling technology for heat mining
- Quantitative LCA of bioenergy options to make good choices
- Thermochemical and biochemical conversion options for biomass feedstocks
Geothermal Energy – a diverse and misunderstood resource

Geothermal Resources
- Hydrothermal – liquid-dominated/super-heated water
- Hydrothermal – vapor-dominated/dry steam
- Geopressed - Methane, hydraulic and thermal energy
- Magma
- Hot dry Rock or conduction-dominated

Looking to “inner space” for Opportunities in the Earth’s Geosphere
The non-electric portion of energy use is large and at relatively low temperatures.

In the US over 30% of our primary energy is actually used at temperatures < 200°C.

Figure 11.5. Fractional energy use distribution as a function of end-use temperature for non-electric applications below 300°C. The function $f_E^i$ at $T_i$ is simply the derivative of the cumulative energy use at that specific temperature $T_i$. Source: Tester (1982).
Geothermal energy today is used for base load electricity, district heating, and heat pumps

- From its beginning in the Larderello Field in Italy in 1904, over 10,000 MW are produced worldwide today
- Additional capacity with geothermal heat pumps (e.g. >100,000 MWt worldwide)
- Current costs -- 7–10¢/kWh
- Attractive technology for dispatchable base load power for both developed and developing countries

A key challenge - not every place is like Iceland
Today there are over 11,000 MWe on-line with much more under construction

Iceland -- 440 MWe up from 202 MWe in 2005
USA -- 6000+ MWe up from 2544 MWe in 2005

But geothermal today is limited to high grade, high gradient sites with hydrothermal fluids contained in natural reservoirs!!

TOTALS Installed 2000: 7,974 MWe, and 2004: 8,912 MWe (Generated 56,798 GWh/y)
The Future of Geothermal Energy

Energy Recovery from Enhanced/Engineered Geothermal Systems (EGS) – Assessment of Impact for the US by 2050

An MIT–led study by an 18-member international panel

Primary goal – to provide an independent and comprehensive evaluation of EGS as a major US primary energy supplier

Secondary goal – to provide a framework for informing policy makers of what R&D support and policies are needed for EGS to have a major impact

For full report http://geothermal.inel.gov
Is there a feasible path from today’s hydrothermal systems with 3000 MWe capacity to tomorrow’s Enhanced Geothermal Systems (EGS) with 100,000 MWe or more capacity by 2050?

Geothermal resources within a continuum from high-grade hydrothermal to high and low grades of EGS
Enhanced/Engineered Geothermal Systems (EGS) could provide a pathway to universal heat mining.

EGS defined broadly as engineered reservoirs that have been stimulated to emulate the production properties of high grade commercial hydrothermal resources.
Geothermal has many desirable characteristics

- **Renewable** – non-depletable on a short time scale -- renewal times of order 2 to 5 of depletion times
- **Large, accessible and well distributed resource** – 14 million EJ available at depths of 3-6 km available in high grade regions and at depths of 6 km everywhere
- **Environmentally friendly** -- emissions free -- minimal to no NO\textsubscript{x}, SO\textsubscript{x}, CO\textsubscript{2}, particulates, etc. small LCA footprints, manageable water and seismic impacts
- **Scalable** – from 5 to 50 MW (t or e) modules- scalable to 2000 MW complements other carbon free sources – nuclear, solar, and wind in their appropriate domains
- **Dispatchable** - high capacity factors(>90%) for base load electricity and distributed heating/cooling and co-gen needs
- **Robust** - relatively simple, reliable, and safe to operate
- **Flexible** - applications for electricity, heat, and cogen
- **Technology feasible** - drilling and fracturing technology, and reservoir productivity proven in hydrothermal fields / within a factor of 3 low in EGS
- **Economically Competitive** -- today for high grade hydrothermal systems

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**Modest Investment of R&D and deployment is needed to enable 100,000 MWe of new capacity by 2050 using advanced EGS methods for heat mining**
Levelized energy costs vary with resource grade and reservoir productivity and drilling costs.

The diagram shows the levelized energy costs (LEC) in cent per kWh at different average temperature gradients (20°C/km, 40°C/km, 60°C/km, 80°C/km) for depths of 6 km and 4 km. The costs are represented for today's drilling technology with 20 kg/s flow rate (blue), today's drilling technology with 80 kg/s flow rate (yellow), and advanced drilling technology with 80 kg/s flow rate (green). The costs are as follows:

- At 20°C/km:
  - 6 km depth: 223.4¢
  - 6 km depth: 64.3¢
  - 6 km depth: 32.3¢
- At 40°C/km:
  - 6 km depth: 41.1¢
  - 6 km depth: 12.9¢
  - 6 km depth: 7.6¢
- At 60°C/km:
  - 6 km depth: 18.0¢
  - 6 km depth: 6.3¢
  - 4 km depth: 4.1¢
- At 80°C/km:
  - 4 km depth: 13.2¢
  - 4 km depth: 5.3¢
  - 4 km depth: 4.3¢

The Future of Geothermal Energy

Massachusetts Institute of Technology
With EGS technology working at depths to 6 km, all of the US becomes a viable geothermal resource.

From Blackwell and Richards (June, 2007)
Research example 2 – Converting biomass to transportation fuels

Wood chips
Switch grass
Poplars
Sugar cane residue
Municipal solid waste
Alfalfa
Vehicles per Thousand People: U.S. Compared to Other Countries

Historical U.S. Vehicles Compared to Vehicles per 1000 People around the World

Sources:
U.S. data
Other countries/regions
Concept of a biorefinery dealing with multiple feeds and products

Different feedstocks
- Municipal Solid Waste
- Forest Thinnings, Short Rotation Trees
- Agricultural Crops, Grasses, and Residues

Different products
- Food
- Animal Feed
- Electricity
- Ethanol
- Hydrogen

Food processing wastes
LCA challenges -- dealing with multiple scales, assumptions and attributes, and uncertainties!

Large system of many decisions with much uncertain information

Harvest → Transport → Biorefinery → Product Use

Input output model

- Hydrolysis
- Solids Filtration
- Product Separation
- Corn Grain

Kinetics, thermodynamics, transport

ASPEN process model

- HYDRLSYS
- FRMNTR
- FEED
- SLDS
- DSTL

Municipal Solid Waste
- Forest Thinnings, Short Rotation Trees
- Agricultural Crops, Grasses, and Residues
- Animal Feed
- Electricity
- Hydrogen
- Food
Incorporating Uncertainty

Seeds
N, F, P
Pesticide
Diesel fuel
Electricity
Natural gas
Irrigation

Corn grain

Fuel
Distribution

Enzymes
Yeast
Chemicals
Electricity
Natural gas

Ethanol
DDGS
Distribution
Fuel

Process, impact assessment, and valuation models

Bayesian updating

Monte Carlo Simulations

Rank correlations

\[
E\{y(\theta)\} \approx \frac{1}{N} \sum_{i=1}^{N} y(\theta_1^i, \theta_2^i, ..., \theta_n^i)
\]

\[
p(\theta | y) = \frac{p(y | \theta)p(\theta)}{\int p(y | \theta)p(\theta)d\theta}
\]

\[
r_s = 1 - \frac{6 \sum (R_i - S_i)^2}{n(n^2 - 1)}
\]
Energy Balance Confusion

Effect of common system boundaries, coproduct credit

Argonne (1999)
USDA (2004)
ORN L (1990)
UC Berkeley A (2006)
UC Berkeley B (2006)
Amoco (1989)
Iowa State (1992)
Pimentel (2005)
MIT (2006)
Key messages for biomass energy

Focus on improving the effectiveness of converting and energy crops, forest & agricultural crop residuals, food processing wastes, municipal solid wastes and sewage sludges to liquid transportation fuels, biogas, thermal energy, and other products

1. Support resource assessment and feedstock logistics efforts on a national scale
2. Development of comprehensive Life Cycle Analysis (LCA) methods for assessment of biomass processing
3. Improved understanding of thermochemical reforming
4. Better catalysts for breaking down lignin-cellulosics
Biomass Energy Summary

- **Resource**: is large, accessible, and diverse – requires full transition to lignin-cellulosic feedstocks – residuals, wastes, and low intensity energy crops
- **Applications**: can provide both transportation fuels and primary thermal energy for electric power and heat
- **Environmental**: large footprint for the fuel cycle – land, water use and embedded energy requirements are substantial - full LCA needed to quantify ecological and environmental impacts
- **Technology**
  - ethanol from grains -- feasible but not sustainable
  - scalability of lignin cellulosics is uncertain but opportunities for improving production and conversion of residuals using methods of modern biology are significant
  - research on thermochemical conversion should be expanded to increase options
  - substantial changes in agricultural, forestry and waste management practices are needed if bioenergy is to scale to meet national needs
- **Economics**
  - projections favorable in today’s energy markets with modest subsidy
  - will need advances in to make lignin-cellulosic feedstocks viable

**Significant investment in R&D is needed to enable economic residual biomass feedstock conversion to liquid fuels and energy on a national scale**
Guiding principles for Sustainable Energy

1. “Raise the bar much higher” -- mandate high performance, high efficiency standards for buildings, cars, appliances, etc.

2. Assess impact of your energy choices in terms of quantitative sustainability metrics
   1. Conduct full life cycle assessment of energy choices
      - Thermo -- All mass and energy, and exergy flows
      - LCA -- Environmental damages and benefits
      - Economics -- Full cost accounting

3. Address critical energy infrastructure and balance of systems issues, including storage, interconnection and transmission and distribution

4. Seek collateral benefits – e.g. co-gen, combined heat and power, e.g. high efficiency buildings with renewable energy capture

5. Be transparent and clear in your analysis -- include assumptions, uncertainties, and risks

Most importantly speak the truth quantitatively, objectively, and fairly when discussing options!
Thank you

For details see
Sustainable Energy – choosing among options

A textbook by
J. Tester, E Drake, M. Driscoll, M. Golay, and W. Peters
22 chapters --- 850 pages

Available in from MIT Press, Cambridge, Massachusetts, USA
http://mitpress.mit.edu