Cheap clean energy for all in the 21st Century?

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A macro view of global population

2 billion in 21\textsuperscript{st} century

Health
Education
Energy
Water
Job Skills

1.5B people in Transition

3 billion in 18\textsuperscript{th} century
with less than $2 \text{ ppp/day}

(Additional 2.5B will start here)
Energy ↔ development

Global Economics and Energy

<table>
<thead>
<tr>
<th>Population</th>
<th>GDP</th>
<th>Energy Demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Billions</td>
<td>Trillion (2000$)</td>
<td>MBDOE</td>
</tr>
<tr>
<td>10</td>
<td>80</td>
<td>350</td>
</tr>
</tbody>
</table>

Average Growth / Yr. 2000 - 2030

- 0.9% for Population
- 2.8% for GDP
- 1.6% for Energy Demand

Non-OECD vs. OECD

- 1.1% growth for Non-OECD
- 0.4% growth for OECD

1.1% growth for energy demand

ExxonMobil
3B poor (~1B homes) need access to energy

- **Cooking and potable water:**
  - 1 liter (1/4 gal) of kerosene per day

- **Light:**
  - 100 watts (7 × 13W florescent bulbs)

- **Entertainment/Communications:**
  - TV/computer at 200-500 watts

These additional resources would revolutionize the development of the poor
250 cubic feet natural gas
3 gallons oil
20 pounds coal
3 1/2 pounds biomass
One ounce uranium ore

Each day, each American uses...
4+1 global grand challenges

• Carbon neutral fossil (coal)
• Solar PV/CSP at capital cost $1/watt
• $H_2$ produced from non-fossil sources
  - Photochemical, thermal splitting of $H_2O$
• Closed nuclear fuel cycle to enable safe, secure, sustainable nuclear energy
• Efficient energy use, storage and transmission
• Fusion – the ultimate “source”

A tale with nine parts
1) The energy infrastructure is huge (~$15 trillion)
2) Climate Change – an uncontrolled experiment
3) Cheap clean energy – an economic opportunity
   ➢ Alternatives have a market niche but are small today
4) USA lacks energy (conventional oil, gas) security
5) Middle East & Russia control oil and gas
6) Increasing competition (China, India)
7) Can we continue to bank on a military solution
8) Unconventional fuels: 2-3X pollution and CO₂
9) Energy efficiency ↔ behavior change
A mind-boggling global infrastructure (~$15 trillion) provides modern energy/mobility to ~3.5 billion people

• Oil and gas contracts, rigs, exploration technology
• Tankers and pipelines
• Refineries, LNG facilities
• Auto industry
• 600 (+220) million cars (+trucks) running on gasoline
• Service stations and gasoline stations
• Existing coal/gas electricity generation plants

1. This cannot be changed overnight!
Current global energy supply is dominated by fossil fuels – oil has been the largest component of the energy mix for many decades; gas has grown strongly since the 1970’s; coal has been growing in the last four years; hydro is constant and nuclear has plateaued.

Source: BP Statistical Review
Global consumption is ~13 trillion watts of primary power in 2006

To sustain an adequate standard of living (4kw) for 8 billion people (population by 2025), and without improvements in efficiency, we need ~2.5 times today’s energy use.

**GOAL:** 32 Twatts ~ 10Ttwatts electric
The simplest solution is unconstrained supplies of

- Gasoline
- Natural gas

Can provide all our needs for electricity, heat, transportation.

Environmental stewardship requires Carbon capture and sequestration.
Burning fossil fuels for next 100 years

Av. (current)  Tera Tons C  CO₂
- OIL: 100 (85) Mbo/day  → 0.5
- Gas: 1.0 (0.3) Tcf/day  → 0.5
- Coal: 21 (14) M tons/day  → 1.4

½ accumulates in the atmosphere & 2.1 GtC = 1 ppm

~1000 ppm
Fossil Fuels and Environment

In the 20th century we started to act on pollution (mercury, NOx, SOx, acid rain, soot, ...) but not CO₂ and the associated global climate change
"CO$_2$ & global average temperature"

Source: Petit et al., *Nature* 399 Vostok, Antarctica Ice Core data
CO$_2$ is a greenhouse gas. It forms a blanket around the earth that causes warming.

Melting of permafrost

http://earthobservatory.nasa.gov/Study/vanishing/

Melting of glaciers in Greenland and around the world. Is it global warming?

CO$_2$ cycle and warming is a non-linear phenomena

Intense storms
Increasing evidence for temperature rise due to fossil-fuel burning

Possibility of catastrophic change:

Shutdown of the thermohaline in 10s of years
Are we in the non-linear regime of CO$_2$ cycle/warming?

- CO$_2$ is the most oxidized form of carbon
  - 10-50 year cycle with terrestrial and shallow ocean (saturated)
  - 400-2000 year cycle – deep ocean

- Thermal capacity of earth ⇒ we are observing response to CO$_2$ loading of 30-40 years back

Sequestration of CO$_2$ ⇒ First capture and then store 25 gigatons CO$_2$ / year!
2. Climate change is the largest, costliest, most dangerous, uncontrolled experiment ever done by mankind
Clean Energy: an Economic Opportunity

• Clean electric power
• Robust electric power grids
• Fuel for Transportation
• Efficient autos/machines/appliances are increasingly value-added products.

10 Terawatts of electric power translates to a $12 billion/day market at $0.05 kWhr
Getting all three – cheap, clean and copious supply – is the challenge

- Plenty of fossil Carbon
  - Oil, natural gas, coal
  - heavy oil, shale, clathrates, …
- Fungible at $50+/barrel (Coal-to-Liquids)

Issues with fossil fuels

- Environmental impact
- Green house gasses

Alternates: How much and how soon?
All alternatives to fossil fuels have a market niche

- Nuclear: ~400 GW
- Hydro: ~400 GW ~600 GW
- Wind: 60 GWp +30%/year
- Solar PV: 4 GWp +30%/year
- Geothermal: 25 GW (e+th)
- Biofuels: 1 Mboe/day

3. But none is large enough!
Paradigm change is needed in order to provide affordable & clean energy to all!
4. Energy Security

Where do we get our oil and natural gas from?

And

Emerging challenges to this supply?
Oil is easy to move and trade

Trade flows worldwide (million tonnes)

USA
Canada
Mexico
S. & Cent. America
Europe & Eurasia
Middle East
Africa
Asia Pacific

BP 2004
US oil consumption: Large (~25% of global) & Growing

EIA, Annual Energy Outlook 2001; "Potential Oil Production from the Coastal Plain of ANWR," - EIA Reserves & Production Division
Problems with business as usual

- USA imports 2/3 of oil it uses
- Share of imported natural gas is set to increase rapidly
- Market saturated, volatile, unstable
- Producing nations are unstable
- CO$_2$ emissions $\rightarrow$ global warming
US imports ~2/3 of its oil

Friendly nations cannot fulfill our oil needs

<table>
<thead>
<tr>
<th>Region</th>
<th>Barrel Amount</th>
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<tbody>
<tr>
<td>Middle East</td>
<td>2.5 M barrels</td>
</tr>
<tr>
<td>Africa</td>
<td>2.4 M barrels</td>
</tr>
<tr>
<td>Russia</td>
<td>0.4 M barrels</td>
</tr>
<tr>
<td>Canada</td>
<td>2.2 M barrels</td>
</tr>
<tr>
<td>Mexico</td>
<td>1.4 M barrels</td>
</tr>
<tr>
<td>Venezuela</td>
<td>1.3 M barrels</td>
</tr>
<tr>
<td>North Sea</td>
<td>0.7 M barrels</td>
</tr>
</tbody>
</table>

(EIA 6-12/06)
Decline in production in friendly nations

North Sea (UK, Norway)

Peaked in 1999 at 6.05 million bbl/day. 1999-2005: average decline at 3.4% to 4.8 million bbl/day in 2005.

EIA, New York Times 3/9/07
Major natural gas trade movements

Trade flows worldwide (billion cubic metres)
Ranking of reserves: 2005

USA 12, 6, 1
Russia 8, 1, 2
China 11, -, 3
India -, -, 5
EU -, -, 4
AT -, -, -
Persian Gulf
- OIL 1, 2, 3, 4, 5
- GAS 2, 3, 4, 5, 10
- No Coal
Fast forward to 2020

USA ?, -, 1
Russia ?, 1, 2
China -, -, 3
India -, -, 5
EU -, -, 4
AT -, -, -

Persian Gulf
OIL 1, 2, 3, 4, 5
GAS 2, 3, 4, 5, 9
No Coal

? → EOR
5. Middle East and Russia control conventional natural gas and oil
Who gets CA, Russian oil and gas?

She who owns the pipelines?
Which countries will get Russian natural gas in 10 years time?

New pipeline from Russia to Germany bypasses Ukraine and Eastern Europe

Natural destination is Europe & Asia
6) The global oil (gas?) situation has been anticipated by the US and has guided its policies since WWII
Oil: key driver of foreign policy

- 1945
  - F. Roosevelt and King Abdel Aziz “oil for security”
- 1947: Truman Doctrine
  - Stop the spread of communism (Greece, Turkey, Iran)
- 1957: Eisenhower Doctrine
  - Protect friendly interests
- 1969: Nixon
  - Protect interests through surrogate friendly rulers
- 1980: Carter Doctrine
  - To protect Saudi Arabia and the free flow of oil from the Persian Gulf
- 1983: Establishment of Central Command
  - Protecting the free flow of oil from the Middle East and Central Asia
A very successful but costly military investment to protect the flow of oil (=prosperity)

6. Can we continue to bank on this solution?
7. Increasing competition for oil and gas

China & India are making deals with Iran, Sudan, …

Oil Imports 1994-2004

<table>
<thead>
<tr>
<th>Country</th>
<th>Growth Rate / year</th>
</tr>
</thead>
<tbody>
<tr>
<td>USA</td>
<td>+4%</td>
</tr>
<tr>
<td>Japan</td>
<td>-1%</td>
</tr>
<tr>
<td>India</td>
<td>+8%</td>
</tr>
<tr>
<td>China</td>
<td>+31%</td>
</tr>
</tbody>
</table>
8) Will coal or natural gas or nuclear or solar dominate power generation?

See 2007 MIT study on the Future of Coal

Starting in 1980s

Coal was dirty
Gas was cheap
Hydro was flat
Nuclear was bad

Need cheap gas

200 GW of New Gas-Fired Capacity Since 1998

U.S. Generation Capacity Additions
Unconventionals: Large reserves

Tar Sands

Coal, Shale

Heavy Oil

Coal

Problem: pollution, environment, CO₂
To use “coal” the US must lead the world by innovating clean coal technology for generating electricity and producing oil.

- Pollution

Need R&D to – CO₂

Worldwide > 1 TW of new coal PP in next 20 years

FutureGen (No emissions) 10+ years away
Nuclear power: “CO₂ clean”

- Principles of nuclear fission are known
- Natural $^{235}$U is limited
- Rapid scale up requires R&D

- Closed fuel cycle
- Gen IV reactors
- Breeder reactors
  - $^{232}$Th $\rightarrow$ $^{233}$U
  - $^{238}$U $\rightarrow$ $^{239}$Pu

- Fear of accidents
- Proliferation ➢ HEU, $^{239}$Pu
- Waste management

Not in my backyard
To replace 10 Terawatts by nuclear power would require 10,000 one GW plants – 1 new plant a day for 30 years.

*Don’t have enough nuclear scientists or engineers*
8) Power generation

Urgent need for timely action:

Need 10-15 years to plan, build and understand costs of commercial plants

What we build today will have a lifetime of 40-70 years (through much of 21st century)

China (and soon India) will build ~1 GW coal power plants a week for next 10 years
9) While people argue about their favorite “solution” (each has drawbacks & potential), there is consensus on energy efficiency.

A factor of ~50% improvement possible with today’s technology.
Short term Option: Behavior Change

- Lighting
- Appliances
- Heating
- Cooling
- Transport

Drive less and Drive fuel efficient cars
The US should lead the world in energy efficiency.

**Tanzania**: fruit seller - flame [above]; 1-watt white LED [below]

*Source: Art Rosenfeld*
Separation/capture of CO₂ from mixed gas streams
Secure and effective long-term storage of CO₂.
  - Geologic, mineralization, …
Hydrogen from water without using fossil energy:
  - Electrolysis of water (inexpensive and efficient electrodes)
  - Photochemical and/or thermo-chemical splitting of water
PV, CSP ($1/watt & 100+ GW/year production)
  - nano and/or bio PV materials & systems integration
Closed nuclear fuel cycle and advanced reactors
  - separation of SNF, transmutation, fuel reassembly, waste
Fusion?

Cannot have cheap clean energy for all (at *tera* scale) without key S&T R&D

No large scale (1 TW) deployment in next 20 years
No source is intrinsically good or bad or clean or dirty. It is a lifecycle systems issue.

<table>
<thead>
<tr>
<th></th>
<th>Gasoline</th>
<th>Nuclear</th>
<th>Solar</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Cost</td>
<td>✓</td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td>2) Density</td>
<td>✓</td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td>3) Storage</td>
<td>✓</td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td>4) Portability and mobility</td>
<td>✓</td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td>5) Scale</td>
<td>✓</td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td>6) Unintended consequences</td>
<td>✓</td>
<td>✓</td>
<td>?</td>
</tr>
</tbody>
</table>

The need is so large that we will exploit all sources. Must close the cycle, determine realistic lifecycle costs and think equity if we want cheap clean energy for all.
Summary

• Need for modern energy is global
• Access should be a global right
• Environmental impact is global

To have affordable access by all and to mitigate environmental impacts we must address the energy challenge as a global responsibility
Energy Security

= National Security
= Economic security
= Environmental Security
= Future of our children

Senator Lugar: “energy is the albatross of U.S. national security”

Brookings: 13 March 2006
Industrialized nations must lead the R&D for clean and affordable energy NOW (= hope for all mankind)

The poor are most vulnerable to climate change and will not have the resources to mitigate the impacts
Hope versus Hunger
As a civilization we understand the threats and we have tools to deal with them
Will we grow the will and act in time?