The Energy Challenge

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<table>
<thead>
<tr>
<th>Units of Power</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1 kW</td>
<td>(100 W) Light Bulb, Laptop Power Supply</td>
</tr>
<tr>
<td>1-5 kW</td>
<td>Household Appliance (Daily average household use)</td>
</tr>
<tr>
<td>150 kW</td>
<td>Typical Car Engine (200 hp)</td>
</tr>
<tr>
<td>1,000 kW</td>
<td>1 Mega Watt (MW): Mid-size Industry</td>
</tr>
<tr>
<td>1,000,000 kW</td>
<td>1 Giga Watt (GW) typical Nuclear or Coal-Fired Plants</td>
</tr>
<tr>
<td>1,000,000,000 kW</td>
<td>1 Tera Watt (TW) US Primary Energy Use</td>
</tr>
</tbody>
</table>
Renewables
(Seek significant fraction of world’s 14 TW consumption)
Potential of Renewables (relative to world use ~14 TW)

- **Solar** could *in principle* power the world – given breakthroughs in energy storage and costs (which should be sought)
- **Hydro** is already significant and could probably be expanded to ~ 1 TW (Not much change during the last 30 years)
- **Wind** and burning biomass are capable in principle of contributing on the TW scale (*perhaps* a lot more in the case of biomass)
- **Geothermal, tidal** and wave energy will not contribute on this scale, but should be fully exploited where sensible

**Conclusions are very location dependent**, e.g. geothermal is a major player in Iceland, Kenya,…; the UK has 40% of Europe’s wind potential and is well placed for tidal and waves; the US south west is much better than the UK for solar; there is big hydro potential in the Congo;…
Evolution of Commercial U.S. Wind Technology

THE EVOLUTION OF COMMERCIAL U.S. WIND TECHNOLOGY

1980's
- Structurally stiff
- 3 bladed - upwind yaw driven
- Constant speed and 2 speed
- Stall regulated/tip brakes or full-span pitch controlled
- Fiberglass blades
- Geared transmission
- Induction generator
- Steel truss or tube tower

1990's
- Structurally stiff
- 3 bladed - upwind yaw driven
- Variable speed and constant speed
- Special airfoils - NREL
- Stall regulated and pitch controlled
- Planetary transmission
- Induction generator
- Large size to reduce COE

Future Innovation
- Scale to larger size
- Advanced blade materials and manufacturing
- Low speed direct drive generators
- Custom power electronics (high efficiency)
- Feedback control of drive train and rotor loads
- More flexible structurally
- O&M reduction features

Rotor Diameter in meters

1980 1990 2000 2010
50kW 100kW 300kW 750kW 1.5 MW 2.5 MW 5 MW
Wind turbines are a developed Technology

- Offshore GE 3.6 MW
  104 meter rotor diameter

- Offshore design requirements considered from the outset:
  - Crane system for all components
  - Simplified installation
  - Helicopter platform

Boeing 747-400
Summary of Wind

- Production costs are close to other conventional sources of energy (intermittency not taken into account).
- Wind resources are vast, but also vary considerably on temporal, regional, and micro levels.
- US wind energy capacity tripled in past decade, to ~7GW today (Green power programs have supported ~2 GW).
- Opposition to on-shore wind turbine in many areas.
- Off-shore wind farms (but with added transmission cost).
Solar Thermal Electric

Trough Technology (Bulk Power)

Dish/Engine Technology (Distributed Power)

Power Tower Technology (Bulk Power)
Concentrated Solar Power Technology: Important Characteristics

- Requires direct-beam solar radiation
  - Resources in Southwest U.S. adequate for 4000 GW
- Uses familiar components – glass, steel, gears, heat exchangers, turbines
- Can provide steady power:
  - Thermal storage easy to incorporate, or
  - Can be hybridized with natural gas
- 350 MW of parabolic trough plants built around 1990 still operating well
- Several power tower demonstration plants have established technology viability.
### Photovoltaic Plants in the U.S.

<table>
<thead>
<tr>
<th>Facility</th>
<th>Power (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Springerville, AZ</td>
<td>4.59</td>
</tr>
<tr>
<td>Rancho Seco, CA</td>
<td>3.9</td>
</tr>
<tr>
<td>Prescott, AZ</td>
<td>2.62</td>
</tr>
<tr>
<td>Twenty-Nine Palms, CA</td>
<td>1.3</td>
</tr>
<tr>
<td>Blythe, CA</td>
<td>1.2</td>
</tr>
<tr>
<td>Oroville, CA</td>
<td>1.18</td>
</tr>
<tr>
<td>Santa Rita, CA</td>
<td>1.18</td>
</tr>
<tr>
<td>Napa, CA</td>
<td>1.158</td>
</tr>
<tr>
<td>Clovis, CA</td>
<td>1.131</td>
</tr>
<tr>
<td>Chico, CA</td>
<td>1.107</td>
</tr>
<tr>
<td>Oroville, CA</td>
<td>1.08</td>
</tr>
<tr>
<td>Hayward, CA</td>
<td>1.01</td>
</tr>
<tr>
<td>Sacramento, CA</td>
<td>1</td>
</tr>
<tr>
<td>Ridge Crest, CA</td>
<td>1</td>
</tr>
<tr>
<td>Farmingdale, NY</td>
<td>1</td>
</tr>
<tr>
<td>Santa Rita, CA</td>
<td>1.18</td>
</tr>
<tr>
<td>Hayward, CA</td>
<td>1.05</td>
</tr>
<tr>
<td>Davis, CA</td>
<td>1</td>
</tr>
<tr>
<td>Camden County, NJ</td>
<td>1</td>
</tr>
<tr>
<td>Del Mar, CA</td>
<td>1</td>
</tr>
</tbody>
</table>
Efficiency of solar photovoltaic
Multi-layer semiconductors and concentrators can increase efficiency.

<table>
<thead>
<tr>
<th>Illumination</th>
<th>Number of Cells</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Sun</td>
<td>1</td>
<td>31.0</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>42.9</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>49.3</td>
</tr>
<tr>
<td></td>
<td>∞</td>
<td>68.2</td>
</tr>
<tr>
<td>100 Suns</td>
<td>1</td>
<td>35.2</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>48.4</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>55.6</td>
</tr>
<tr>
<td></td>
<td>∞</td>
<td>76.2</td>
</tr>
<tr>
<td>46,300</td>
<td>1</td>
<td>40.8</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>55.7</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>63.9</td>
</tr>
<tr>
<td></td>
<td>∞</td>
<td>86.8</td>
</tr>
</tbody>
</table>

GaInP/GaAs/Ge 3-Cell Device

38.8% Efficiency @ 241 Suns (Spectrolab, 2005)

D. Friedman (NREL), April, 2002

Note: High efficiency should be achieved without a high price (Cost/power matters)
Best Research-Cell Efficiencies

- **Multijunction Concentrators**
  - ▼ Three-junction (2-terminal, monolithic)
  - ▲ Two-junction (2-terminal, monolithic)

- **Crystalline Si Cells**
  - ■ Single crystal
  - ◇ Multicrystalline
  - ♦ Thin Si

- **Thin Film Technologies**
  - ★ Cu(In,Ga)Se₂
  - ○ CdTe
  - ○ Amorphous Si:H (stabilized)

- **Emerging PV**
  - ○ Dye cells
  - ● Organic cells
    - (various technologies)

The timeline shows the evolution of solar cell efficiencies from 1975 to 2005, highlighting advancements in technology and efficiency improvements.
Major Issues of Renewables

- **High Cost:** Mainly driven by low power density.

- **Location:**

- **Intermittency:**
  - Average power production ~ 1/3 of rated power
  - May require Energy Storage which can double or triple the price. (NREL study indicates a maximum of 10% of electricity production by intermittent sources before major grid instabilities).
  - Other solutions: Smart grids, hybridization (in conjunction with natural gas), matching demand with production.
Projected cost of photovoltaic solar power?

$1/W_p\text{AC} \rightarrow 5 \text{ cents/kWhr in California}
- requires cost \sim \text{cost of glass!}
PV Module Production Experience (or “Learning”) Curve

“80% Learning Curve: Module price decreases by 20% for every doubling of cumulative production

1976
2002
75 GW
90%
80%
70%
levelised costs of electricity generation

Cost of Electricity Generation
9% IRR ($/MWh)

- CCGT, gas $4/mmbtu
- Coal $40/tonne
- Hydrogen Power Gas, $4/mmbtu
- Hydrogen Power Coal $40/tonne
- Nuclear
- Onshore Wind
- Offshore Wind
- Biomass Gasification
- Wave / Tidal
- Solar (Retail Cost)

Source: BP Estimates, Navigant Consulting
UK Royal Academy of Engineering study of generating costs:

Possible Scenario

- Coal-Fire PF
- Coal-Fired CFB
- Coal-Fired IGCC
- Gas-Fired OCGT
- Gas-Fired CCGT
- Nuclear
- Poultry Litter BFB
- Offshore Wind Farm
- Wave & Marine

- Higher Gas Prices (2005)
- CO2 costs (£14.80/tonne)
- Wind "back-up" (System Model)
- Nuclear 15% Discount Rate
- Cost of generating electricity

Nuclear base cost assumes 7.5% discount rate.
impact of CO₂ cost on levelised Cost of Electricity

Source: IEA Technology Perspectives 2006, IEA WEO 2006 and BAH analysis
Any Questions?