Solar High: Making It Happen

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Image Source: APOD/NASA
Electricity Consumption, 2009-2035

Source: DOE EIA
Generating Capacity, 2010 & 2035

Source: DOE EIA
The Electric Problem

- There are only four available technologies that can conceivably supply electric power on a sufficient scale:
  - Nuclear (probably Gen IV fast neutron reactor)
  - Coal (perhaps “Clean Coal”)
  - Natural gas (shale gas, methane from hydrates, etc.)
  - Solar

- The first three face public resistance (whether or not justified) on environmental or NIMBY grounds.
Why Wind Will Remain a Minor Source

4,400 wind turbines like this are needed to match one 2 GW power satellite

1.5 MW wind turbine
Annual output: 4 million kWh

Natural gas well annual output: 44 million cubic feet (typical), which gives 13 million kWh heat or 4.5 million kWh electricity

Sources: Danish Technical University & DOE EIA
The Need for Cheap Energy

- The present average US residential price of electricity is 11.45 ¢/kWh; the average wholesale price is 5.72 ¢/kWh.
- Accepting significantly higher US prices will
  - Lower the US standard of living.
  - Impose a regressive tax on people with low income.
  - Drive US industry and jobs overseas.
  - Encourage Third World countries to maximize their advantage by keeping energy cheap (i.e., burning coal), thus increasing global CO$_2$ emissions.
- Some overseas markets may accept higher prices, at least initially. Ireland, Italy and Denmark are among the most expensive, but they are not large markets (probably < 8 GW total new capacity by 2035).
Solar Dreams

- Vision: the ultimate renewable energy source
- Reality, 2009: 0.3% of US electricity
  - EIA prospect, 2035: 0.8% of US electricity
- Goal, 2035: Grid-connected central solar plants supplying baseload, dispatchable power
- Capacity goal, 2035: 15% of new generation capacity, worldwide
  - US: 40 GW
  - Other OECD: 60 GW
  - Non-OECD: 300 GW
  - Total: 400 GW
The Solar Problem

Normalized Solar Output & Utility Load

Tucson Insolation

ERCOT Load

Date

1/1 1/29 2/26 3/26 4/23 5/21 6/18 7/16 8/13 9/10 10/8 11/5 12/3 12/31
Energy Storage Requirements
### Terrestrial Solar Parameters, per kW

<table>
<thead>
<tr>
<th></th>
<th>ERCOT</th>
<th>Baseload</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV array area, m²</td>
<td>40.9</td>
<td>44.2</td>
</tr>
<tr>
<td>Peak storage, kWh</td>
<td>491</td>
<td>606</td>
</tr>
<tr>
<td>Max array output, kW</td>
<td>4.9</td>
<td>5.3</td>
</tr>
</tbody>
</table>

**Costs:**

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>Solar farm</td>
<td>$12,270</td>
<td>$13,260</td>
</tr>
<tr>
<td>Pumped storage</td>
<td>$2,400</td>
<td>$2,400</td>
</tr>
<tr>
<td>HVDC lines</td>
<td>$3,770</td>
<td>$4,080</td>
</tr>
</tbody>
</table>

**Total:** $18,440 $19,740

EIA Annual Energy Outlook 2010: "solar technologies are too costly for widespread use in wholesale power applications."
## Terrasolar Power vs Solar High

<table>
<thead>
<tr>
<th></th>
<th>Tucson</th>
<th>GSO</th>
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</thead>
<tbody>
<tr>
<td>Sun-track</td>
<td>Expensive</td>
<td>Easy</td>
</tr>
<tr>
<td>Concentration ratio</td>
<td>1</td>
<td>30 to 1000</td>
</tr>
<tr>
<td>Photovoltaic cells</td>
<td>CdTe, etc.</td>
<td>Multijunction</td>
</tr>
<tr>
<td>Hazards</td>
<td>Storm, flood, dust, birds</td>
<td>Radiation, micrometeors</td>
</tr>
<tr>
<td>Average insolation, W/m²</td>
<td>285</td>
<td>1,360</td>
</tr>
<tr>
<td>Array area, m²/kW</td>
<td>&gt;40</td>
<td>5.5</td>
</tr>
<tr>
<td>Energy storage, kWh/kW</td>
<td>600</td>
<td>0</td>
</tr>
<tr>
<td>Transmission line, km</td>
<td>2,400</td>
<td>100?</td>
</tr>
<tr>
<td>Land area (for 2GW), km²</td>
<td>400</td>
<td>70</td>
</tr>
<tr>
<td>Delivered energy, $/kWh</td>
<td>&gt;$0.20</td>
<td>$0.08?</td>
</tr>
</tbody>
</table>
The Solar High Challenge

Amortization Revenue: $0.05/kWh

Real Interest: 1%

Real Interest Rate = Nominal Interest Rate - Inflation Rate
Meeting the Challenge

We need

• Cheap mass production of rectennas.
• High overall efficiency, from sun to utility grid.
• Very light solar conversion devices, microwave transmitters and gossamer space structures.
• High specific impulse electric propulsion from LEO to GSO, through the radiation belts.
• Efficient (robotic?) assembly of large structures in space.
• Cheap launch to LEO

Launch to LEO is the most controversial, but all it really needs are fully reusable vehicles.
Deployment Scenario

Launch Rate

Cumulative Capacity, GW

Year

2015 2017 2019 2021 2023 2025 2027 2029 2031 2033 2035

0 50 100 150 200 250 300 350 400

0 25,000 50,000 75,000 100,000 125,000 150,000 175,000 200,000

Launch Rate (MT/year)
Nansen/Talay TSTO Full RLV

- Launch site: Equatorial
- Payload: 47 MT
- Horizontal mating; vertical fueling and launch
- Final orbit: 0° inclination; 250 nmi circular
- Booster flyback with deployable jet engines
- Payload bay = 10 m dia x 13.5 m
- Mated length: 103 m (339 ft)
- Based on Saturn technology
- Wet wings
- Booster: 5 x RD-171 engines; Orbiter: 6 x J-2X engines
- Orbiter OMS: 2 x RL-10A4 engines
Expendable Upper Stage Version

- Payload: 100 MT to 0°, 250 n.m. circular
- Same Booster • Payload: bay: 10 m X 21 m
- Orbiter: same 6 J-2X engines
- Needs gantry for vertical mating, fueling and launch

Span: 138 ft
The Magical Economies of Scale

Launch Cost, $/kg

Year

$0  $200  $400  $600  $800  $1,000  $1,200  $1,400  $1,600

Launch Enterprise Cash Flow

Cumulative Cash Flow, $B

Year


$300

$250

$200

$150

$100

$50

$0

-$50

-$100

$500/kg

$400/kg

$300/kg
Recommendations

- Present space-based solar power (SBSP) as a natural extension to terrestrial solar -- and a great opportunity for the solar energy industry.

- Do not claim that we need SBSP to avoid anthropogenic global warming (AGW). Instead, point out that SBSP is a “no regrets” approach to that problem, more effective than regulation, with no penalty if AGW proves unimportant.

- We can and we must make SBSP cost-competitive with nuclear power, natural gas and coal, without subsidies or artificial incentives.
Anthropogenic global warming (AGW) is controversial.

Opinions don’t matter: the observational evidence will eventually prevail.

There is a growing body of evidence that the problem has been greatly exaggerated.

Citing climate change as a principal reason for SBSP or relying on high energy prices related to it risks cancellation of the program if or when the theory of AGW is discredited.

Let’s look at some actual data…
Absorption of CO₂ after Nuclear Airburst

In 1962, the USSR detonated 141 megatons at the Novaya Zemlya test site.

The ¹⁴C half-life is 5700 years.

The CO₂ absorption time constant is 16.4 ± 0.7 years.
Sunspots and Galactic Cosmic Rays

Graph showing the correlation between Sunspot Number and Galactic Cosmic Rays from 1950 to 2010.

- Sunspot Number
- Galactic Cosmic Rays

Year


Neutron Flux (hundred counts/hour)
The Holocene Climate

Data from GISP2, Greenland
Antarctic Cooling

Extent (millions of square kilometers)

Jul Aug Sep Oct Nov

2010 — 2009 --
1979–2000 Average
±2 Standard Deviations

National Snow and Ice Data Center, Boulder CO
Cautionary Quotations

• “An hypothesis is always preferable to the truth, for we tailor an hypothesis to fit our opinion of the truth, whereas the truth is only its own awkward self. Ergo, never discover the truth when an hypothesis will do.”
  -- attributed to Niccolo Machiavelli (1513)

• “No matter if the science is all phony…Climate change [provides] the greatest chance to bring about justice and equality in the world.”

• “The largest threat to freedom, democracy, the market economy and prosperity is no longer socialism. It is, instead, the ambitious, arrogant, unscrupulous ideology of environmentalism.”
  -- Václav Klaus, President of the Czech Republic, 2008