SuperCities and SuperGrids:
A Vision for Long-term Sustainable and Environmentally Compatible Energy

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Principal, W2AGZ Technologies
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www.w2agz.com

Fuel Cell and Hydrogen Energy Seminar
15 December 2004
CLP Research Institute
Hong Kong, PRC (SAR)
Journey to the West

Paul Grant goes to China seeking wisdom...
Epiphanies Undergone...

“I have seen the future…and it works!”

Lincoln Steffens, 1920

“A wise Communist will not be afraid of learning from a capitalist.”

V. I. Lenin, 1922
Earth at Night - 2050
# US Energy Consumption (2001)

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>Percentage of total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Petroleum</td>
<td>42%</td>
</tr>
<tr>
<td>Coal</td>
<td>24%</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>20%</td>
</tr>
<tr>
<td>Nuclear</td>
<td>8%</td>
</tr>
<tr>
<td>Hydro power</td>
<td>2%</td>
</tr>
<tr>
<td>Solar, Wind, etc.</td>
<td>2%</td>
</tr>
</tbody>
</table>
US Oil Imports (2003)

US 39%
Canada 13%
Saudi Arabia 10%
Mexico 10%
Venezuela 9%
Nigeria 4%
Iraq 4%
UK 3%
Norway 3%
Angola 2%
Algeria 2%
Other 2%

DATA FROM EIA
MAP BY R.I. GIBSON
Hydrogen for US Surface Transportation

**The "25% 80-80-80 400 GW" Scenario**

http://www.w2agz.com

<table>
<thead>
<tr>
<th>Hydrogen per Day</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Tonnes</td>
<td>Shuttles</td>
</tr>
<tr>
<td>230,000</td>
<td>2,225</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Water per Day</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Tonnes</td>
<td>Meters</td>
</tr>
<tr>
<td>2,055,383</td>
<td></td>
</tr>
</tbody>
</table>
Hydrogen for US Surface Transportation

The "25% 80-80-80 400 GW" Scenario
http://www.w2agz.com

<table>
<thead>
<tr>
<th>Technology</th>
<th>Area (km²)</th>
<th>Equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind</td>
<td>130,000</td>
<td>New York State</td>
</tr>
</tbody>
</table>
| Solar        | 20,000     | 50% Denmark
              |                          | Death Valley + Mojave      |
| Biomass      | 271,915    | 3% USA
              |                          | State of Nevada            |
# China-USA Electricity Statistics (2001)

Source (CIA & EIA)

<table>
<thead>
<tr>
<th>Production Source (%)</th>
<th>China</th>
<th>USA (NA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fossil</td>
<td>80.2</td>
<td>71.4 (15% NG)</td>
</tr>
<tr>
<td>Hydro</td>
<td>18.5</td>
<td>5.6</td>
</tr>
<tr>
<td>Other</td>
<td>0.1</td>
<td>2.3</td>
</tr>
<tr>
<td>Nuclear</td>
<td>1.2</td>
<td>20.0</td>
</tr>
</tbody>
</table>

| Annual Producton (TkWh) | 1.42 | 3.72 |
China – Installed Generation Capacity

7%/year increasing (now > 380 GW)

根据预测，2010年将达到6.5亿千瓦左右，2020年达到9.5亿千瓦左右。

USA: ~ 1050 GW

Power Generation Installed Capacity (10MW)

Years


15000 17000 19000 21000 23000 25000 27000 29000 31000 33000 35000 37000 39000 41000 43000 45000

400 GW

USA: ~ 1050 GW
电荒, 2004年中国仲夏夜之恶梦

Electrical power shortage (30GW),
the midsummer nightmare of 2004.
2月全国发电量1581.77亿千瓦时（日均发电量54.54亿千瓦时），比上年同期增长31.36%。

全国发电装机容量已达3.85亿千瓦，在建电力项目1.3亿千瓦。

Capacity 385GW,

Shortage 30GW,

线损率 line losses 7% (Three Gorges Project: 18 GW)

130GW under construction

It is said that 2006 could be better

Could be worse
China “Factoid”

- Current Population: 1.3 Billion Souls
- All want to live like Americans
- Chinese Family Priorities:
  - (1) TV, (2) Washer, (3) Fridge…
  - Next an Air Conditioner (200 USD, 1 kW)
- Assume an average family size of three, then…

An extra 500 GW of generation capacity must be added just to keep them cool!
China-USA Recoverable Coal Reserves (2002)

<table>
<thead>
<tr>
<th></th>
<th>Million Short Tons</th>
<th>Years Left*</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>126,215</td>
<td>273</td>
</tr>
<tr>
<td>USA (NA)</td>
<td>280,464</td>
<td>309</td>
</tr>
</tbody>
</table>

*One Short Ton = 6150 kWh

Efficiency Conversion – 40%
US Natural Gas Imports (BCF, 2003)

<table>
<thead>
<tr>
<th>Country</th>
<th>Reserve estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>World</td>
<td>4,980 trillion cubic feet</td>
</tr>
<tr>
<td>1. Russia</td>
<td>1,748 trillion cubic feet</td>
</tr>
<tr>
<td>2. USA</td>
<td>1,475 trillion cubic feet</td>
</tr>
<tr>
<td>3. Iran</td>
<td>742 trillion cubic feet</td>
</tr>
<tr>
<td>4. Qatar</td>
<td>245 trillion cubic feet</td>
</tr>
<tr>
<td>5. Abu Dhabi</td>
<td>188 trillion cubic feet</td>
</tr>
</tbody>
</table>
The 21st Century Energy Challenge

Design a communal energy economy to meet the needs of a densely populated industrialized world that reaches all corners of Planet Earth.

Accomplish this within the highest levels of environmental, esthetic, safe, reliable, efficient and secure engineering practice possible.

...without requiring any new scientific discoveries or breakthroughs!
Its Solution

A Symbiosis of

Nuclear/Hydrogen/Superconductivity

Technologies supplying Carbon-free, Non-Intrusive Energy for all Inhabitants of Planet Earth
Past & Future Energy Supply

Fig. 1 Production Volume of Energy Resources

Year (Modern Era)

Relative Units

Energy civilization
Fossil fuels
Nuclear energy,
Natural gas
Coal
Oil
Fission
Hydrogen
The Hydrogen Economy

• You have to make it, just like electricity
• Electricity can make H₂, and H₂ can make electricity (2H₂O ⇌ 2H₂ + O₂)
• You have to make a lot of it
• You can make it cold, -419 F (21 K)

SuperCity

P.M. Grant, The Industrial Physicist, Feb/March Issue, 2002
Reading Assignment

1. **Garwin and Matisoo**, 1967 (100 GW on Nb$_3$Sn)
2. **Bartlit, Edeskuty and Hammel**, 1972 (LH$_2$, LNG and 1 GW on LTSC)
3. **Haney and Hammond**, 1977 (Slush LH$_2$ and Nb$_3$Ge)
4. **Schoenung, Hassenzahl and Grant**, 1997 (5 GW on HTSC, 1000 km)
5. **Grant**, 2002 (SuperCity, Nukes+LH$_2$+HTSC)

*These articles, and much more, can be found at [www.w2agz.com](http://www.w2agz.com), sub-pages SuperGrid/Bibliography*
Diablo Canyon
California Coast Power

Diablo Canyon 2200 MW Power Plant

Wind Farm Equivalent
Co-Production of Hydrogen and Electricity

Source: INEL & General Atomics
Nuclear “Hydricity” Production Farm

Source: General Atomics
The Discovery of Superconductivity

Leiden, 1914

La-Ba-Cu-O

Zürich, 1986
$T_C$ vs Year: 1991 - 2001

Temperature, $T_C$ (K)

Year

1900 1920 1940 1960 1980 2000

Low-$T_C$ 164 K

High-$T_C$ MgB$_2$
HTSC Wire Can Be Made!

But it's 70% silver!
Finished Cable
Innost/Innópower Cable

- Former ID/OD (with Braiding): 30/35 mm
- Layers of HTS tape: 4
- Number of HTS tape: 90 (21, 24, 24, 21)
- Ic of HTS tape: 60-80 A (77K, self field)
- ID/OD of cryostat: 43/70 mm
- Dielectric material: XLPE
- Thickness of dielectric: 11.9 mm
- Overall linear specific weight: 9.2 kg/m
Puji Substation (Kunming City)
Reading Assignment

1. Garwin and Matisoo, 1967 (100 GW on Nb₃Sn)
2. Bartlit, Edeskuty and Hammel, 1972 (LH₂, LNG and 1 GW on LTSC)
3. Haney and Hammond, 1977 (Slush LH₂ and Nb₃Ge)
4. Schoenung, Hassenzahl and Grant, 1997 (5 GW on HTSC, 1000 km)
5. Grant, 2002 (SuperCity, Nukes+LH₂+HTSC)

These articles, and much more, can be found at www.w2agz.com, sub-pages SuperGrid/Bibliography
1967: SC Cable Proposed!

Superconducting Lines for the Transmission of Large Amounts of Electrical Power over Great Distances

R. L. GARWIN AND J. MATISOON

100 GW dc, 1000 km!
“Hydricity” SuperCables

Multiple circuits can be laid in single trench
SuperCable

- HV Insulation
- "Super-Insulation"
- Flowing Liquid Hydrogen

- Al "core" of diameter $D_C$ wound with HTSC tape $t_s$ thick
- Superconductor "Conductor"
Power Flows

\[ P_{SC} = 2|V|J A_{SC}, \text{ where} \]

- \( P_{SC} = \text{Electric power flow} \)
- \( V = \text{Voltage to neutral (ground)} \)
- \( J = \text{Supercurrent density} \)
- \( A_{SC} = \text{Cross-sectional area of superconducting annulus} \)

\[ P_{H2} = 2(Q \rho v A)_{H2}, \text{ where} \]

- \( P_{H2} = \text{Chemical power flow} \)
- \( Q = \text{Gibbs H}_2 \text{ oxidation energy (2.46 eV per mol H}_2\text{)} \)
- \( \rho = \text{H}_2 \text{ Density} \)
- \( v = \text{H}_2 \text{ Flow Rate} \)
- \( A = \text{Cross-sectional area of H}_2 \text{ cryotube} \)
Power Flows: 5 GW_e/10 GW_th

### Electrical Power Transmission (+/- 25 kV)

<table>
<thead>
<tr>
<th>Power (MW_e)</th>
<th>Current (A)</th>
<th>HTS J_c (A/cm²)</th>
<th>D_c (cm)</th>
<th>t_s (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5,000</td>
<td>100,000</td>
<td>25,000</td>
<td>3.0</td>
<td>0.38</td>
</tr>
</tbody>
</table>

### Chemical Power Transmission (H_2 at 20 K, per "pole")

<table>
<thead>
<tr>
<th>Power (MW_th)</th>
<th>D_H-effective (cm)</th>
<th>H_2 Flow (m/s)</th>
<th>D_H-actual (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5,000</td>
<td>40</td>
<td>4.76</td>
<td>45.3</td>
</tr>
</tbody>
</table>

Al "core" of diameter D_c wound with HTSC tape t_s thick
Radiation Losses

\[ W_R = 0.5\varepsilon\sigma (T_{amb}^4 - T_{SC}^4), \text{ where} \]

- \( W_R \) = Power radiated in as watts/unit area
- \( \sigma = 5.67 \times 10^{-12} \text{ W/cm}^2\text{K}^4 \)
- \( T_{amb} = 300 \text{ K} \)
- \( T_{SC} = 20 \text{ K} \)
- \( \varepsilon = 0.05 \text{ per inner and outer tube surface} \)
- \( D_H = 45.3 \text{ cm} \)

\[ W_R = 16.3 \text{ W/m} \]

Superinsulation: \( W_R^f = W_R/(n-1), \text{ where} \)

\[ n = \text{number of layers} = 10 \]

Net Heat In-Leak Due to Radiation = 1.8 W/m
Fluid Friction Losses

\[ W_{\text{loss}} = \frac{M P_{\text{loss}}}{\rho}, \]

Where \( M \) = mass flow per unit length
\( P_{\text{loss}} \) = pressure loss per unit length
\( \rho \) = fluid density

\[ 1 / \lambda^{1/2} = -2.0 \log_{10} \left[ \frac{2.51}{(\text{Re} \lambda^{1/2})} \right] + \left( \frac{\varepsilon}{d_h} \right) / 3.72 \]

<table>
<thead>
<tr>
<th>Fluid</th>
<th>( \text{Re} )</th>
<th>( \varepsilon ) (mm)</th>
<th>( D_h ) (cm)</th>
<th>( v ) (m/s)</th>
<th>( \Delta P ) (atm/10 km)</th>
<th>Power Loss (W/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H (20K)</td>
<td>2.08 ( \times 10^6 )</td>
<td>0.015</td>
<td>45.3</td>
<td>4.76</td>
<td>2.0</td>
<td>3.2</td>
</tr>
</tbody>
</table>
Heat Removal

\[ \frac{dT}{dx} = \frac{W_T}{(\rho v C_p A)_{H_2}}, \text{ where} \]

- \( \frac{dT}{dx} \) = Temp rise along cable, K/m
- \( W_T \) = Thermal in-leak per unit Length
- \( \rho \) = \( H_2 \) Density
- \( v \) = \( H_2 \) Flow Rate
- \( C_p \) = \( H_2 \) Heat Capacity
- \( A \) = Cross-sectional area of \( H_2 \) cryotube

<table>
<thead>
<tr>
<th>SuperCable Losses (W/M)</th>
<th>K/10km</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiative</td>
<td>Friction</td>
</tr>
<tr>
<td>1.8</td>
<td>3.2</td>
</tr>
</tbody>
</table>
# SuperCable H₂ Storage

<table>
<thead>
<tr>
<th>Some Storage Factoids</th>
<th>Power (GW)</th>
<th>Storage (hrs)</th>
<th>Energy (GWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TVA Raccoon Mountain</td>
<td>1.6</td>
<td>20</td>
<td>32</td>
</tr>
<tr>
<td>Scaled ETM SMES</td>
<td>1</td>
<td>8</td>
<td>8</td>
</tr>
</tbody>
</table>

One Raccoon Mountain = 13,800 cubic meters of LH₂

LH₂ in 45 cm diameter, 20 km bipolar SuperCable = Raccoon Mountain
Relative Density of H2 as a Function of Pressure at 77 K wrt LH2 at 1 atm

H₂ Gas at 77 K and 1850 psia has 50% of the energy content of liquid H₂ and 100% at 6800 psia
“Hybrid” SuperCable

- HV Insulation
- “Super-Insulation”
- Flowing High Pressure Hydrogen Gas
- Al “core” of diameter $D_C$ wound with HTSC tape $t_s$ thick
- Superconductor “Conductor”
- Flowing liquid $N_2$ cryogen in flexible tube, diameter $D_N$
Electricity Generation - June 2004

- Coal: 49%
- Oil: 2%
- Hydro: 7%
- Nukes: 20%
- Gas: 18%
- Renewable: 2%
Al-Can Gas Pipeline Proposals

Source for graphic:
T.J. Glauthier,
Deputy Secretary,
U.S. Department of Energy,
“Testimony to the Senate Committee on Energy and Natural Resources”
(September 14, 2000).
Mackenzie Valley Pipeline

1300 km
18 GW-thermal
LNG SuperCable

- Electrical Insulation
- “Super-Insulation”
- Thermal Barrier to LNG
- Liquid Nitrogen @ 77 K
- Superconductor
- LNG @ 105 K 1 atm (14.7 psia)
Electrical Issues

• Voltage – current tradeoffs
  – “Cold” vs “Warm” Dielectric

• AC interface (phases)
  – Generate dc? Multipole, low rpm units (aka hydro)

• Ripple suppression
  – Filters

• Cryogenics
  – Pulse Tubes
  – “Cryobreaks”

• Mag Field Forces

• Splices (R = 0?)

• Charge/Discharge cycles (Faults!)

• Power Electronics
  – GTOs vs IGBTs
  – 12” wafer platforms
  – Cryo-Bipolars
Construction Issues

- Pipe Lengths & Diameters (Transportation)
- Coax vs RTD
- Rigid vs Flexible?
- On-Site Manufacturing
  - Conductor winding (3-4 pipe lengths)
  - Vacuum: permanently sealed or actively pumped?
- Joints
  - Superconducting
  - Welds
  - Thermal Expansion (bellows)
SuperCable Prototype Project

H₂ Storage SMES

Cryo I/C Station

500 m Prototype

“Appropriate National Laboratory”
2005-09
Regional System Interconnections

New York Control Area Potential Transmission Upgrades

Legend:
- 765 kV
- 500 kV
- 345 kV
- 230 kV

Potential Upgrades:
1 2 Clay-Edic #1 & #2
3 Marcy-Edic
4 5 Porter-Adirondack #1 & #2
6 Buchanan N-Eastview
7 Rock Tavern-Ramapo
8 Oakdale-Fraser
9 10 Moses-Adirondack #1 & #2

3/21/01
China: Present

Regional Grids Interconnection in 2001-2002
China: 2015 - 2020
The Vision of Prof. Zheng-He Han!
Postcard from China

Helping to Promote US – Chinese Relations

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Glad you’re not here,
Dr. Grant & Friend

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Stone Forest
Yunan Province, PRC
June, 2004
Will China Build the World’s First SuperGrid?