

SuperCities and SuperGrids

A Vision for Long-term Sustainable
and Environmentally Compatible
Energy Independence for the World

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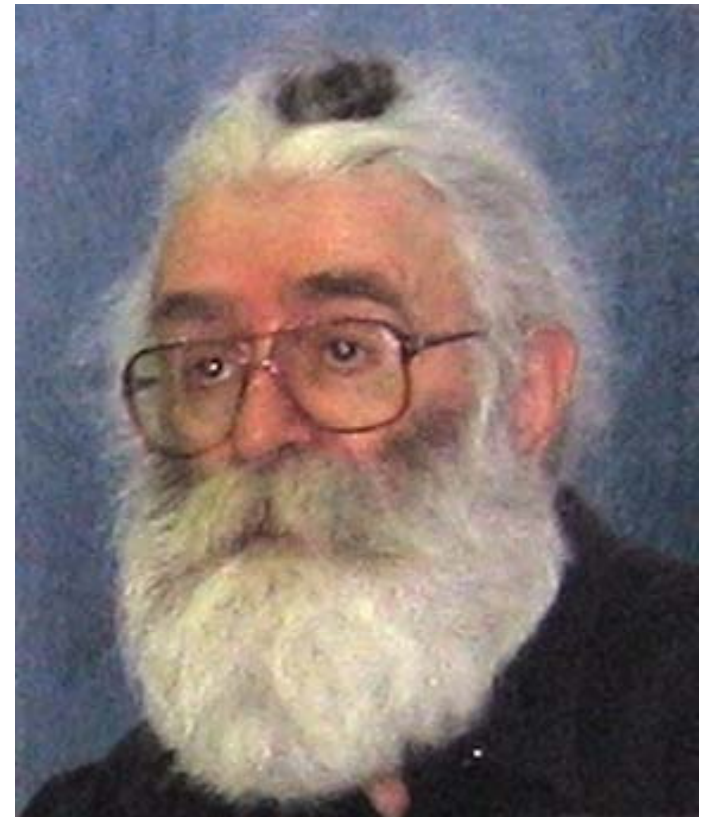
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I AM NOT Radovan Karadzic!



Physics World, October 2009

Extreme energy makeover

With the world's population expected to reach 10 billion by 2050, how will we cope with the energy demand? **Paul Michael Grant** presents the SuperGrid concept



From [The Times](#)

October 3, 2009

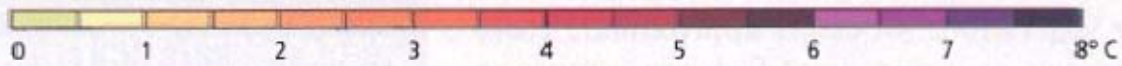
Science: Stand by for the Supergrid

Why the world needs an 'extreme energy makeover'

[Anjana Ahuja](#)



...a future editor of
Physical Review Letters



SCENARIO 1
Low emissions

2020-2029



2090-2099

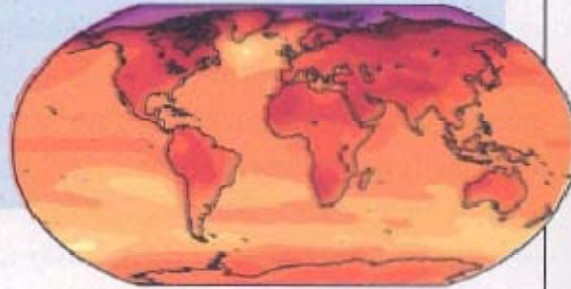


SCENARIO 2
Moderate emissions

2020-2029



2090-2099

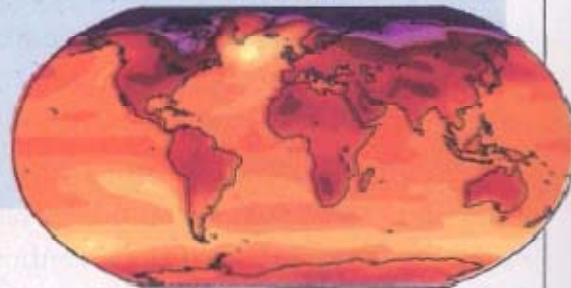


SCENARIO 3
High emissions

2020-2029



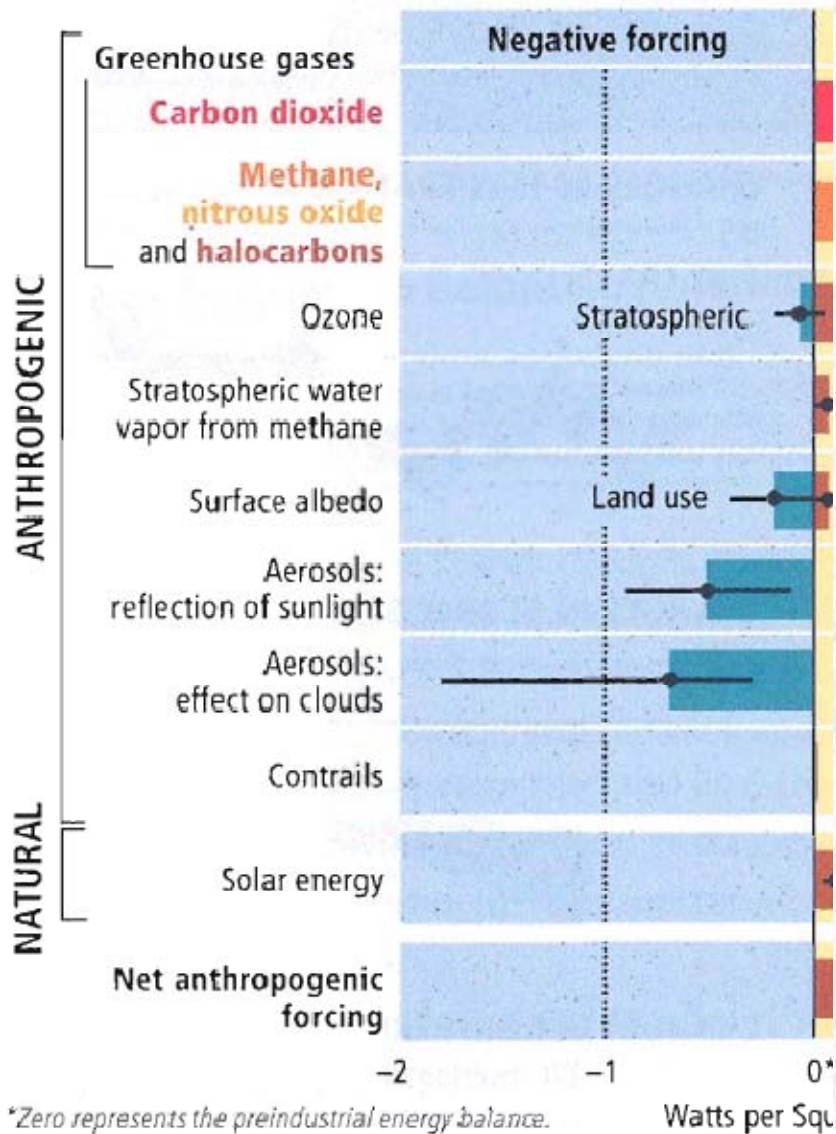
2090-2099



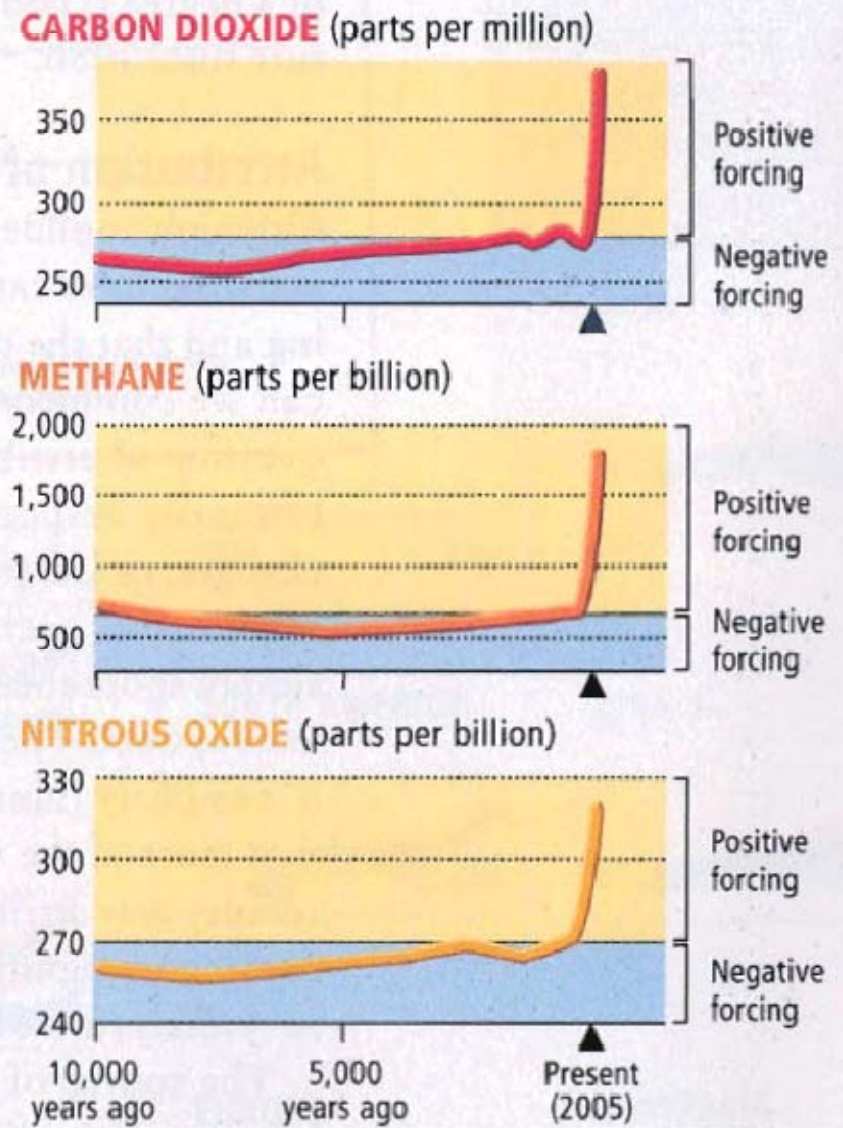
DANIEL A. SACHS/MODERN SOLUTIONS FOR CLIMATE CHANGE 2007 THE CLIMATE CHANGE COMMISSION REPORT

SciAm – August, 2007 Issue

Radiative Forcing: The Overview



Greenhouse Gases: The Major Forcings

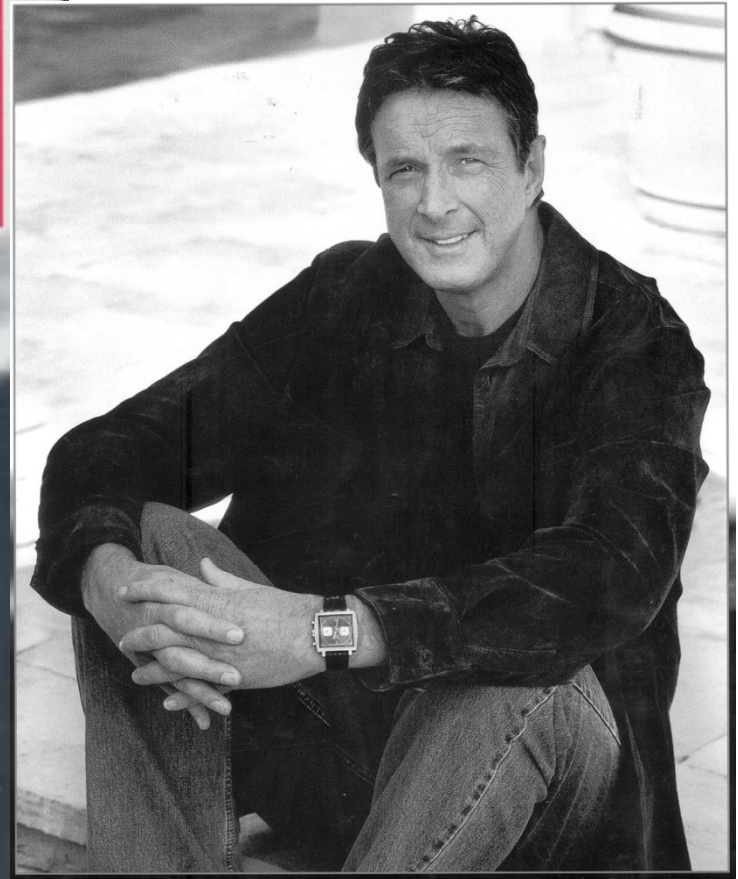
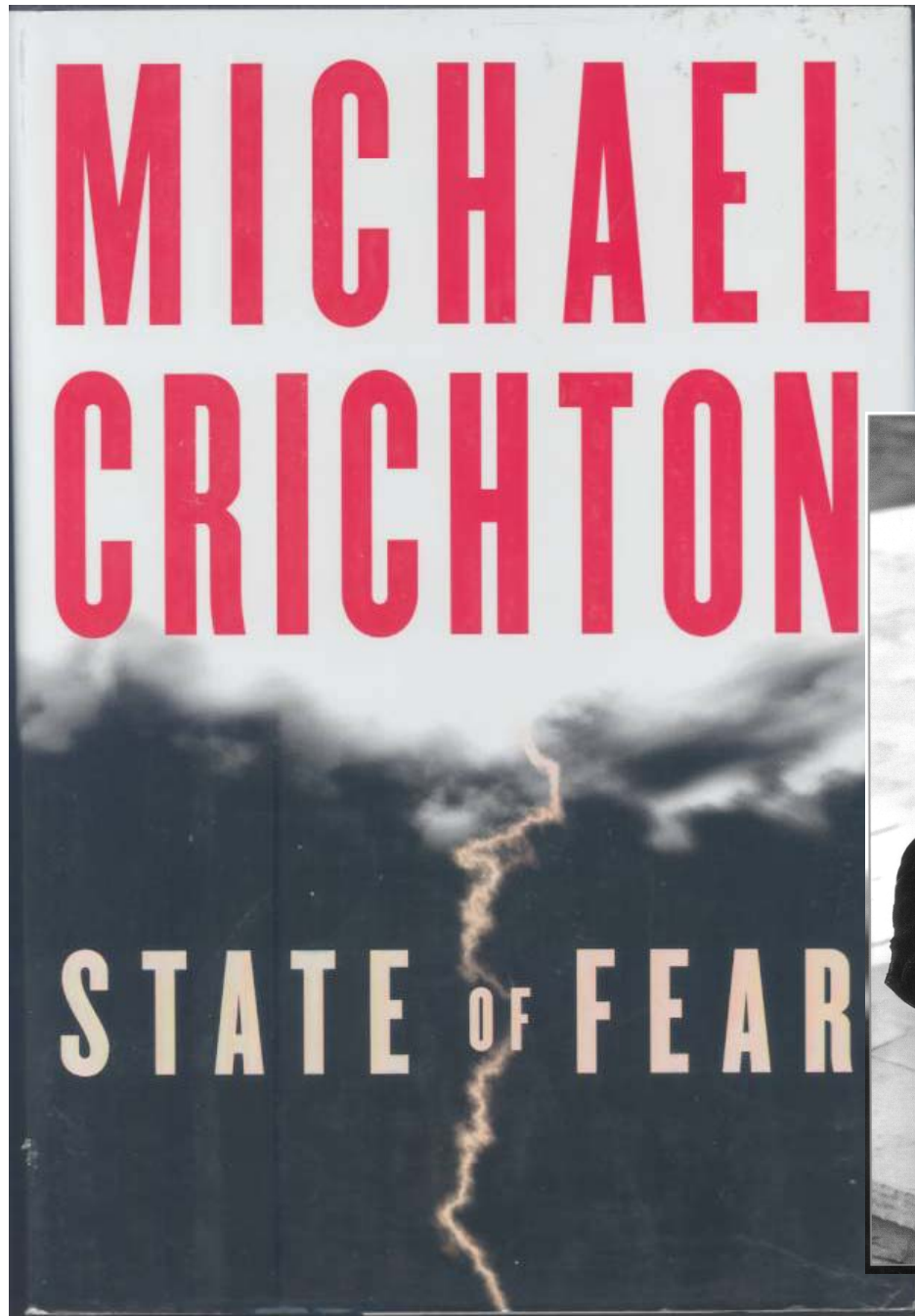


The Day After Tomorrow



An Inconvenient Truth





“Greenhouse Gases”



“Expert Opinion”

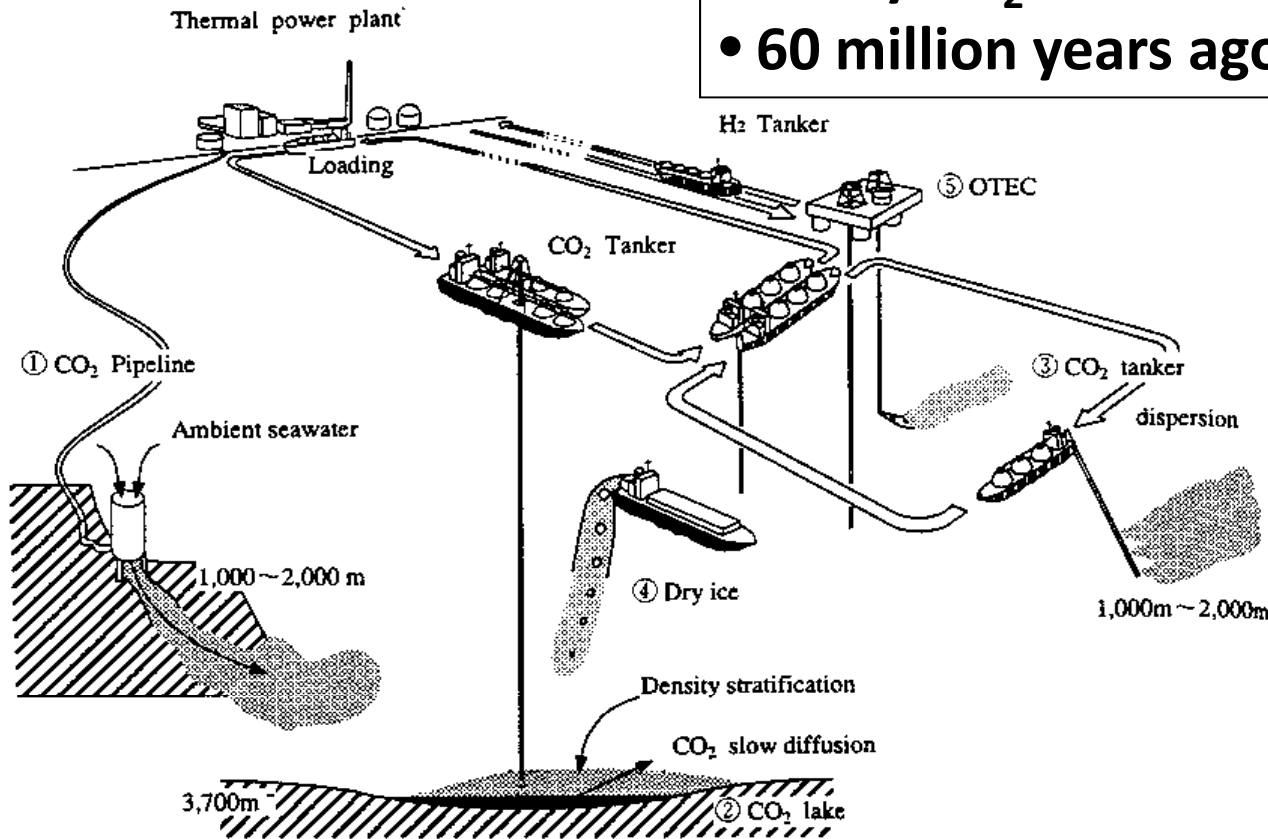
- Nate Lewis
 - Mitigation is more or less hopeless without massive skewing of the “laws of economics” through government intervention
- Bill Nordhaus
 - By 2100, the global economy will be rich enough to afford adapting to 500-600 ppm CO₂
- Fred Singer
 - No problem (GCC is good for you...)
- William Ruddiman
 - Invention of agriculture 8000 years ago and subsequent methane emissions saved the planet from undergoing a “scheduled cyclic ice age.”
- Jesse Ausubel
 - To propose significant deployment of renewables is a “heresy.”
- Sean Hannity
 - It’s all due to Al Gore, Sean Penn and Leonardo DiCaprio flying around in private jets.

“Not-so-Expert Opinion”

- Exactly what is “clean coal?”
 - Is it “heavy metal free?”
 - Is it “sulfur free?”
 - Is it “zero emissions?”
 - Is it “all of the above?”
- Don’t ask George Bush or Barack Obama, because they haven’t a clue

Carbon Dioxide – Where do we put it?

- Today CO₂ is at 400 ppm
- 60 million years ago, it was 7000!



...maybe the best place is in the atmosphere 😊

Carbon dioxide ocean disposal options

(Adapted from Fujioka et al, 1997)

Theory of Everything

$$\mathcal{H} = - \sum_j \frac{\hbar^2}{2m} \nabla_j^2 - \sum_a \frac{\hbar^2}{2M_a} \nabla_a^2 - \sum_{j,a} \frac{Z_a e^2}{|r_j - R_a|} + \sum_{j,k} \frac{e^2}{|r_j - r_k|} + \sum_{a,b} \frac{Z_a Z_b e^2}{|R_a - R_b|}$$

- | | | |
|--------------------|-----------------|------------------|
| • Hydrogen atom | • Proteins | • Flowers |
| • Methane molecule | • DNA | • Trees |
| • Water | • Viruses | • Cars |
| • Air | • Bacteria | • Cheese |
| • Rocks | • Yeast | • Sauce Bernaise |
| • Concrete | • Slime mold | • Computers |
| • Steel | • Butterflies | • Television |
| • Glass | • Sharks | • Cars |
| • Plastic | • Rats | • Jets |
| • Buildings | • Lawyers | • Lawnmowers |
| • Cities | • Ebola virus | • Sewage |
| • Continents | • Legislatures | • Spotted Oats |
| | • Civilizations | ... |

Bob Laughlin's "Theory of Everything" (that's important!)

- $3 \rightarrow 10^2$
 - Chemistry
- $10^2 \leftrightarrow 10^3$
 - Thermodynamics
- $10^3 \leftrightarrow 10^{10}$
 - Cooperative Phenomena
- $10^{10} \leftrightarrow 10^{20}$
 - Emergent Behavior (Us)



- $> 10^{20}$
 - CLIMATE !
- **SIZE MATTERS !**

Overture

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!

The Solution

A Symbiosis of

Nuclear/Hydrogen/Superconductivity

*Technologies supplying Carbon-free, Non-
Intrusive Energy for all Inhabitants of Planet
Earth*

Chauncey Starr 1912 - 2007



Obituary, Nature, 14 June 2007

Boundary Conditions

- Carbonless
 - No CO₂
- Non-Eco-Invasive
 - Minimal land/ecology impact
- Off-the-table
 - Large scale renewables (wind, solar, bio)
 - Sequestration

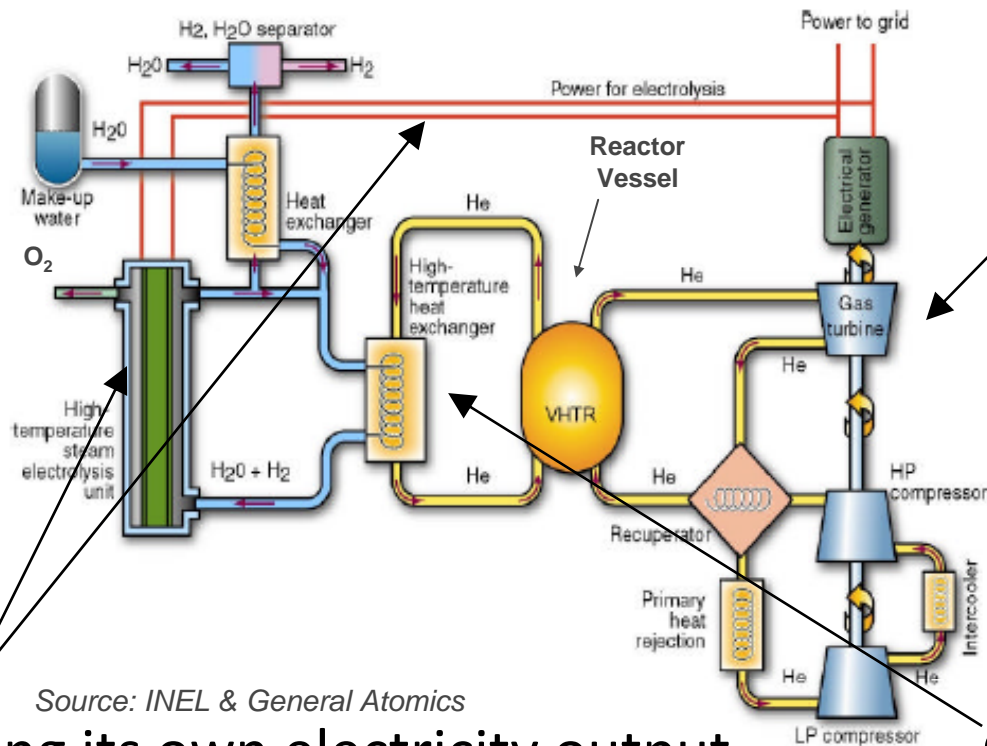
Technology Menu

- Generation
 - HTGCR Nuclear (80%)
 - electrons
 - protons
 - PV Solar Roofs (20%)
- Transmission
 - Hydricity SuperCable
- Storage
 - Hydrogen + Hydricity Fuel Cell
- End Use Power
 - Electricity
 - Hydrogen

Implementation Technology I

HTGCR Nuclear Power

- Gen IV High Temperature Gas-Cooled Reactors can make electricity the old fashioned way by spinning turbines
- The same reactor can make hydrogen from water in *two* ways...



Source: INEL & General Atomics

Using its own electricity output to perform electrolysis...



Or with heat drawn from the reactor...



Implementation Technology II

The Hydricity Economy



Hydrogen for:

- Personal Transportation
- Storage of Electricity
- Industrial Thermal/Chemical Processing
- Residential/Commercial Heating

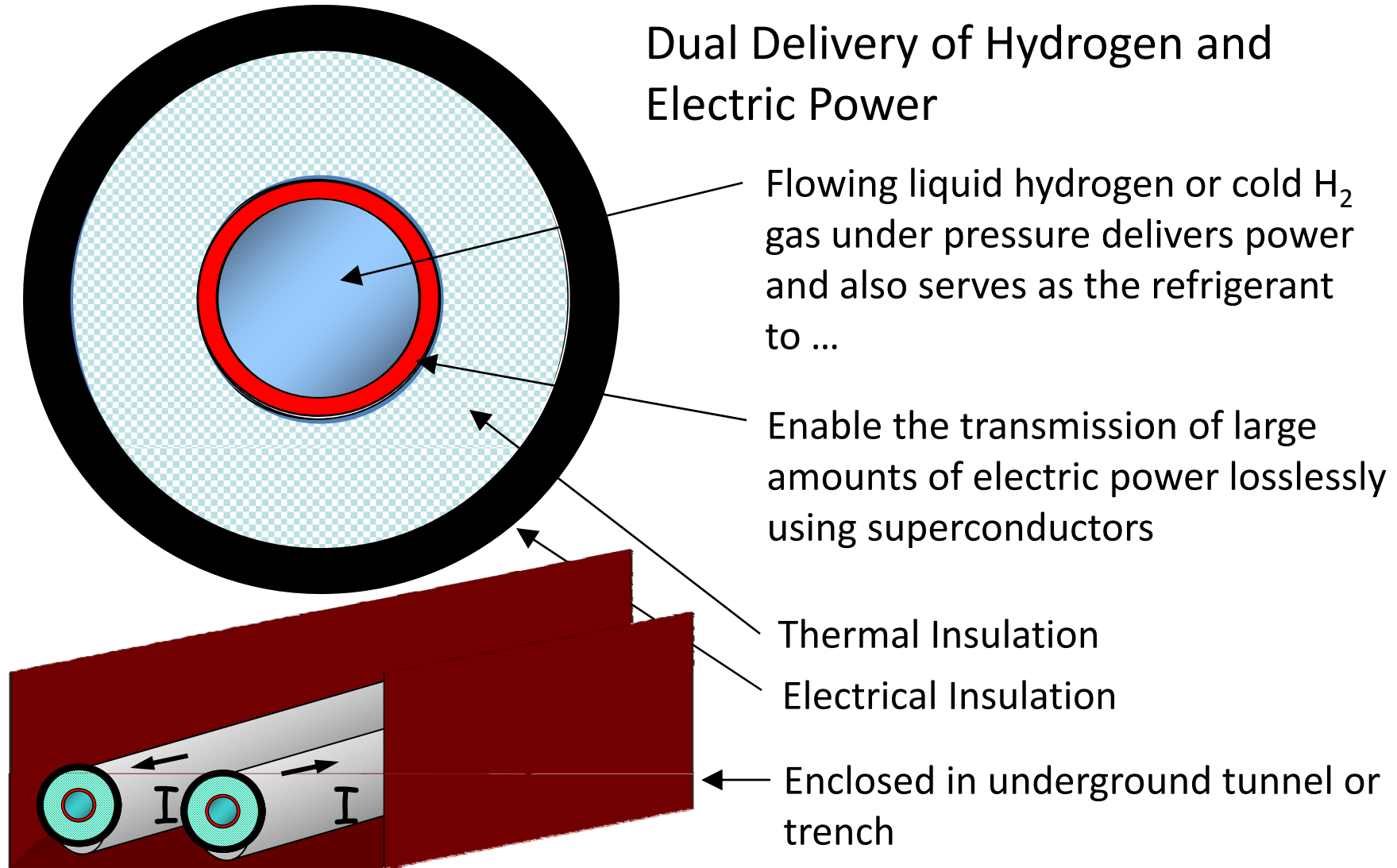


Electricity for:

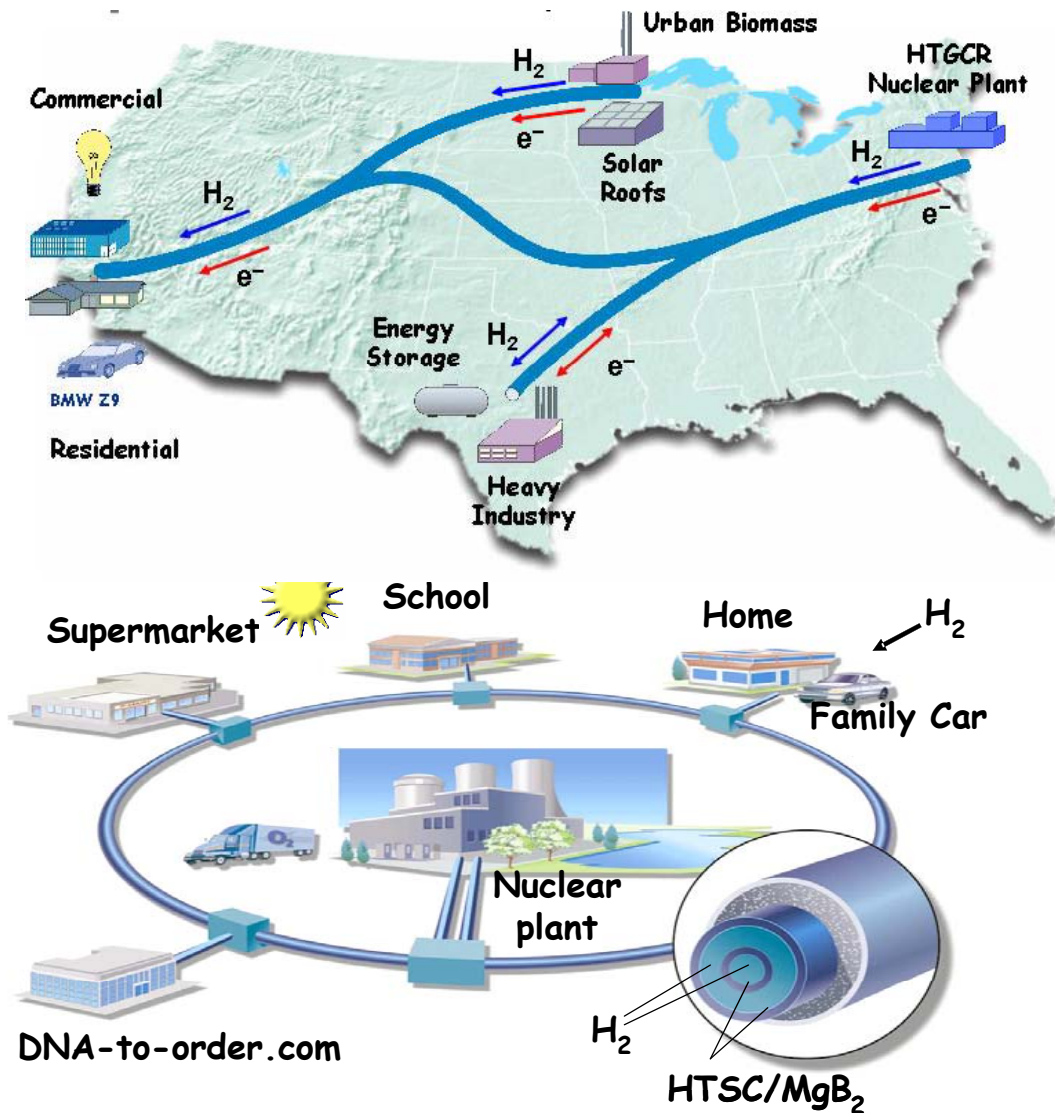
*-Just about everything else!
(maybe even space heating, as well)*

Implementation Technology III

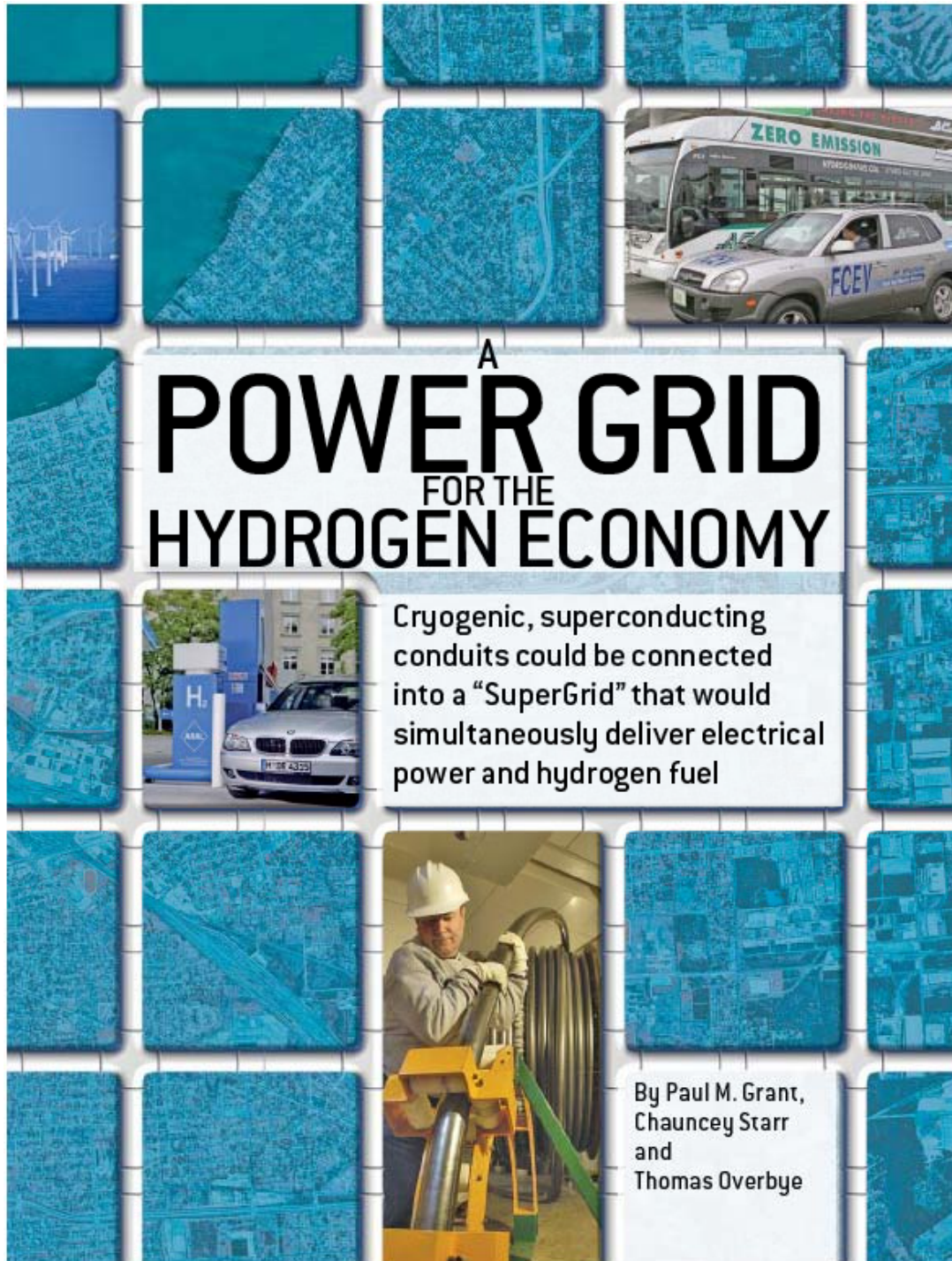
The Hydricity SuperCable



SuperCities & SuperGrids



- Nuclear Power can generate both electricity and hydrogen – “Hydricity”
- Hydricity can be distributed in underground pipelines like natural gas
- The infrastructure can take the form of a **SuperGrid**
- ...or a **SuperCity**



On the afternoon of August 14, 2003, electricity failed to arrive in New York City, plunging the 10 million inhabitants of the Big Apple—along with 40 million other people throughout the northeastern U.S. and Ontario—into a tense night of darkness. After one power plant in

Published in
**SCIENTIFIC
AMERICAN**
July, 2006

“System Crash”
Omni Productions,
Vancouver, BC
CBC Broadcast October, 2008

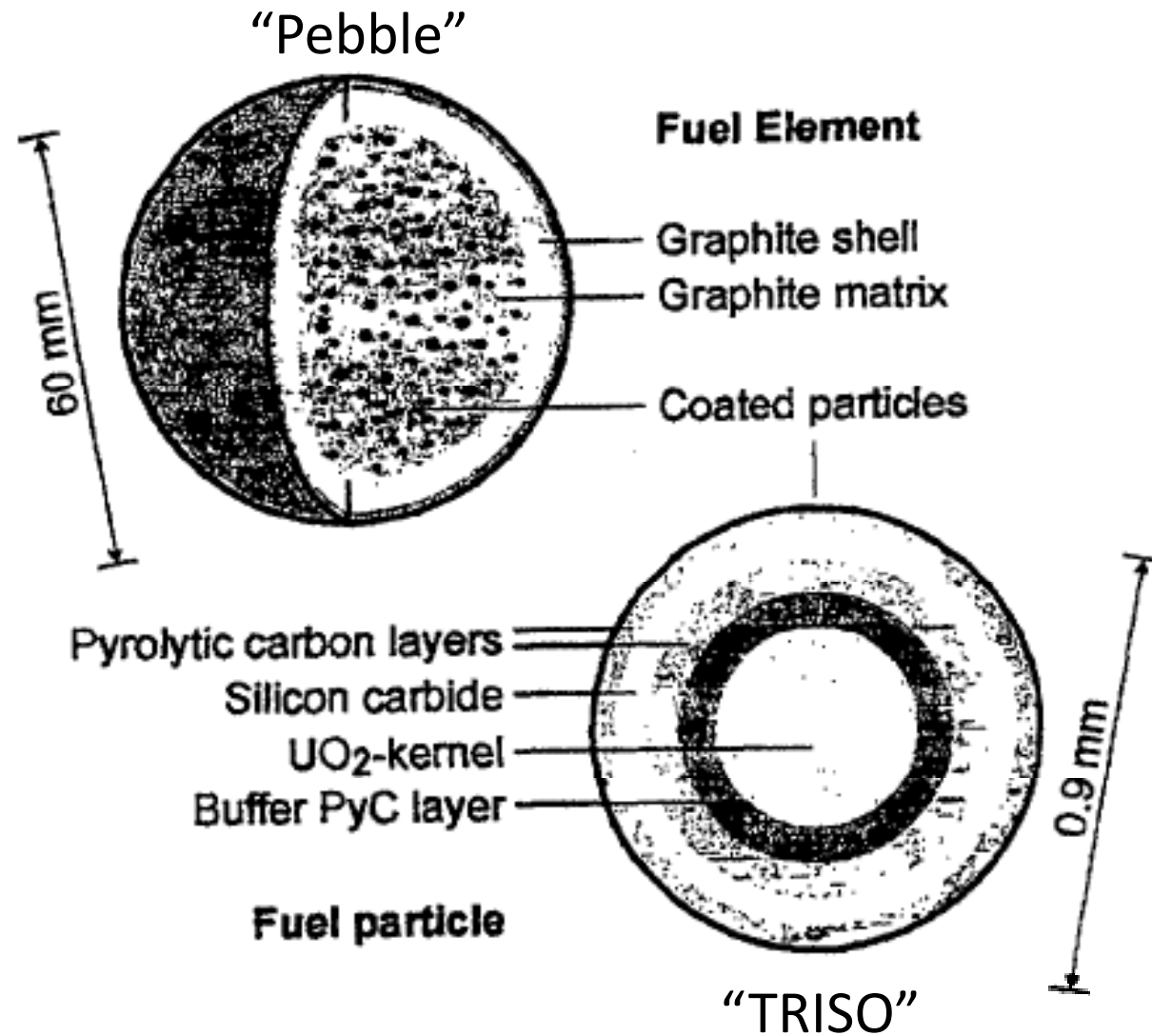
Nuclear

Oklo “Natural” Reactor



- Pu was created 2 billion years ago!
- Reactor produced 100 kW of power for 500,000 years!
- “Waste” has moved less than one meter.

Particle/Pebble Nuclear Fuel



Eskom Pebble Bed Modular Reactor

- Helium gas cooled (Brayton Cycle)
 - Won't melt down
 - Direct turbine drive
- “Baseball” packaged fuel
 - Continuous fuel replenishment and removal
 - Theoretical 100% availability
- Modular Design
 - Scalable: 100 – 500 MW units
 - High safety and security factor
- Economical
 - 1.2 cents/kWh ... cheaper than coal

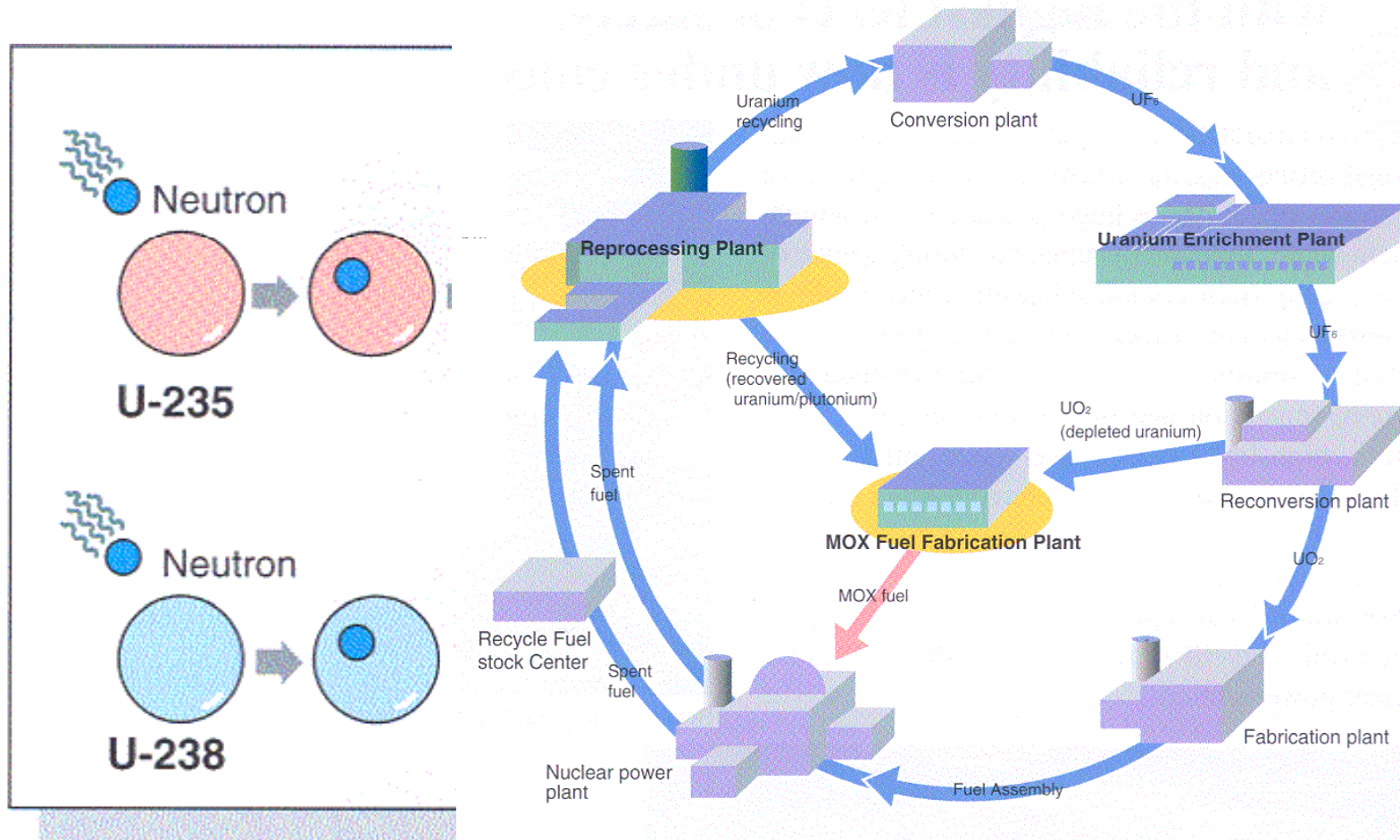


Yucca Mountain

Created by Emma Hill, 2002



Reprocessing "Spent" Fuel

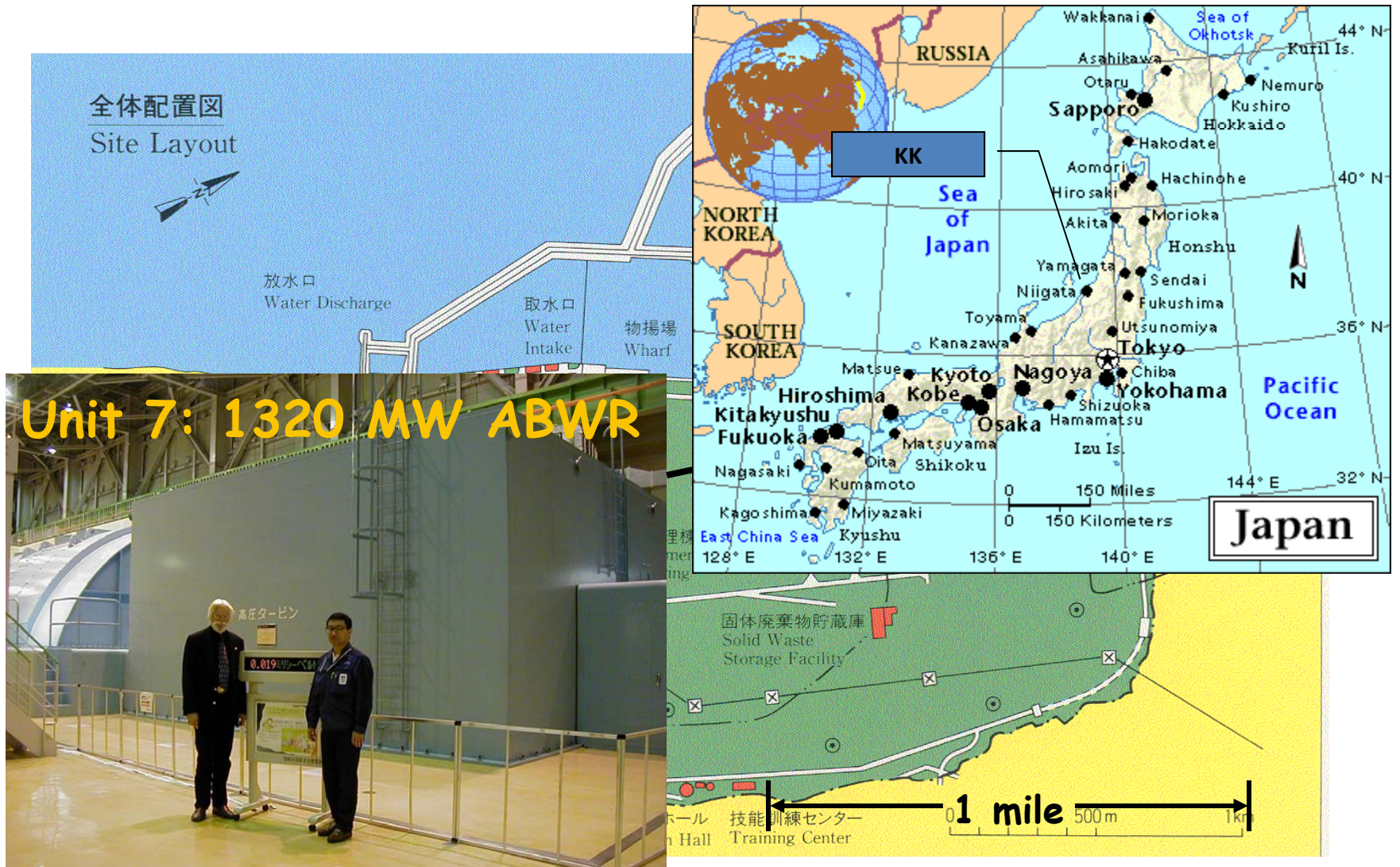


JNFL Rokkasho Reprocessing Plant



<http://www.jnfl.co.jp/english/contact/visitor-center.html>

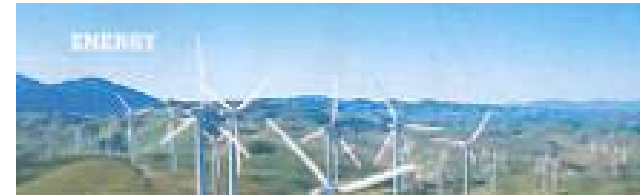
Kashiwazaki Kariwa: 8000 MW



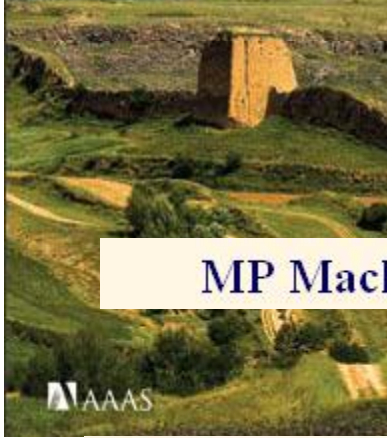
Unit 7: 1320 MW ABWR

Diablo Canyon

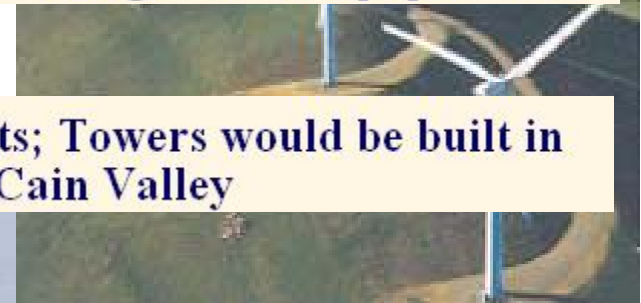




Wind farm poses danger to bird populations



Wind farm plan irks activists; Towers would be built in remote McCain Valley

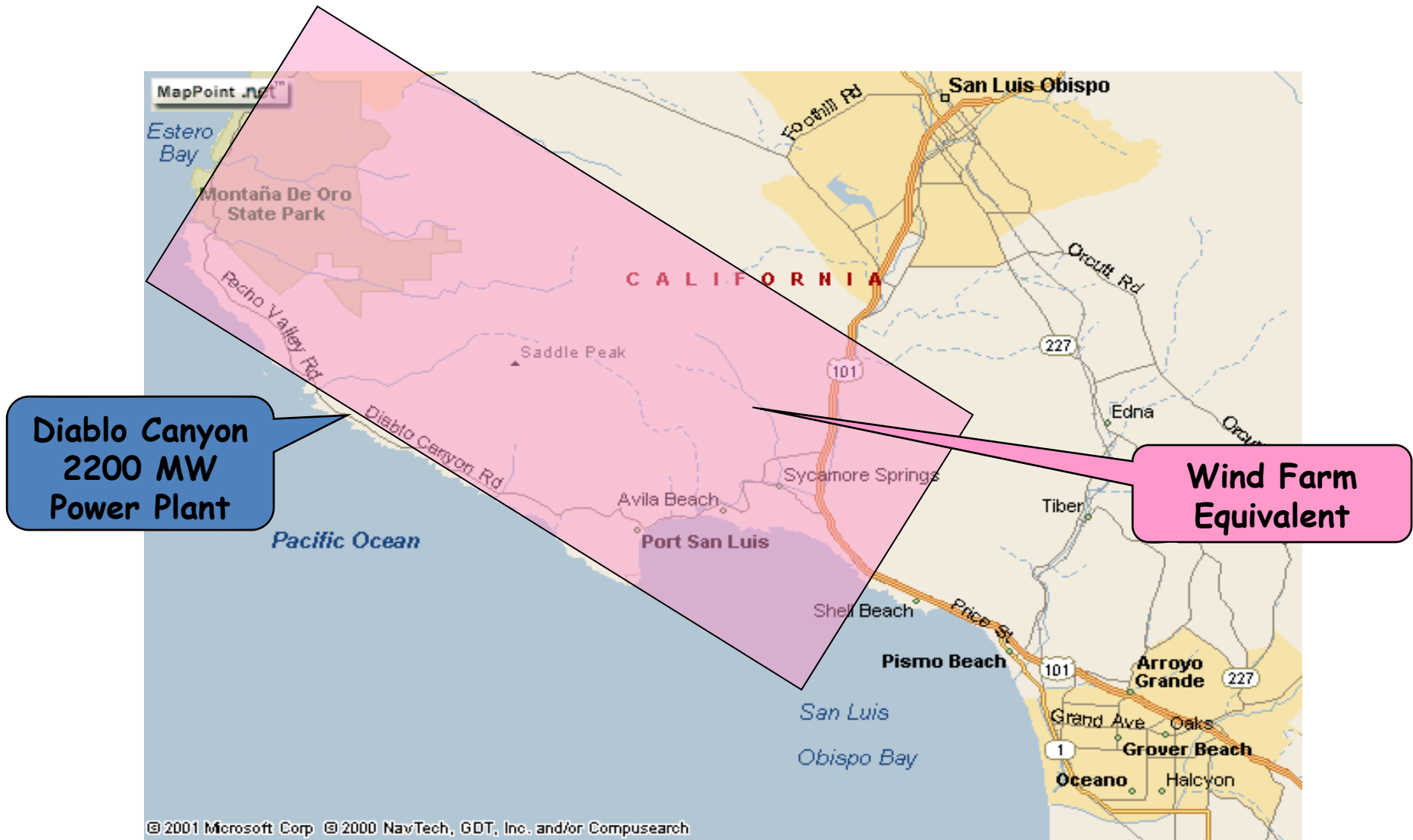


MP Maclean slams plans for windfarm



Residents' anger as BT puts forward plans for windfarm

California Coast Power





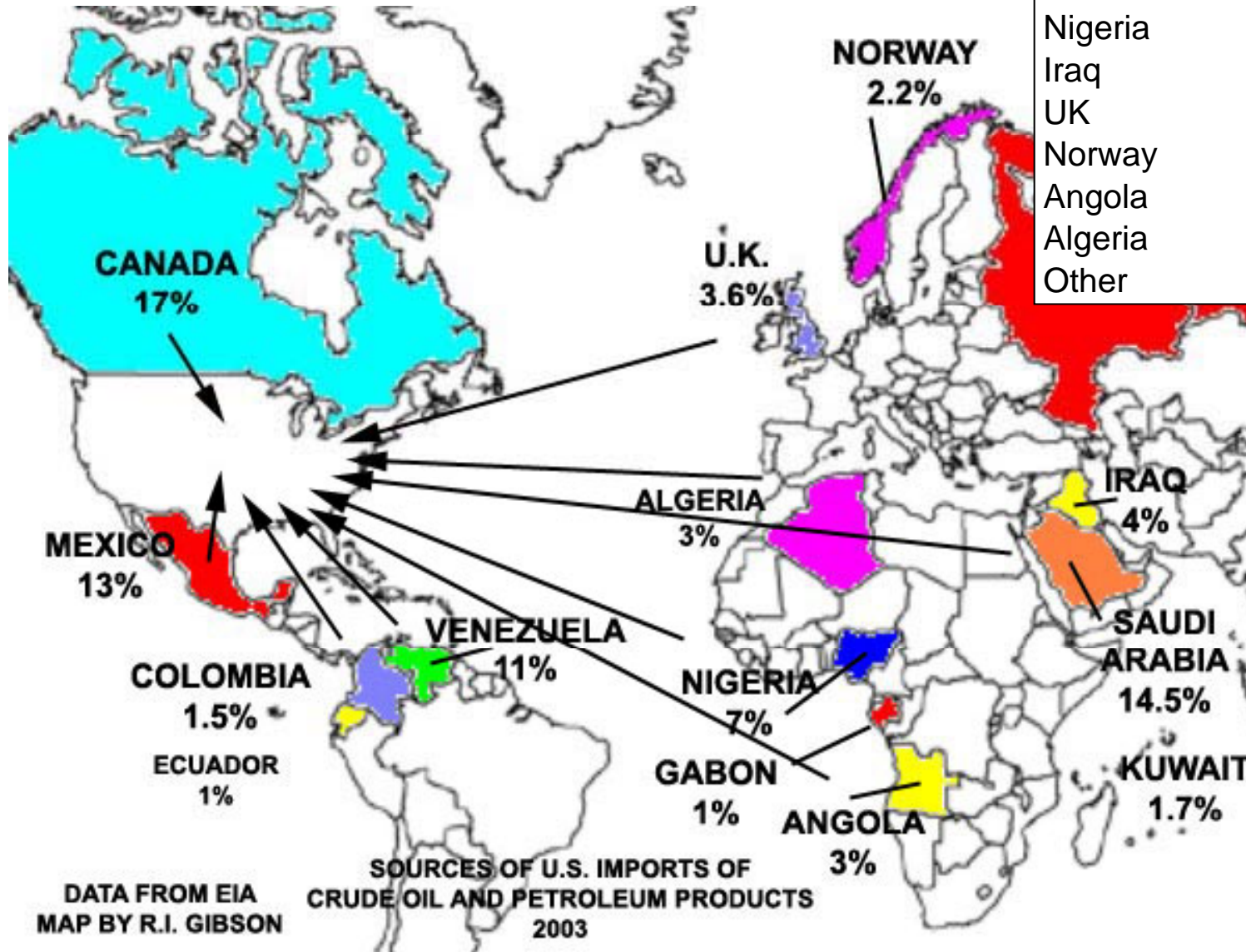
Hydrogen

Overview of a Hydrogen Economy

P.M. Grant, "Hydrogen lifts off...with a heavy load," *Nature* 424, 129 (2003)

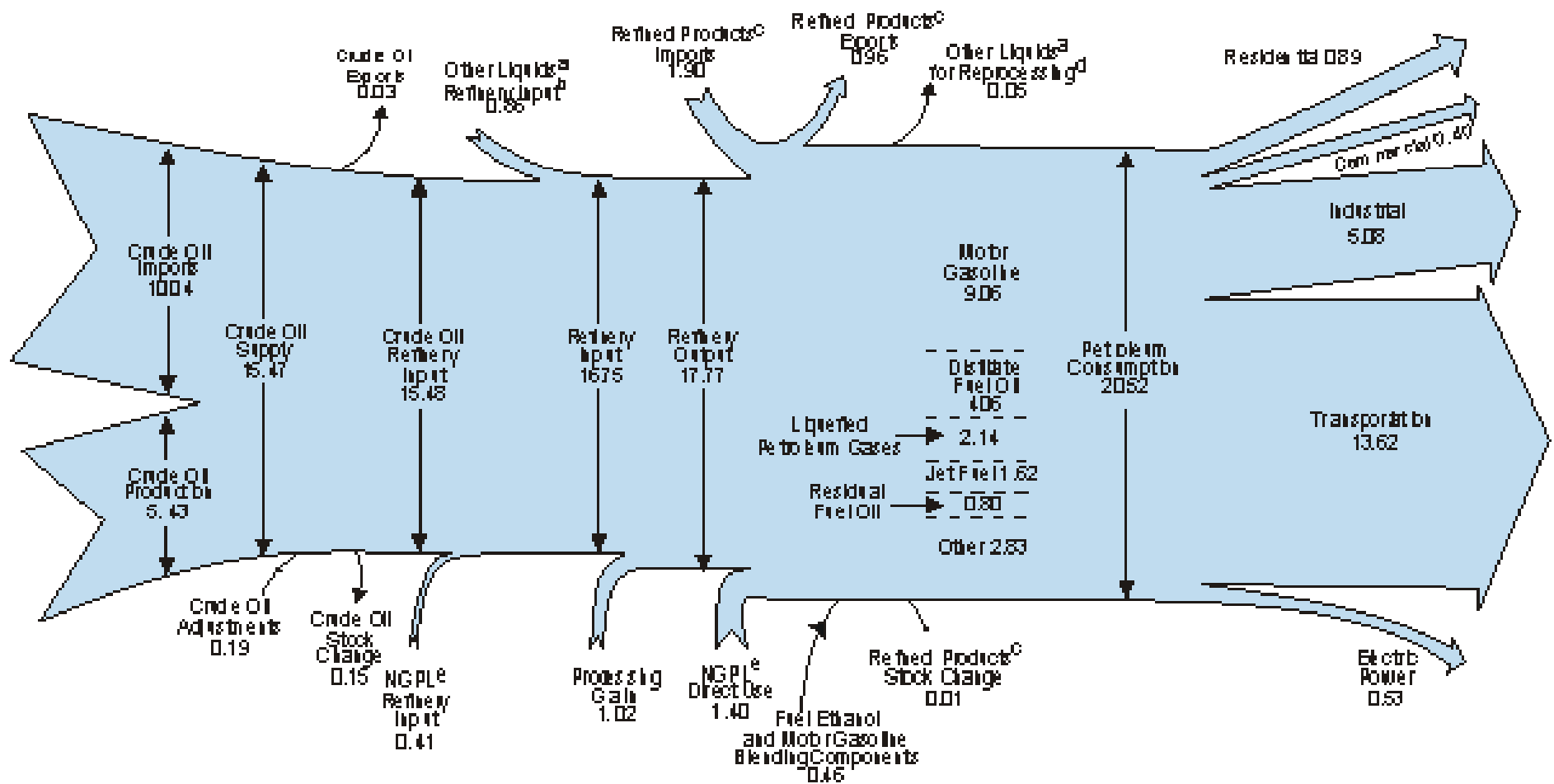
- How much oil do we produce and import?
- Can we replace the portion used for domestic surface transportation with hydrogen?
 - You're going to have to make a lot of hydrogen!
 - How will we make it?
 - Obviously from water, but from how much water?
 - Any side effects?

US Oil Imports (2003)

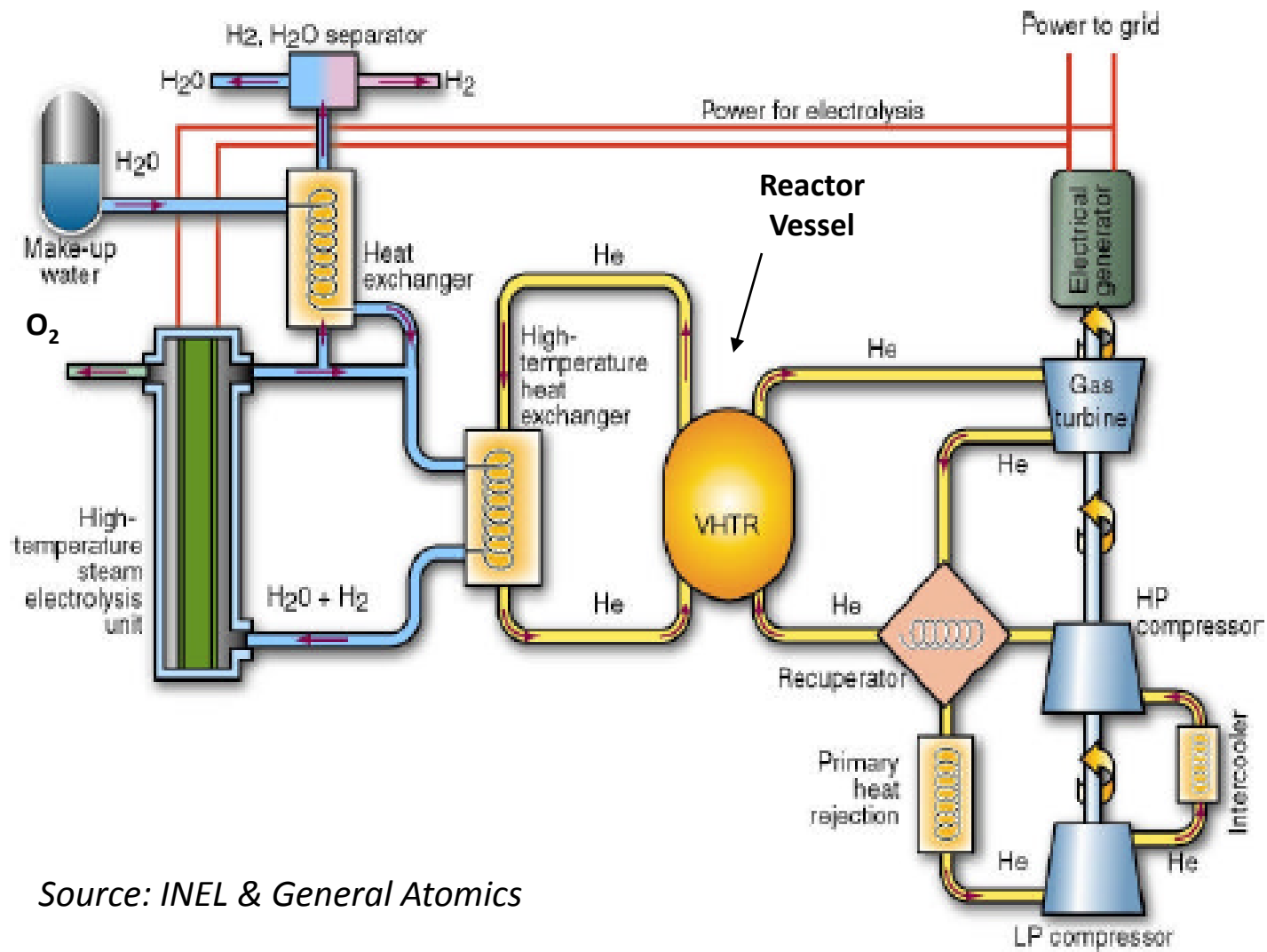


US	39%
Canada	13%
Saudi Arabia	10%
Mexico	10%
Venezuela	9%
Nigeria	4%
Iraq	4%
UK	3%
Norway	3%
Angola	2%
Algeria	2%
Other	2%

Oil: Source to End Use (2005)



Co-Production of Hydrogen and Electricity



Source: INEL & General Atomics

Hydrogen for US Surface Transportation

“You have to make a lot of it”

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

P.M. Grant, “Hydrogen lifts off...with a heavy load,” *Nature* 424, 129 (2003)

Factoids & Assumptions

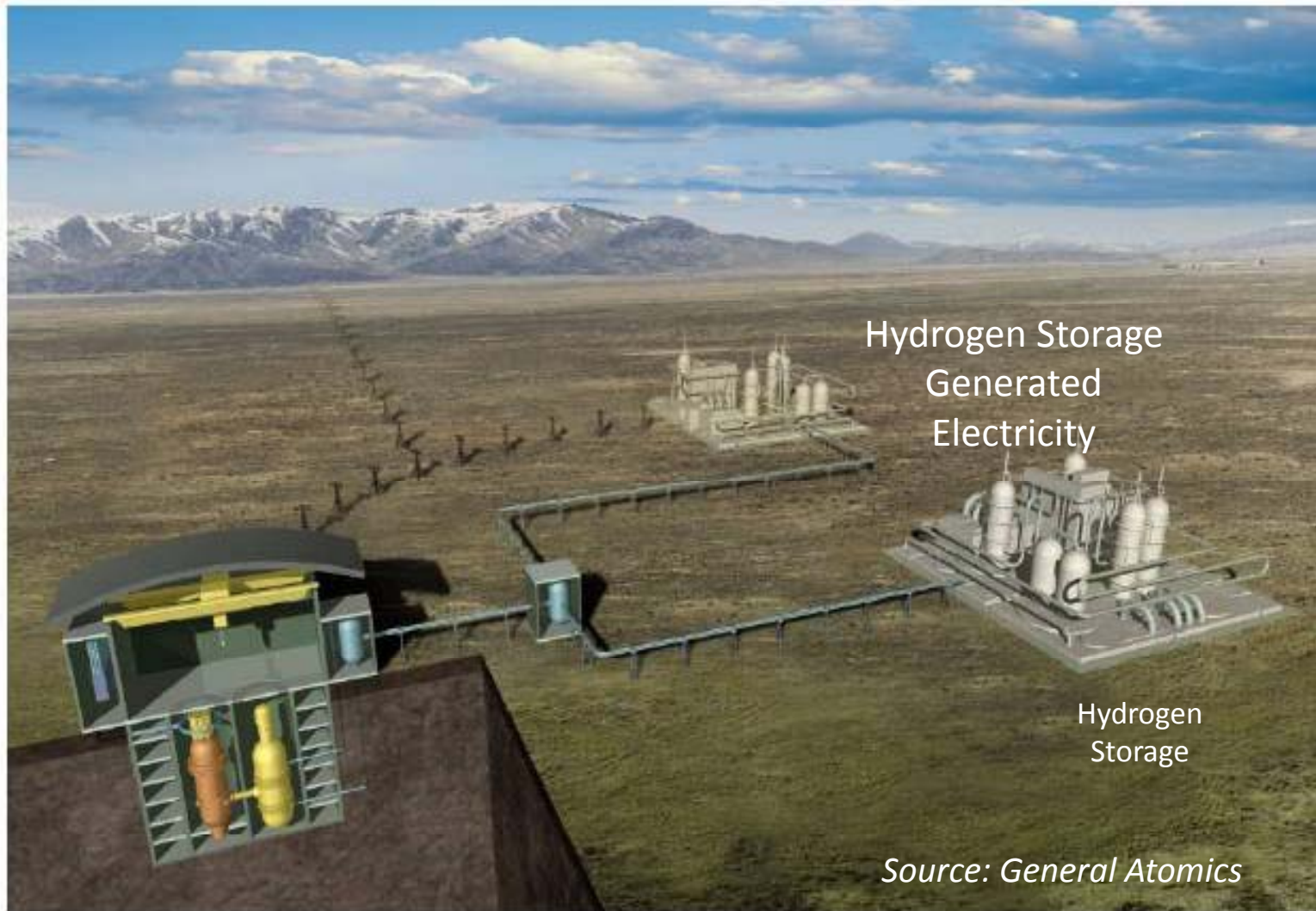
Daily consumption of gasoline and diesel by US cars & Trucks	8.6 Billion barrels/day
Effective Otto Cycle Efficiency (Useful conversion to drive chain)	25 %
Water Electrolysis Efficiency (Source Electricity-to-Hydrogen)	80 % (aggressive)
Fuel Cell Efficiency (Onboard Hydrogen-to-Electricity)	80 % (very aggressive)
Conversion/drive chain Efficiency	80 % (nominal)
Additional Electric Generation Plant Capacity for Hydrogen Vehicles	400 GW

Hydrogen for US Surface Transportation: Generation by Renewable Electricity

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

Land Area Required to Supply by Renewables		
Technology	Area (km ²)	Equivalent
Wind	130,000	New York State
Solar	20,000	50% Denmark Death Valley + Mojave
Biomass	271,915	3% USA State of Nevada

Nuclear “Hydricity” Production Farm



Hydrogen for US Surface Transportation: Water Requirements

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

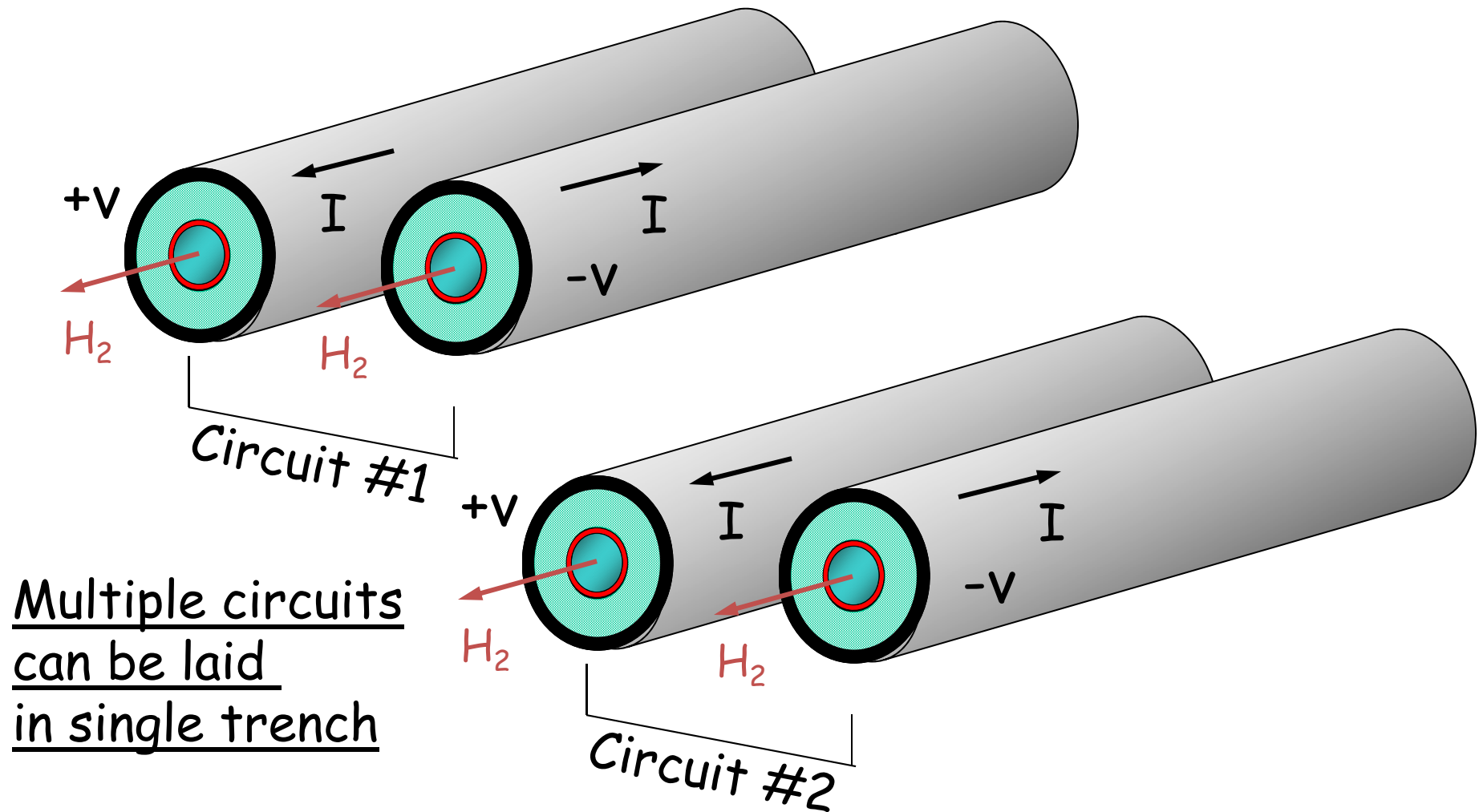
Hydrogen per	
Tonnes	Shuttles
230,000	2,225

Water per D	
Tonnes	Surface
2,055,383	

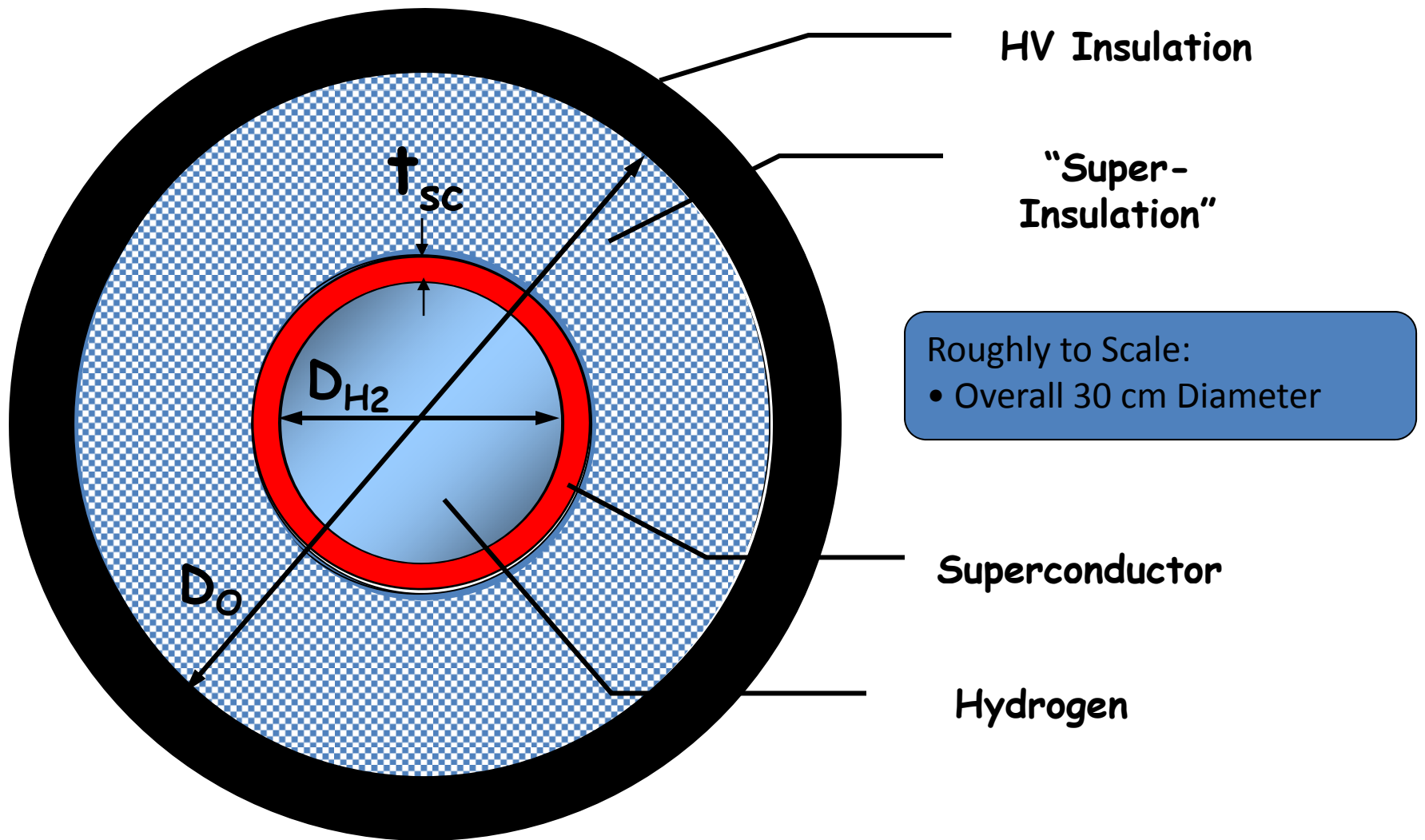


Hydricity SuperCables

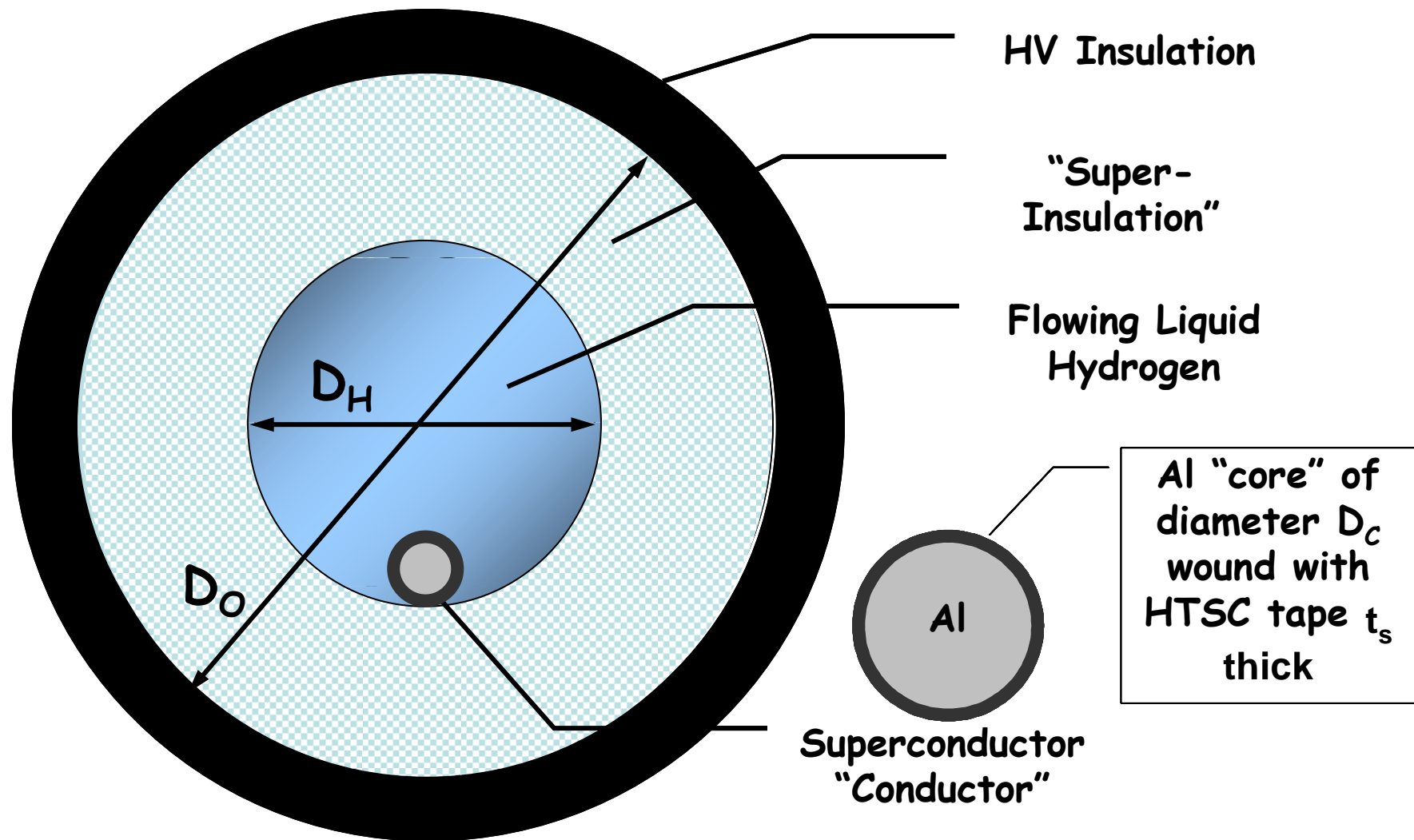
“Hydricity” SuperCables: “Proton/Electron Power (PEP) to the People”



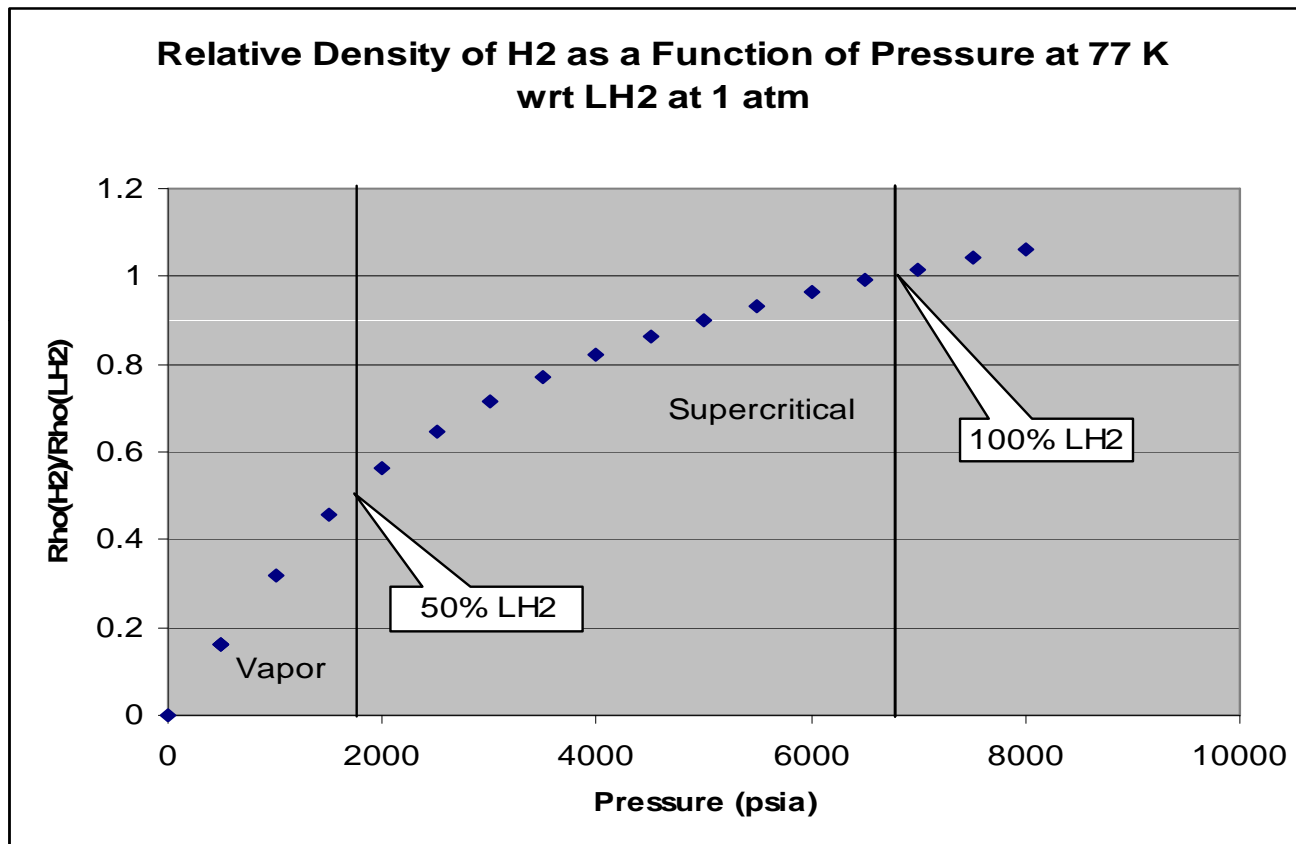
LH₂ SuperCable



SuperCable Monopole (Alternative)

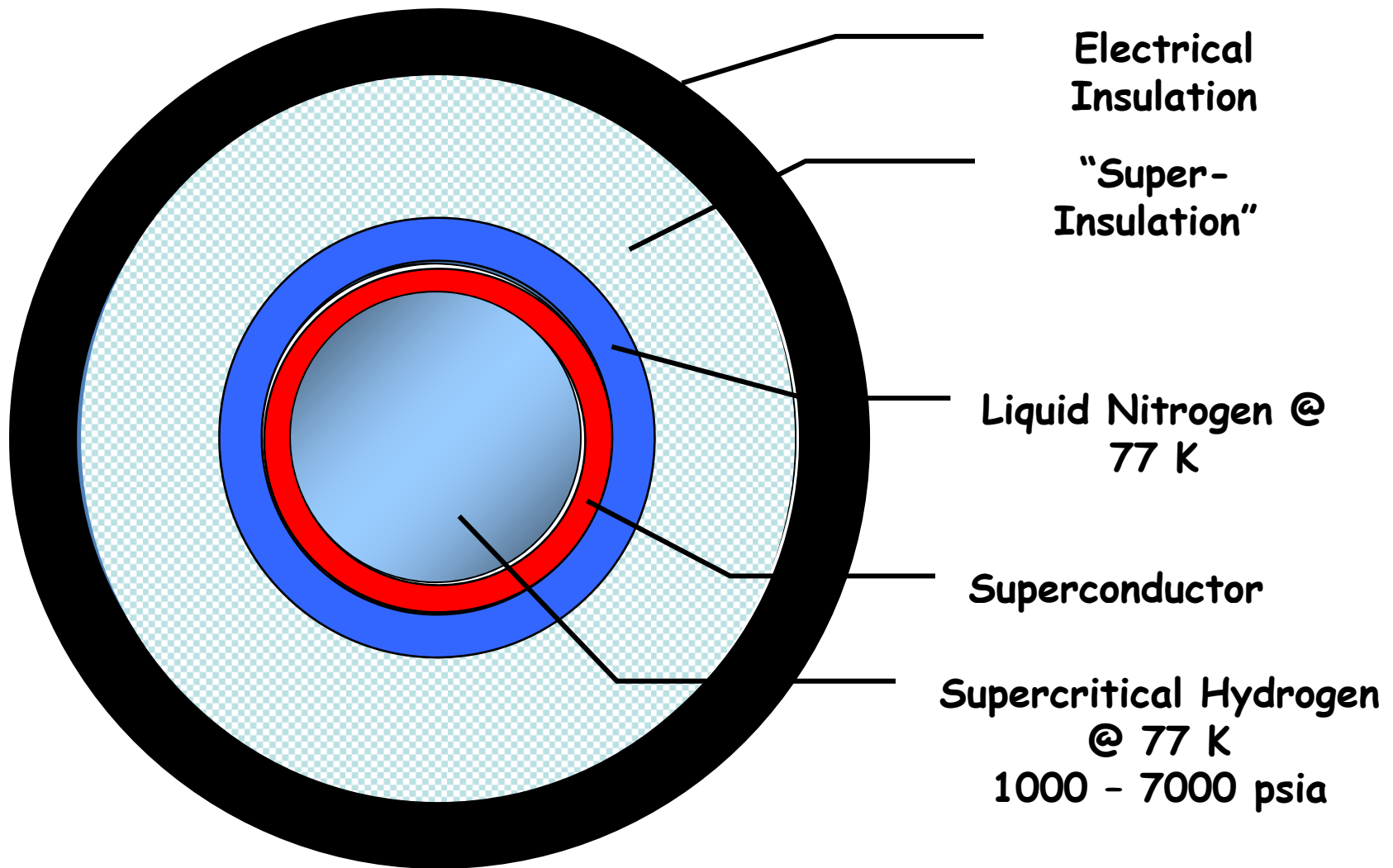


Hydrogen Mass-Density Energy Content

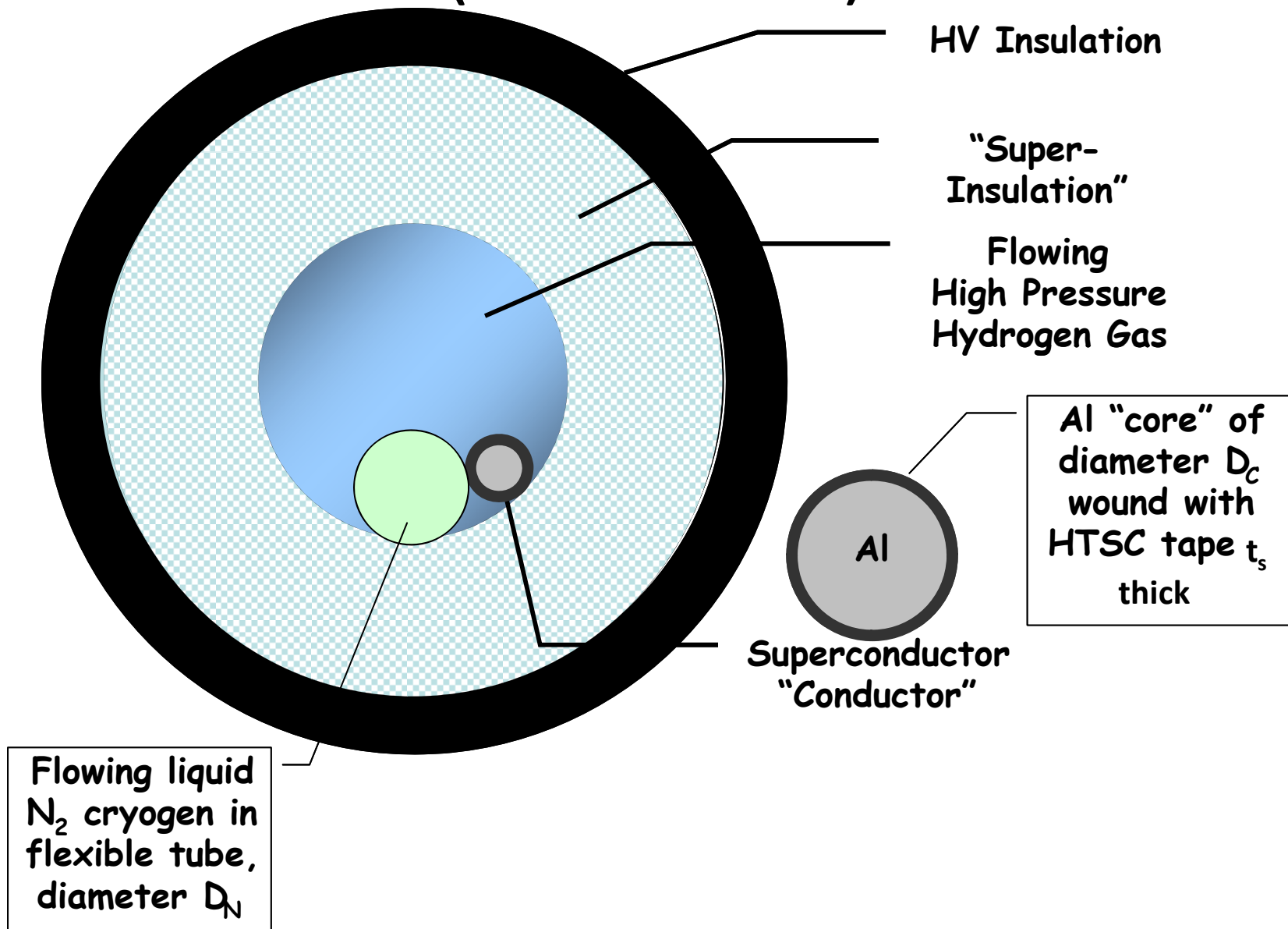


H₂ Gas at 77 K and 1850 psia has 50% of the energy content of liquid H₂ and 100% at 6800 psia

Supercritical H₂ SuperCable

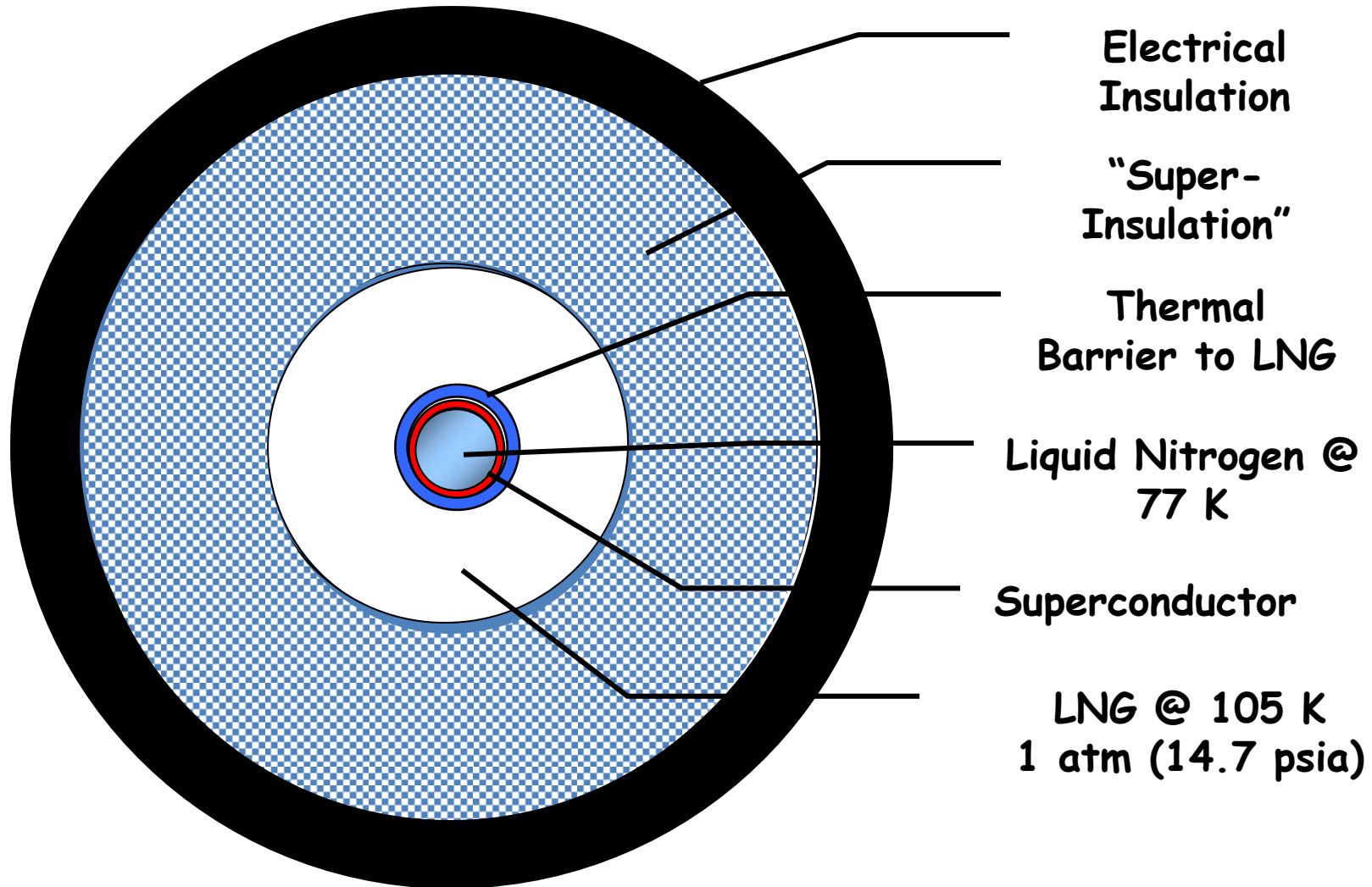


Supercritical H₂ SuperCable (Alternative)



Design for eventual
conversion to high
pressure cold or liquid H_2

LNG SuperCable



Relative Power Flows

$$P_{SC} = 2|V|JA_{SC}, \text{ where}$$

Electricity

P_{SC} = Electric power flow

V = Voltage to neutral (ground)

J = Supercurrent density

A_{SC} = Cross-sectional area of superconducting annulus

$$P_{H_2} = 2(Q\rho vA)_{H_2}, \text{ where}$$

Hydrogen

P_{H_2} = Chemical power flow

Q = Gibbs H_2 oxidation energy (2.46 eV per mol H_2)

ρ = H_2 Density

v = H_2 Flow Rate

A = Cross-sectional area of H_2 cryotube

Hydricity Scaling Factor

Dimensionless, geometry-independent scaling factor defines relative amounts of electricity/hydrogen power flow in the SuperCable:

$$R_{e/h} \equiv (J / Q\rho)(|V| / v)$$

“Energy Density”

“Pressure”

Thermal Losses

$$W_R = 0.5\epsilon\sigma (T_{amb}^4 - T_{sc}^4), \text{ where}$$

W_R = Power radiated in as
watts/unit area

$$\sigma = 5.67 \times 10^{-12} \text{ W/cm}^2\text{K}^4$$

$$T_{amb} = 300 \text{ K}$$

$$T_{sc} = 20 \text{ K}$$

$\epsilon = 0.05$ per inner and outer tube surface

$$D_{sc} = 10 \text{ cm}$$

$$W_R = 3.6 \text{ W/m}$$

Radiation
Losses

Superinsulation: $W_R^f = W_R/(n-1)$, where
 n = number of layers

Target: $W_R^f = \underline{0.5 \text{ W/m}}$ requires ~10 layers

Other addenda (convection, conduction): $W_A = \underline{0.5 \text{ W/m}}$

$$W_T = W_R^f + W_A = \underline{1.0 \text{ W/m}}$$

Heat Removal

$$dT/dx = W_T / (\rho v C_p A)_{H_2}, \text{ where}$$

dT/dx = Temp rise along cable, K/m

W_T = Thermal in-leak per unit Length

ρ = H_2 Density

v = H_2 Flow Rate

C_p = H_2 Heat Capacity

A = Cross-sectional area of H_2 cryotube

Take $W_T = 1.0 \text{ W/m}$, then $dT/dx = 1.89 \times 10^{-5} \text{ K/m}$,
Or, 0.2 K over a 10 km distance

Fluid Properties Comparison of Liquid to Gaseous Hydrogen Transporting 500 MW_t in a 10-cm Diameter Pipe

T °K	P psia	ρ kg/m ³	μ μPa·s	μ²/ρ ndyne	V m/s	Re 10 ⁶
20	14.7	70.8	13.6	261	4	2.08
77	1850	35.4	5.6	87	8	5.06

$$Re = \rho V D / \mu \approx \frac{\text{Inertial Forces}}{\text{Viscous Forces}}$$

Thus, it takes only 0.5 dynes “push” on an object with the above Reynolds Numbers on the gas to overcome viscous forces exerted by the given fluid

Fluid Friction Losses

$$p_{loss} = \lambda (l / d_h) (\rho v^2 / 2)$$

where

p_{loss} = pressure loss (Pa, N/m²)

λ = friction coefficient

l = length of duct or pipe (m)

d_h = hydraulic diameter (m)

$$W_{loss} = M P_{loss} / \rho,$$

Where M = mass flow per unit length

P_{loss} = pressure loss per unit length

ρ = fluid density

$$1 / \lambda^{1/2} = -2,0 \log_{10} [(2,51 / (Re \lambda^{1/2})) + (\epsilon / d_h) / 3,72]$$

Colebrook's Equation

$\epsilon = 0.015$ mm (stainless steel)	
	W_{loss} (W/m)
22 K	0.72
77 K	1.30

SuperCable H₂ Storage

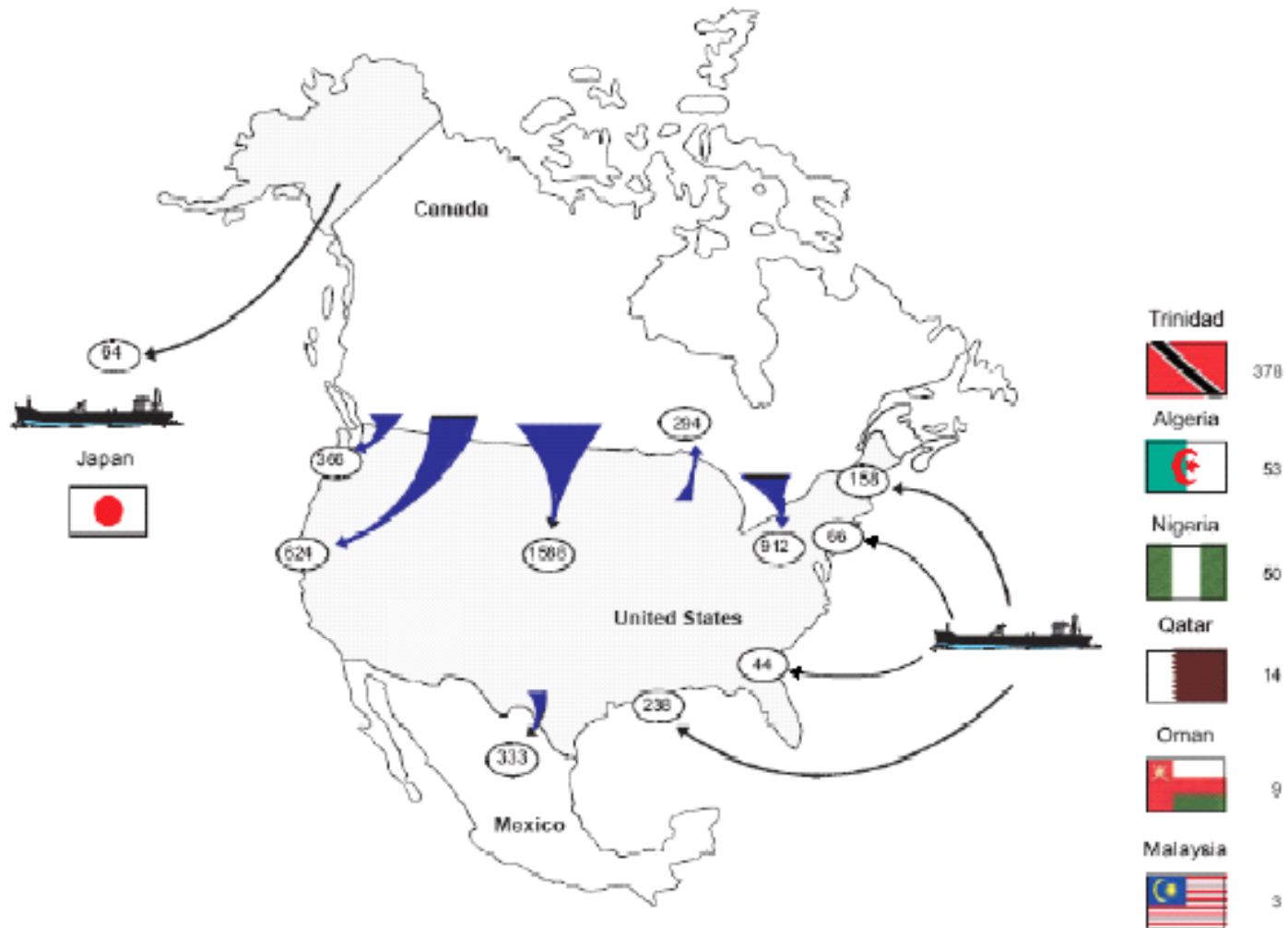
<u><i>Some Storage Factoids</i></u>	Power (GW)	Storage (hrs)	Energy (GWh)
TVA Raccoon Mountain	1.6	20	32
Alabama CAES	1	20	20
Scaled ETM SMES	1	8	8

One Raccoon Mountain = 13,800 cubic meters of LH₂

**LH₂ in 10 cm diameter, 250 mile bipolar SuperCable
= Raccoon Mountain**

Super Grids

US Natural Gas Imports (BCF – 2003)



A Canadian's View of the World



The Mackenzie Valley Pipeline

<http://www.mackenziegasproject.com>



1220 km
18 GW-thermal
2006 - 2010

MVP Specs

Pipeline Length	1220 km (760 mi)
Diameter	30 in (76 cm)
Gas Pressure	177 atm (2600 psia)
Pressurization Stations	~250 km apart
Flow Velocity	5.3 m/s (12 mph)
Mass Flow	345 kg/s
Volume Flow	1.6 Bcf/d (525 m ³ /s)
Power Flow	18 GW (HHV Thermal)
Construction Schedule	2006 - 2010
Employment	25,000
Partners	Esso, APG, C-P, Shell, Exxon
Cost	\$18 B (all private)

Constructing Gas Pipelines

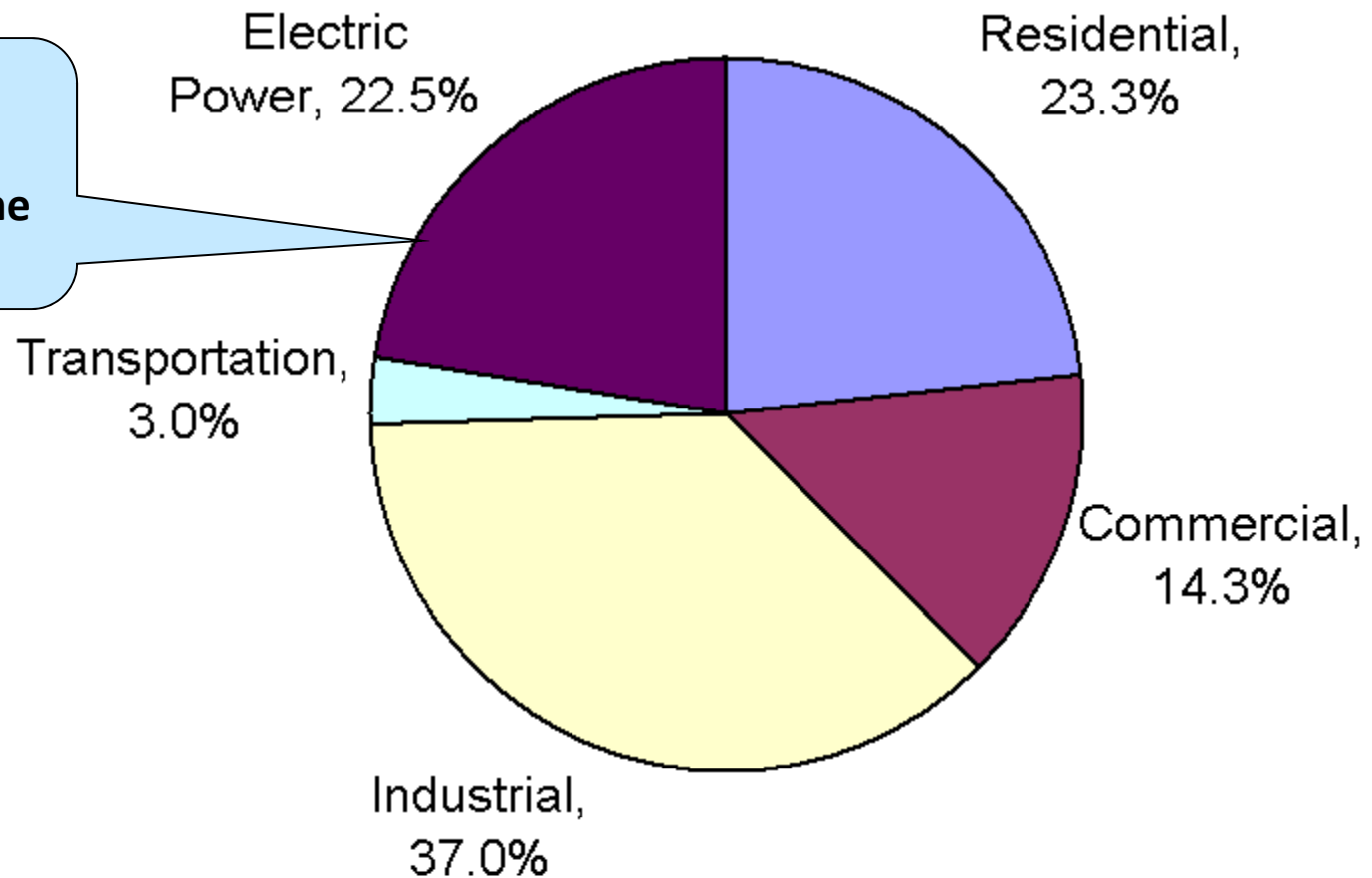


Mackenzie
Gas Project

2004 Natural Gas End Use

Schoenung, Hassenzahl and Grant, 1997
(5 GW on HTSC @ LN₂, 1000 km)

Why not
generate this
electricity at the
wellhead?



Wellhead LNG + Electricity

MVP Scenario

Electricity Conversion Assumptions

Wellhead Power Capacity	18 GW (HHV)
Fraction Making Electricity	33%
Thermal Power Consumed	6 GW (HHV)
Left to Transmit as LNG	12 GW (HHV)
CCGT Efficiency	60%
Electricity Output	3.6 GW (+/- 18 kV, 100 kA)

SuperCable Parameters for LNG Transport

CH ₄ Mass Flow (12 GW (HHV))	230 kg/s @ 5.3 m/s
LNG Density (100 K)	440 kg/m ³
LNG Volume Flow	0.53 m ³ /s @ 5.3 m/s
Effective Pipe Cross-section	0.1 m ²
Effective Pipe Diameter	0.35 m (14 in)

It's 2030

- *The Gas runs out!*
- We have built the LNG SuperCable years before
- Put HTCGR Nukes on the now empty gas fields to make hydrogen and electricity (some of the electricity infrastructure, e.g., I/C stations, already in place)
- Enable the pre-engineered hydrogen capabilities of the LNG SuperCable to now transport protons and electrons.

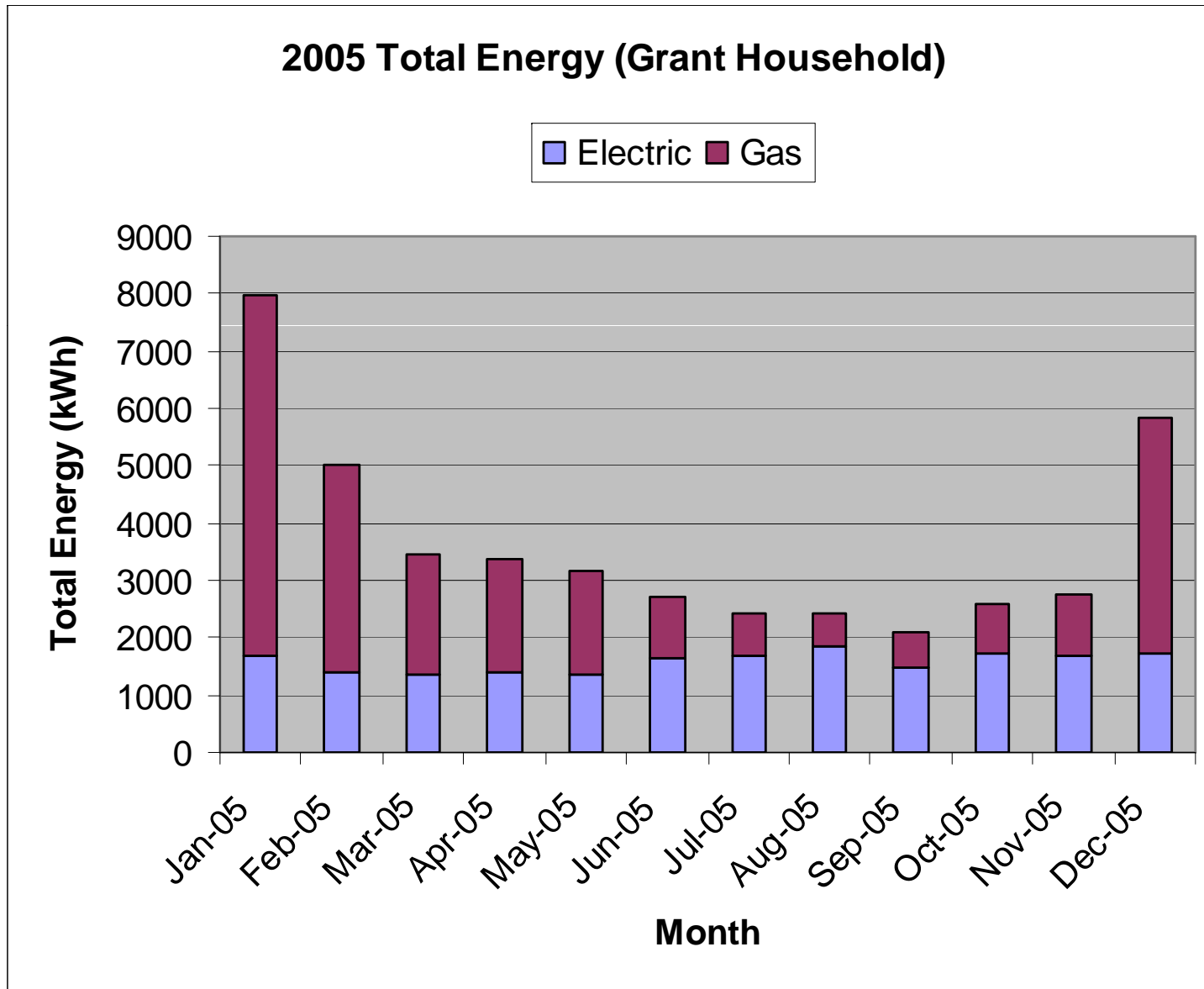
SuperCities (SuperSuburbs)

ICEC-ICMC, Seoul, 2008

SuperSuburb Parameters

- Electricity for residential appliances, lighting, space conditioning and cooking
- Hydrogen for storage of electricity and personal transportation
- Off the Agenda:
 - Commercial business; shopping centers
 - Electric rail/rapid transport
 - Street lighting

California Living!



**Baseline Electric Power and Energy Storage Requirements
per GHE in SuperSuburb**

Baseline Power (kW)	Energy Stored (kWh)	Hydrogen Mass Equivalent (kg)	Volume as Liquid (21 K, 14.7 psia) (cube edge in meters)	Volume as Gas (300 K, 2000 psia) (cube edge in meters)
5.99	6129	187	1.38	2.63

GHE Transportation Energy Consumed

Miles/Year	DOE H ₂ Mileage (kWh/mile)	H ₂ Daily Mass Consumption (kg)	SuperCable H ₂ Delivery Power (kW)
30,000	0.76	1.91	2.61

Baseline Electric and Hydrogen Power Needs of a “San Jose” SuperSuburb of GHEs

GHE Households	Base Electric Power (MW)	Electricity to be Stored as H ₂ (tonnes)	Base H ₂ Power (MW)	H ₂ Stations
300,000	1798	56,104	782	748

The Cryogenic Neighborhood

SuperSuburb

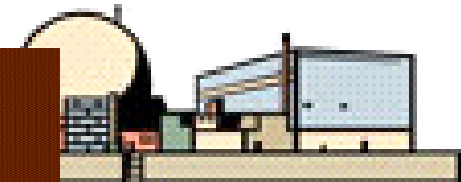
Households: 300,000
Electricity: 1800 MW
Hydrogen: 800 MW



~ "San Jose"

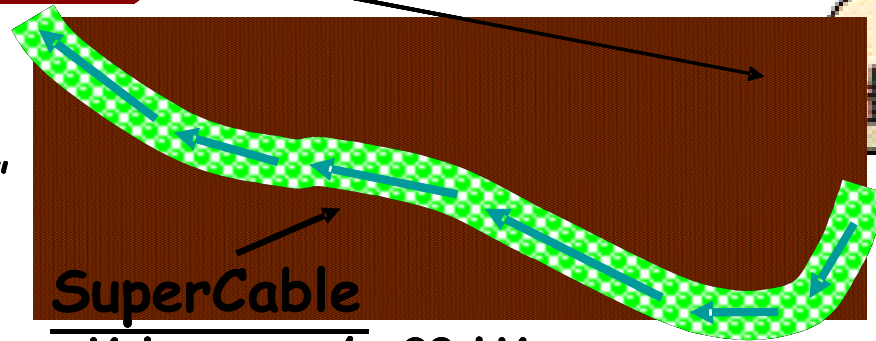
SuperNuke

electrons + protons
=> 2600 MW



~ "Diablo Canyon"

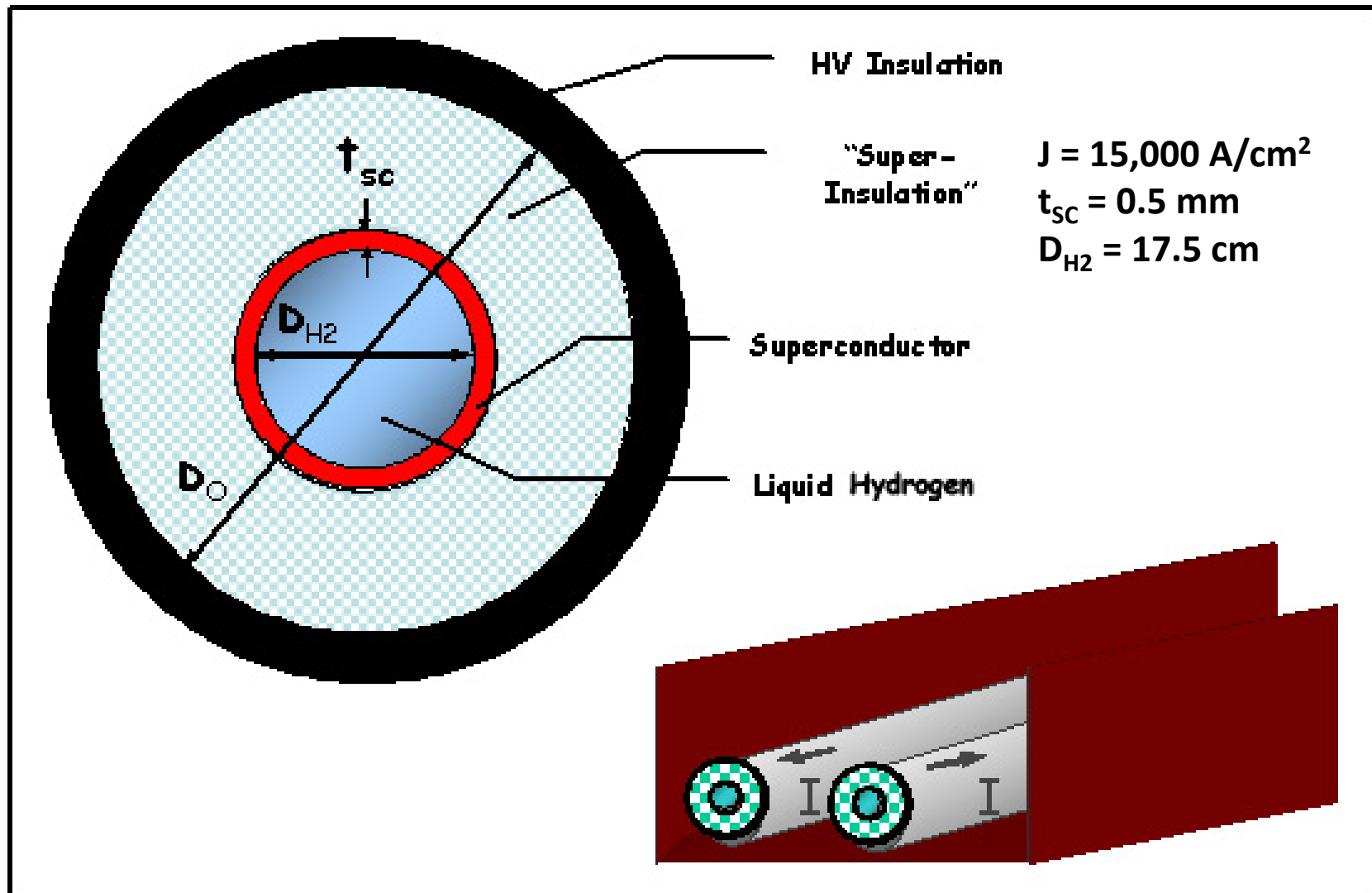
250 km



SuperCable

Voltage: +/- 20 kV
Current: 45 kA
H₂ Storage: 28 GWh
H₂ Flow: 2 m/s => 6.8 kg/s

The CryoNet



SuperCable Physical Parameters

Operating Current Density, J (A/cm ²)	t _{sc} (cm)	Hydrogen Flow Rate (m/s)	D _{H2} (cm)	Maximum Magnetic Field (T)
15,000	0.05	2	17.5	0.10

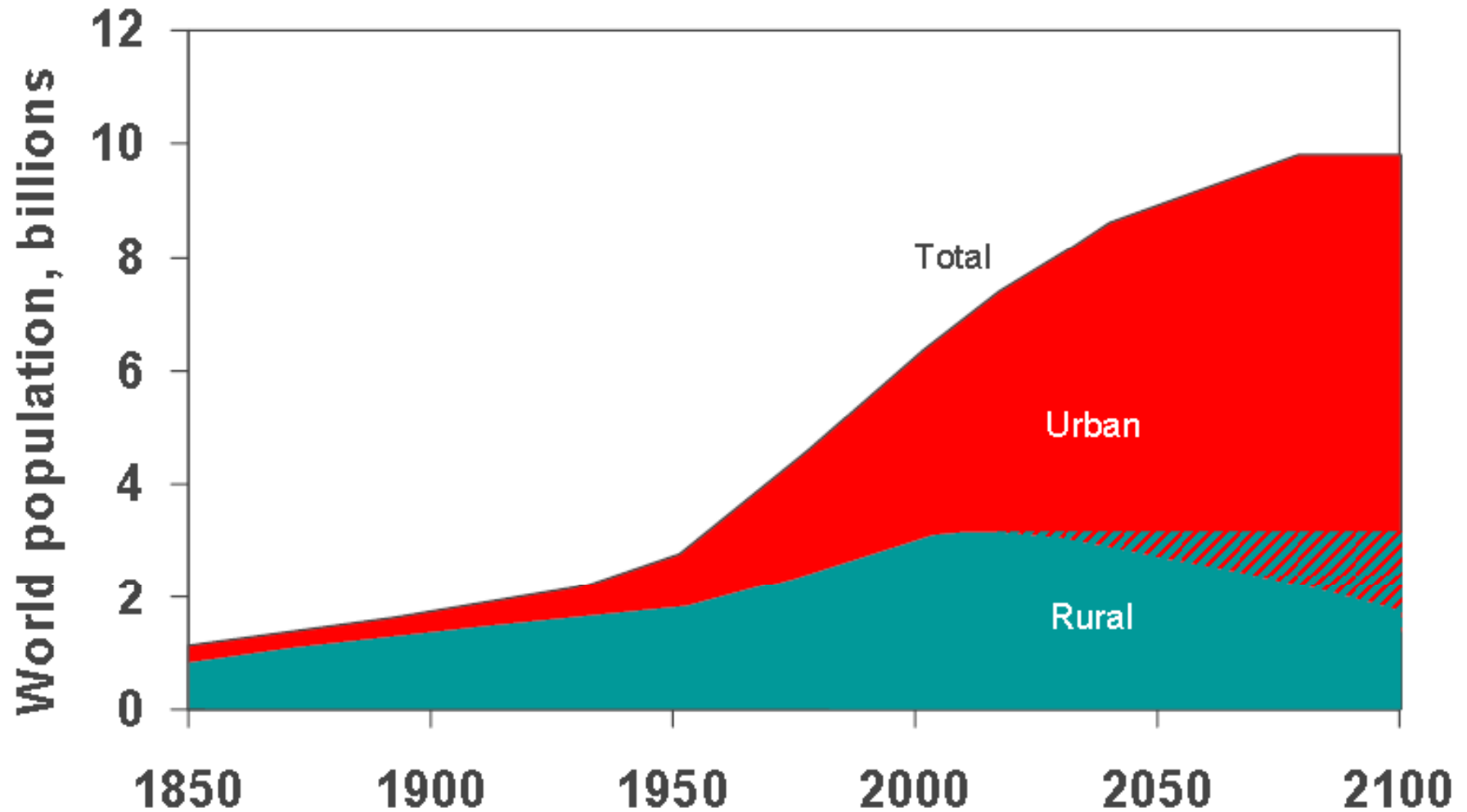
Bottom Line

SuperSuburb SuperCable Economic Factors.

Cost of Electricity (\$/kWh)	Line Losses in Conventional Transmission (%)	Annual Value of Losses on 1800 MW Transmission Line (M\$)	Additional Capital Costs for HTSC and Refrigeration (M\$)	FRB Discount Rate (%)	Period for ROI (Years)
0.05	5 %	39.4	1185	5.5 %	18

Finale

World Population: 1850 - 2100



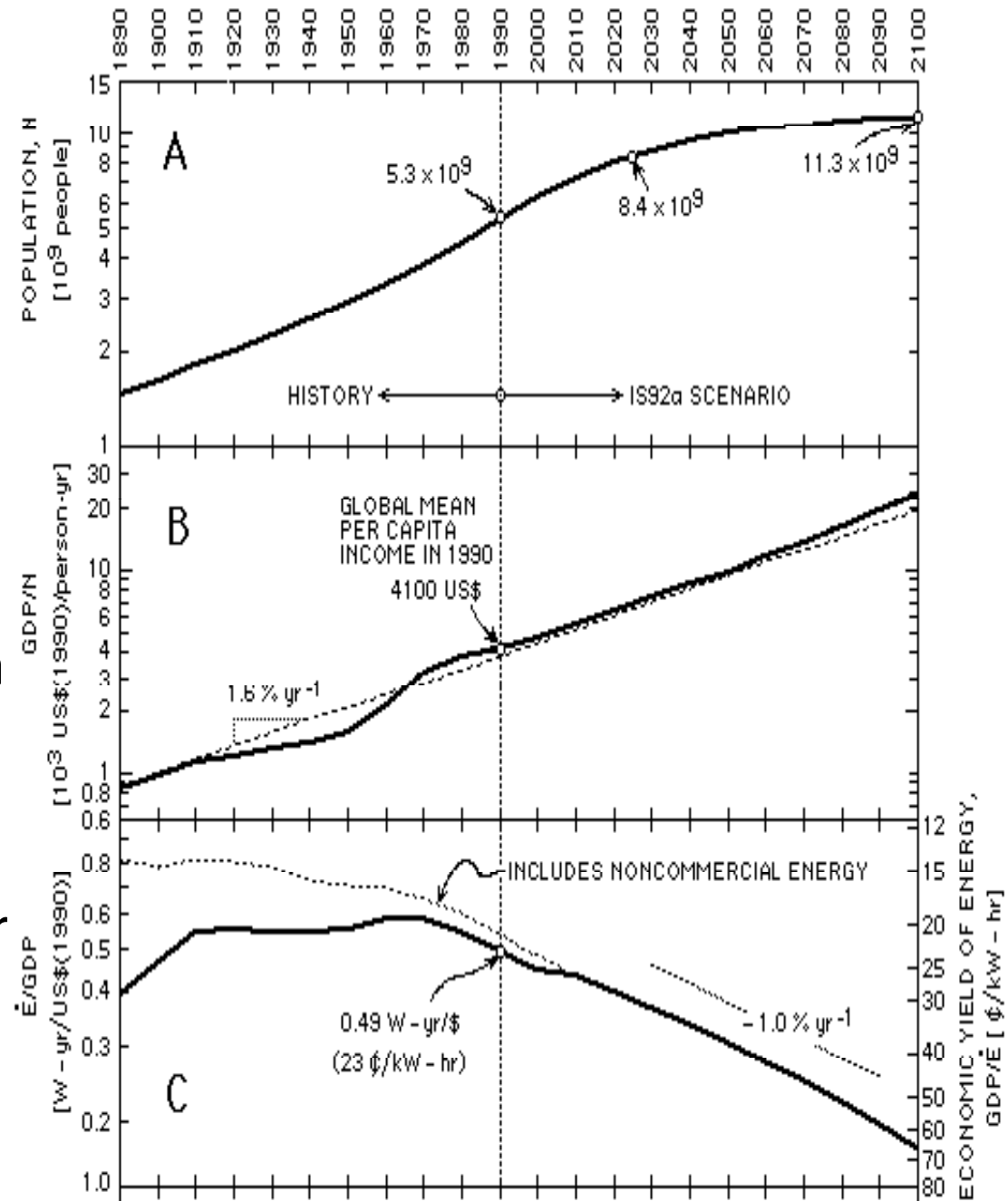
From Global Energy
Perspective – 2007

Nate Lewis, Cal Tech

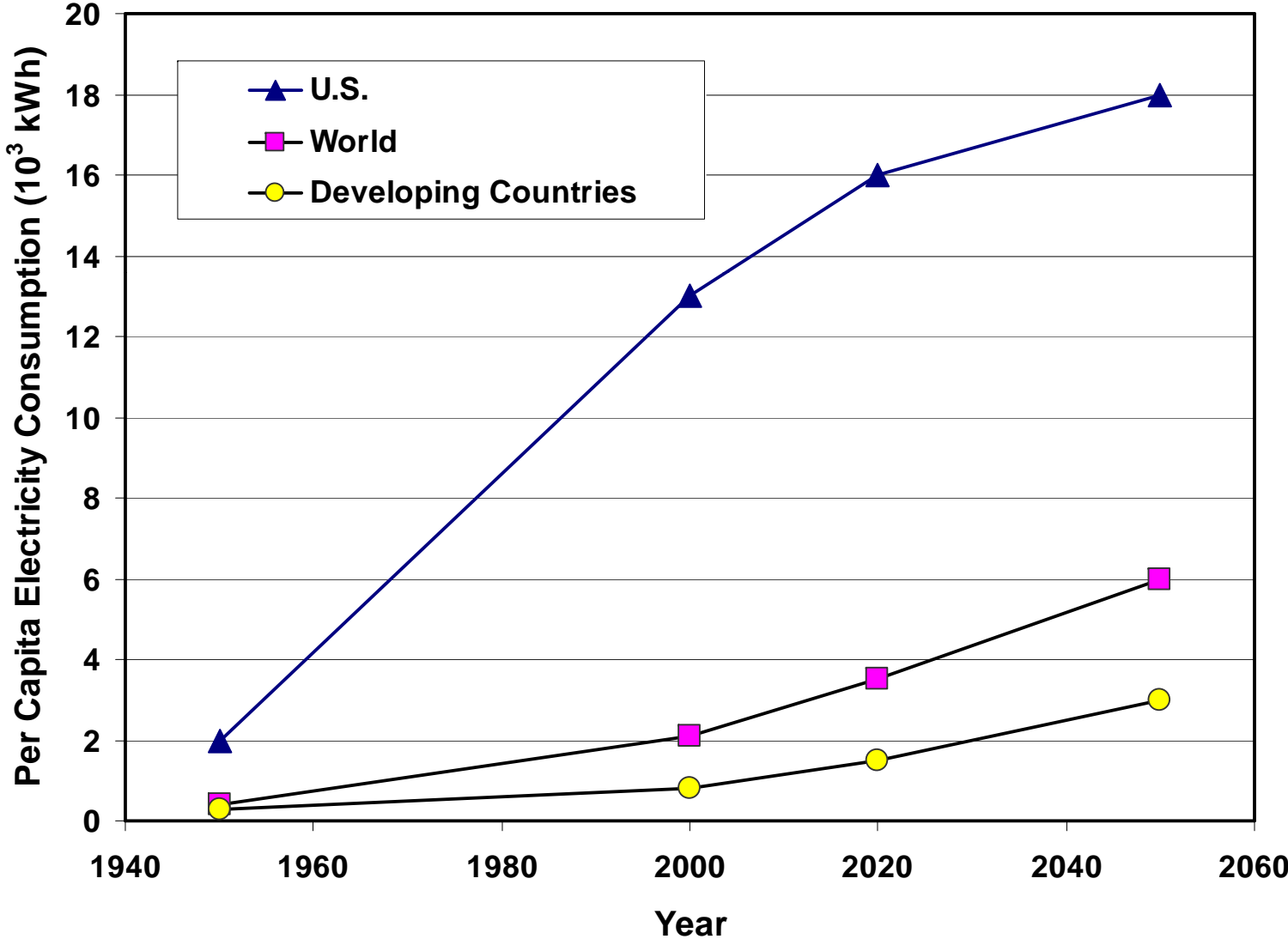
Population Growth to
10 - 11 Billion
People in 2050

Per Capita GDP Growth
at 1.6% yr⁻¹

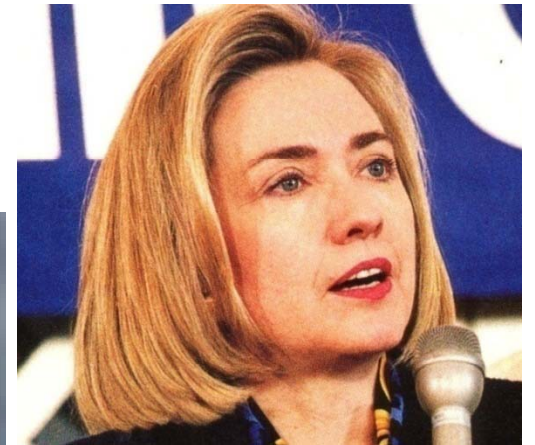
Energy consumption per
Unit of GDP declines
at 1.0% yr⁻¹



Trends in Per Capita Electricity Consumption



Enfranchisement of Women



...But There Are Always Exceptions!



Where there is no vision,
the people perish...

Proverbs 29:18

“You can’t always get what you want...”



“...you get what you need!”

