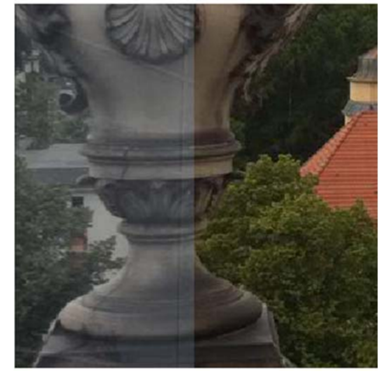


The Garwin-Matisoo Vision After 45 Years

Electric Power Via Superconducting Cables: Economic and Environment Issues

Paul Michael Grant

Principal, W2AGZ Technologies

Visiting Scholar, Stanford (2005-2008)
EPRI Science Fellow (*retired*)
IBM Research Staff Member Emeritus
w2agz@w2agz.com
www.w2agz.com

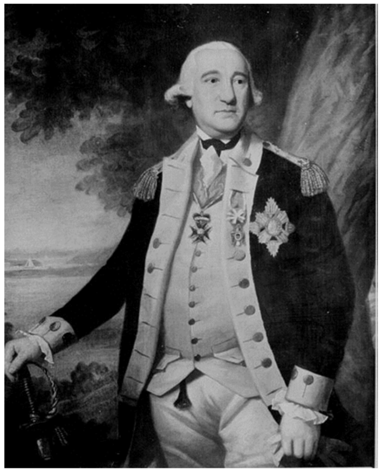
Brainstorming Workshop

Transporting Tens of Gigawatts of Green Power to the Market

12-13 May 2011

IASS, Potsdam, Germany

The Germans in America



Friedrich Wilhelm
von Steuben

Taught the Rebels how to fight!

Frederick
Muhlenberg

First US Speaker of the House…aka in Europe as “Prime Minister”

Discovery Anniversaries

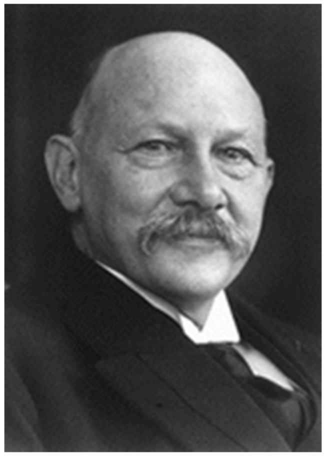
100 | 25

1911 (4.2 K)

Gilles Holst

1986 (20-40 K)

Georg Bednorz



H. Kammerlingh-Onnes

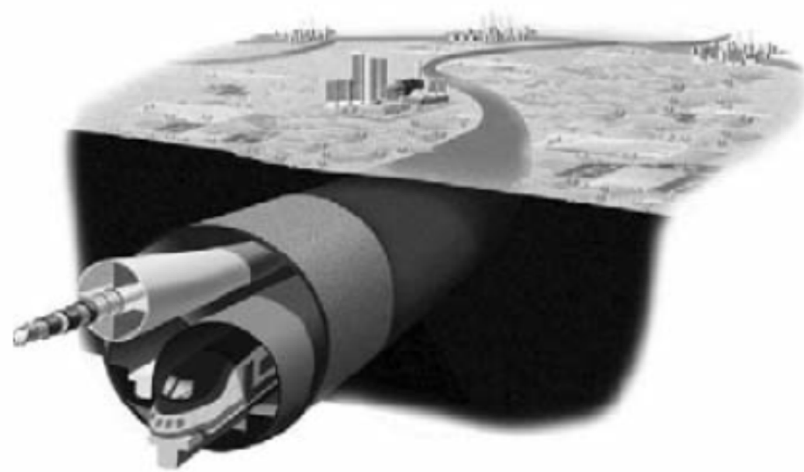
Alex Mueller

Superconductivity: 100 Years and Counting

First in a year-long series of editorial pieces celebrating the history and progress of superconductivity

by Dr. Paul Michael Grant, W2AGZ Technologies, w2agz@w2agz.com, www.w2agz.com

The following invited article is based on a presentation by Dr. Paul Grant at the July 2010 ICEC/ICMC in Wroclaw, Poland. It is the first in a year-long series of articles in which Cold Facts will be celebrating the 100th anniversary of the discovery of superconductivity.



Superconductivity: 100 years of history physicsworld.com

Down the path of least resistance

Since its discovery 100 years ago, our understanding of superconductivity has developed in a far from smooth fashion. **Paul Michael Grant** explains exactly why this beautiful, elegant and profound phenomenon continues to confound and baffle condensed-matter physicists today

physicsworld.com Superconductivity: Top five applications

Five of the best

Superconductivity may be a beautiful phenomenon, but materials that can conduct with zero resistance have not quite transformed the world in the way that many might have imagined. Presented here are the top five applications, ranked in terms of their impact on society today

1. Wires & Films **2. Medical Imaging** **3. High Energy Physics**

4. Rotating Machinery **5. Dark Matter**

Some Axioms of History

- There is nothing new under the sun

  Ecclesiastes 1:9-14

- What's past is prologue

  The Tempest, by Bill S.

- Those who cannot remember the past are bound to repeat it

  George Santayana

- When I was a boy of 14, my father was so ignorant I could hardly stand to have the old man around. But when I got to be 21, I was astonished at how much the old man had learned in seven years

  Mark Twain

Prologue

England, 1966

PROCEEDINGS

THE INSTITUTION OF ELECTRICAL ENGINEERS

Volume 113 Power

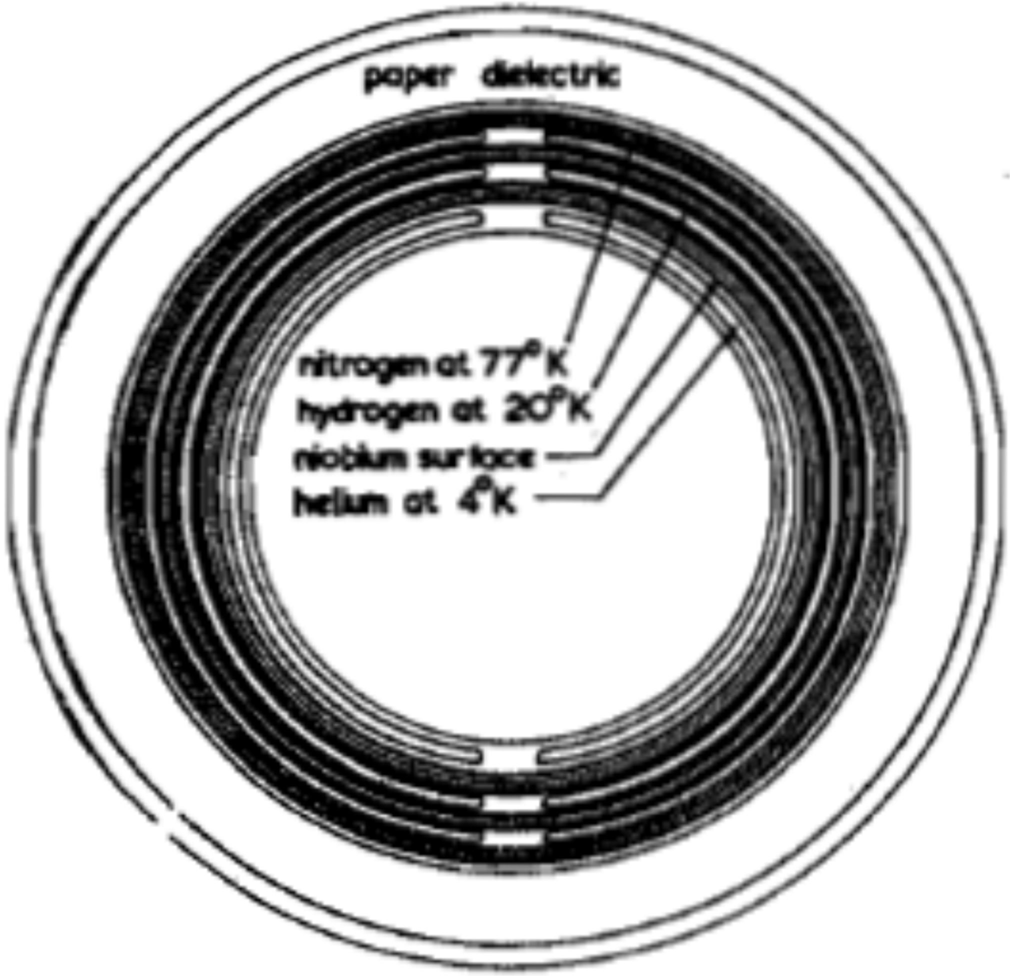
Prospect of employing conductors at low temperature in power cables and in power transformers

K. J. R. Wilkinson, D.Sc., C.Eng., M.I.E.E.

Submitted 28 February 1966

PROC. IEE, Vol. 113, No. 9, SEPTEMBER 1966

- ac Cables: 760 MVA (3ϕ), 275 kV, 1600 A
  - Be 77 K
  - Al 20 K
  - Nb 4 K (a “soft” superconductor!)
- *Objective: Efficiency, not increased capacity!*



Wheeling Watts into Central London More Efficiently

Fig. 2

Superconducting thin-walled niobium core cooled internally by liquid He and protected externally by liquid H_2 and liquid N_2

H_{C1} = 0.16 T
Fault I = 40 kA

Cable Properties

Operating I = 1.6 kA
Surface H = 7 mT

Metal	T (K)	ρ (Ω×cm)	Outer Diameter (cm)	Loss (W/km)
Cu	340	2×10^{-6}	6[illegible]	46,500
Be	77	2×10^{-8}	[illegible].0	460
Al	20	3×10^{-9}	6.0	470
Nb	4	0	10.4	0

Table 7

A COMPARISON OF COSTS, EXCLUDING CONSTRUCTION AND LAYING, BUT INCLUDING THOSE OF LOSSES, REFRIGERATION PLANT, AND CONDUCTOR MATERIAL

Core	Refrigerant	Capitalised costs of cable			
		I^2R loss	Plant and drive power	Conductor material	Approximate total
		£/km	£/km	£/km	£/km
Cu	—	3200	—	10000	13000
Al	H_2, N_2	17	21260	3000	24000
Be	N_2	62	5170	800000	800000
Nb	He, N_2	—	9203	3000	12000

Cost of "Extra" Generation to Offset I^2R Losses (CEGB, 1965): 220 £/kw

Note: A Perfect Conductor is not Absolutely Required!

Wilkinson's Conclusion (1966)

- "...only niobium has any hope of defraying its refrigeration costs by savings in conductor material" *(True, but not by much…)*
- "But its impracticably large core diameter" (10.4 cm rules out Type I superconductors) *(True, even today…)*
- A Type II superconductor with $J_C = 10^6$ A/cm^2 at a diameter of 6 cm would quench under a fault current of 40 kA *(Hoy, no hay problema con HTSC)*
- "Such a hazard is clearly unacceptable." *(Entonces solamente ayer avec LTSC!)*

Garwin-Matisoo

USA, 1967

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

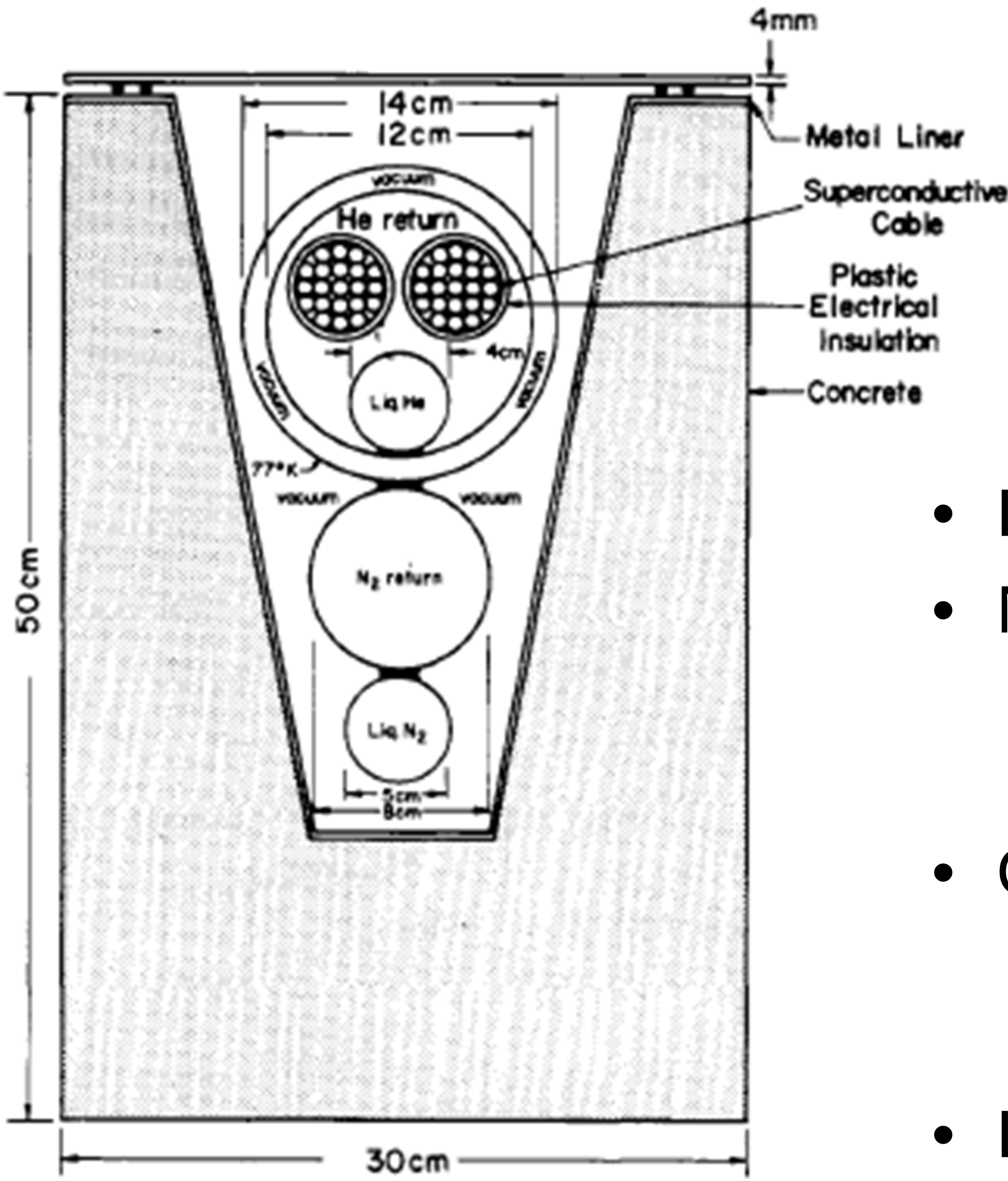
R. L. GARWIN AND J. MATISOO

Submitted 24 June 1966

PROCEEDINGS OF THE IEEE, VOL. 55, NO. 4, APRIL 1967

Rationale: Huge growth in generation and consumption in the 1950s; cost of transportation of coal; necessity to locate coal and nuke plants far from load centers.

Furthermore, the utilities have recently become aware of the advantages of power pooling. By tying together formerly independent power systems they can save in reserve capacity (particularly if the systems are in different regions of the country), because peak loads, for example, occur at different times of day, or in different seasons. To take advantage of these possible economies, facilities must exist for the transmission of very large blocks of electrical energy over long distances at reasonable cost.



Specs

- LHe cooled
- Nb_3Sn (T_C = 18 K)
  - J_C = 200 kA/cm^2
  - H* = 10 T
- Capacity = 100 GW
  - +/- 100 kV dc
  - 500 kA
- Length = 1000 km

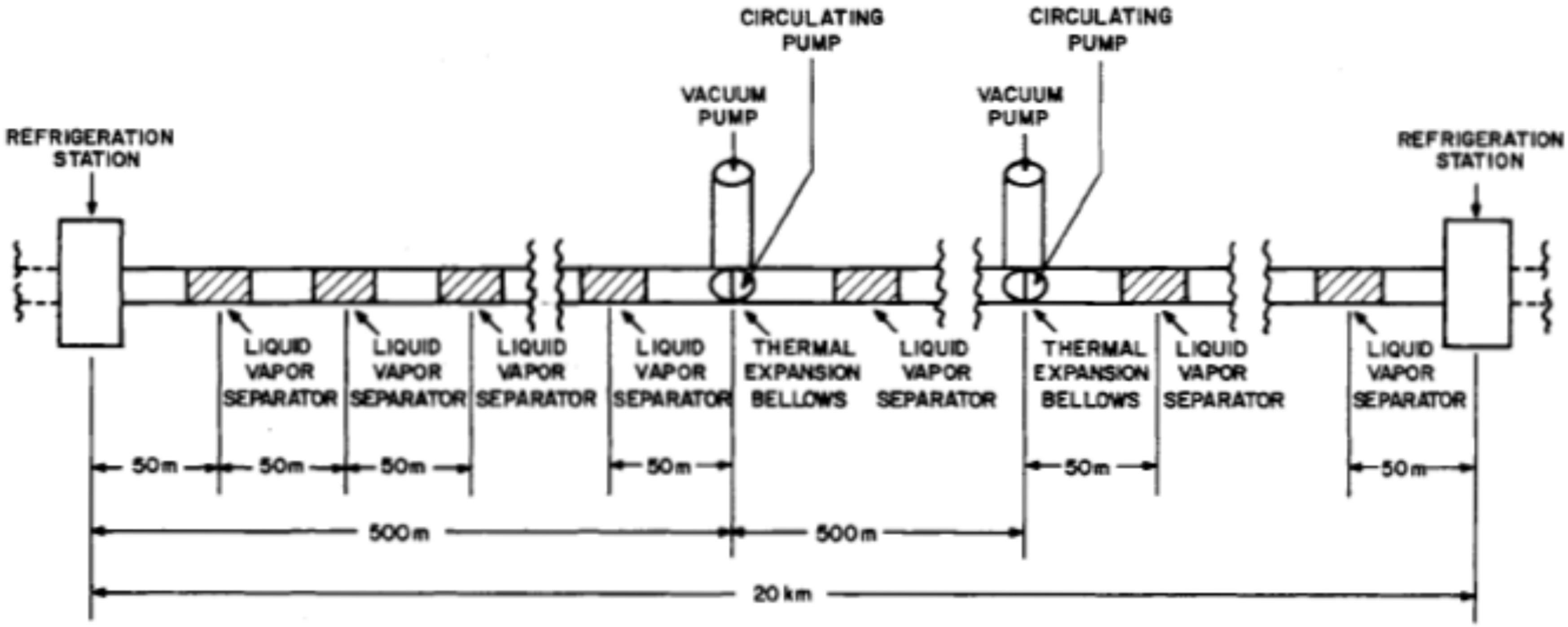


Fig. 2. A 20-km module of the 1000-km, 100-GW line.

• Refrigeration Spacing	20 km
• G-L Separator Distance	50 m
• Booster Pump Intervals	500 m
• Vacuum Pump Spacing	500 m

G-M Engineering Economy - Yesterday & Today -

VARIOUS COMPONENT COSTS OF A 1000 KM, NB-SN CABLE IN 1966 AND NOW

Item	Description/Quantity	1966 Cost (M$)	2006 Cost (M$)*
Superconductor	10^4 Tons Nb_3Sn	550	3405
Line Refrigeration	0.5 M$ for 1 kW LHe station every 20 km	25	155
End-Station Refrigeration	10 kW each	5	31
Vacuum Pumps	$500 per station (2000)	1	6
Fabricated Metal	$1/lb, linear line weight = 100 gm/cm	20	124
Concrete	$10/yd^3 for a total volume of 0.5 yd^2 times 1000 km	5	31
ac/dc Converters	Thyristors at $1/kW	200	1238
Total:		806	4990 5390

*2006 costs relative to 1966 are estimated from the Bureau of Labor Statistics table of annual Consumer Price Indices that can be found at ftp://ftp.bls.gov/pub/special.requests/cpi/cpiai.txt. The 2006/1966 ratio used above is 6.19. The YE2010 costs would be about **8%** higher that YE2006.

Additional LTSC Cables (1975-1985)

Graz, Austria – Late 70s

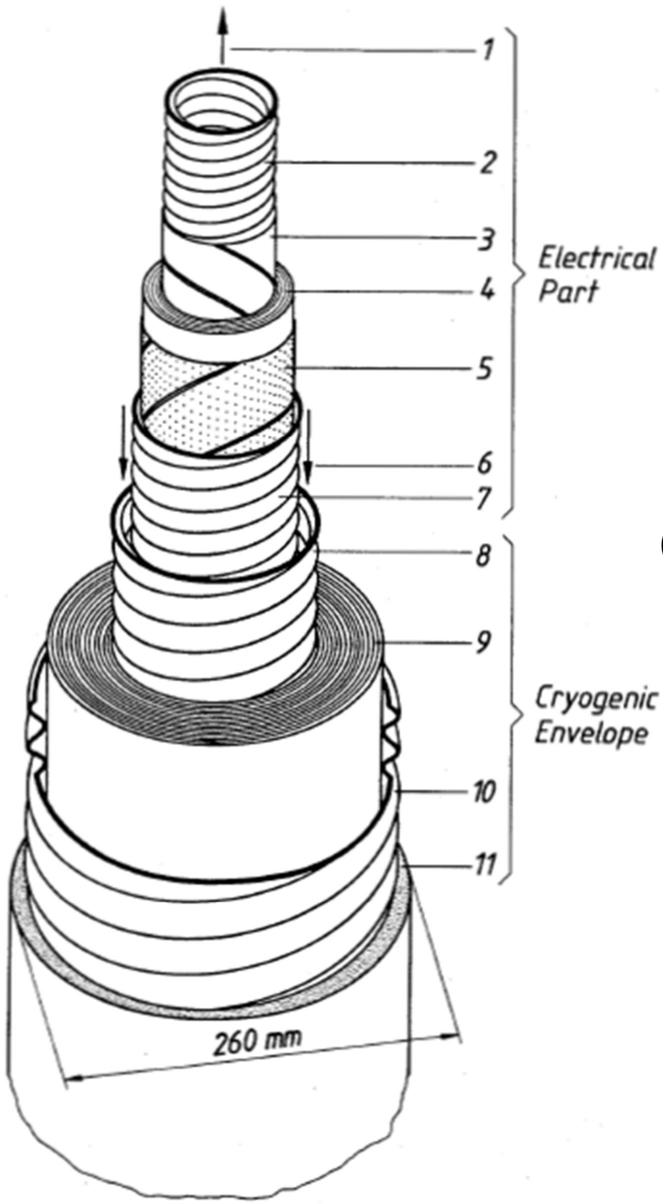


Fig. 5. Fully Flexible Superconducting Cable for 1/3 GW / 110 kV (Design Klaudy-Kabelmetal). 1-Cooling helium 2-Corrugated copper tube with superconducting niobium layer as the phase conductor 3-Smoothing compound 4-Helium impregnated paper tape insulation 5-Electrostatic screen 6-Cooling helium 7-Corrugated copper tube with niobium layer as the shield conductor 8-Inner corrugated tube of the cryogenic envelope 9-Superinsulation in vacuum 10-Outer corrugated tube of the cryogenic envelope 11-PVC-sheath.

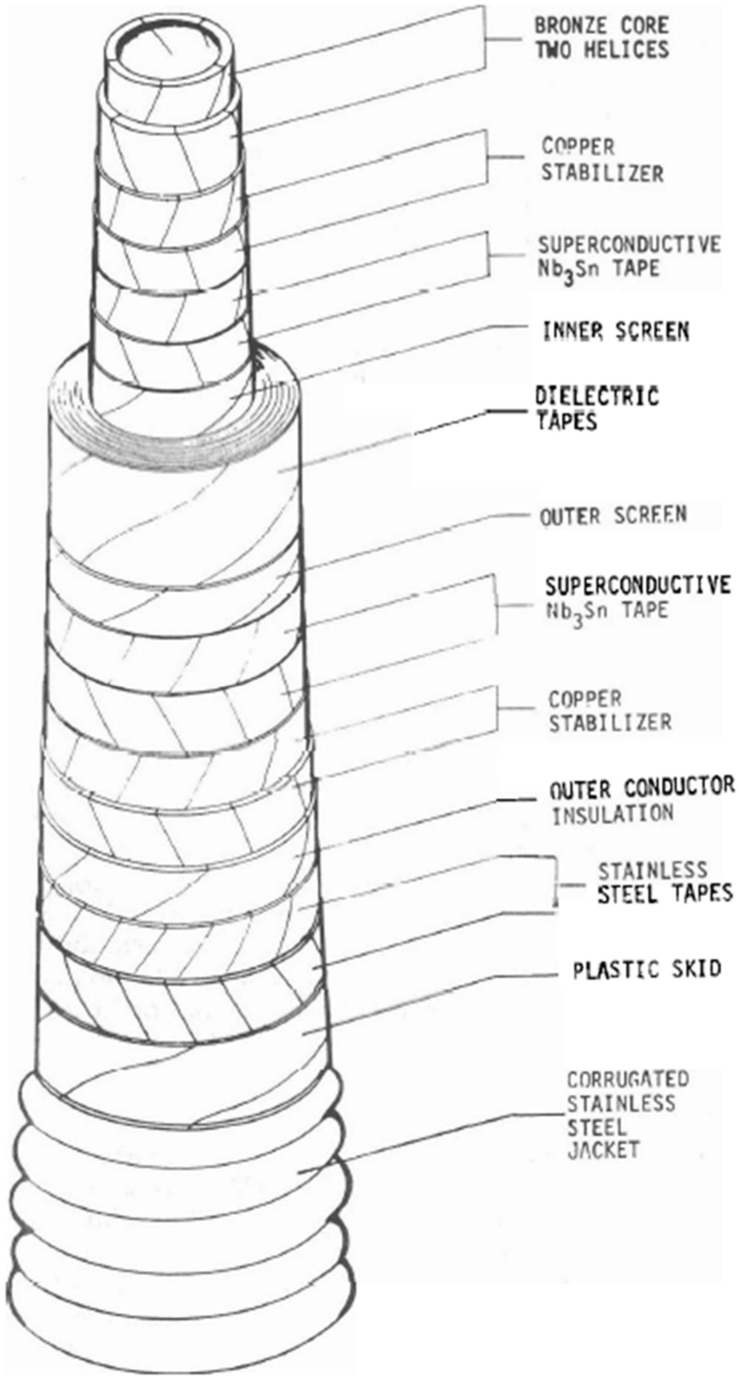


Table 1 Characteristics of the 1000 MVA test system

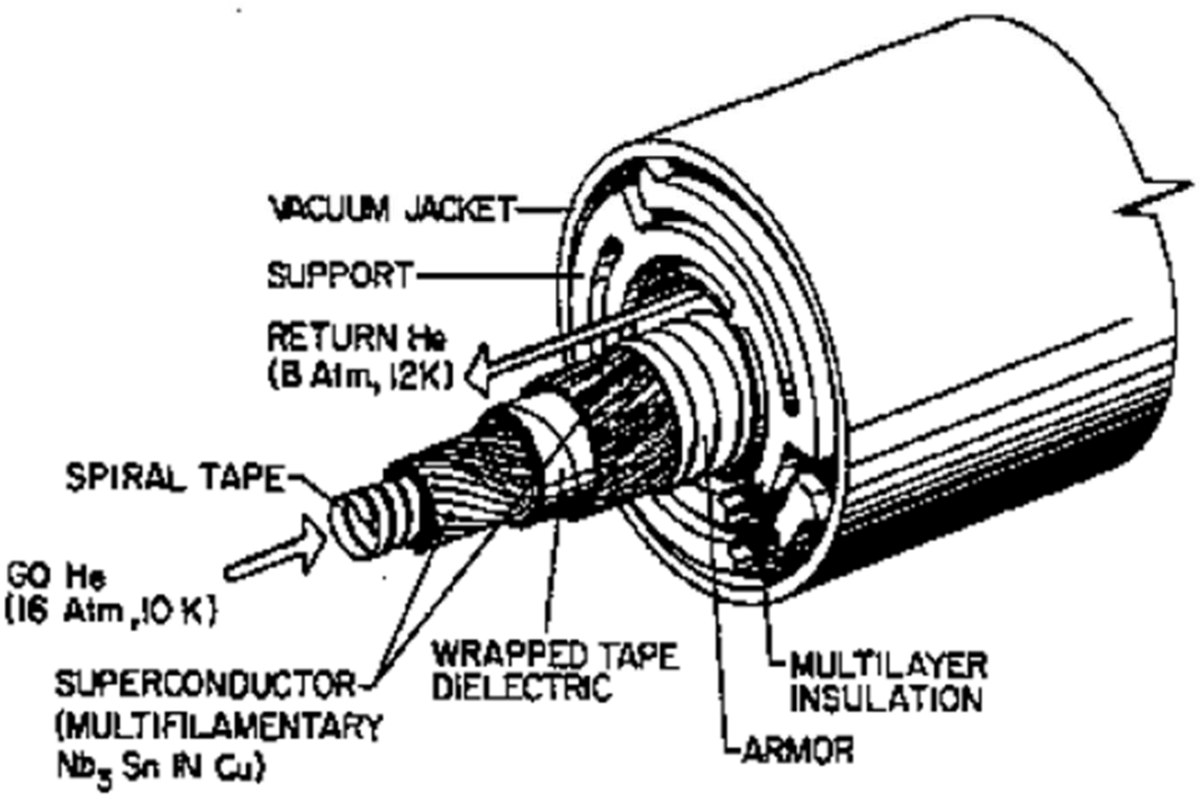
Number of cables	2
Length of each cable (m)	115
Cable outer diameter (over armour) (cm)	5.84
Inner conductor diameter (cm)	2.95
Enclosure outer diameter (cm)	40
Maximum operating temperature (K)	9
Operating pressure (MPa)	1.55
Cooldown time (h)	100
Rated voltage (3-phase) (kV)	138
Rated impulse withstandability (kV)	650[a]
Maximum steady state power rating (MVA)	980
Emergency power level (MVA) (1 h)[b]	1430
Surge impedance load (MVA)	872
Surge impedance (Ω)	25
Current-dependent loss at rated power, 3-3-phase (7.5K) (Wm^{-1})	0.8
Voltage-dependent loss at rated power, 3-phase (7.5 K) (Wm^{-1})	0.15
Enclosure heat in-leak, 3-phase (7.5 K) (Wm^{-1})	0.45

Brookhaven – Late 70s, Early 80s

LANL dc Cable

100 kV, 50 kA, 5000 MW, 300 m

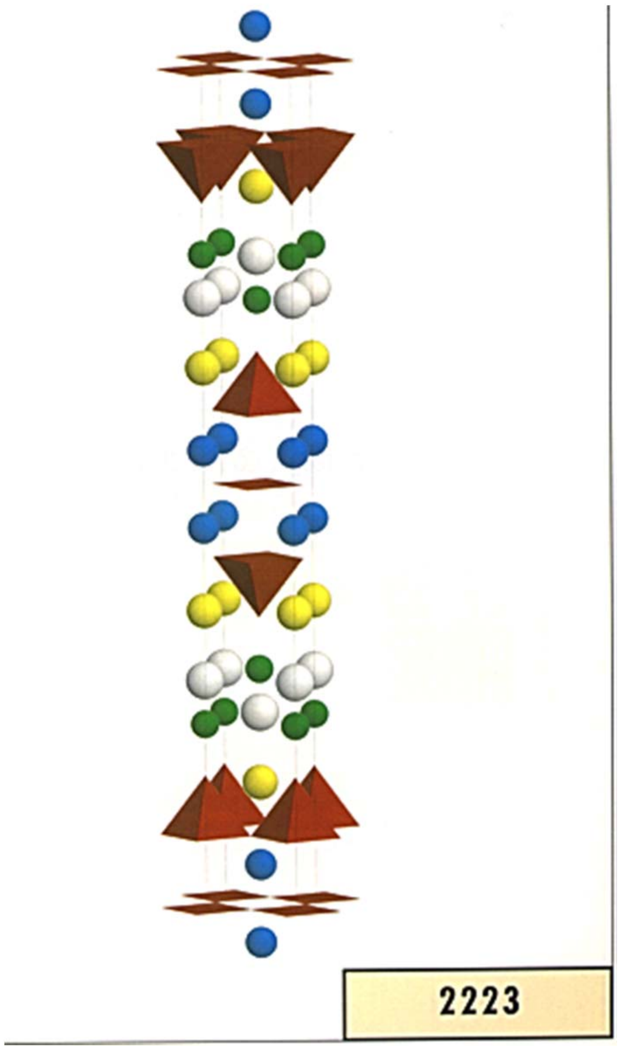
Nb_3Sn, 10 K, 16 Atm

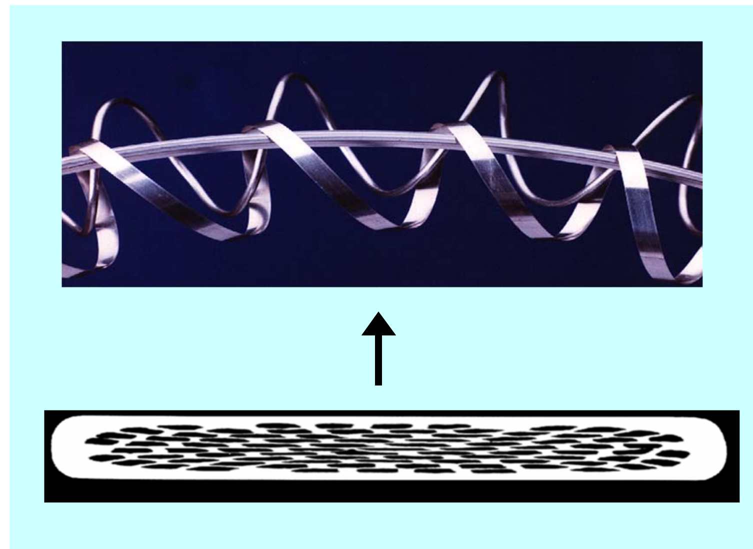


The HTSC Era

Wires & Cables

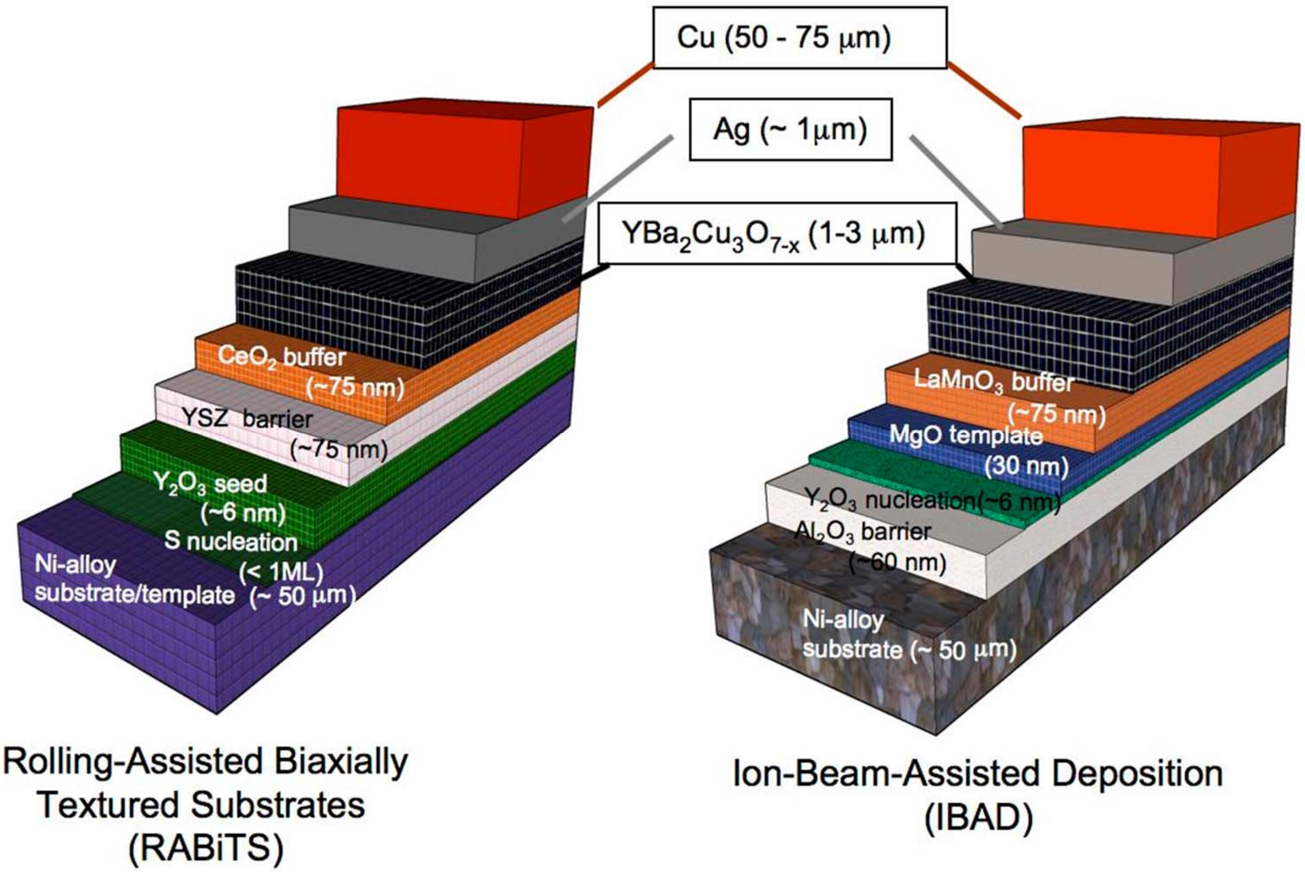
First HTSC "Wire"





Gen 1

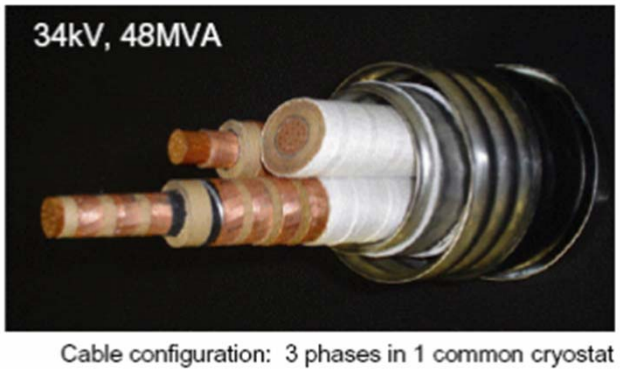
Gen II Coated Conductor



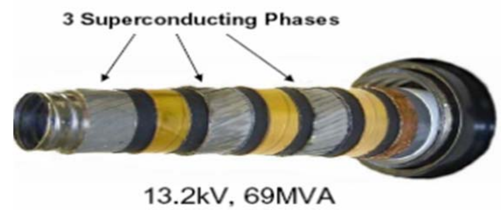
American Superconductor

SuperPower

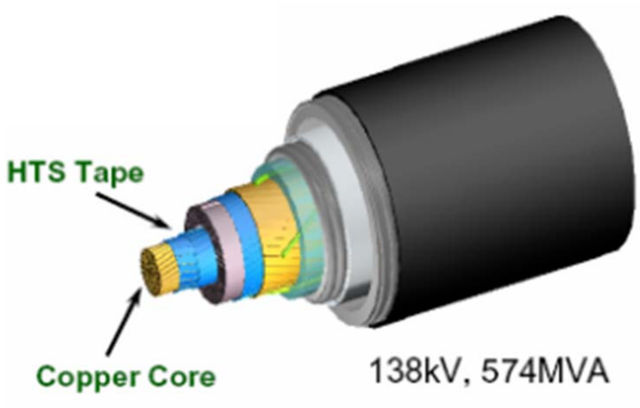
Various ac HTSC Cable Designs



Sumitomo



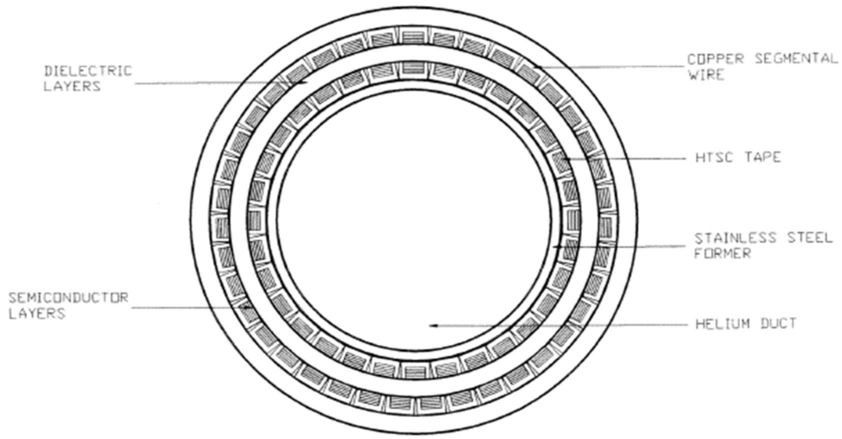
Ultera-
ORNL



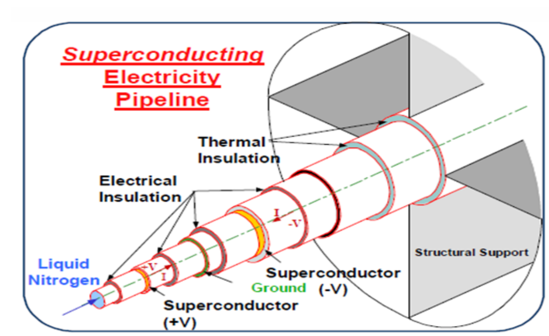
Nexans-
AMSC

Pirelli

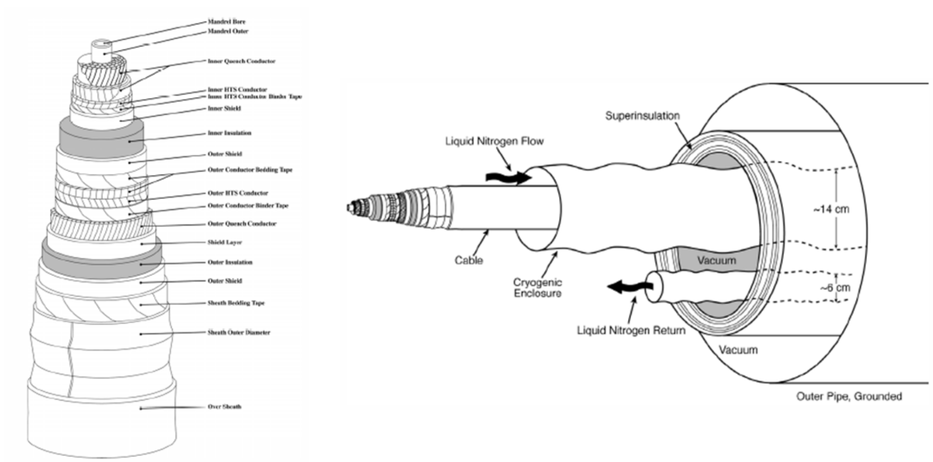
Various dc HTSC Cable Designs



BICC: Beales, et. al, (1995)
40 K, +/- 20 kV, 10 kA, 400 MW



EPRI: Schoenung, Hassenzahl, Grant (1997)
+/- 50 kV, 50 kA, 5 GW



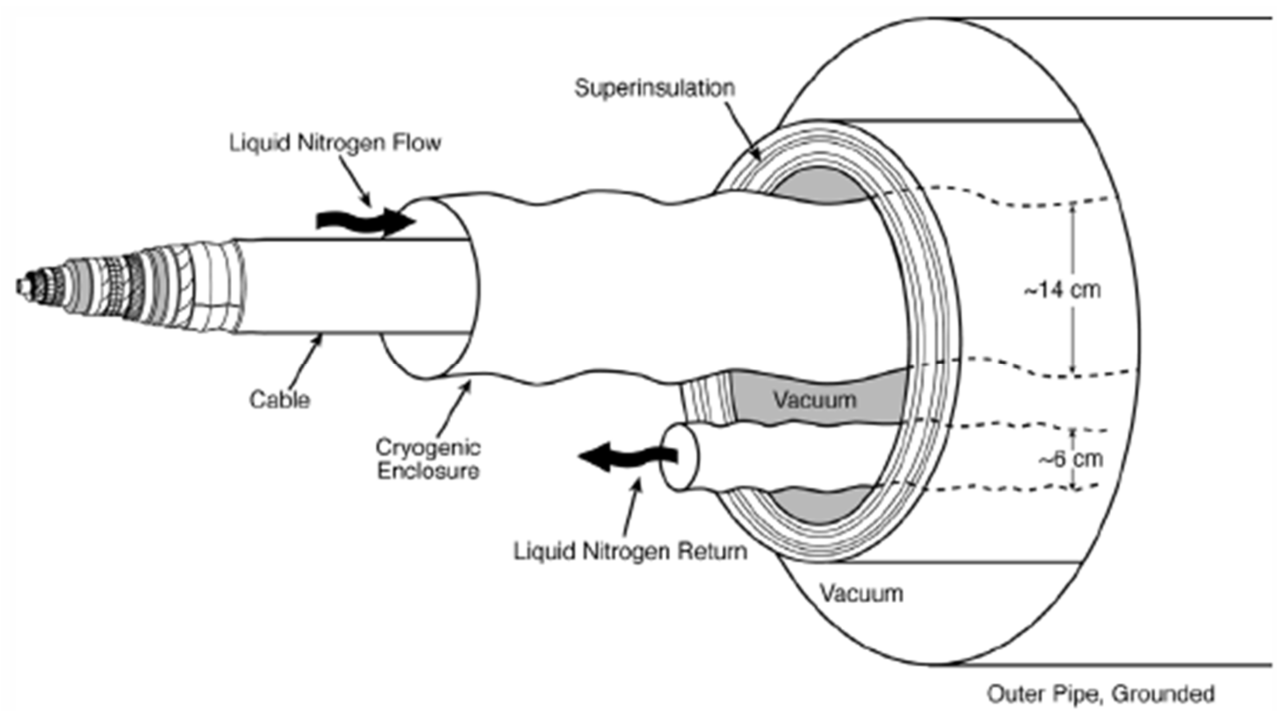
EPRI: Hassenzahl, Gregory, Eckroad, Nilsson, Daneshpooy, Grant (2009)
+/- 50 kV, 100 kA, 10 GW

A Superconducting dc Cable

EPRI Report 1020458 (2009)

Hassenzahl, Gregory, Eckroad, Nilsson, Daneshpooy, Grant

See Also: Hassenzahl, Eckroad, Grant, Gregory, Nilsson, IEEE Trans. Appl. Supercon. 19, 1756 (2009)



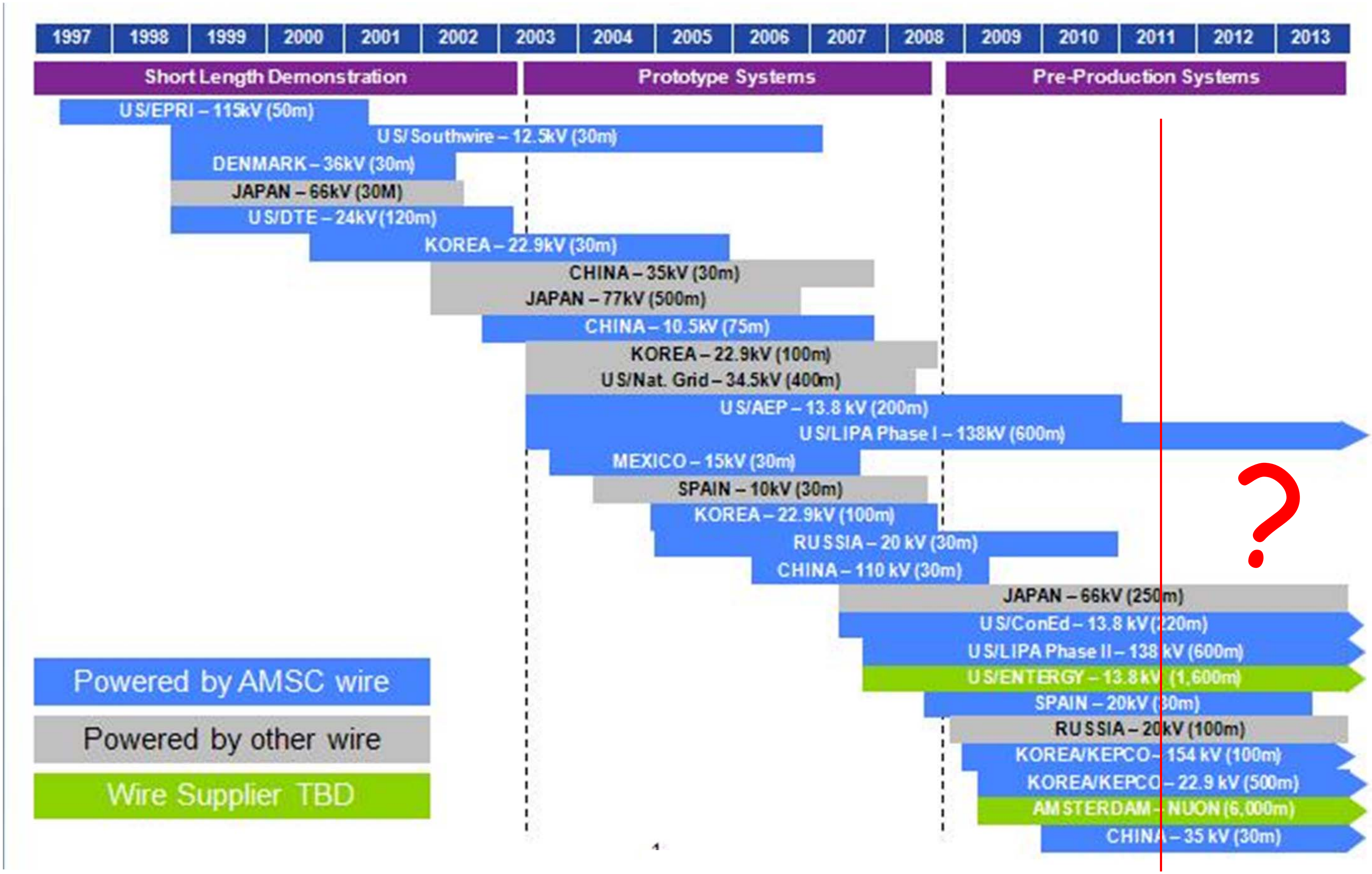
<u>Monopole Specs</u>

100-kV, 100-kA,
10-GW
66 K < T< 69 K

Stay tuned for Steve's upcoming talk…then go build it!

US HTSC Cable Demonstrations

HTSC Cable Demonstration Projects Worldwide Past, Present…Future?



US Department of Energy

Budget of the Office of Electricity Delivery and Energy Reliability: FY 2010-11 (10^3 USD)

	FY 2009		FY 2010	FY 2011
	Current Appropriation	ARRA Appropriation	Current Appropriation	Congressional Request
Research and Development				
High Temperature Superconductivity	23,130		?	?
Visualization and Controls	24,461			
Energy Storage and Power Electronics	6,368			
Renewable and Distributed Systems Integration	29,160			
Clean Energy Transmission and Reliability			38,450	35,000
Smart Grid Research and Development			32,450	39,293
Energy Storage			14,000	40,000
Cyber Security for Energy Delivery Systems			40,000	30,000
SUBTOTAL Research and Development	**83,119**		**124,900**	**144,293**
Permitting, Siting, and Analysis	5,271		6,400	6,400
Infrastructure Security and Energy Restoration	6,180		6,187	6,188
Program Direction	21,180		21,420	29,049
Congressionally Directed Activities	19,648		13,075	
American Recovery and Reinvestment Act, 2009		4,495,712		
Use of prior year balances	-769			
TOTAL	**134,629**	**4,495,712**	**171,982**	**185,930**

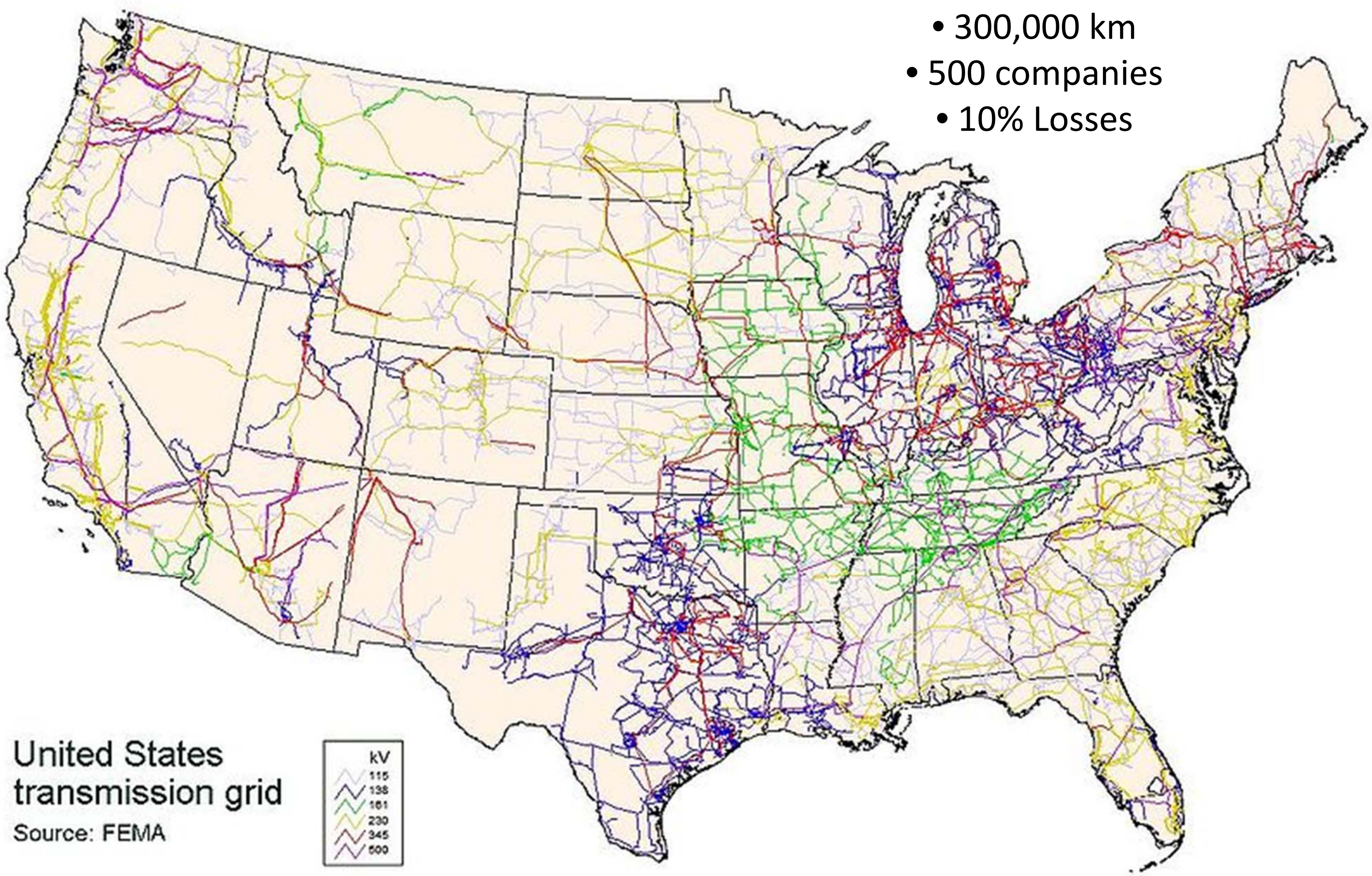
WOW ! “Obama Cash”

HTSC Cables

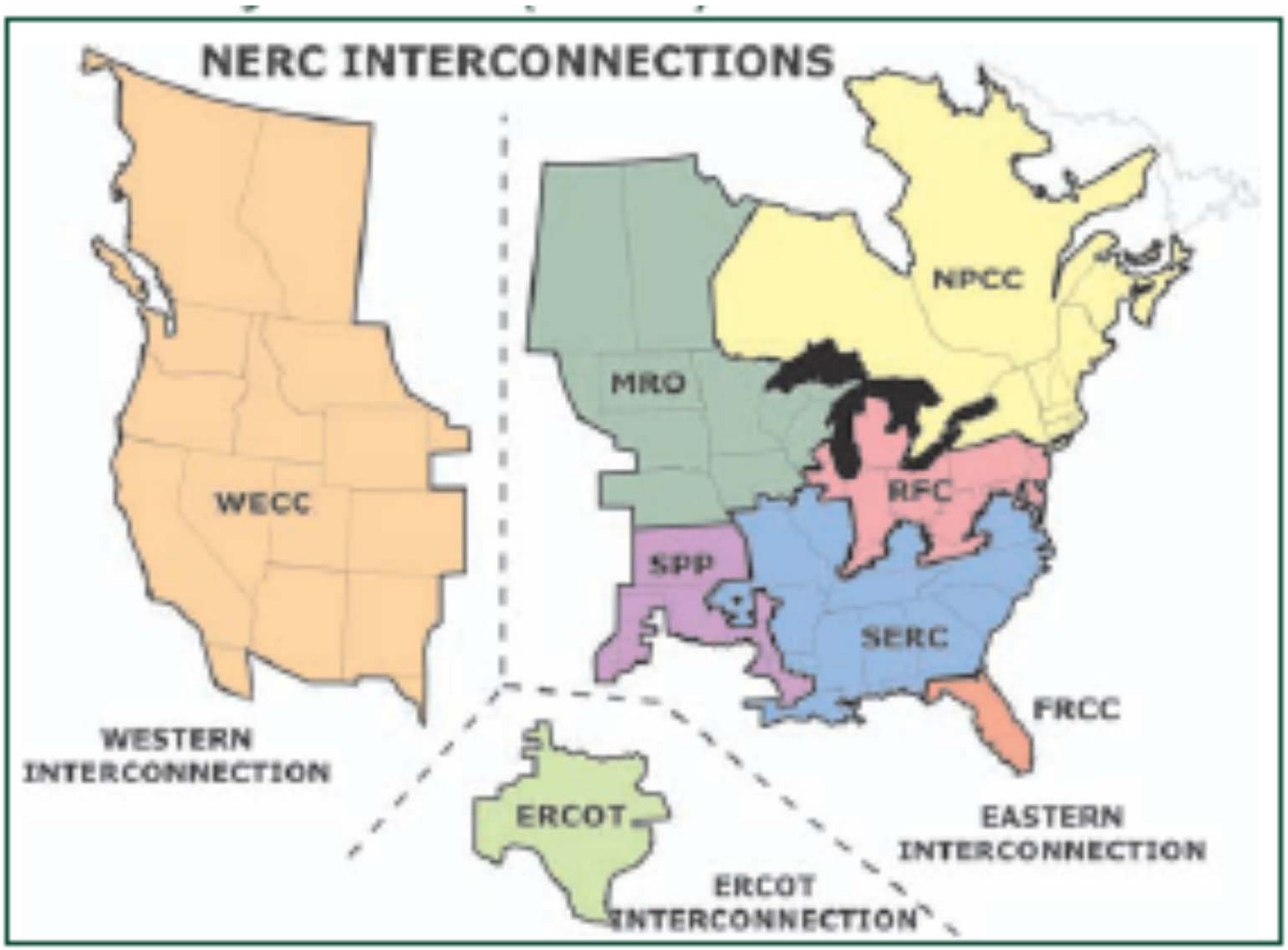
- Deployment Opportunities -

The US Transmission Grid(s)

- 300,000 km
- 500 companies
- 10% Losses



NERC Interconnects



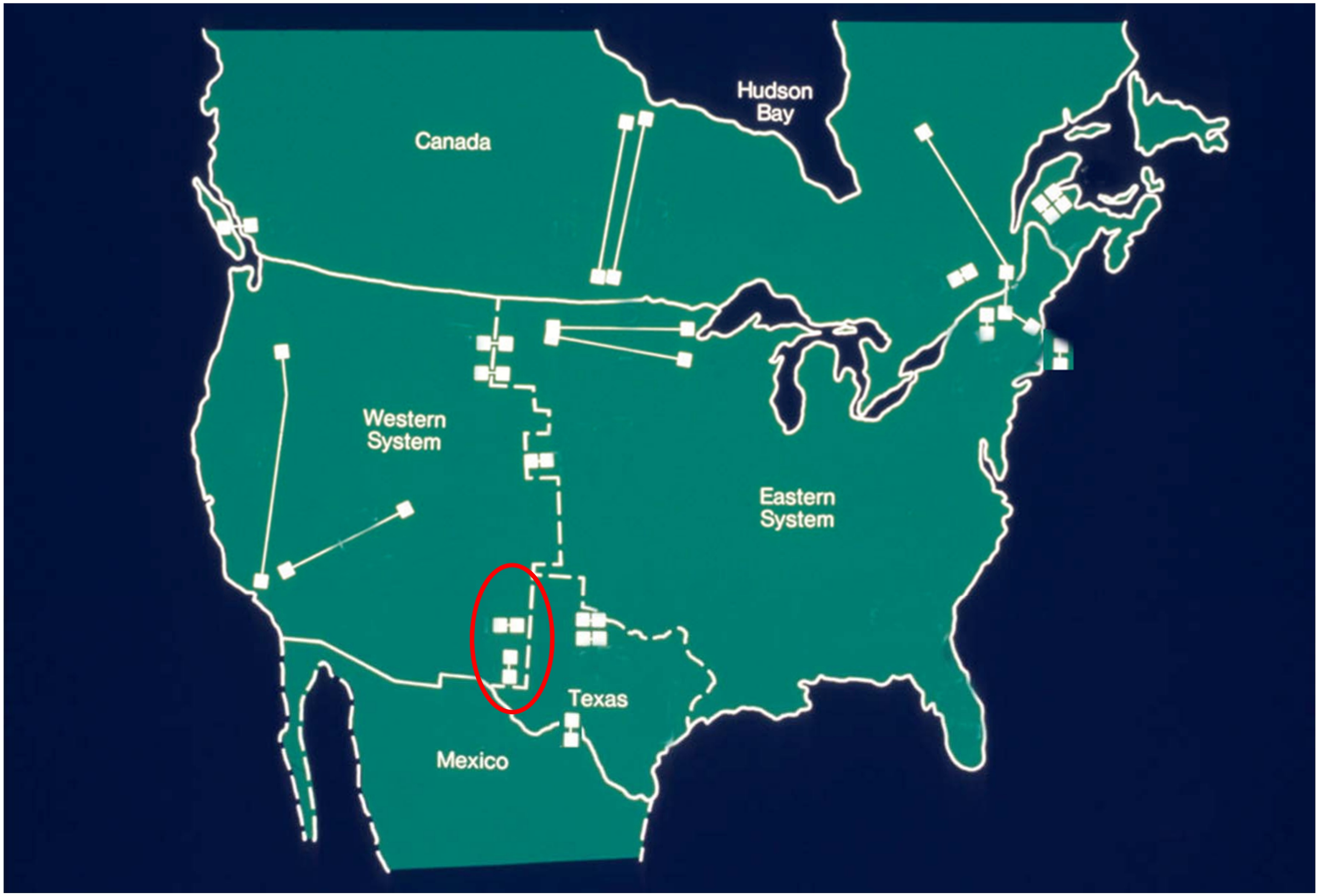
<u>*Source:*</u> DOE 2006 National Electric Transmission Study

Pacific Intertie

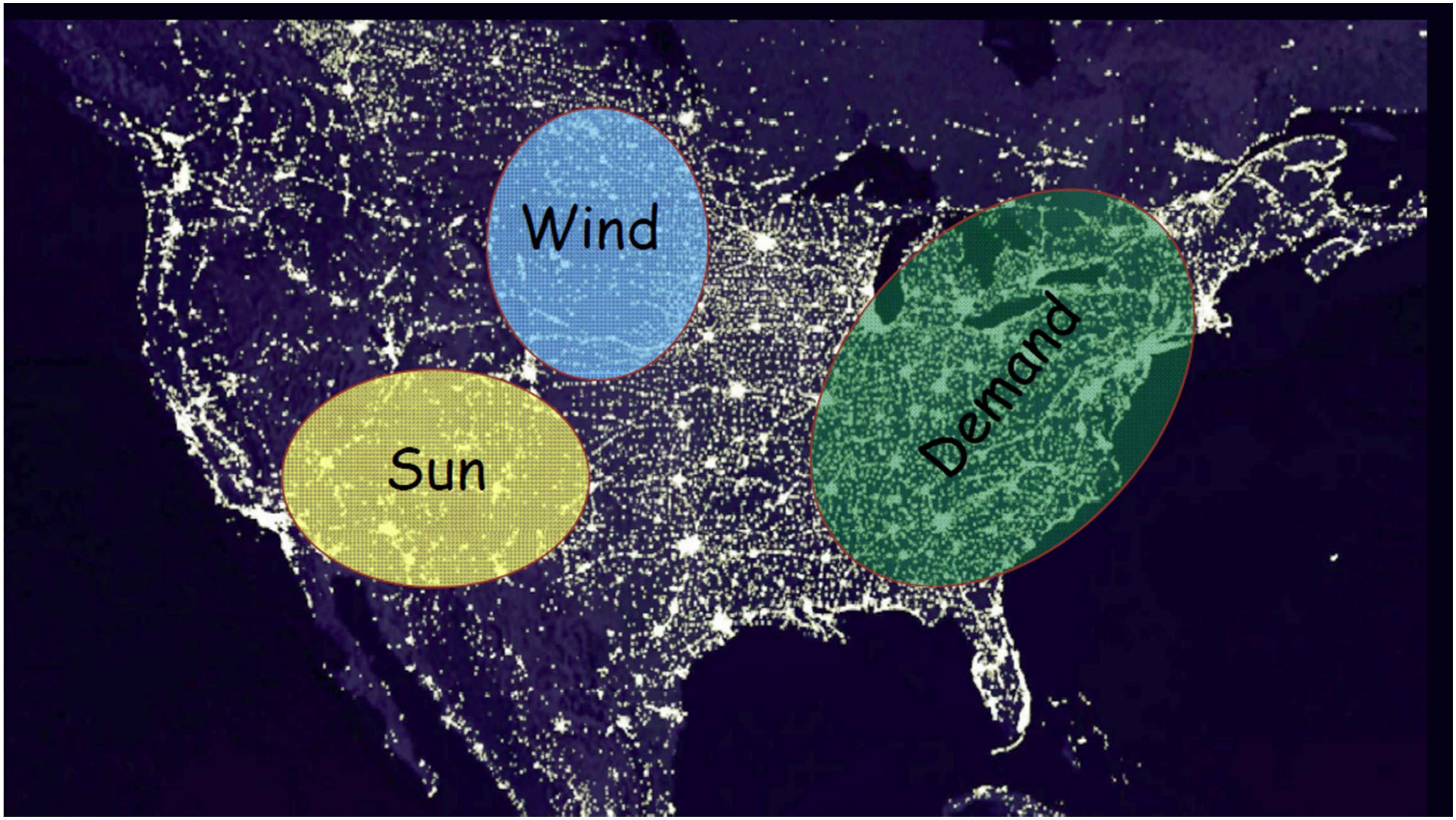
- HVDC, +/- 500 kV, 3.1 kA, 3.1 GW
- 1,362 km
- ~50% of LA Power Consumption
- Converter/Inverter Losses ~ 5%
- Ohmic Losses ~10%

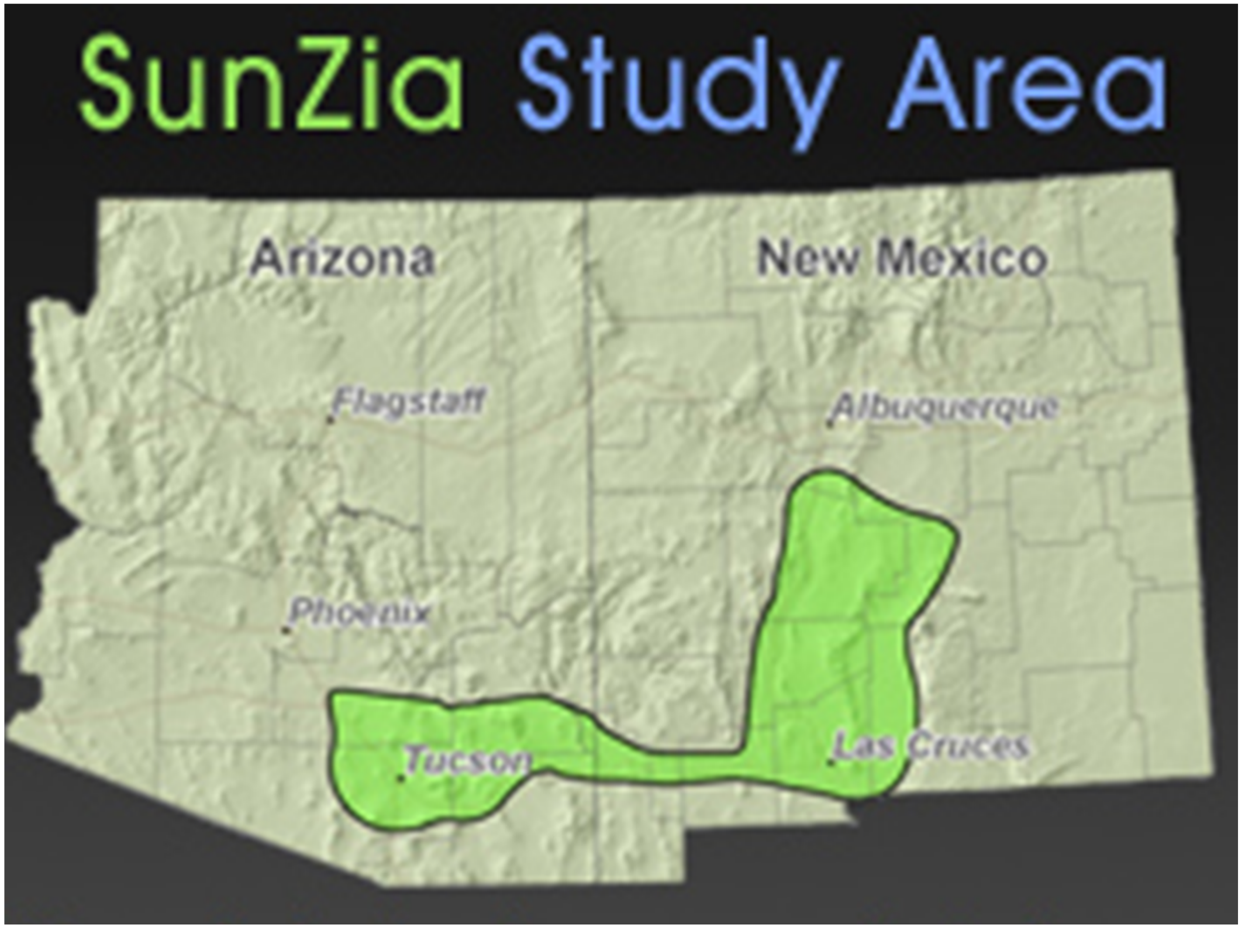
Celilo I/C Station
“A Mountain of Silicon”

North American HVDC



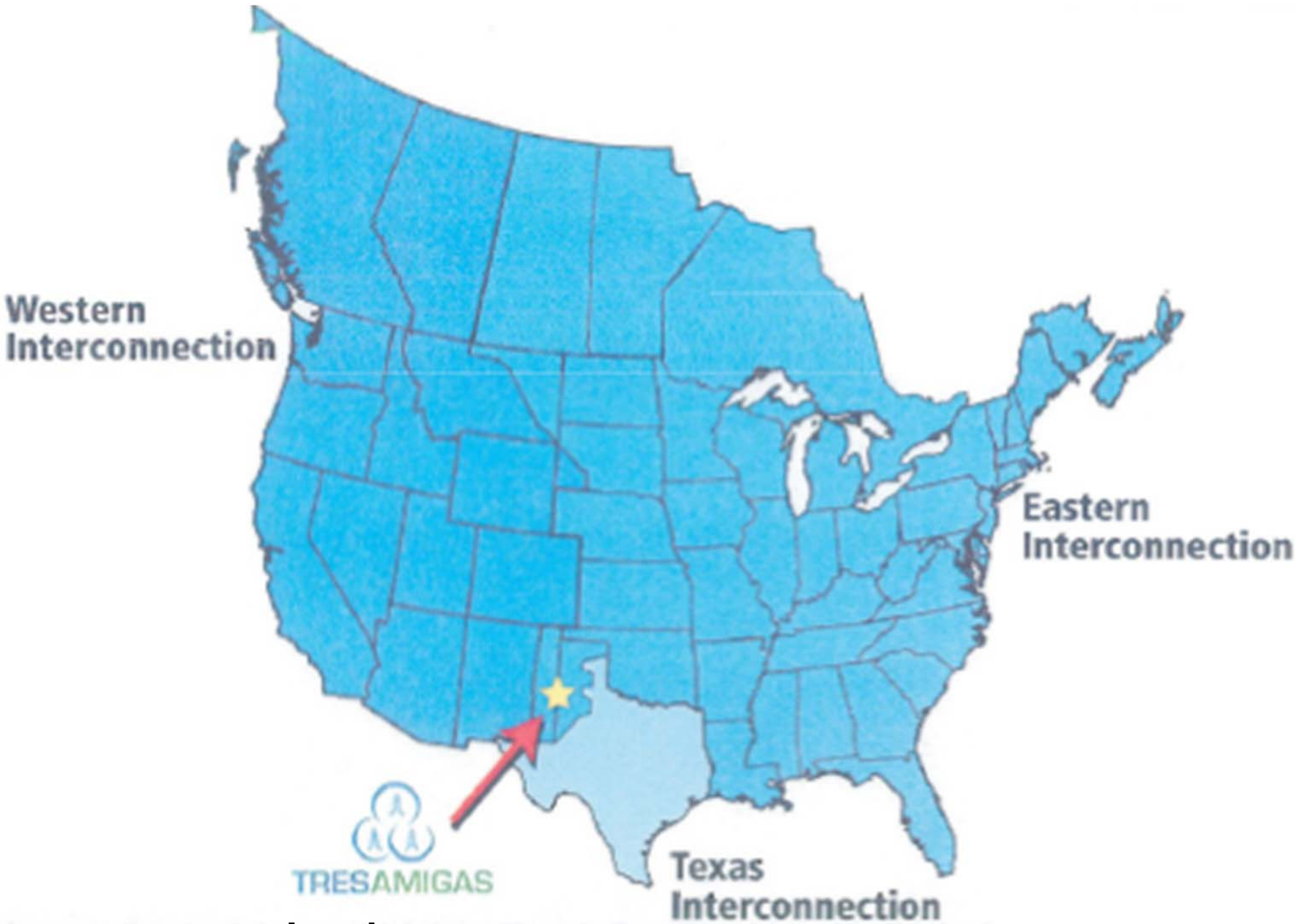
The "Green" Energy Economy





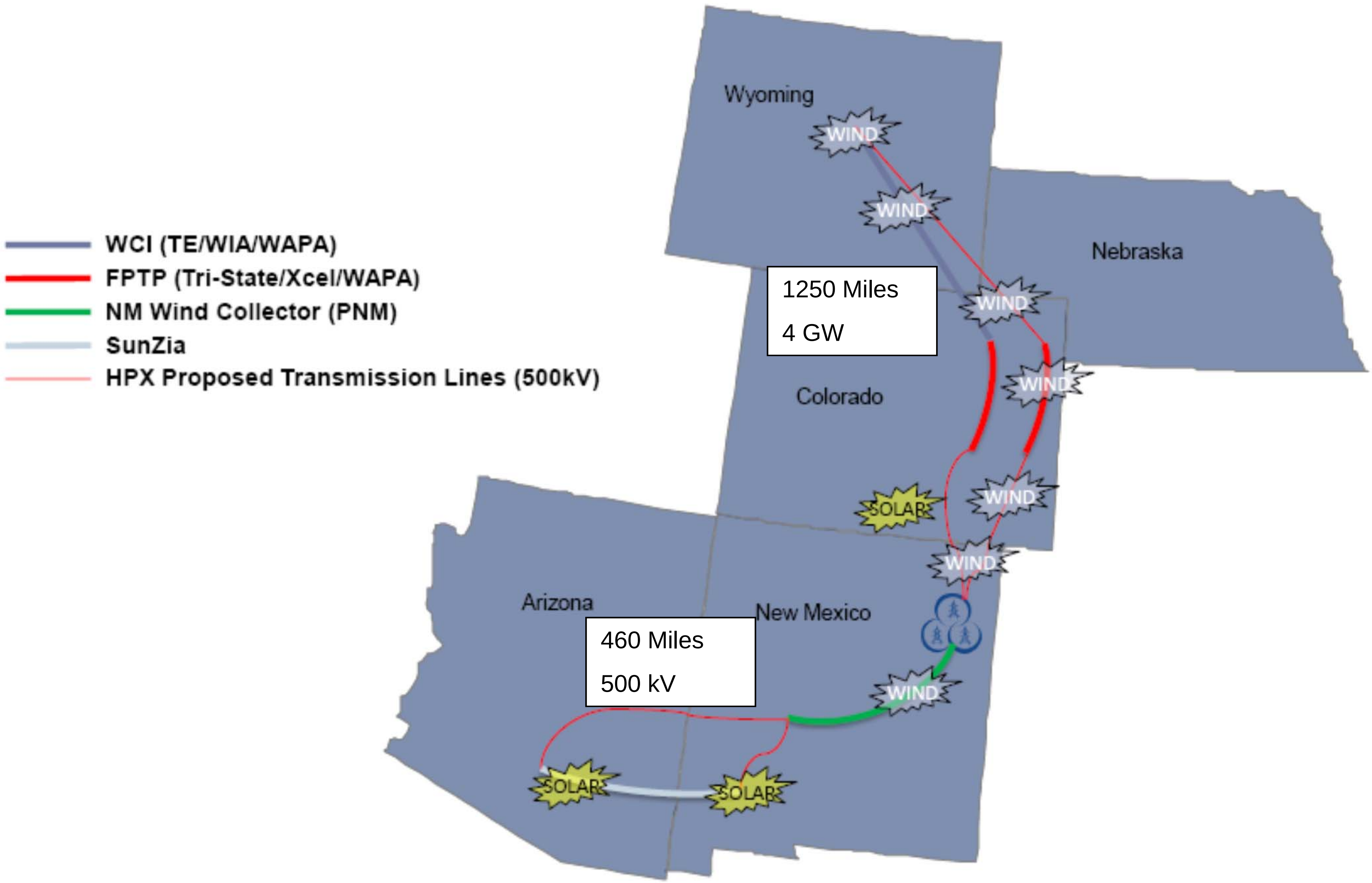
www.sunzia.net

“Three Girl Friends”



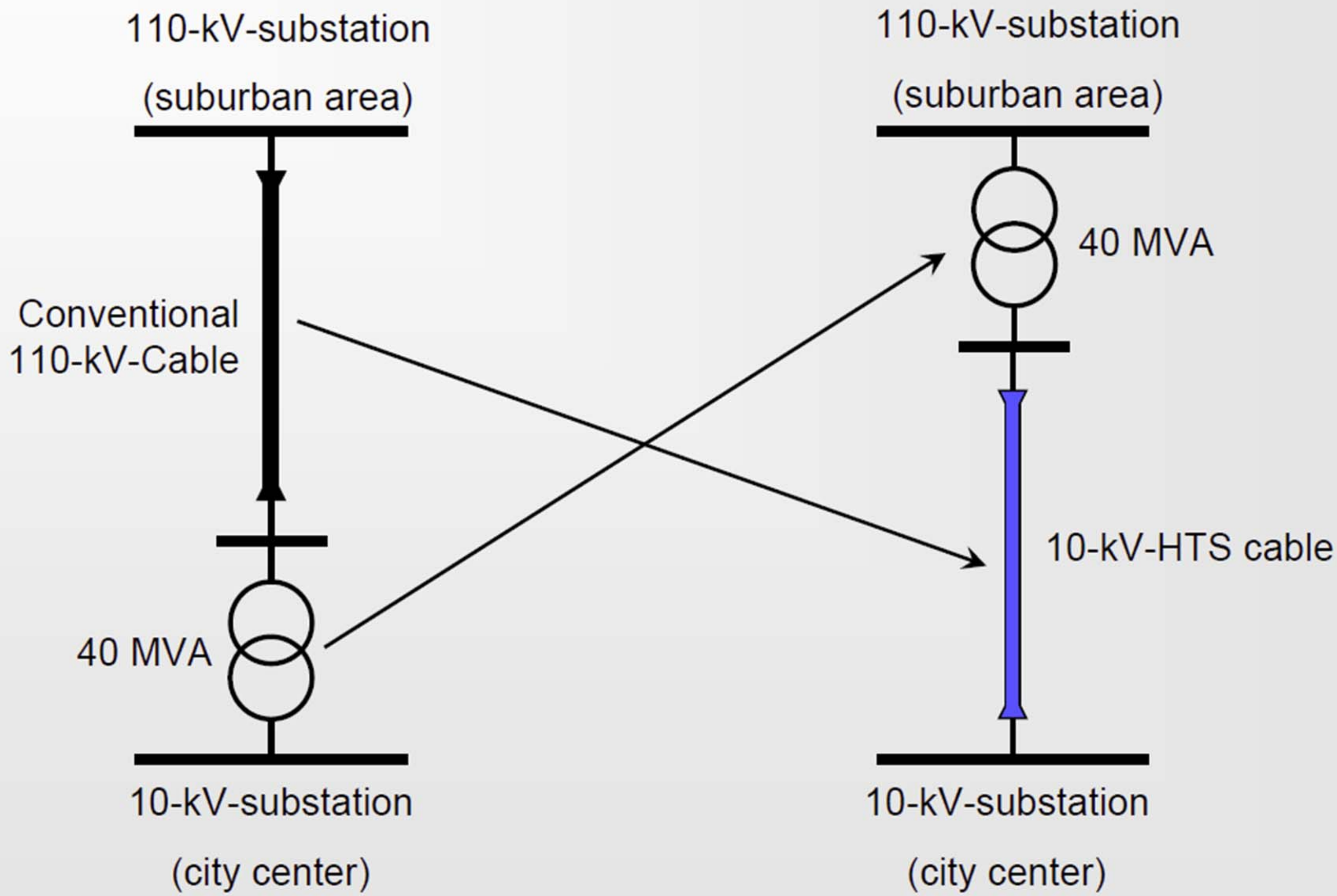
Clovis, NM

Potential Beneficiaries in WECC



Nexans

Project SupraCity

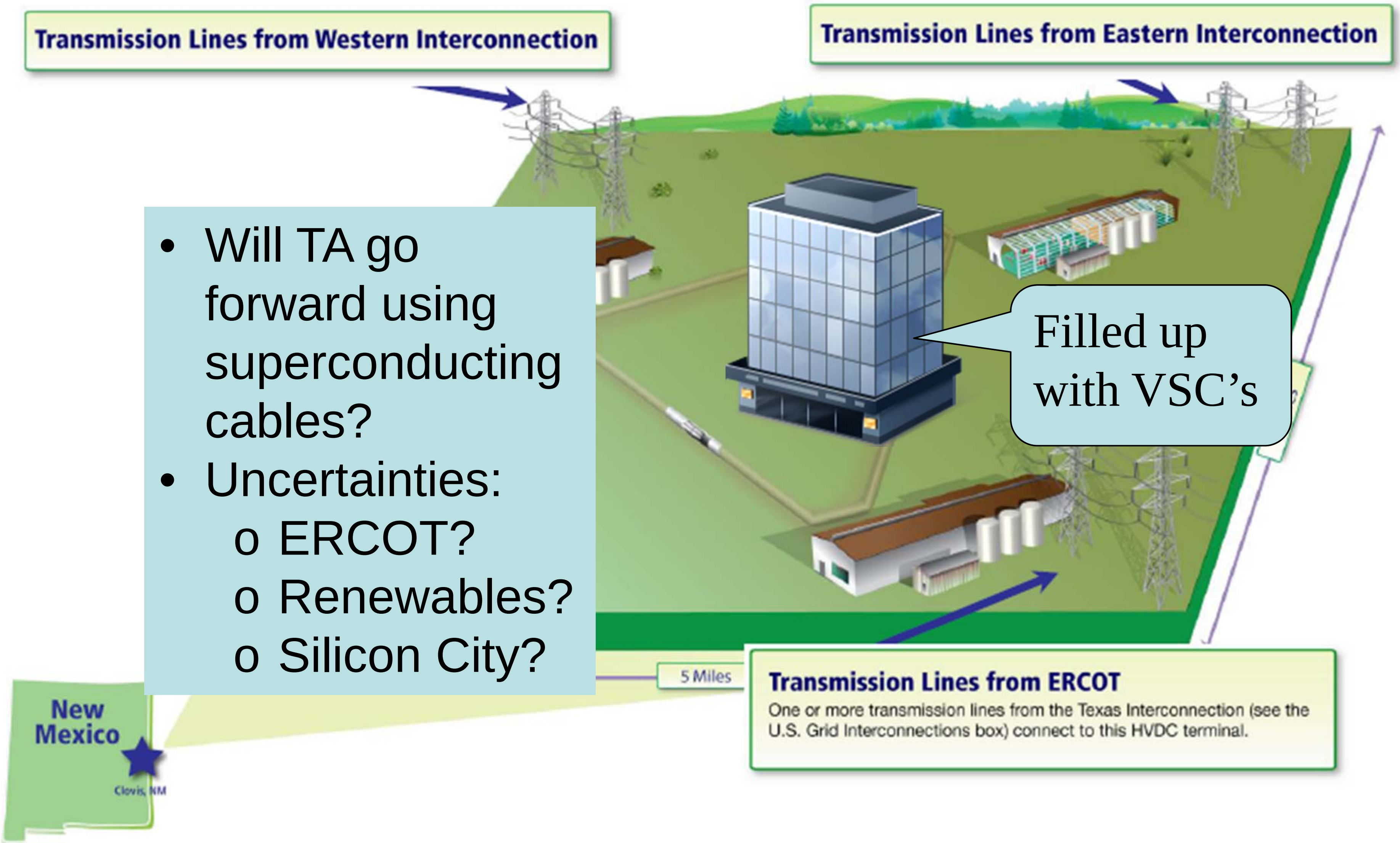


Supply of city center by MV HTS cable

HTSC Cables

- Deployment Realities -

The Tres Amigas SuperStation



- Will TA go forward using superconducting cables?
- Uncertainties:
  - ERCOT?
  - Renewables?
  - Silicon City?

A Modest Proposal*

-"Upbraiding" the Utilities-

- More than a half-century of successful demonstrations/prototyping power applications of superconductivity (1950s -> "beyond" 2000, in Japan and US…and elsewhere)…low- and high-Tc…now sitting "on the shelf."
- Why aren't they "in the field" today?
- Is their absence due to…
  - Cost?
  - Hassle?
  - or "lack of compelling" need?
  - or "all of the above?"

*Apologies to Jonathon Swift

- US utilities have long claimed to "want"…
  - Efficient long-length cables
  - Oil-free transformers
  - Energy Storage
  - Fast fault current limiters at high voltage (FCLs)
  - Efficient rotating machinery (aka, motors and generators)
- Well, we got 'em. Utilities claim:
  - They're too high-cost, because,
    - The wire is too expensive.
    - They have to be kept too cold.
    - Electricity is cheap, and "in field" energy efficiency is not a "compelling" driver
  - Anyway, we can solve our needs by incrementally improving the "old" ways (don't ever underestimate the ingenuity of a utility engineer to improvise, adopt and adapt)

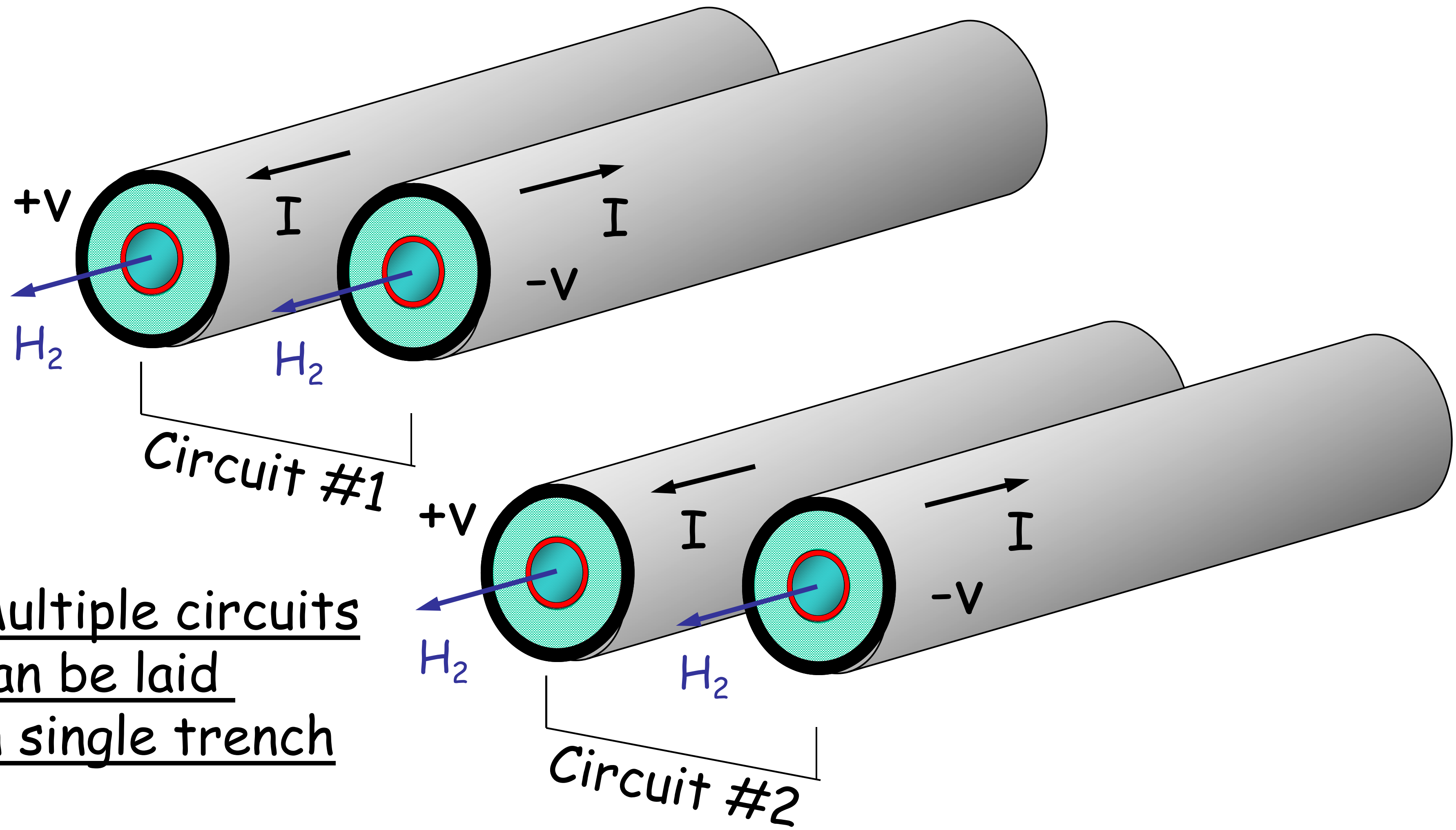
Hence, “my modest proposal”

- If the “cost” of the wire in any given application were to be “zero,”…
- Would the utilities then “buy them?” And sign a “letter of intent” to purchase “x” number?
  - e.g., Fault Current Limiters, for which US utilities have long claimed a need
- “Zero cost” would be obtained as a Federal or State “tax credit” for the wire cost of the quantity purchased by the utility equipment vendor or the utility itself…
- Well?

HTSC Cables

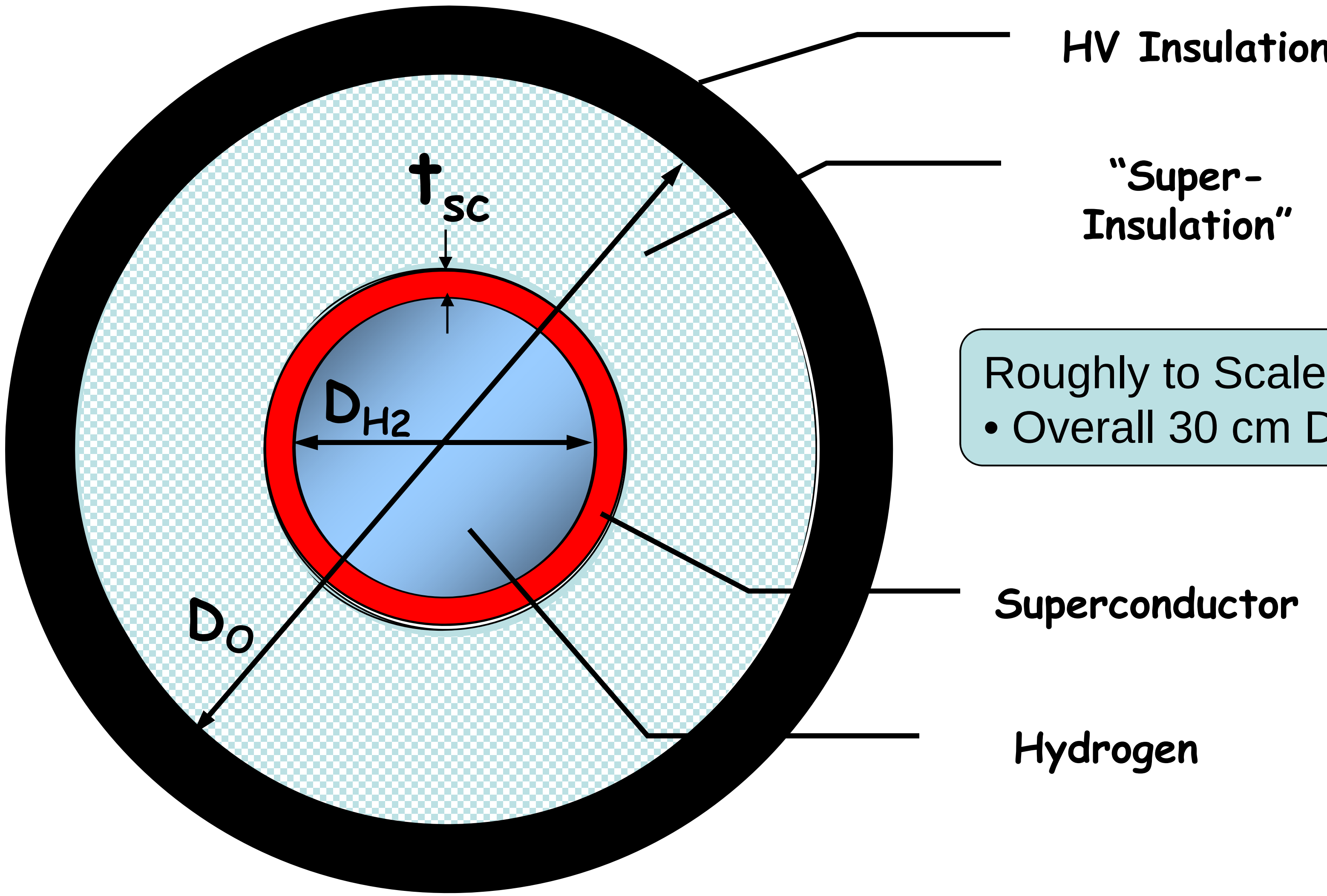
- SuperCables -

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



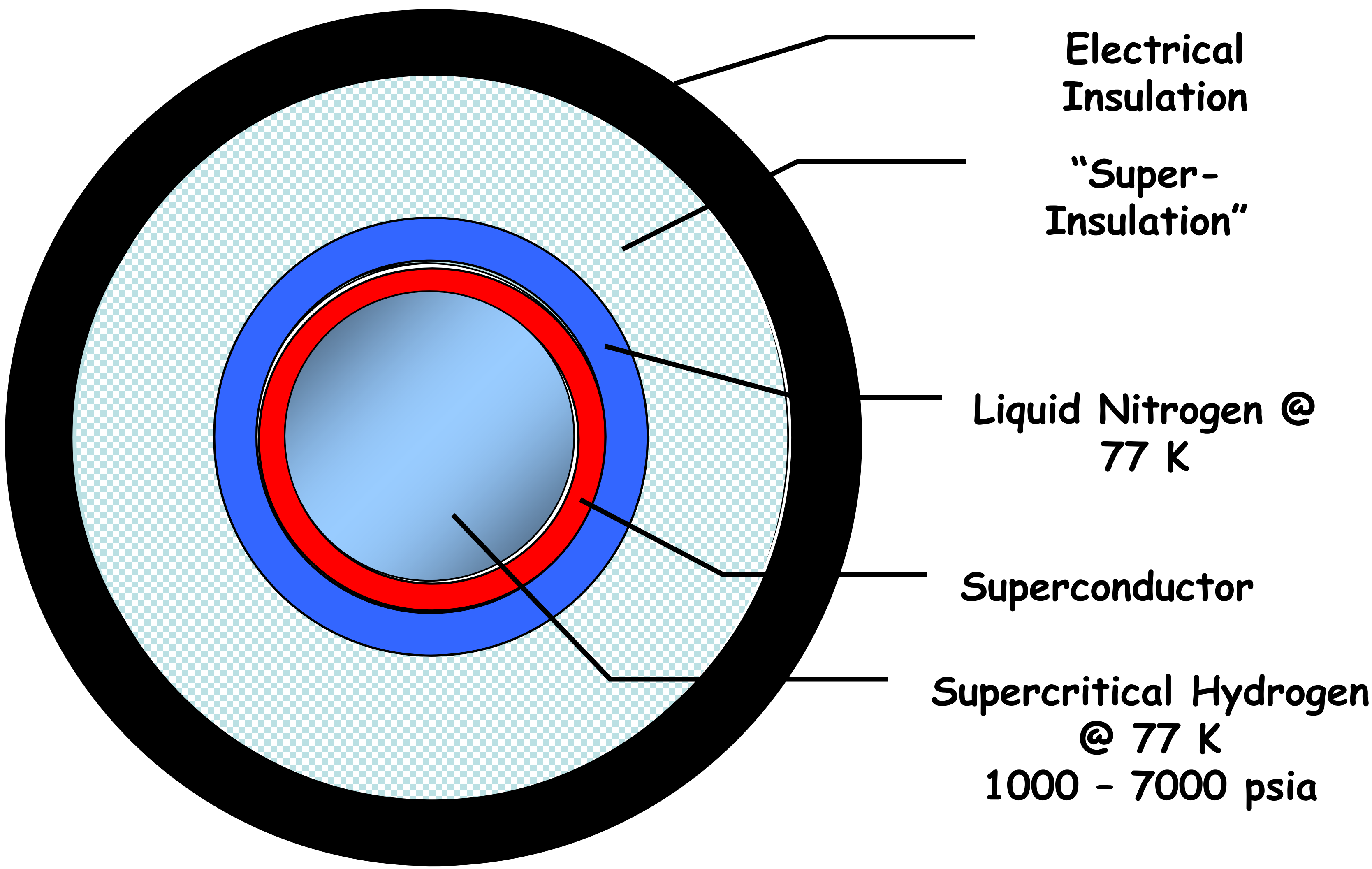
Multiple circuits can be laid in single trench

LH_2 SuperCable



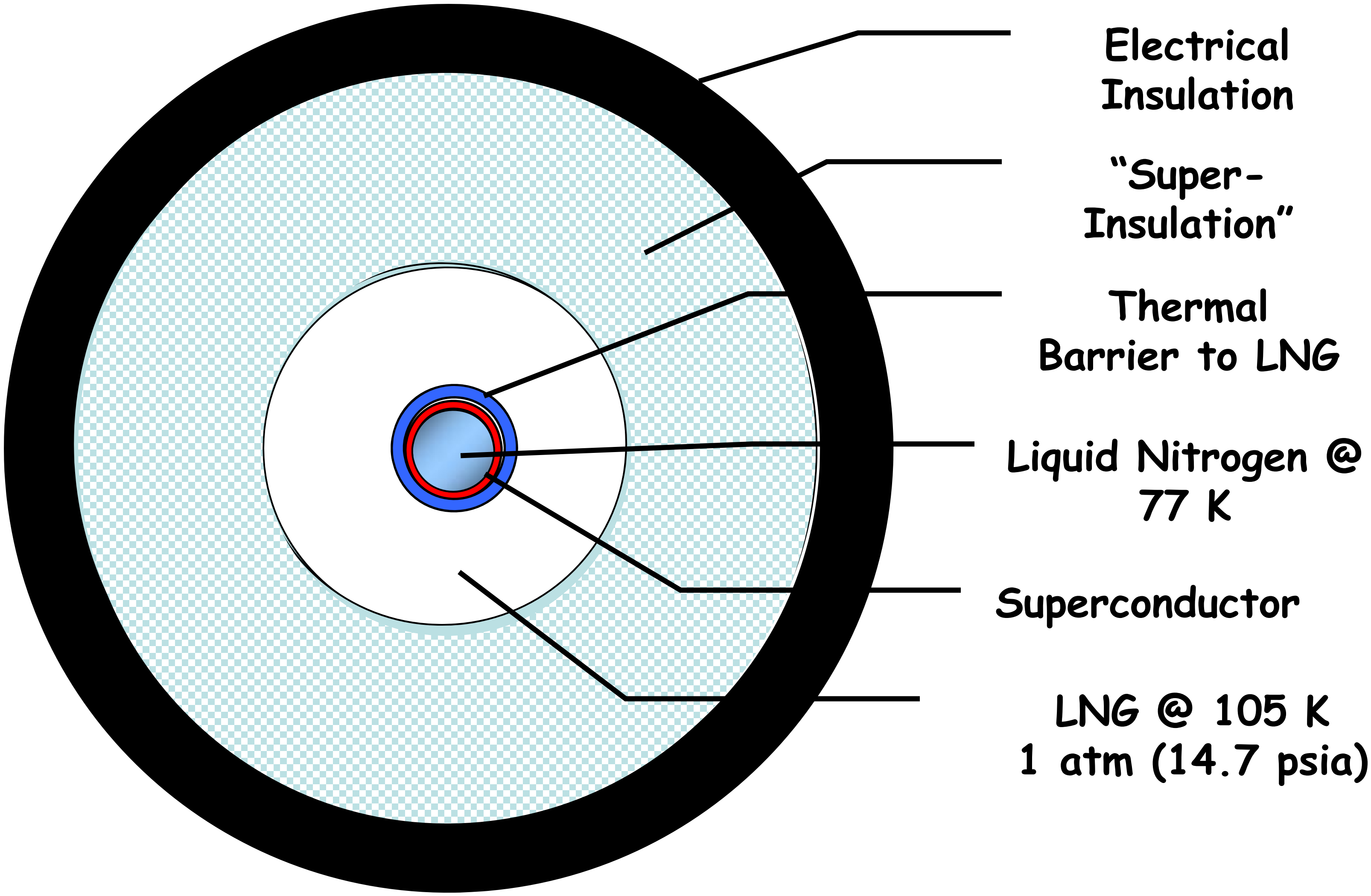
Roughly to Scale:
- Overall 30 cm Diameter

Supercritical H_2 SuperCable



LNG SuperCable

Design for eventual conversion to high pressure cold or liquid H_2



Hg-1223 !

(12) **United States Patent**
Chu et al.

(10) **Patent No.: US 6,329,325 B1**
(45) **Date of Patent: Dec. 11, 2001**

(54) **HIGH TEMPERATURE SUPERCONDUCTING TAPE AND METHOD OF MANUFACTURE**

(75) Inventors: **Ching-Wu Chu**; **Ruling L. Meng**; **Yu-Yi Xue**, all of Houston, TX (US)

(57) **ABSTRACT**

Highly oriented $HgBa_2Ca_2Cu_3O_{8+\delta}$ on Ni-tapes with a buffer layer of Cr/Ag or Cr/(Ag—Pd) have been described with a high transition temperature are described along with, one and two step methods of manufacture.

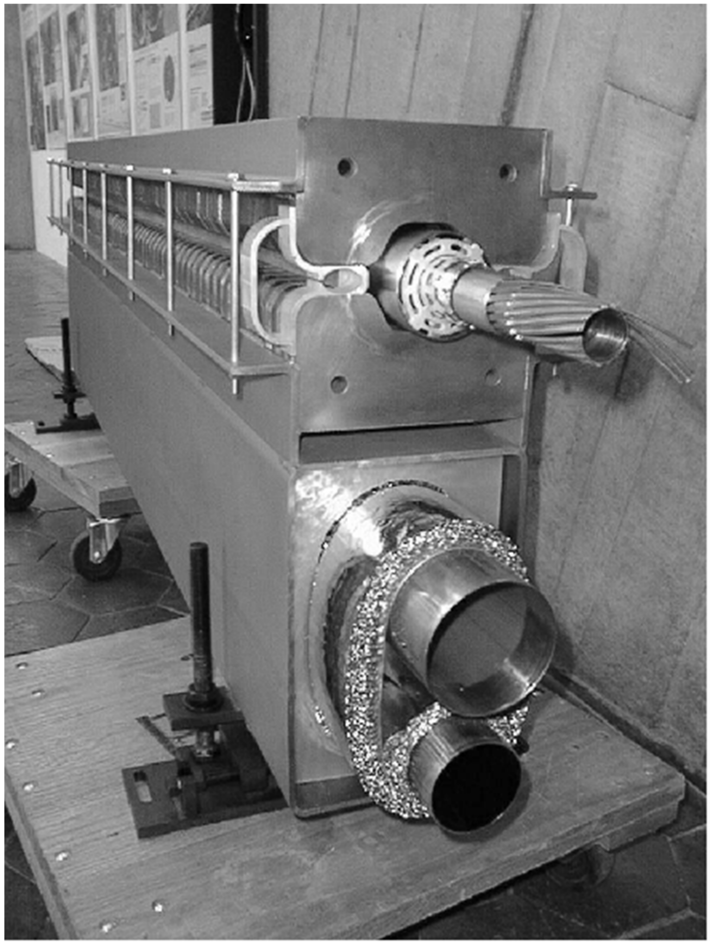
…funded by EPRI

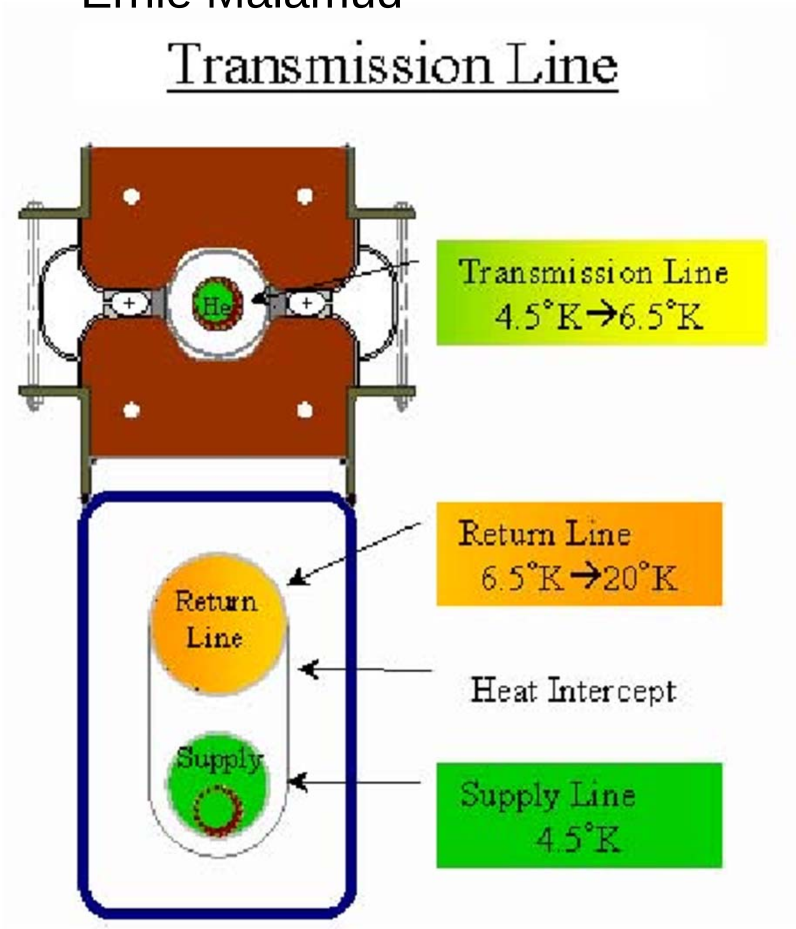
HTSC Cables

- MegaProjects -

The Next American Big-Bang-a-Tron

Bob Wilson
Bill Foster
Peter Limon
Ernie Malamud





The Pipetron…Stay tuned for Lance Cooley's Talk This Afternoon!

Powering the Middle East
- "*The e-Pipe*" – The Ultimate Vision!

Concept:

- Wellhead generation by natural gas in Qatar
- Transport power via HTSC cable to the Levant

Specifications:

- 1610 km
- 50 kA, +/- 50 kV
- 5 GW
- 1.3 x Pacific Intertie !

See EPRI Report WO8065-12 (1997)

A Canadian's View of the World

The Mackenzie Valley Pipeline

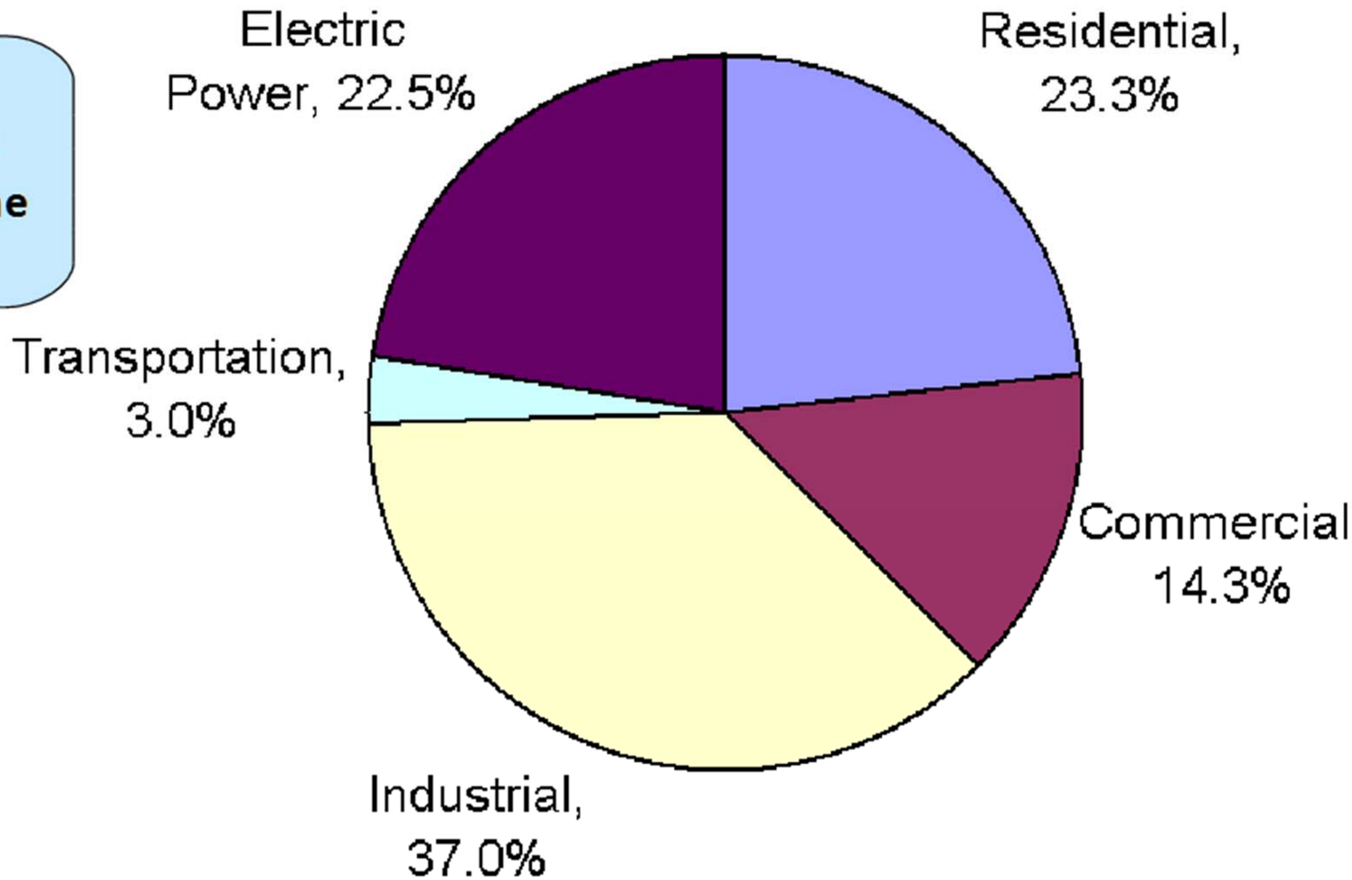
http://www.mackenziegasproject.com

1220 km
18 GW-thermal
2006 - 2010

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)

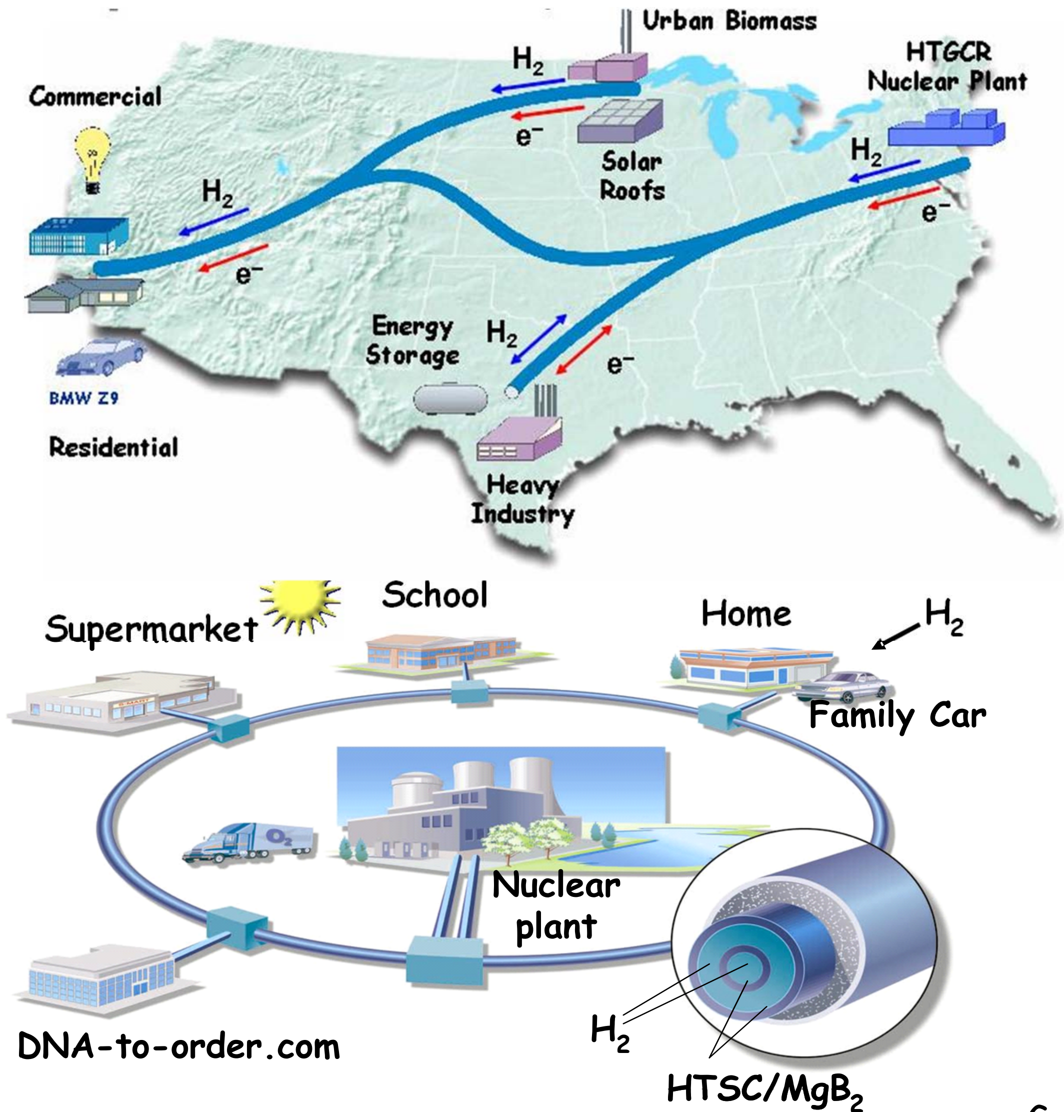
SuperCable Parameters for LNG Transport

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.

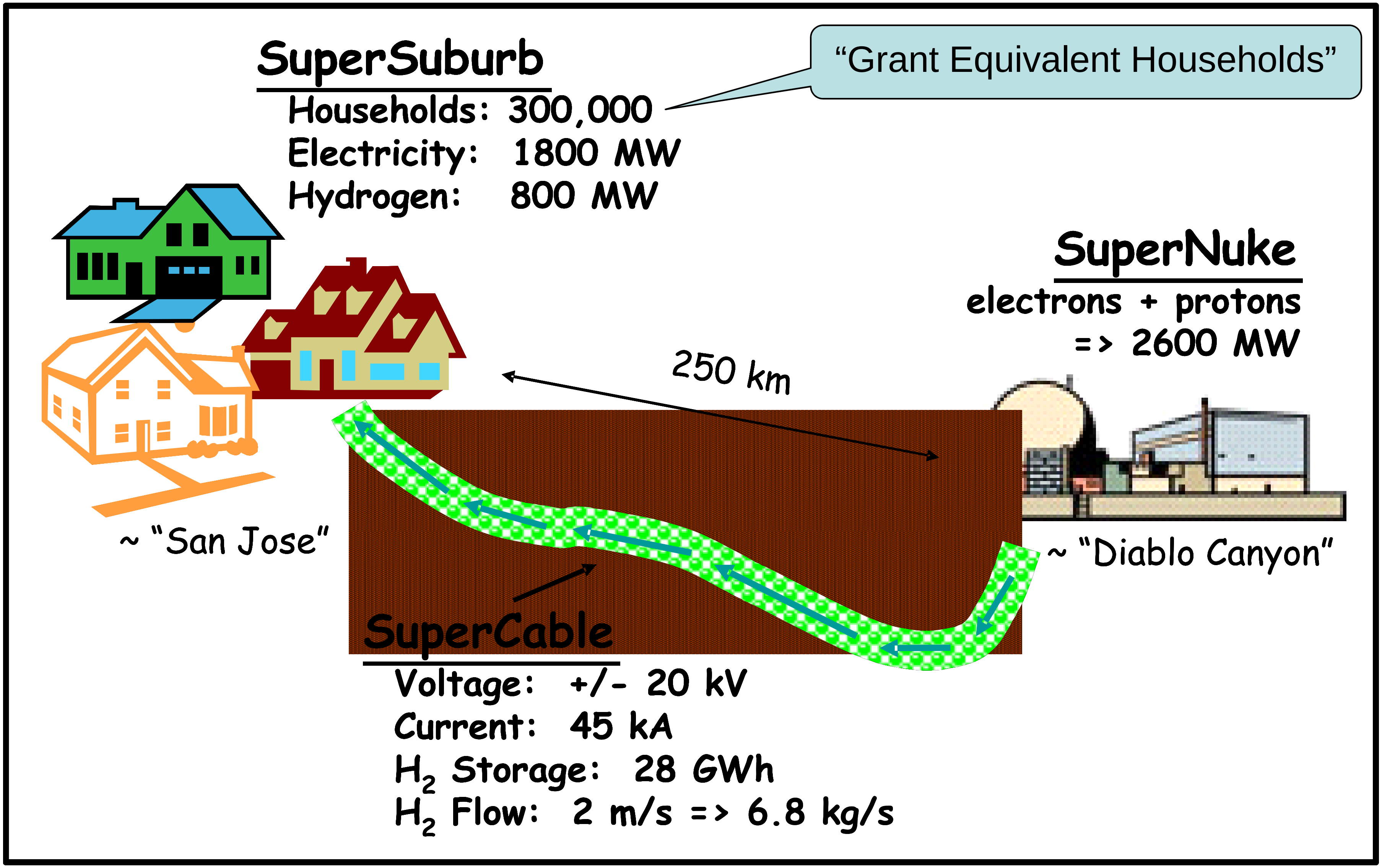
SuperCities & SuperGrids



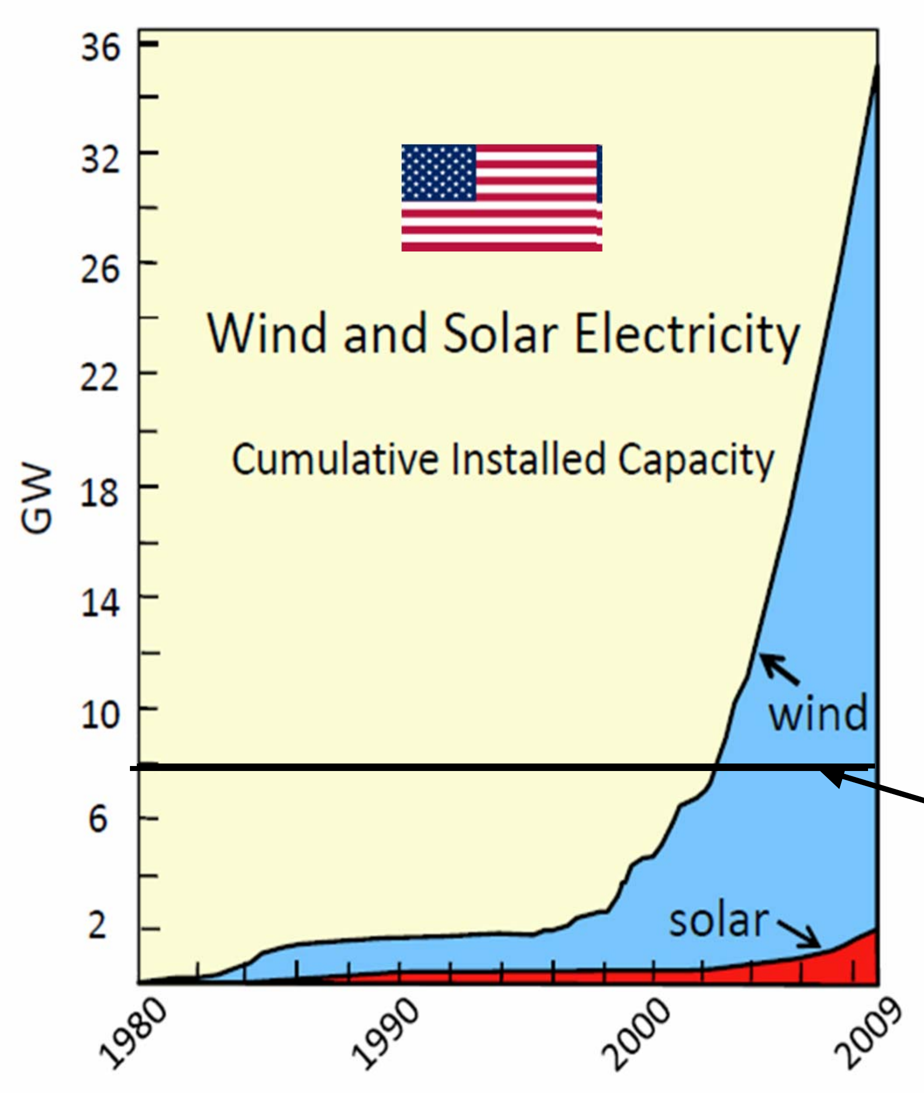
- Nuclear Power can generate both electricity and hydrogen – "Hydricity"
- Hydricity can be distributed in underground pipelines like natural gas
- The infrastructure can take the form of a **SuperGrid**
- ...or a **SuperCity**

Grant, Starr, Overbye, SciAm, July 2006

SuperSuburb

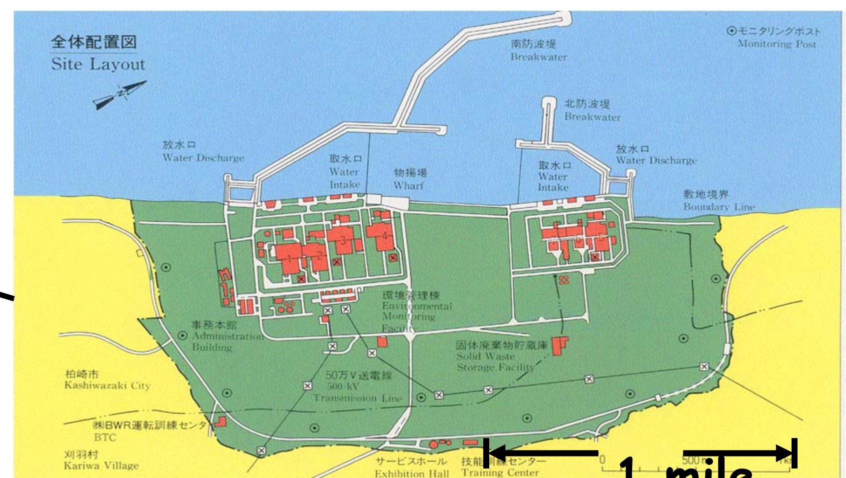


Wind Power Factoids



KK Wind Equivalent (8 GW)

• Power per Tower	8 MW
• Number of Towers	1000
• Inter-tower Distance	1000 ft
• Total Area (miles x miles)	43.5 x 43.5



Kashiwazaki Kariwa: 8 GW !

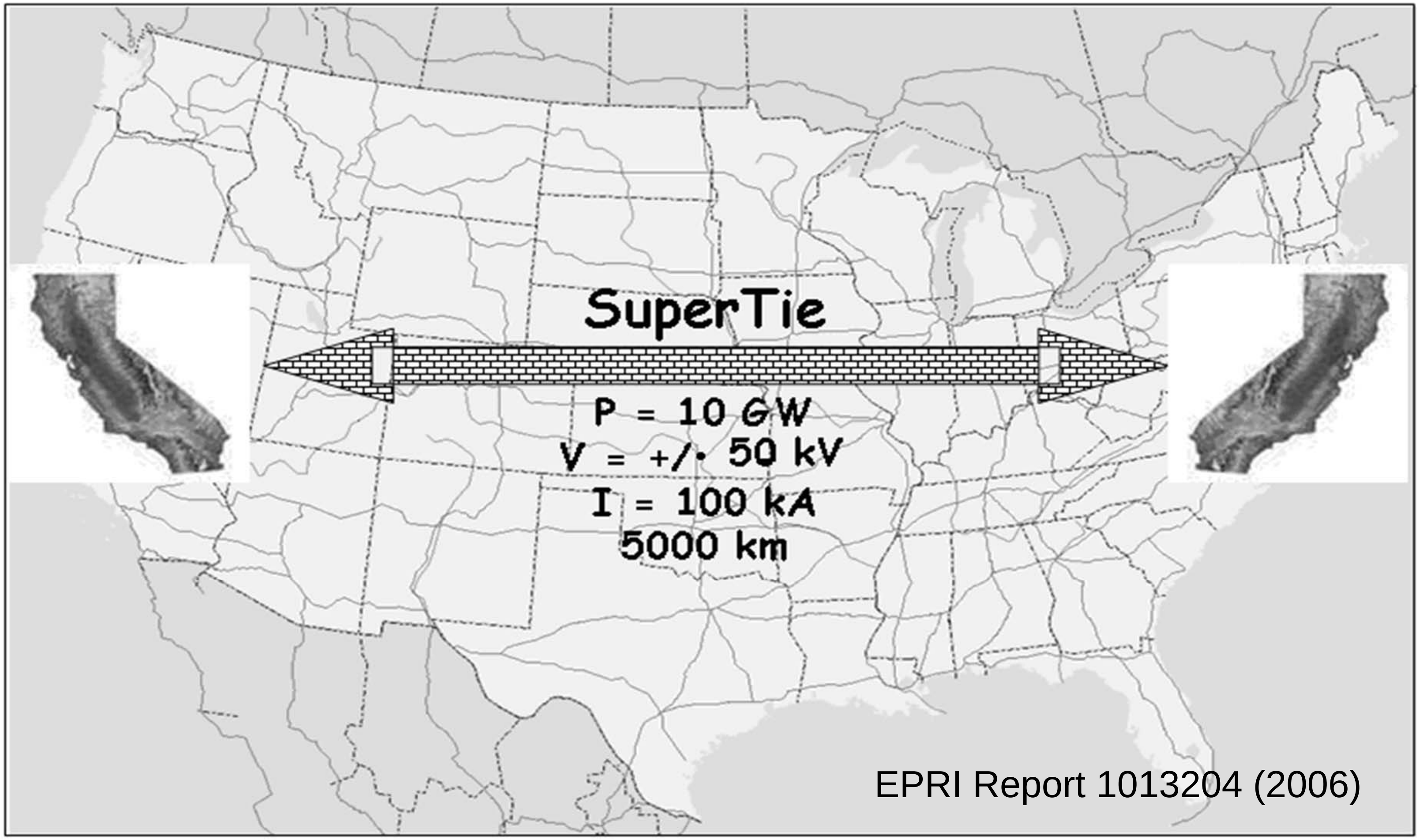
Diablo Canyon

My Virtual Grandfather (@ 94)

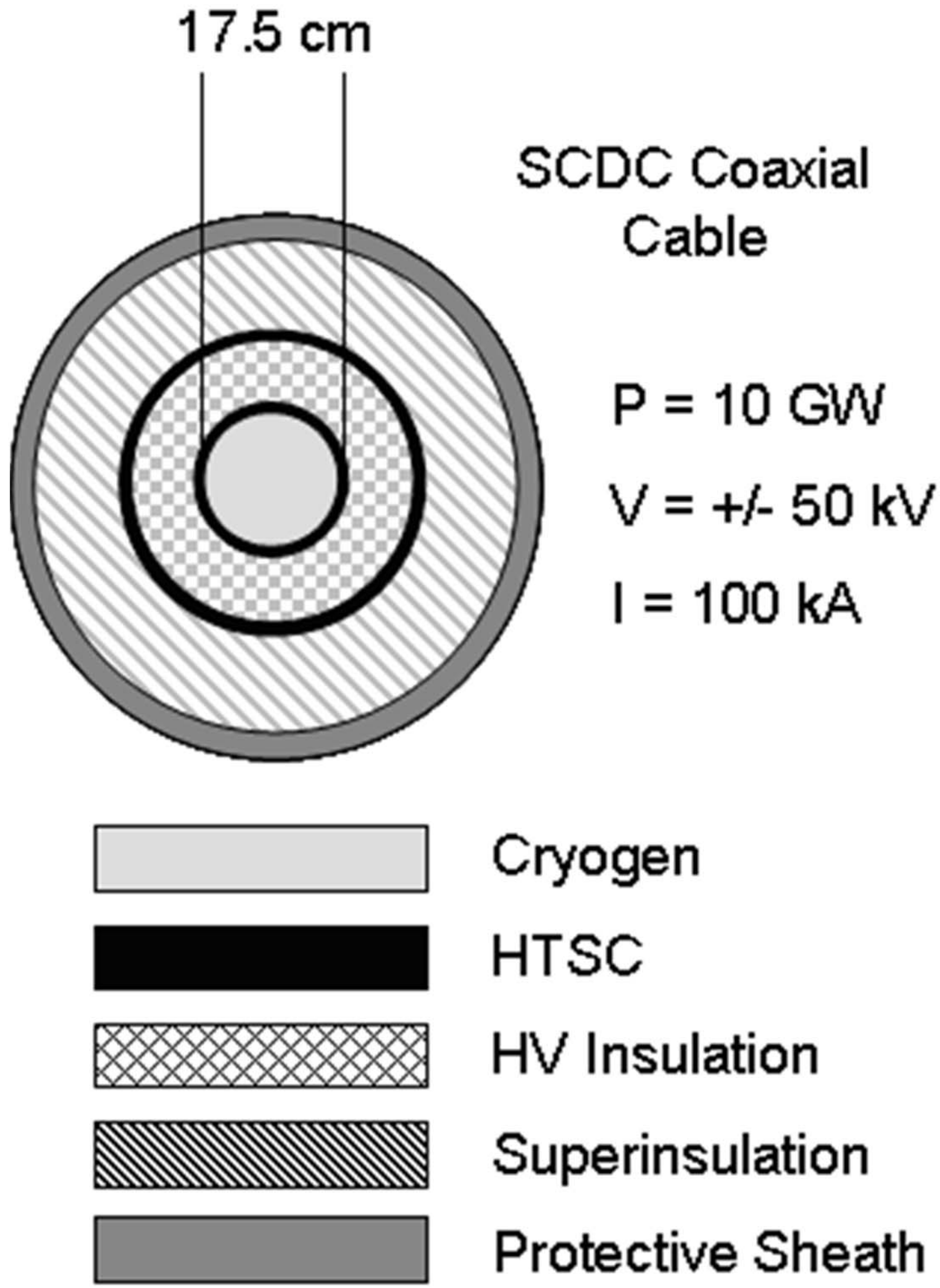
SuperTies

- “Hotel California” -

"Paired Californias"
(Garwin-Matisoo Reborn)



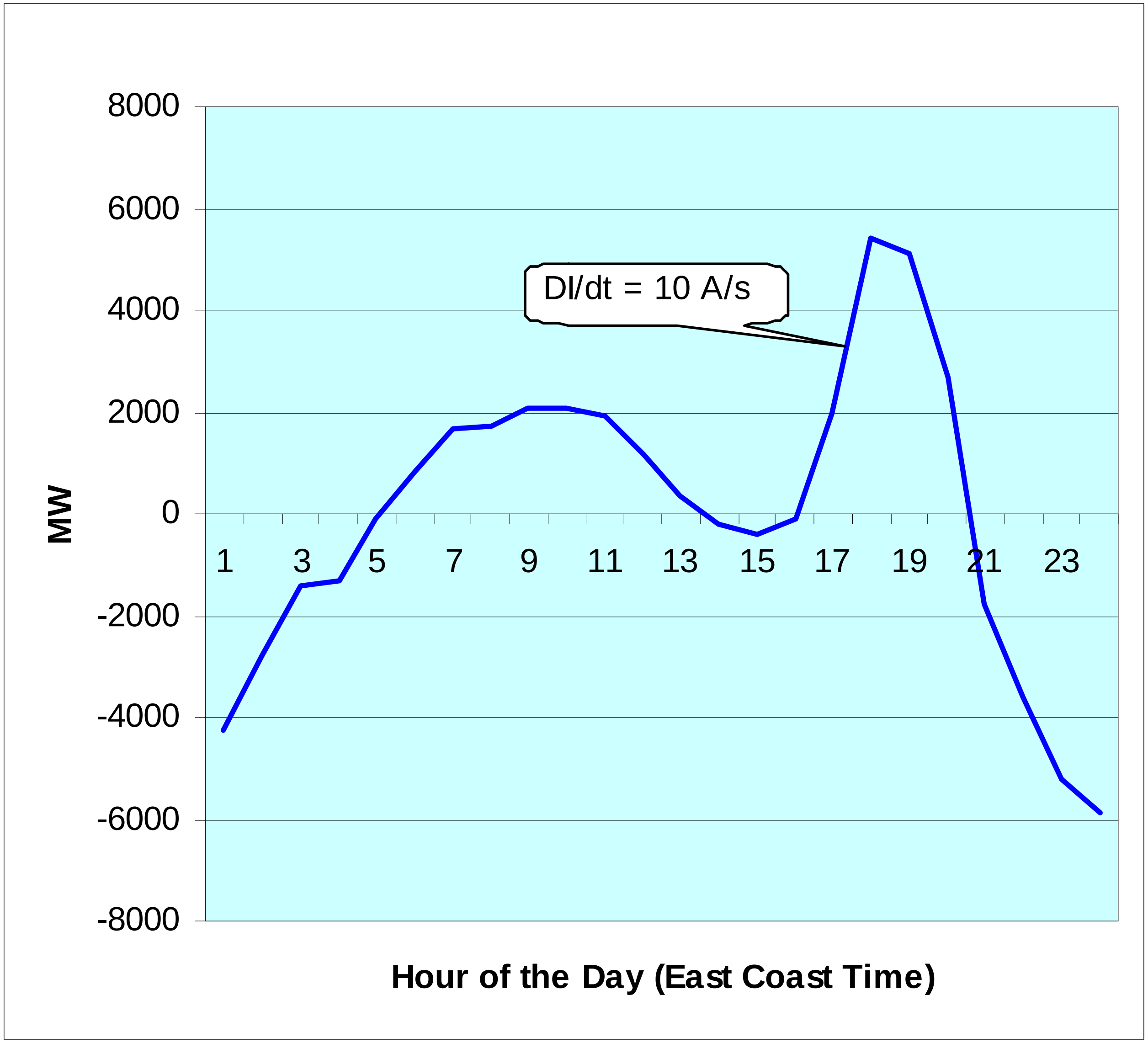
EPRI Report 1013204 (2006)


17.5 cm
SCDC Coaxial Cable
P = 10 GW
V = +/- 50 kV
I = 100 kA
Cryogen
HTSC
HV Insulation
Superinsulation
Protective Sheath

SCDC SUPERTIE CABLE DESIGN AND PERFORMANCE PARAMETERS

Item	Value/Quantity	Units
HTSC Tape Parameters		
(77 K, 0.3 T)		
- Critical Current Density, J_C	15,000	A/cm^2
- Tape Critical Current, I_C	150	A/tape
- Cost/Performance	50	\$/(kA×m)
- Width	0.4	cm
- Thickness	0.025	cm
- Single Tape Length	800	m
- Integration "wasteage"	5	%
- Joint Resistance	0.92	mW
- I^2R Dissipation per Joint	0.8	mW/m
SuperTie SCDC Cable		
Parameters and Performance		
- Overall Length	5000	km
- Number of Conductors*	2	1 per pole
- Conductor Annular Radius	8.75	cm
- Maximum Power	10	GW
- dc Voltage	50	kV per pole
- dc Amperage	100	kA
- Field at Conductor Surface	0.23	T
- Conductor X-Section Area	6.62	cm^2
- # HTSC Tapes/X-Section	667	
- Total Tape Length/Pole	3,475,600	km per Conductor-Pole
- Total # Joints per Pole	4,345,000	
- Power Lost in Joints/Pole	4.0	kW
- HTSC Tape Cost per Pole	26.3	B\$

“Difference between Day and Night”



“Sanity Check”

- Worst Case: Assume a “toleration loss” no larger than 1 W/m, then the entire SuperTie could be reversed in only 2 hours.
- The “fastest” change would be ~ 10 A/s between 5 and 6 PM EST. Compare with 1% ripple on 100 kA at the 6th harmonic of 60 Hz which is 720,000 A/s!

5000 km SuperTie Economics

Base Assumption: C/P "Gen X" = $50/kA×m

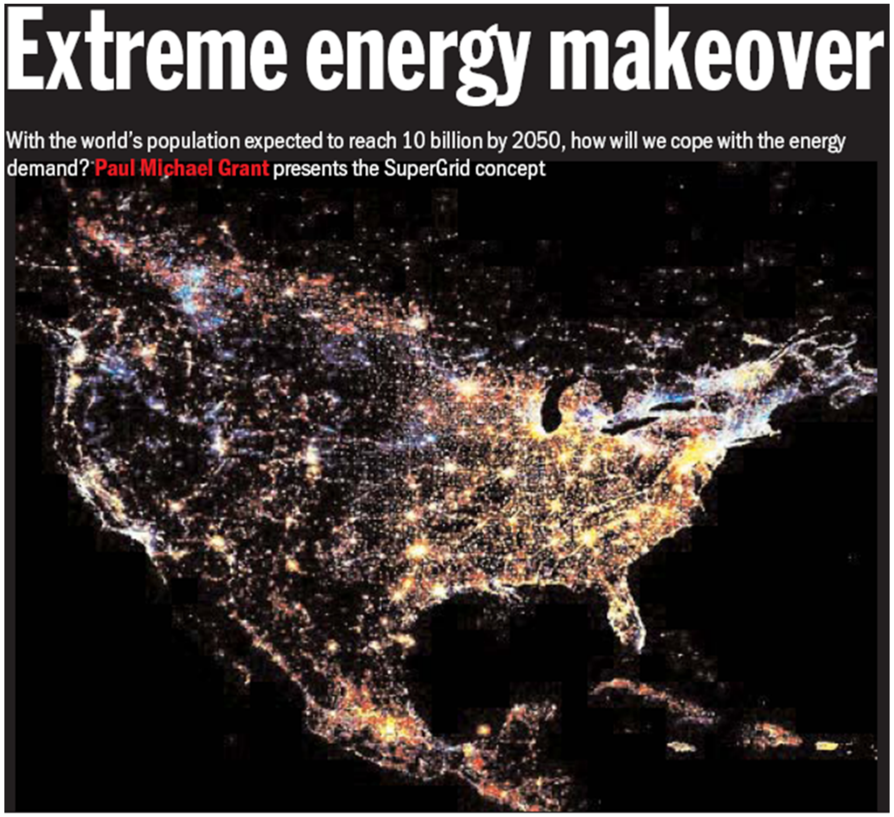
Cost of Electricity ($/kWh)	Line Losses in Conventional Transmission (%)	Annual Value of Losses on 10 GW Transmission Line @ 50% Capacity (M$)	Additional Capital Costs for HTSC and Refrigeration (M$)	FRB Discount Rate (%)	Period for ROI (Years)
0.05	5 %	110	52,574	5.5 %	62

"Deregulated Electricity" will <u>not</u> underwrite this ROI, only a "public interest" investment analogous to the Interstate Highway system makes sense

Possible SuperTie Enablers

- Active public policy driving energy efficiency
- Carbon tax
- Tariff revenue from IPPs accruing from massive diurnal/inter-RTO power transactions

Physics World, October 2009



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 Nature…?

Some Other Axioms of History

- History is more or less bunk

  Henry Ford

- I can't think about tomorrow...I'm as lost as yesterday

  Tomorrow, by Bob Seger

- If I'm not smart enough to solve it (a problem), neither is anyone else!

  Anon.

Superconductors
- The Long Road Ahead –
Foner & Orlando (1988)

"Widespread use of these
[high temperature] superconducting
technologies will have far more to do with
questions of public policy and economics
than with the nature of the new materials."

“You can’t always get what you want…”

"…you get what you need!"