IASS POTSDAM

Transporting electric power with superconductivity ?

(Introductory remarks)

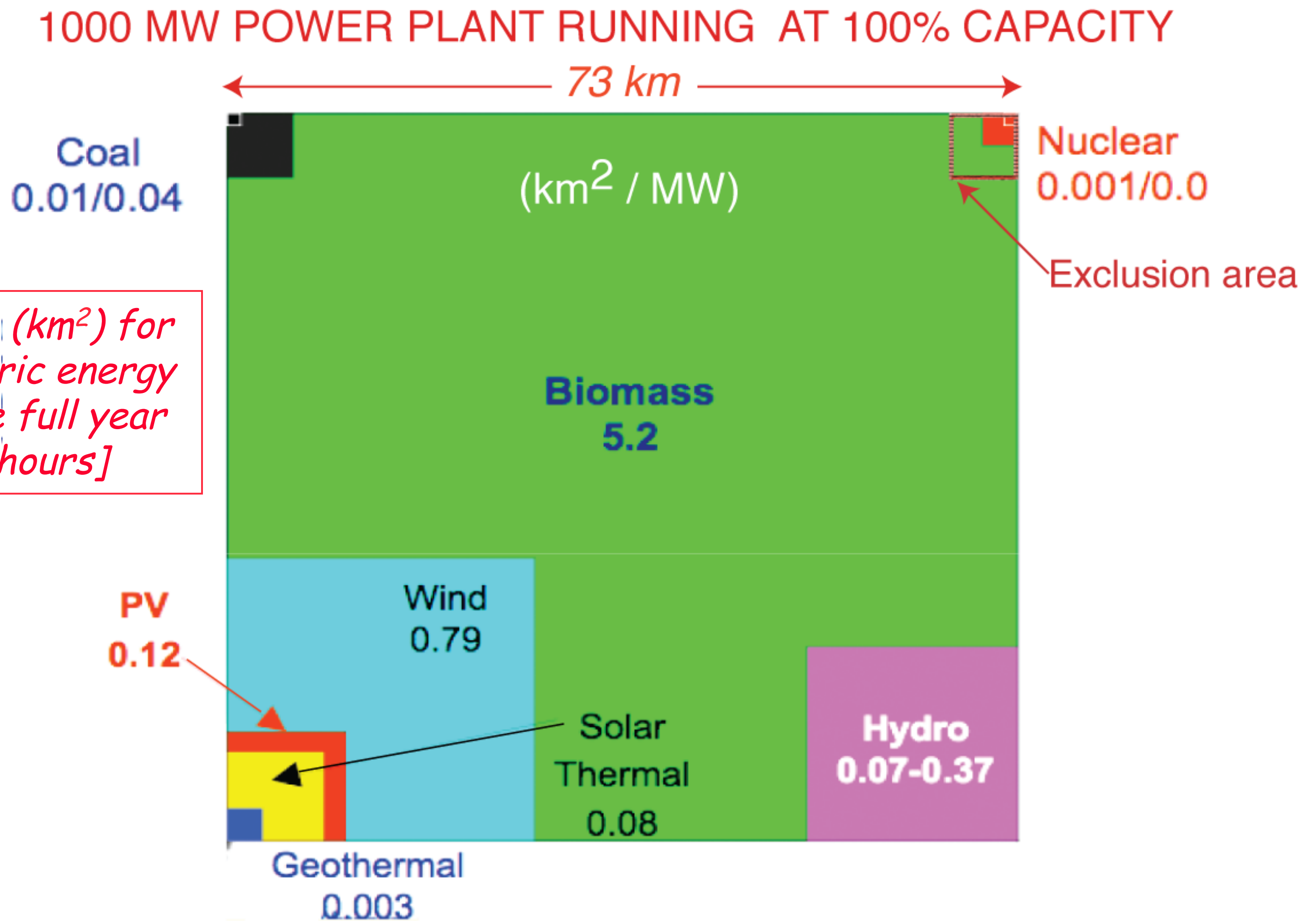
Carlo Rubbia

May 18th, 2012

Introduction

- The current worldwide energy supply is based mainly on the availability of fossil fuels.
- Although there is much concern the exhaustibility of these resources, they will remain indispensable in decades to come.
- The development of renewable energy sources and a more efficient and friendly utilization of fossils fuels has become an urgent necessity.
- The transformation of existing energy technologies into low-emission innovative solutions with a quantitatively significant management of CO_2 is one of the most important scientific and technological challenges of our times.
- Renewable energies at the required level of generation imply:
  - dominance of electric over thermal energy transmission.
  - far more extended distances between source and users.

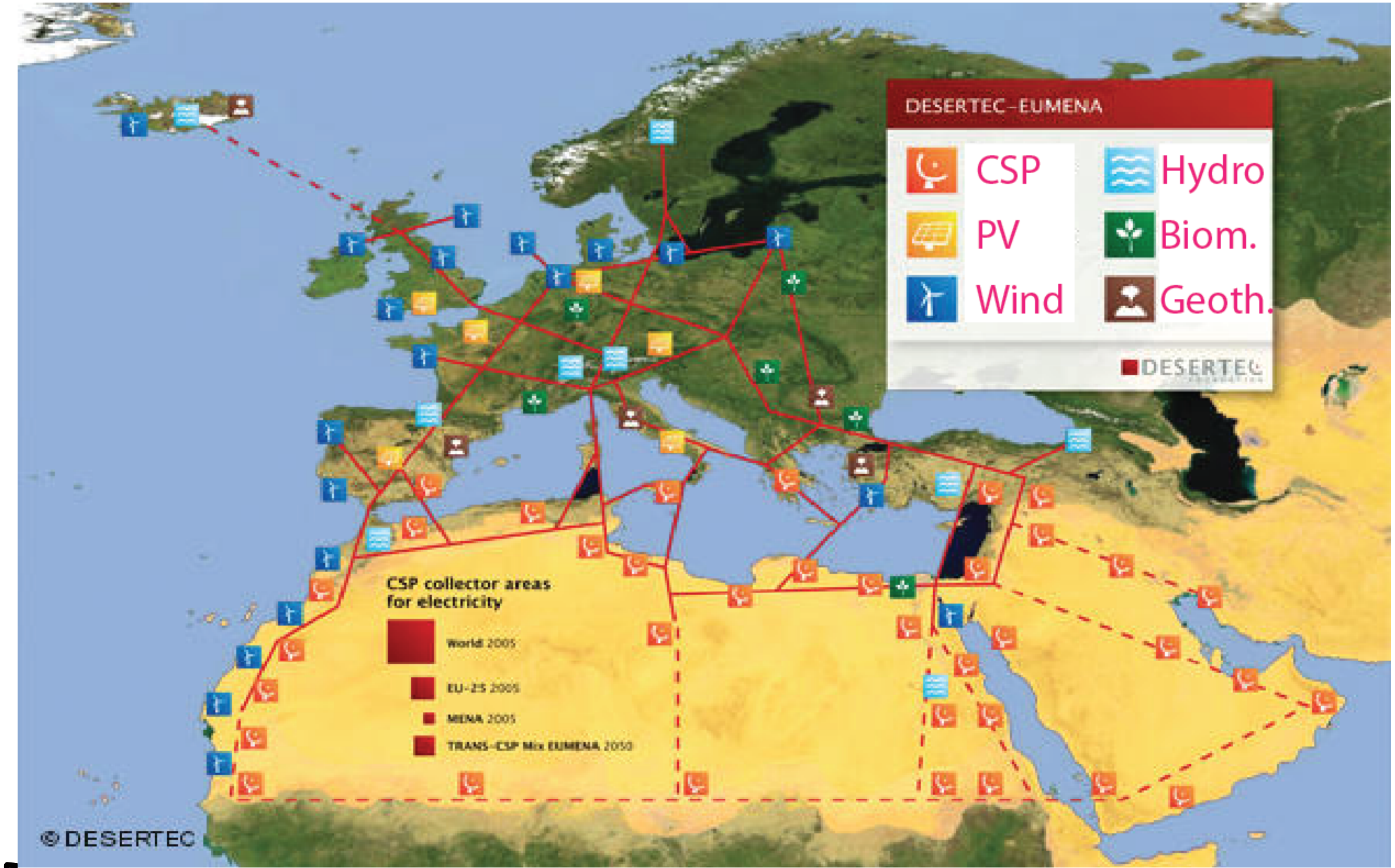
Environmental Impacts: Area requirements



Average land surface (km^2) for 1 MW x year of electric energy [integrated over the full year 24 x 365= 8760 hours]

Source: J. Davidson 2006

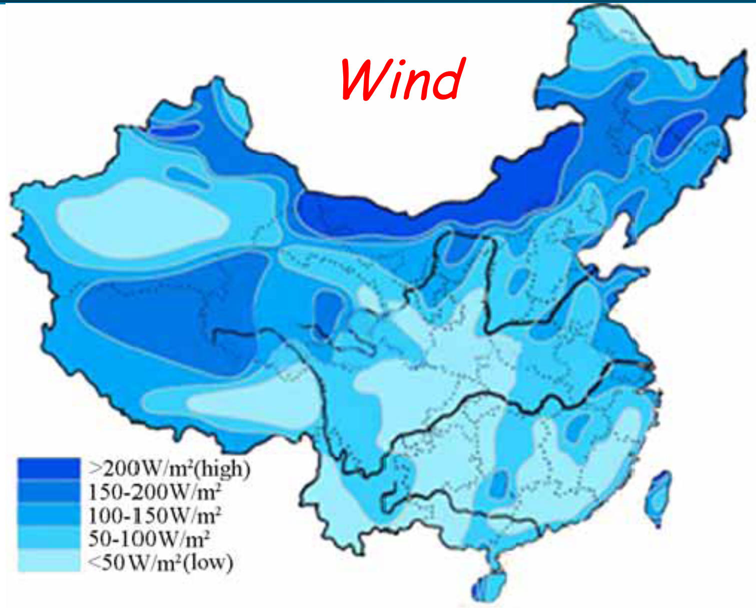
Long-distance energy transport



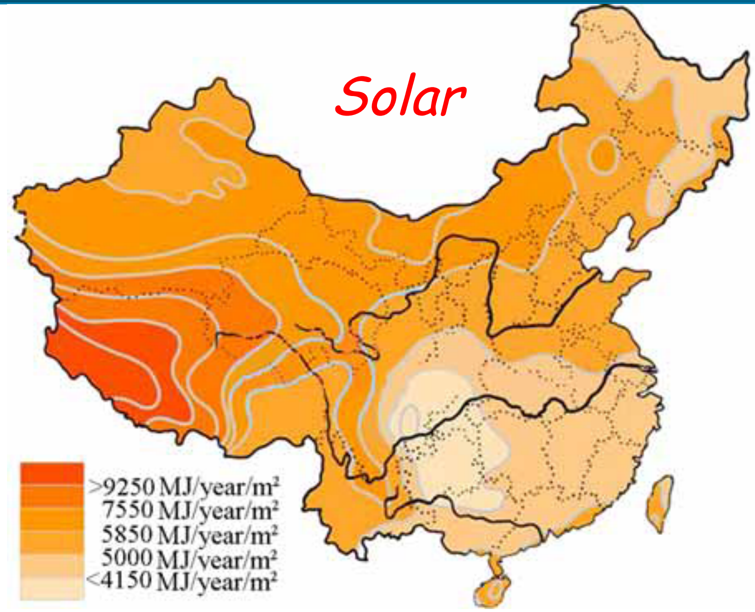
- Remote renewable energy sources require an efficient transfer of electrical energy over long distances.
- High power lines should have lengths of more than 4000 km

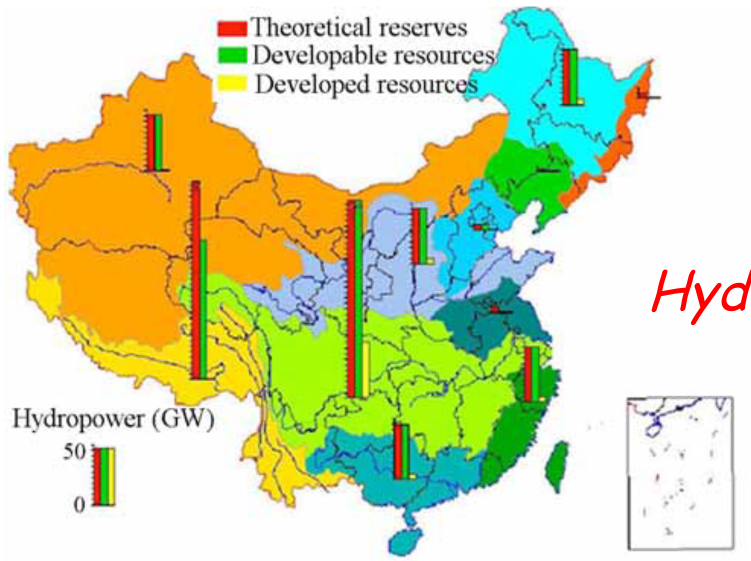
Renewable energies in China

Wind



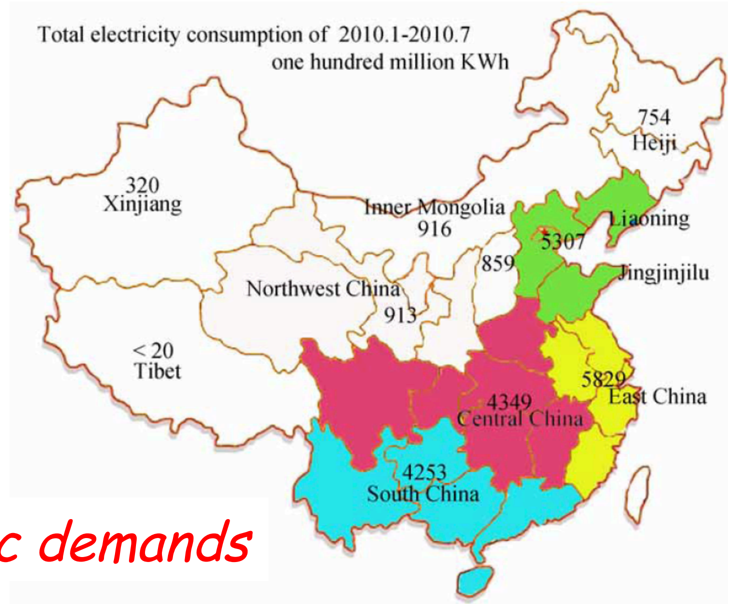
Solar





Different color in the map mean different drainage areas.

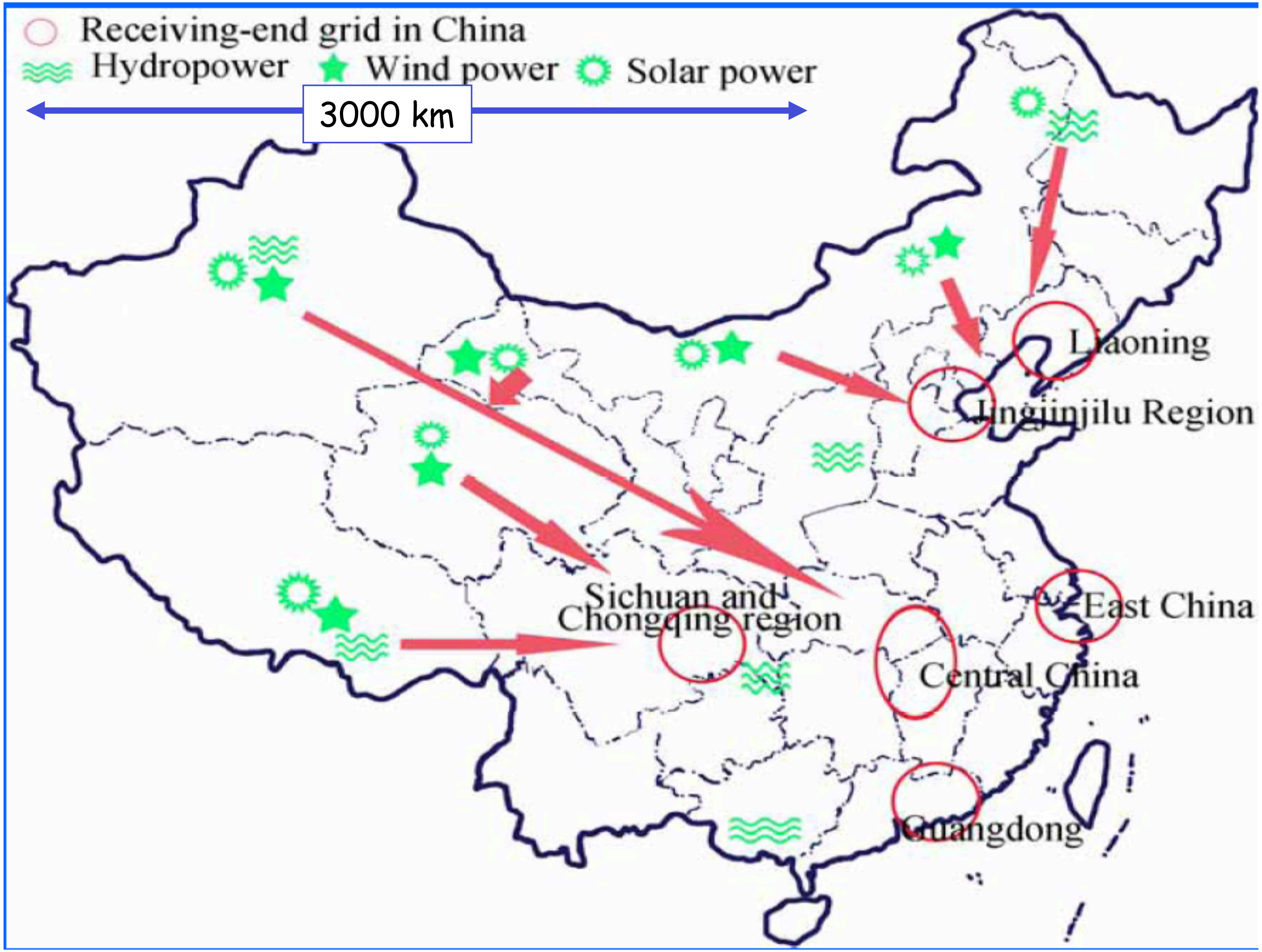
Hydro



Electric demands

Liye Xiao, Institute of Electrical Engineering, CAS

Power transmission of China in the future

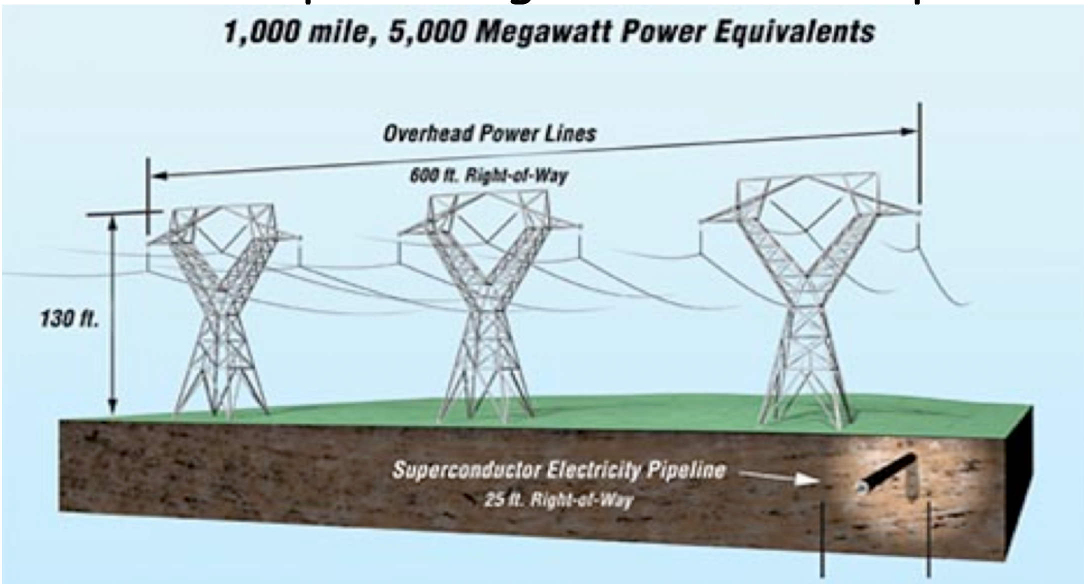


A new development: very long distance power lines

- Renewables and liberalisation require bulk transmission capacity to ensure electricity transport over many thousand kms from off-shore wind and CSP
- Electricity transport over ≈3000 km:
  - AC / HVAC lines: high cost and 45% / 25% energy losses
  - 800 kV HVDC lines: lowest costs and 10% energy losses
  - Superconducting (SC) power lines: new promising line for development

European Academies easac Science Advisory Council

Example.
A 20 x 5 GW system of 800 kV HVDC proposed by EU-MENA by 2050 to supply 15 % of the EU electricity, with an average distance of 3000 km and a loss of 15% has a current of 140'000 ampere, a conductor cross section of 2400 cm² and it requires 1.2 million tons of Aluminium conductor. The annual power losses for an electricity cost of 6¢/kWh are 7.9 billions.



With 800 kV HVDC, the overhead surface for the EU-MENA-2050 lines is 3600 km², to be compared with 2500 km² for the CSP plant itself: SC lines are almost a necessity.

Advantages of superconducting lines

- Superconductor DC cable are possible with very high, continuous power capacities of 5 to 20GW.
- The economics of the design favor higher power ratings; a 10GW design is less than one third more expensive as a 5GW design.
- A superconductor DC cable as a solution appropriate for very high power transfer situations.

5000 MW, 1600 km	Overhead AC Transmission			DC Transmission	
Type of Line	345 kV	500 kV	765 kV	Overhead 800 kV	Super-conductor
Reference	[2]	[3]	[2][4]	[4]	
Right-of-Way Requirement	410m	300m	120-180m	80m	8m

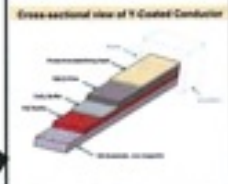
TRANSMISSION LINE POWER AND DISTANCE REQUIREMENTS / **SUITABLE TRANSMISSION SOLUTIONS**

Power	Distance	Overhead Solutions: AC	Overhead Solutions: Point-to-Point HVDC	Overhead Solutions: Multi-terminal VSC HVDC	Underground Solutions: AC	Underground Solutions: Point-to-Point HVDC	Underground Solutions: Multi-terminal VSC HVDC	Underground Solutions: Multi-Terminal Superconductor Pipeline
Low Power (<1GW)	Short (<100 mile) lines	✓			✓	✓	✓	
Low Power (<1GW)	Moderate (100-400 mile) lines	✓	✓	✓		✓	✓	
Low Power (<1GW)	Long (>400 mile) lines	✓	✓	✓				✓
Moderate Power (1-5GW)	Short (<100 mile) lines	✓				✓	✓	
Moderate Power (1-5GW)	Moderate (100-400 mile) lines	✓	✓	✓		✓	✓	
Moderate Power (1-5GW)	Long (>400 mile) lines	✓	✓	✓		✓		✓
High Power (>5GW)	Short (<100 mile) lines	✓						
High Power (>5GW)	Moderate (100-400 mile) lines	✓	✓					✓
High Power (>5GW)	Long (>400 mile) lines	✓	✓					✓

Fit of DC superconductor cables for underground, long distance, high power, multi-terminal transmission

Different types of superconducting wires

Superconducting wires presently available on the market

	NbTi	Nb_3Sn	MgB_2	BSCCO	YBCO
Wire type					
T_c (K)	9 K	18 K	39 K	108 K	90 K
B_{c2} (T)	10 T	28 T	Up to 70 T	>100 T	>100 T
Operation in dry magnets above 10 K	NO	NO	**YES**	YES	YES
Ductile compound	YES	NO	NO	NO	NO
Flexible wires	**YES**	NO	**YES**	YES	YES
Superconducting splices	**YES**	YES	**YES**	NO	NO
Low cost (< 5 $/m)	**YES**	NO	**YES**	NO	NO (not before 5 years)
Long lengths (>2 Km)	**YES**	YES	**YES**	NO	NO

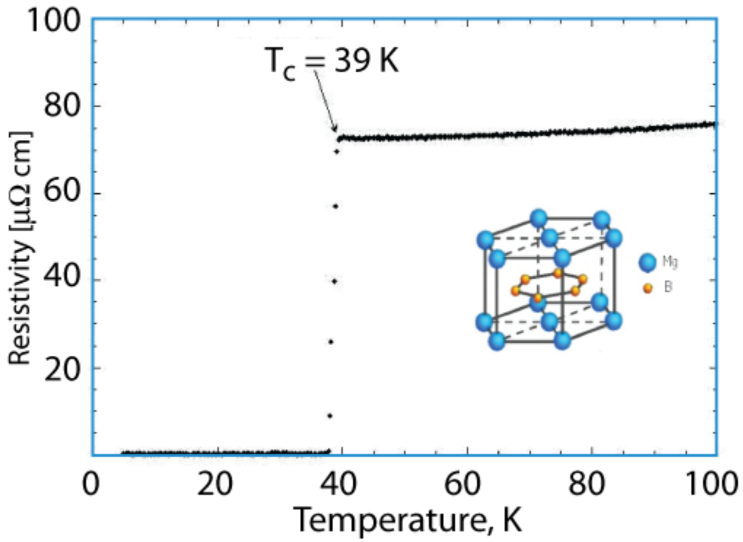
Choice of the SC alternative

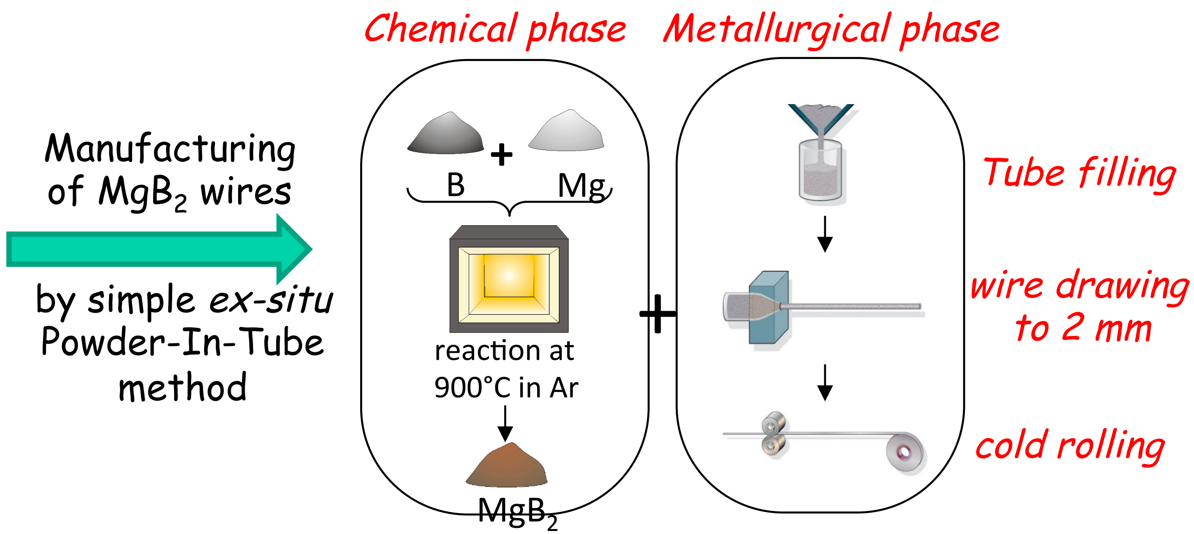
- Existing superconducting materials and cryogenic components do not deliver a competitive alternative to existing technologies.
- Both recent progress and ongoing research promise to improve performance and reduce costs so that a competitive parity with conventional transmission is expected in a few years' time.
- The relatively recent development of MgB_2 superconductor appears the most desirable solution which may provide a low cost cable and a sufficiently high cryogenic temperature.

SC Material	*Main Coolant*	*T (K)*	*Thermod factor*	*Cable wire costs*	*kryogenic-complexity*	*cable complexity*
NbTi	liquid He	1.9-4.3	400	low (≈1 kA m)	high	low
HTS	liquid N_2	60-75	9	high (>50 kA m)	low	high
MgB_2	liquid H_2 or gasHe+LN_2	15-20	40	low (<1 kA m)	low	low

The new choice in long power lines: MgB_2

- In January 2001 superconductivity was announced of a simple new compound, the Magnesium Diboride, MgB_2.
- MgB_2 is under development and relatively small quantities of cable have been manufactured so far at the laboratory scale.

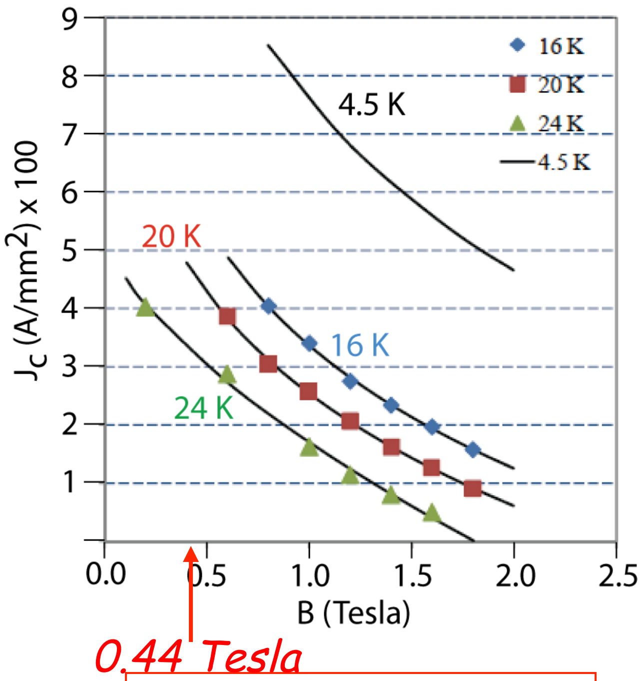


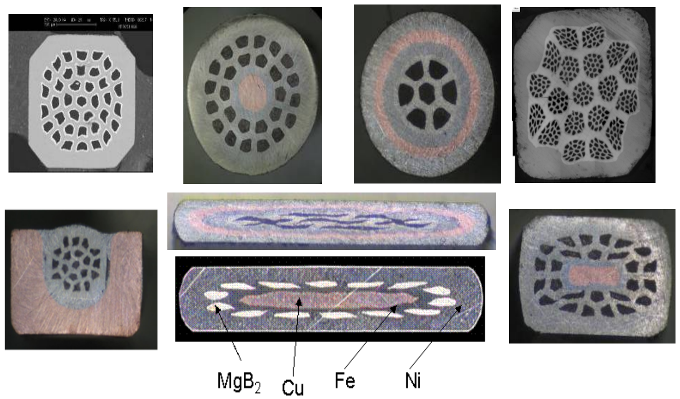


- An extremely simple method of producing the cheap chemicals and of drawing the wire, in analogy with Nb-Ti.
- Wire unit length today up to 4 Km in a single piece, easily scalable by increasing billet size/length.
- Conductor cost at 15-20K, 1T: No longer the dominant term

MgB_2 produced by Columbus (Italy)

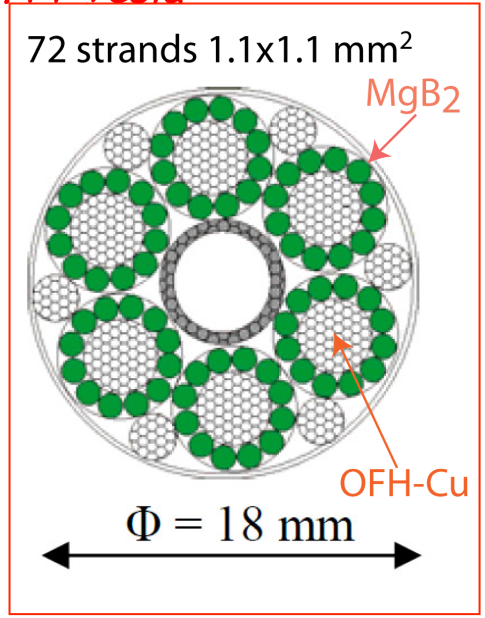
- Wires are produced with diameters of 1.1 (1 mm²) and 1.6 mm (2 mm²)
- J_c= 1kA (0.5kA)/mm² at 20K, 1T or 25K, 0.5T (*1 kA expected, 0.5 kA achieved*)
- More flexibility on design than HTS
- No need for texture allows any shape
- Sandwich conductor is the best proposal for a magnet wire – for instance a 30%, adjustable Copper fraction.





Royal_Society_Solar

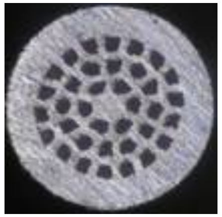
- Example of Cu stabilized 1.1 mm cable CERN/ Columbus, Φ = 1.8 cm
- J_c = 72 x 1.2 kA *(0.6 kA)* = 86.4 kA *(43.2 kA)* adequate for 20 kA and and 10 GW (±250 kV)

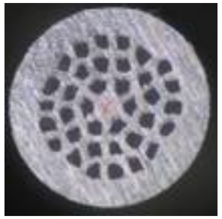


Columbus programme

Conductor manufacturing for cable applications

We are in the advanced development phase of MgB_2 round wires for cable applications

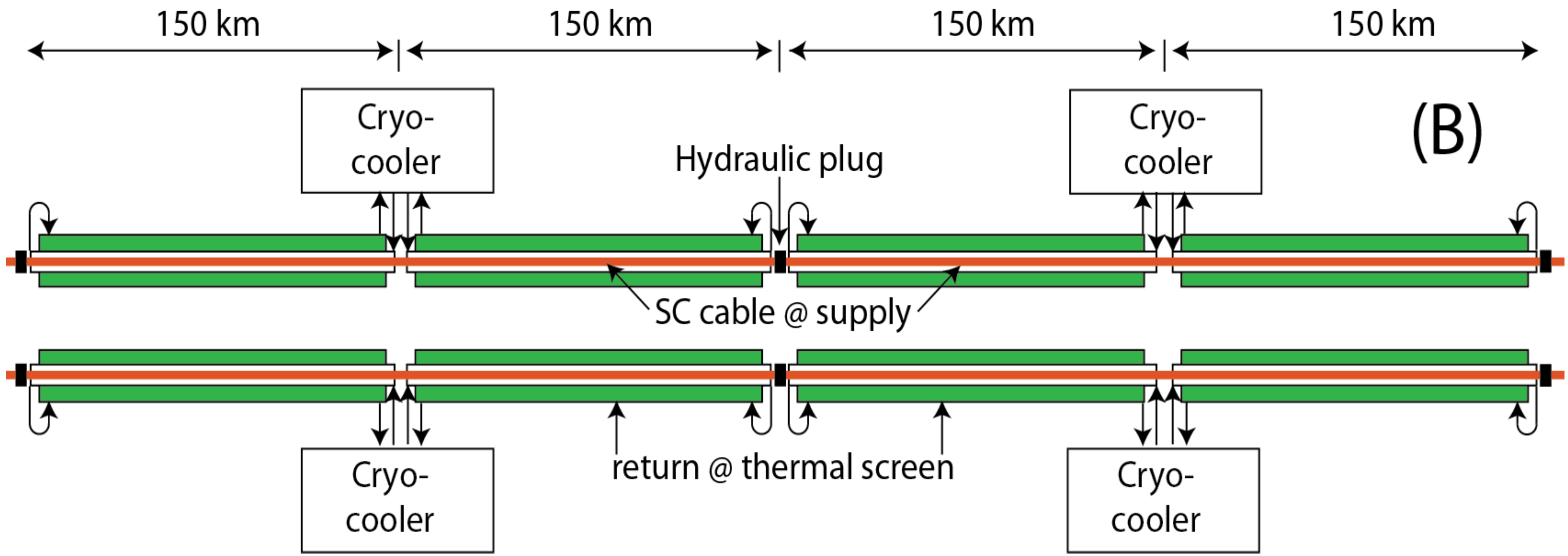




Wires are produced with different outer diameter of 1.1 (1 mm^2) and 1.6 mm (2 mm^2)

1.6 mm wire	Today	In 3 years time
MgB_2 filling factor %	23%	35%
Critical current at 20K, 1 T	1'000 A	2'000 A
Critical current at 25K, 0.5 T	1'000 A	2'000 A
Boron purity	95-97%	99%
Boron price	0.1 €/m	0.25 €/m
Other constituents price	0.4 €/m	0.25 €/m
Manpower price	1 €/m	0.5 €/m
Conductor cost **at 20K, 1T**	**1.5 €/kAm**	**0.5 €/kAm**

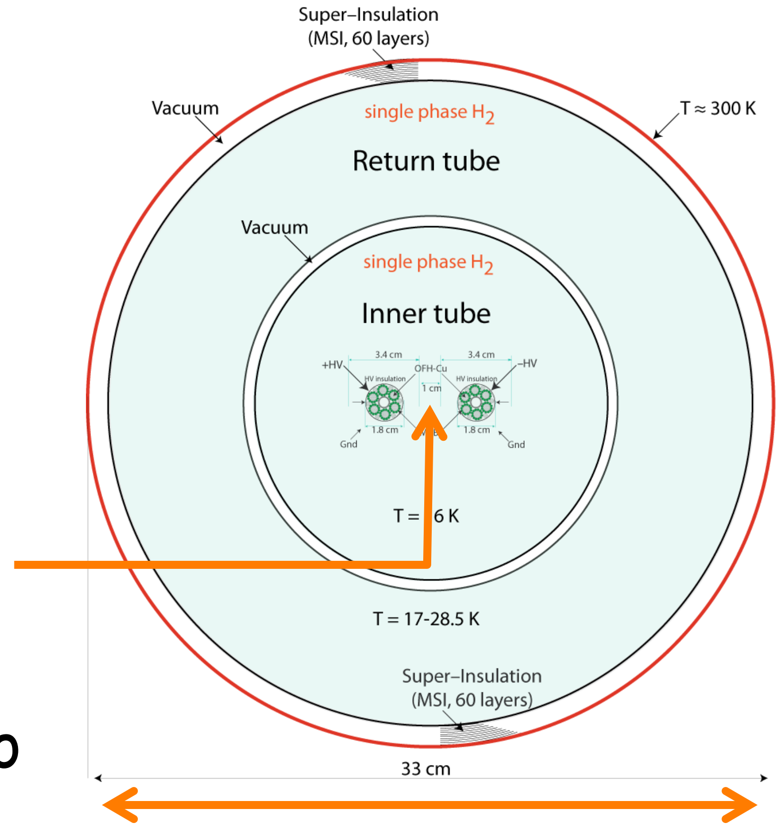
A 10 Gwatt totally duplicated SC line.



- Two redundant lines with a totally independent return. An appropriate hydraulic plug is located at the middle of the line, ensuring the reversal of the cryogenic flow .
- Each cryo-cooler has a nominal cryogenic power of about 200 kWatt for each of the pairs of lines about 300 km away and a hydrogen supply of about 6 ton/hour.

The tube configuration

- The return pipe is arranged coaxially around the inner, cable carrying tube.
- A good vacuum insulation is foreseen between the two tubes and evacuated highly reflective thin foils (MLI) under vacuum around the outside tube.
- HV insulation between SC cables is guaranteed by the liquid coolant itself.
- During normal operation the cryogenic flow is closed and no hydrogen is lost to the environment.
- The very low density ofliquid H_2 ensures changes in altitude with minimal pressure differences ($\Delta h \approx 1500$ m for Δp = 10 bar)

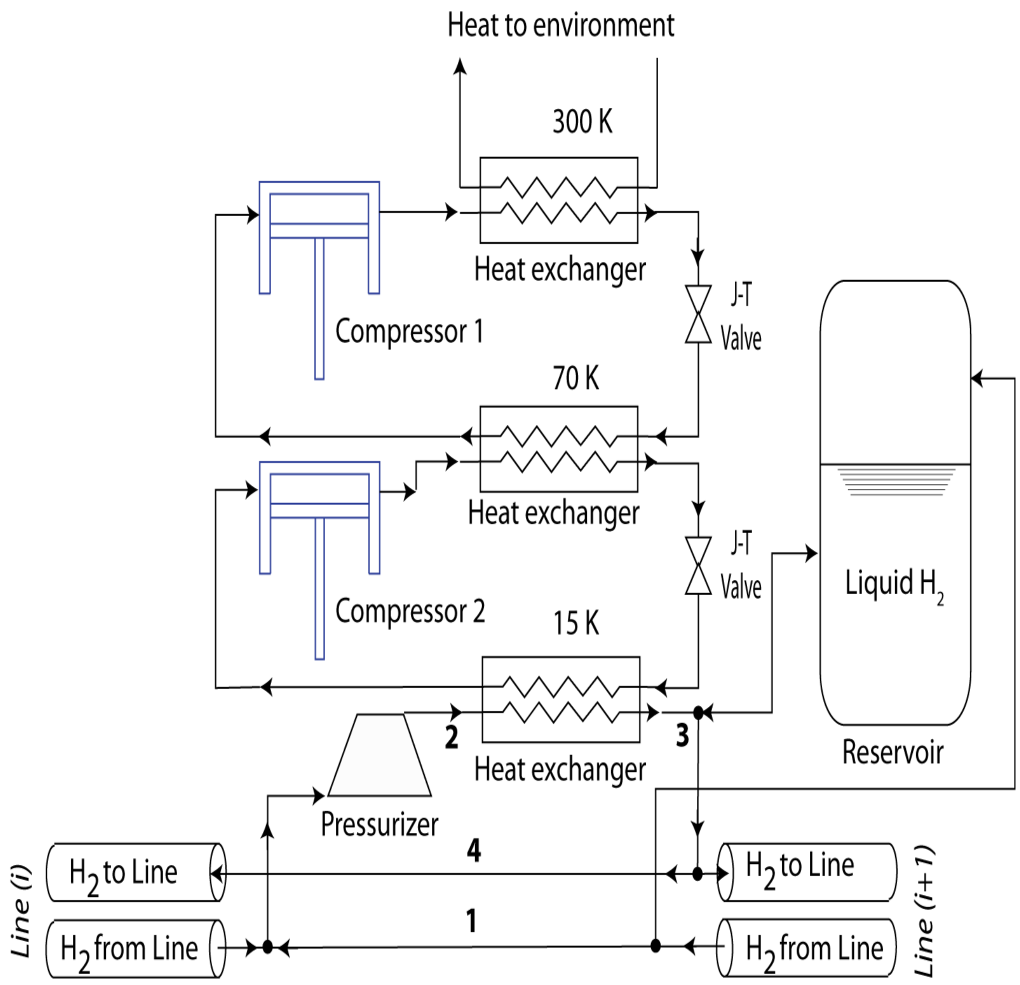


Tube diameter ≈ 33 cm

Nominal power:
10 GWatt at ≈100 kVolt

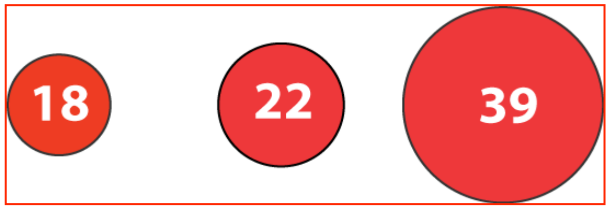
Refrigeration

- Simplified para-hydrogen refrigerating unit generated by two liquefiers in succession at 70 K and at 15 K, with mechanical energy and heat to the environment at 300 K.
- The hydrogen reservoir provides for further capacity.
- Two of such units are required in total at each station.



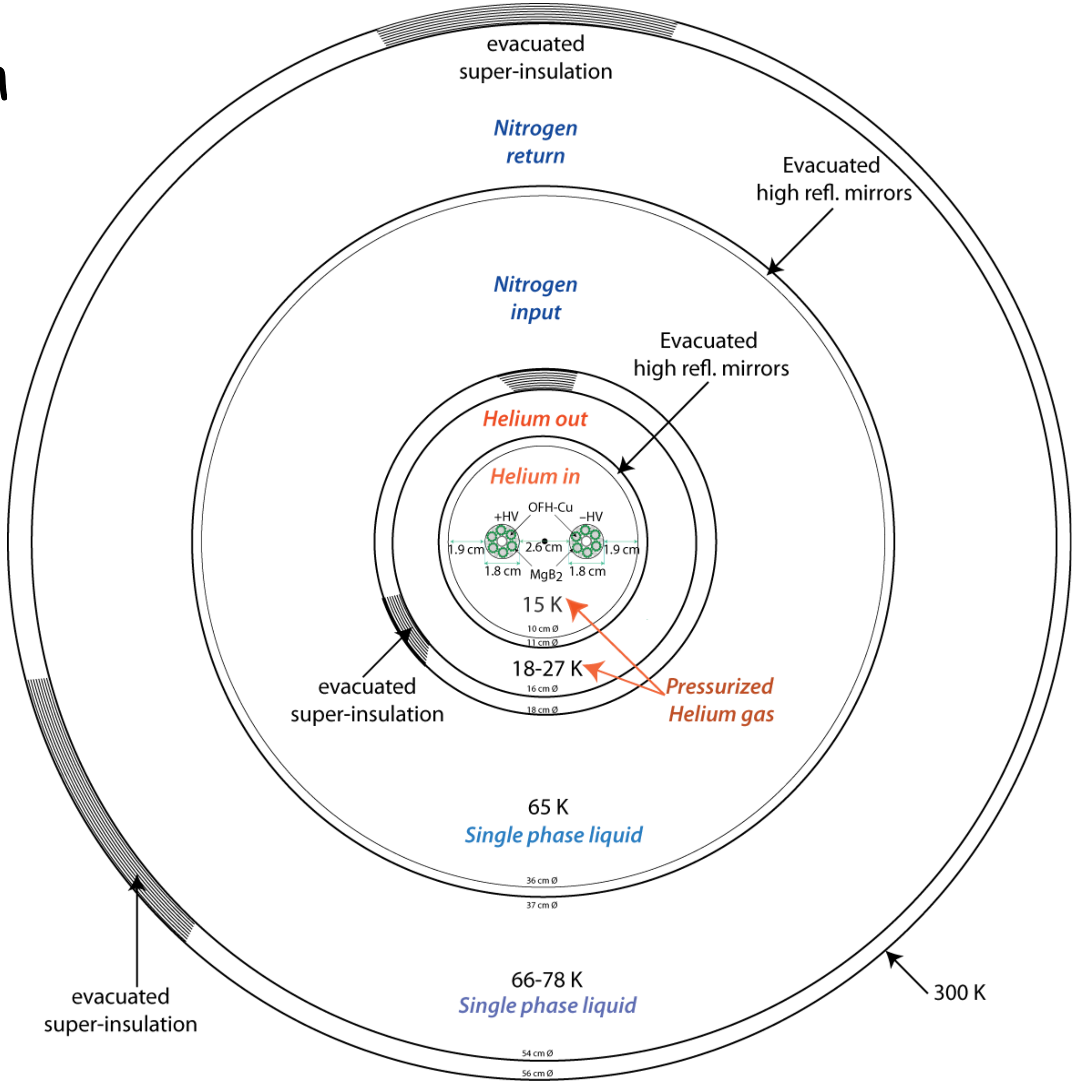
Length of each sector	*50*	*100*	*300*	*km*
H_2 outer diameter	14.0	18.0	35.0	cm
External diameter	18.0	22.0	39.0	cm
Initial H_2 pressure	20.0	20.0	20.0	bar
Final H_2 pressure	15.0	14.1	17.7	
Initial H_2 temperature	16.0	16.0	16.0	K
Final H_2 temperature	26.3	26.7	29.5	K
Specific cryogenic power	527.8	678.6	1320	W/km
H_2 specific mass	20.16	25.2	33.6	kg/(h km)

Relative diameters



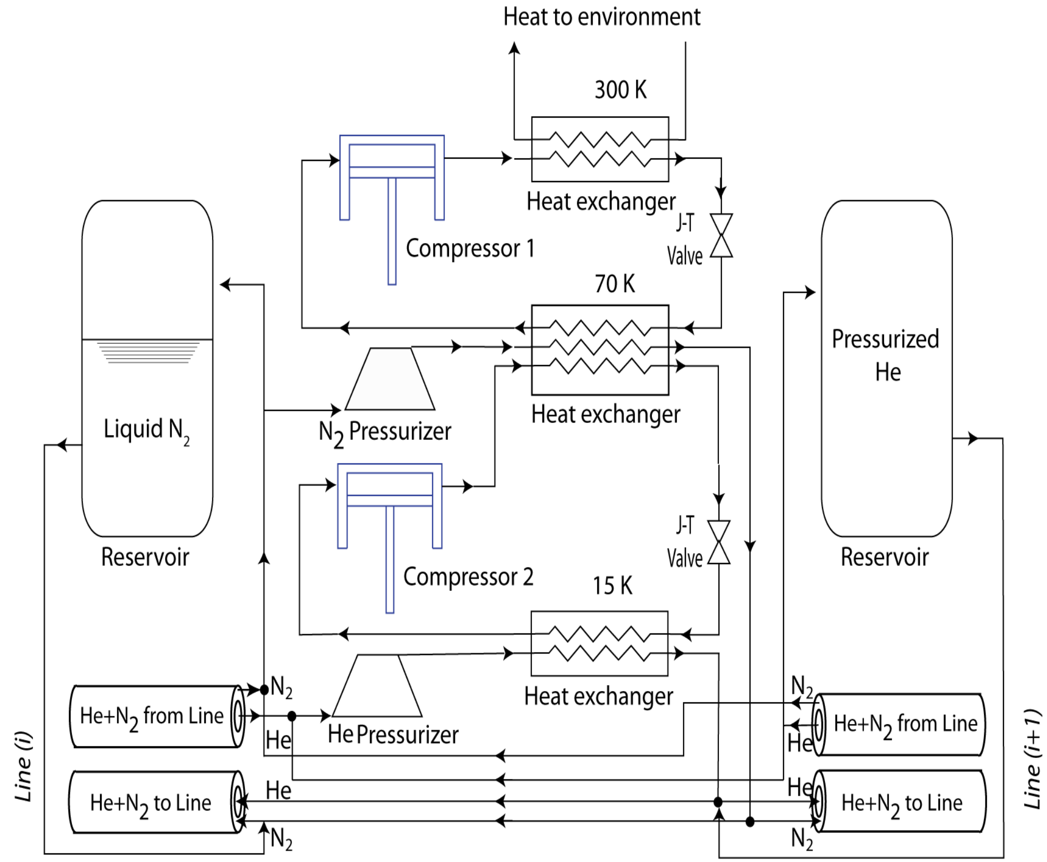
Alternative solution with He+ N_2

- General layout of a pressurized helium tube with MgB_2 superconductor at an initial pressure of 30 bar and a temperature of 15 K, followed by a single phase nitrogen coolant to room temperature.
- The inlet temperature of liquid nitrogen is set to 65 K at an initial pressure of 30 bar.
- The distance between cryogenic stations has been set to L= 300 km



Non combustive He + N_2 configuration

- Simplified refrigerating unit for nitrogen and helium generated by two liquefiers in succession at 65 K and at 15 K, with mechanical energy and heat to the environment at 300 K.
- The liquid nitrogen and the compressed helium reservoirs provide for further capacity.
- Two of such independent units are required in total at each location.



General parameters

	Single tube H2	*Dual tube He*	*Dual tube N2*	
Number of segments/cryocooler	2	2		
Number of cryocoolers/location	2	2		
Number of segments/location	4	4		
Distance between cryocoolers	300.	300		km
Length of each segment	150	150		km
Temperature at inlet	15	15	65	K
Carnot ratio factor	55	55	9	
Cryogenic segment incoming	–	2.35	6.79	kW
Cryogenic segment returning	94.95	5.18	165.4	kW
Cryogenic segment total	97.0	7.53	172.2	kW
Mass flow/segment	0.8	0.1	7	kg/s
Mass flow/segment/hour	2.88	0.36	25.2	ton/h
Volume flow at entry/segment	37.7	3.89	29.26	m^3/h
Pump work/segment	5.335	0. 41	1.55	MW
Pump work/cryocooler	10.67	0.82	3.1	MW
Total mechanical work/location	**21.34**	**1.64**	**6.2**	**MW**
		7.84		**MW**

Nominal electric transported power 5'000-20'000 MW

Comparing with natural gas pipelines

- The practical realization of a SC-DC line has several elements in common with the established practice of Natural Gas pipelines.
- They are both “cross-country“ transmission systems, with many features associated with changes of elevation, temperature variations and other similar situations.
- In the case of natural gas pipelines these problems have been successfully solved and they are expected to be so also for the realization of SC-DC lines.
- In both cases, the mechanical equipment is above ground, and the pipes are below ground.
- A conventional natural gas pipeline carries a flammable gas in amounts that are vastly greater than the ones of liquid hydrogen for the described alternative.

Comparing with natural gas pipelines

- Therefore in spite of their very substantial differences, the mechanical work for a dual pipeline of 12 GWatt(thermal) and a dual SC-DC electric line of 10 GWatt are rather similar. They may require also comparable capital costs.
- The primary differences of a SC-DC application with respect to a natural gas pipeline are
  - at least a factor two smaller diameter;
  - about a factor 3 smaller pressures;
  - a high voltage of the order of about ± 100 kV and of cryogenic temperatures that require an appropriate steel
  - good vacuum insulation.
- These changes should not introduce major changes neither in the technology nor on the cost.

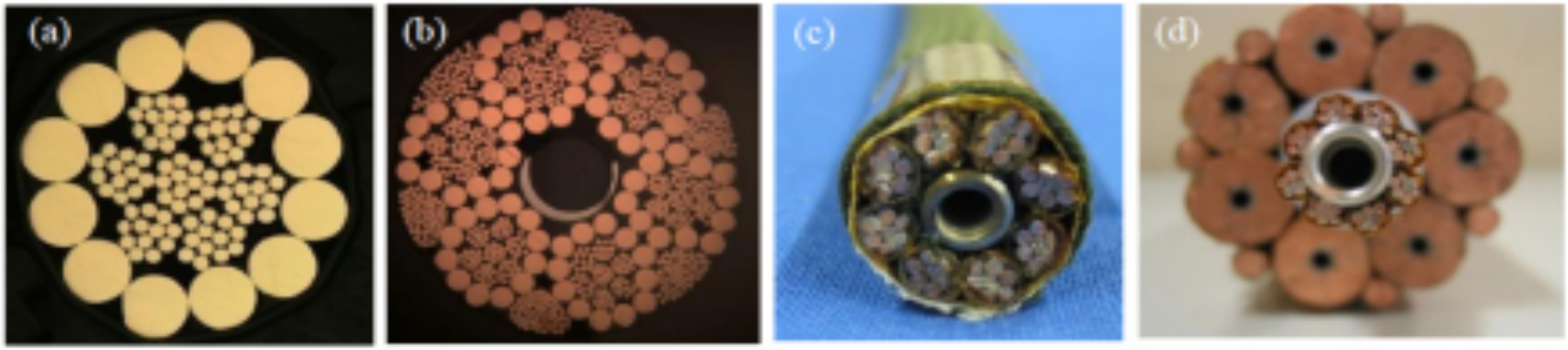
Thank you !

International Advisory SC Committee

- **Carlo Rubbia**, Scientific Director IASS (Chair)
- **Steve Eckroad**, Electric Power Research Institute (EPRI), USA
- **Paul Grant**, W2AGZ Technologies, USA
- **Jochen Kreusel**, Head of Smart Grids Programme, Asea Brown Boveri Ltd (ABB)
- **Werner Prusseit**, President, Industrieverband Supraleitung, Germany
- **Claudia Kemfert**, Director, Transport and Environment, DIW- Berlin, Germany
- **Michael Laskowski**, Project Leader E-DeMa – RWE, Germany (pending)
- **Reinhard Dietrich**, Managing Director, Bruker HTS GmbH, Germany
- **Frédéric Lesur**, Centre National d'Expertise Réseaux, Réseau de transport d'électricité (RTE), France
- **Jean-Maxime Saugrain**, Corporate Vice-President Technical, Nexans, France
- **Vitaly Vysotsky**, Head, Russian Scientific R&D Cable Institute,Moscow, Russia
- **Liye Xiao**, Director Institute of Electrical Engineering, CAS, China
- **Satarou Yamaguchi**, Director Center of Applied Superconductivity and Sustainable Energy Research Electrical and Electronic Engineering, Chubu University, Japan

The KIT + CERN + IASS cooperation on MgB_2

- The purpose of this original and unique programme is the one of realizing and testing a 10 GWatt DC equivalent closed current loop of an appropriate length (≈ 100 m) in order to simulate the operation of a DC cable at the full current.
- The cable will be made with MgB_2 commercially produced SC wire and copper stabilization.
- Operation will be maintained in the temperature range 15-20 K.
- Cryogenic operation will be initially performed with Helium, to be followed later by liquid hydrogen cooling



Earth, Energy and Environment - (E^3) Cluster

- Sustainable development should meet the requirements of the present without compromising the ability of future generations to meet their own needs.
- Moving towards sustainability involves expanding the definition of cost beyond just short-term economic implications to include long-term economic, environmental and social concerns.
- The current worldwide energy supply is based mainly on the availability of fossil fuels and though there is much talk of the exhaustibility of these resources, they will remain indispensable in the decades to come.
- In addition to the development of renewable energy sources and in consideration of the to climate change, a more efficient and friendly utilization of fossils fuels has become an urgent necessity.
- The transformation of existing energy technologies into low-emission and innovative solutions with a quantitatively significant management of CO_2, is one of the most important scientific and technological challenges of our times.

Main scientific programmes

- Besides the study and evaluation of existing research worldwide, the (E^3) Cluster will actively engage in some research projects on its premises in Potsdam and in collaboration with other research groups and institutions.
- The organisation of workshops and the research opportunities for scientific fellows will further the exchange of results and new ideas.
- Five major scientific subjects are presently under study, dedicated to the following wide research programmes:
  1. Combustion of methane without CO2 emission
  2. Long-distance energy transport through superconducting lines
  3. Advanced concepts of concentrating solar energy systems
  4. Recovery of CO2 for the production of methanol
  5. Properties of methane clathrates

Point 2 will be hereby further discussed