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## Superconducting power cables: today and tomorrow

Loic Queval

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ESAS'2023 School - Col de Porte, France

# Superconducting power cables: today and tomorrow

Loïc Quéval

<sup>1</sup> University of Paris-Saclay, CentraleSupélec, CNRS, Group of electrical engineering - Paris, 91192, Gif-sur-Yvette, France

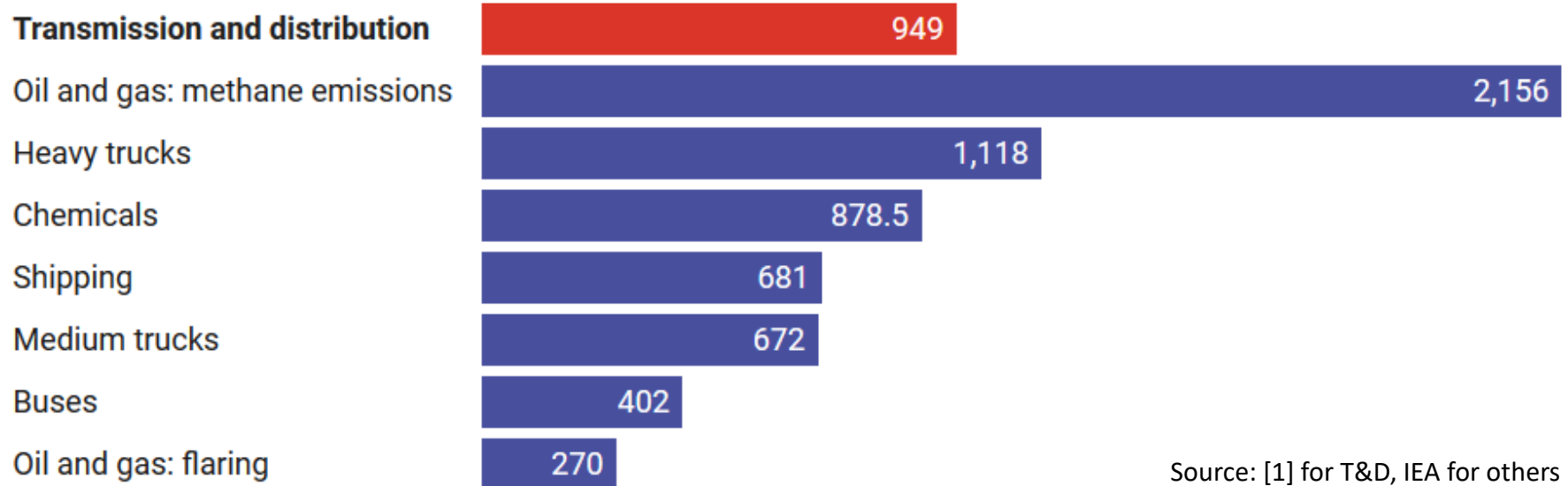
<sup>2</sup> Sorbonne University, CNRS, Group of electrical engineering - Paris, 75252, Paris, France

# Content

- I. (Superconducting) power cables
- II. Today
- III. Tomorrow

# World annual emissions from some industries

Measured in millions of tons of CO2 equivalents.

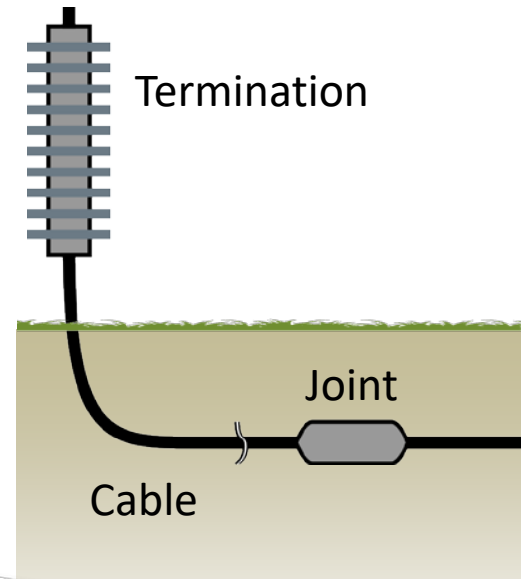
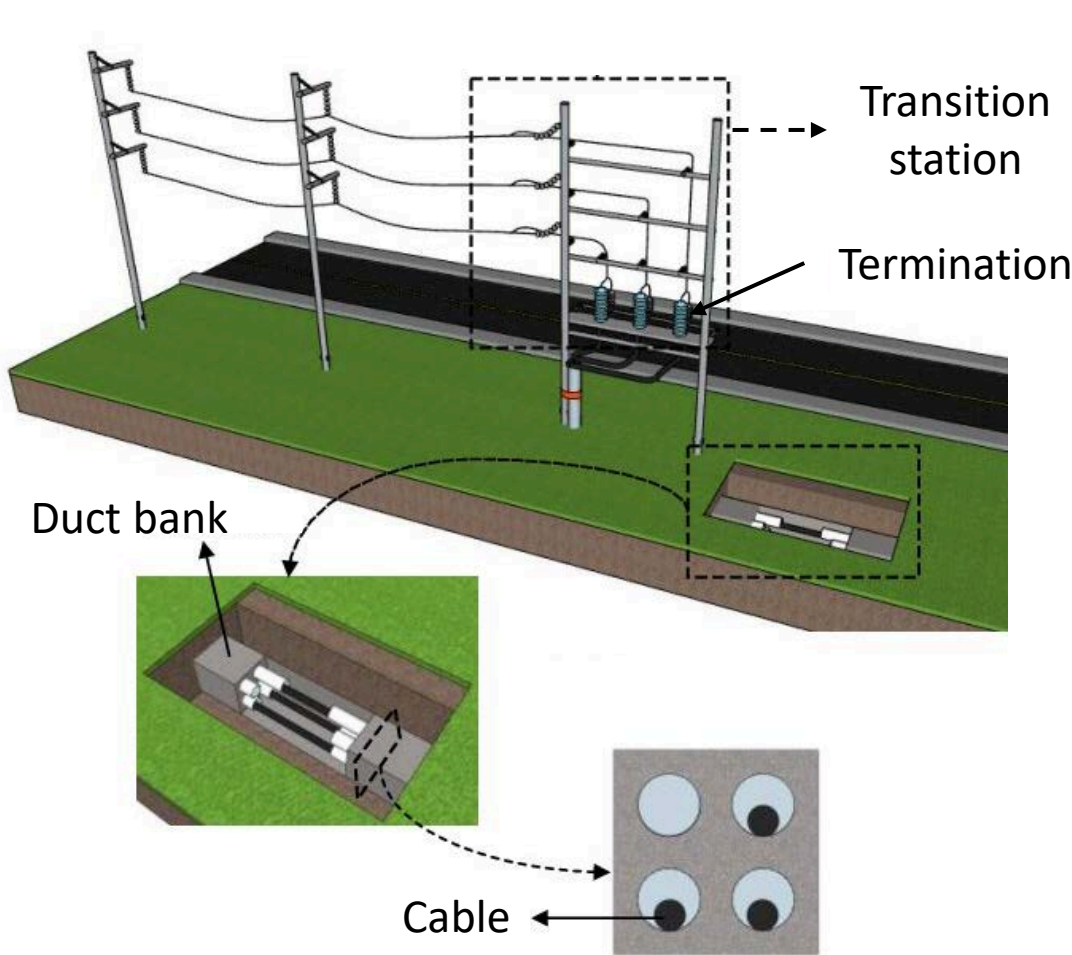


Source: [1] for T&D, IEA for others

[1] K. Surana, S.M. Jordaan, "The climate mitigation opportunity behind global power transmission and distribution," Nature Climate Change, vol. 9, pp. 660–665, 2019. Chart: The Conversation, CC-BY-ND.

# I. (Superconducting) power cable

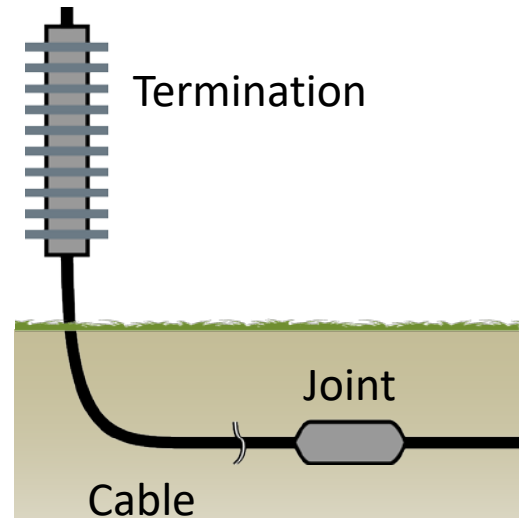
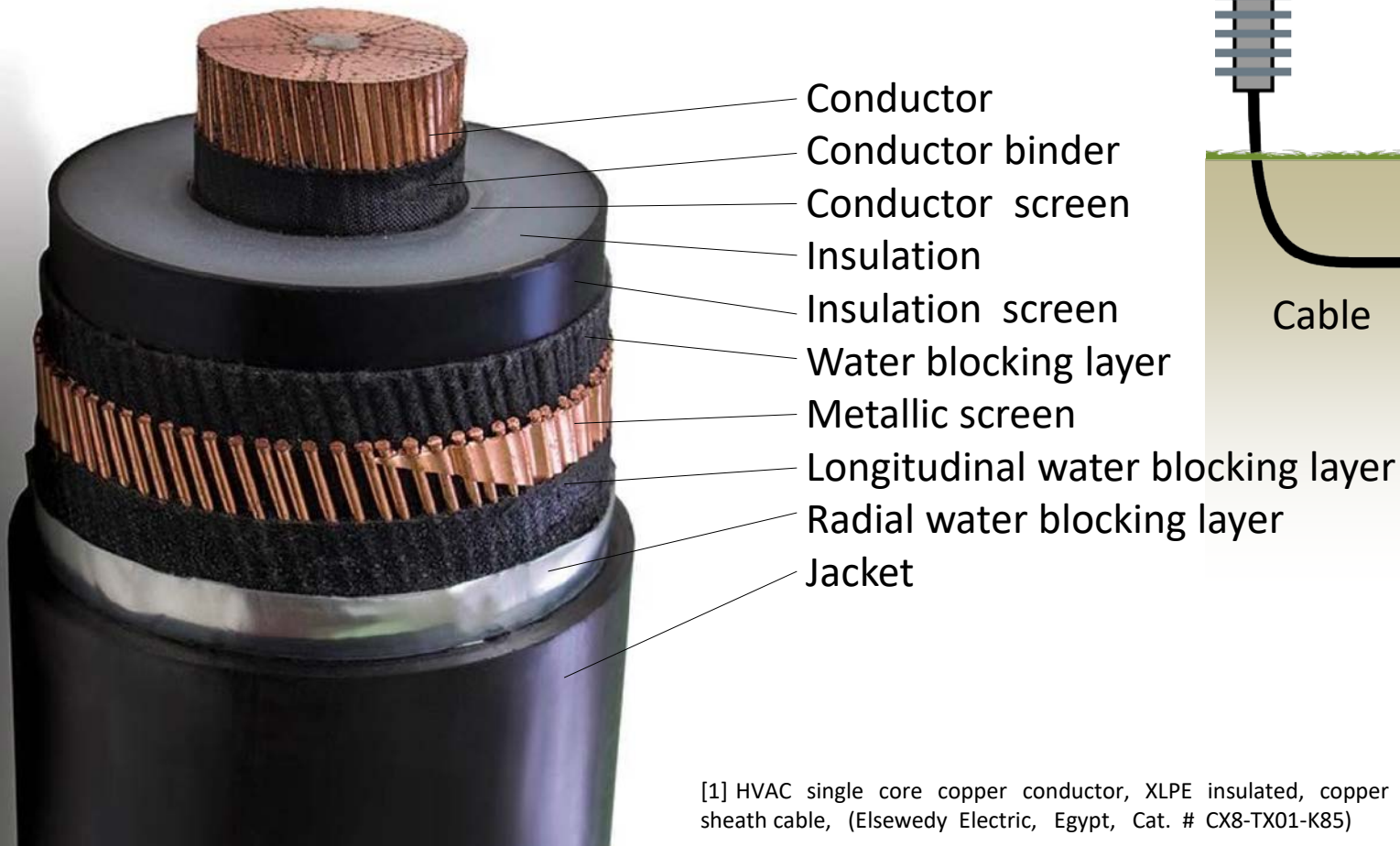
# HVAC resistive power cable system



Adapted from [1] J. Klomjit, A. Ngaopitakkul, "Comparison of artificial intelligence methods for fault classification of the 115-kV hybrid transmission system" *Applied Sciences*, vol. 10, no. 11, pp. 3967, 2020.

# HVAC resistive power cable system

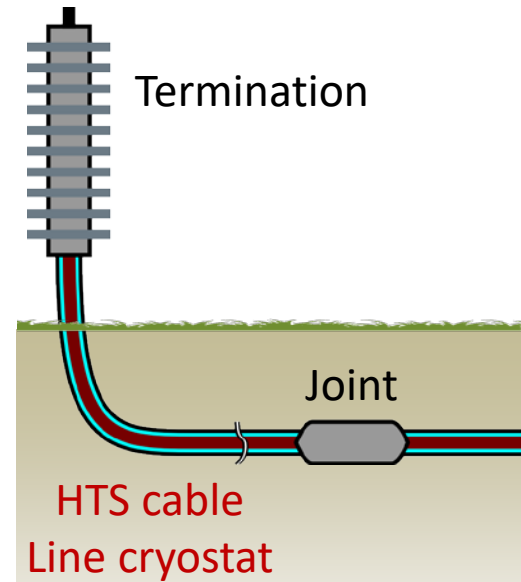
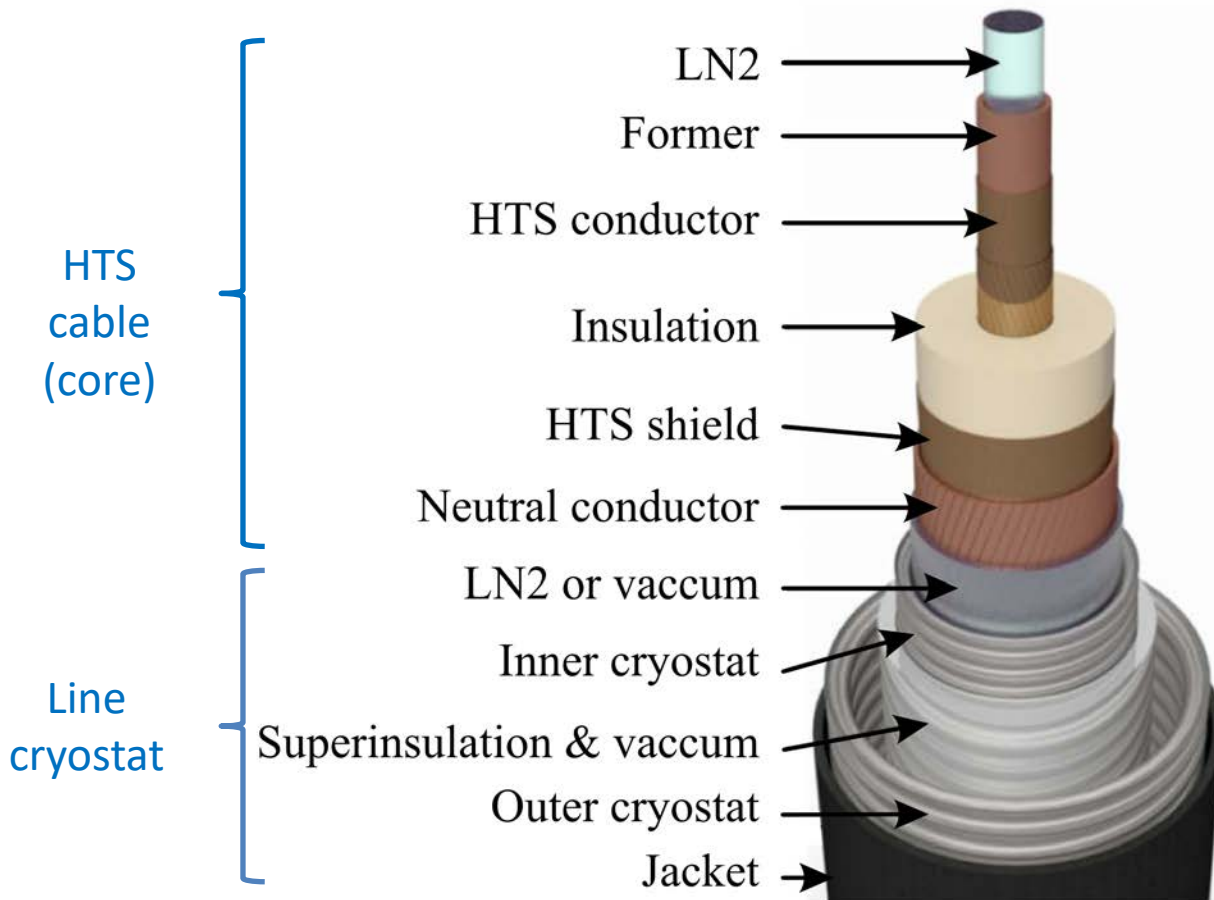
220 kV (L-N RMS) single core copper conductor, XLPE insulated, copper wire screen and HDPE



[1] HVAC single core copper conductor, XLPE insulated, copper wire screen and HDPE sheath cable, (Elsewedy Electric, Egypt, Cat. # CX8-TX01-K85)

# HVAC HTS power cable system

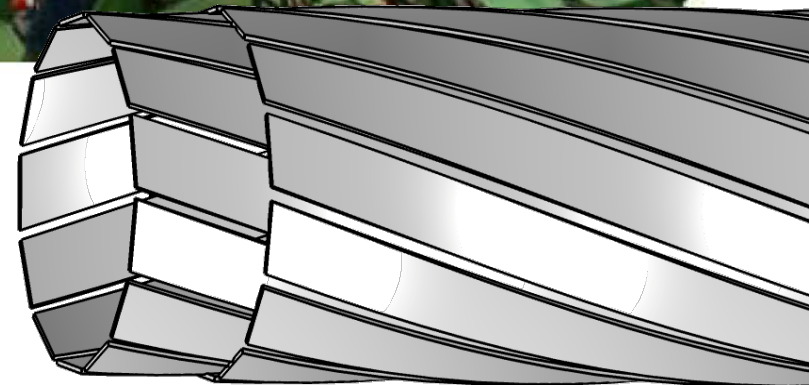
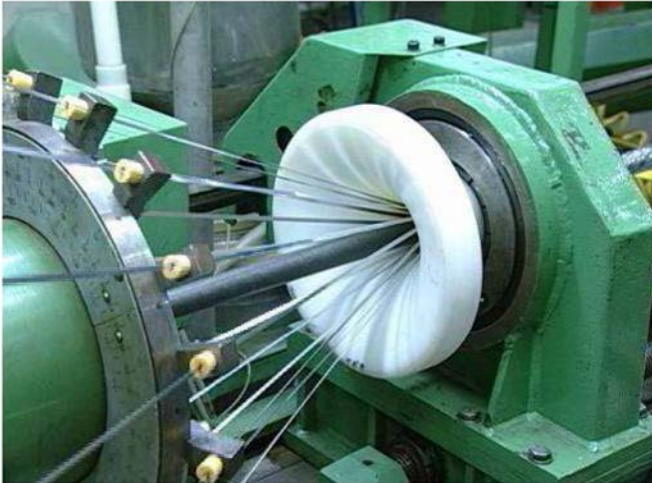
HVAC HTS cable: single core corrugated tube former cold dielectric LN2 cooled



Adapted from [1] M. Noe, "EUCAS short course on power applications: superconducting cables", 13th European Conference on Applied Superconductivity (EUCAS2017), Geneva, Switzerland, Sep. 2017.



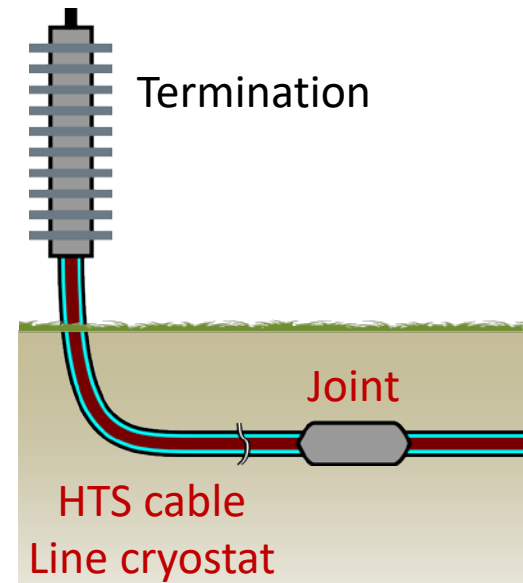
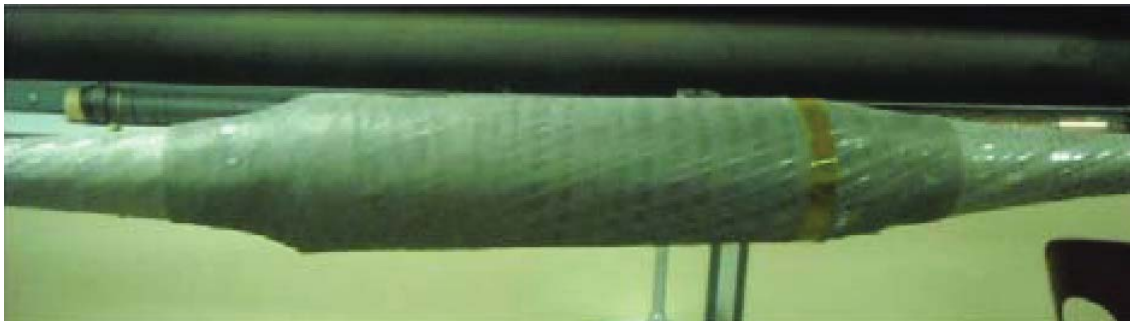
# HVAC HTS power cable system



[1] F. Merschel, "AmpaCity, Energieverteilung von Morgen mit Hochtemperatur-Supraleiterkabeln und Strombegrenzern für Zentren mit hoher Lastdichte," VDE / IHK Forum Technische Innovationen, Köln, Germany, Sept. 2015.

# HVAC HTS power cable system

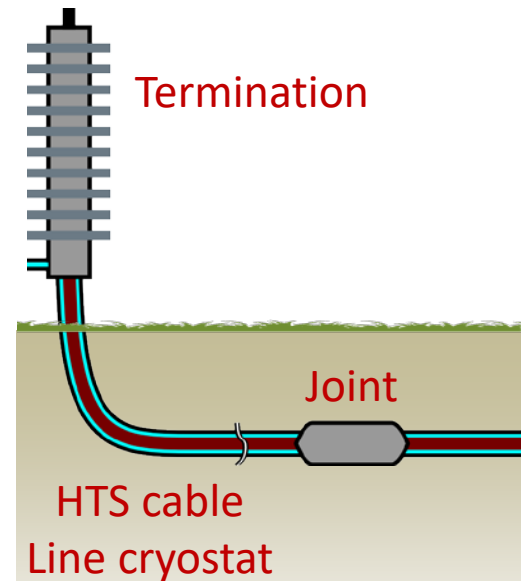
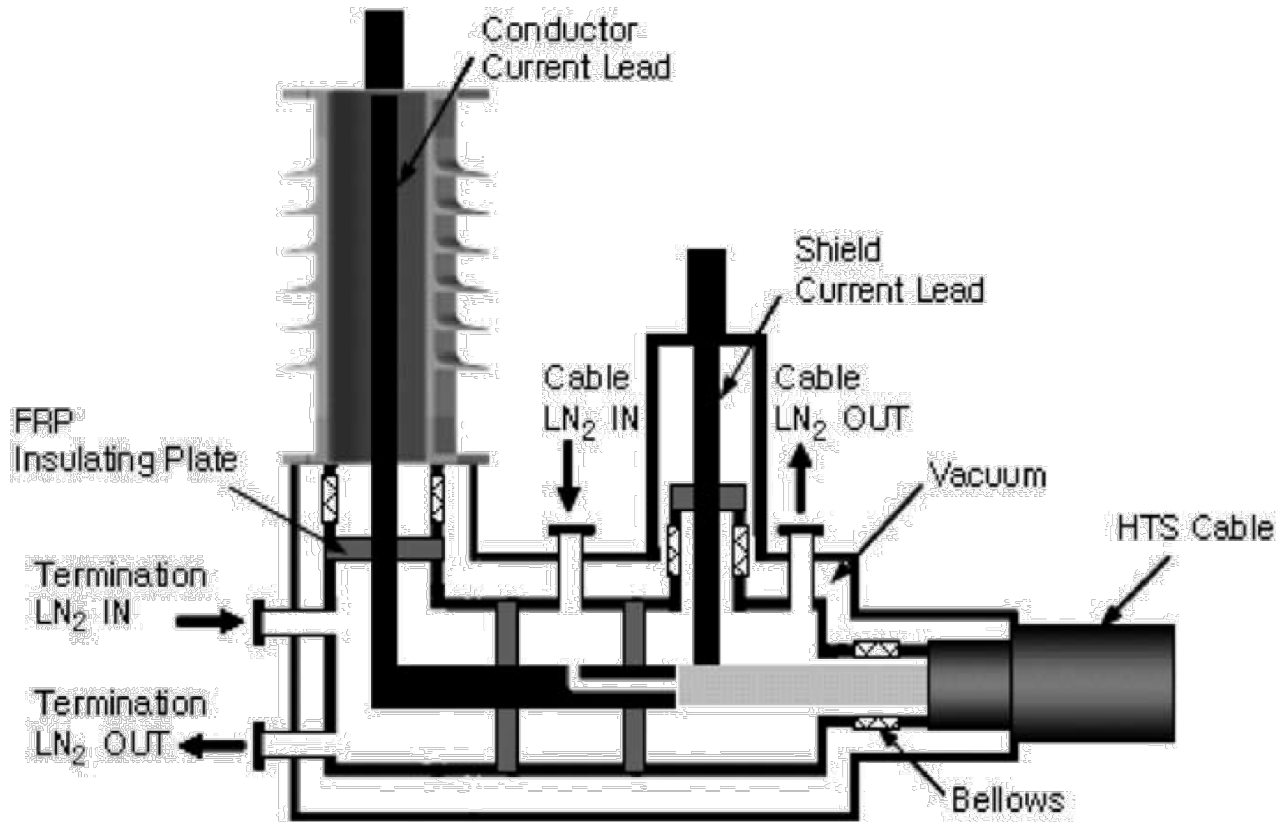
## Joint



[1] F. Schmidt, J. Maguire, T. Welsh, S. Bratt, "Operation experience and further development of a high-temperature superconducting power cable in the Long Island Power Authority grid," *Physics Procedia*, vol. 36, pp. 1137-1144, 2012.

# HVAC HTS power cable system

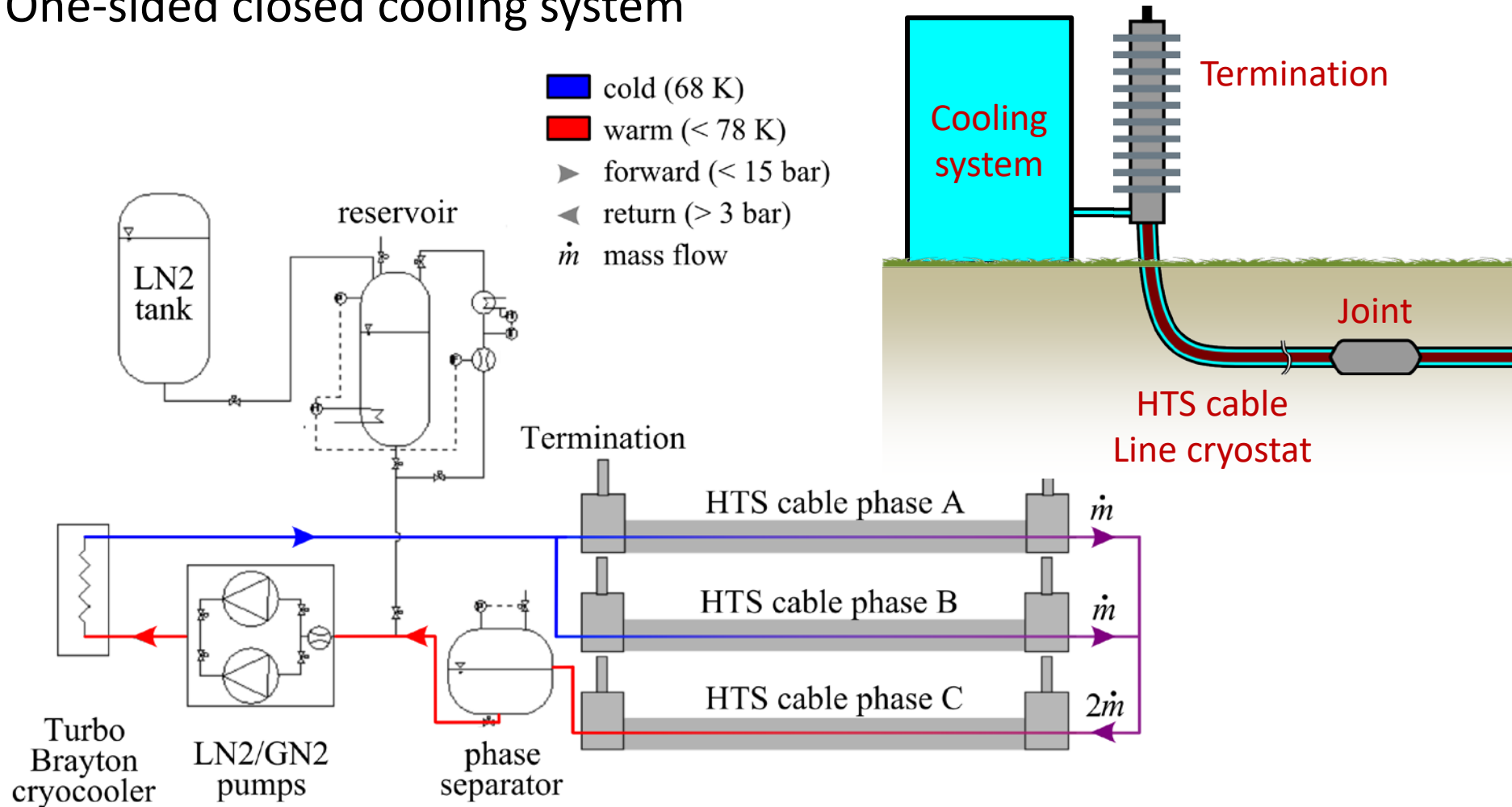
## Termination



[1] J. Cho, J.-H. Bae, H.-J. Kim, K.-D. Sim, S. Kim, H.-M. Jang, C.-Y. Lee, D.-W. Kim, "Development of a single-phase 30m HTS power cable," Cryogenics, vol. 46, no. 5, pp. 333-337, 2006.

# HVAC HTS power cable system

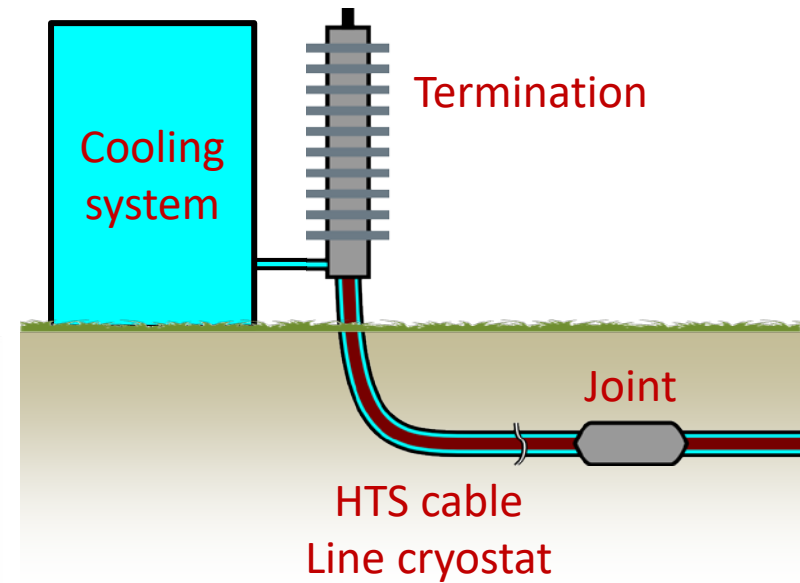
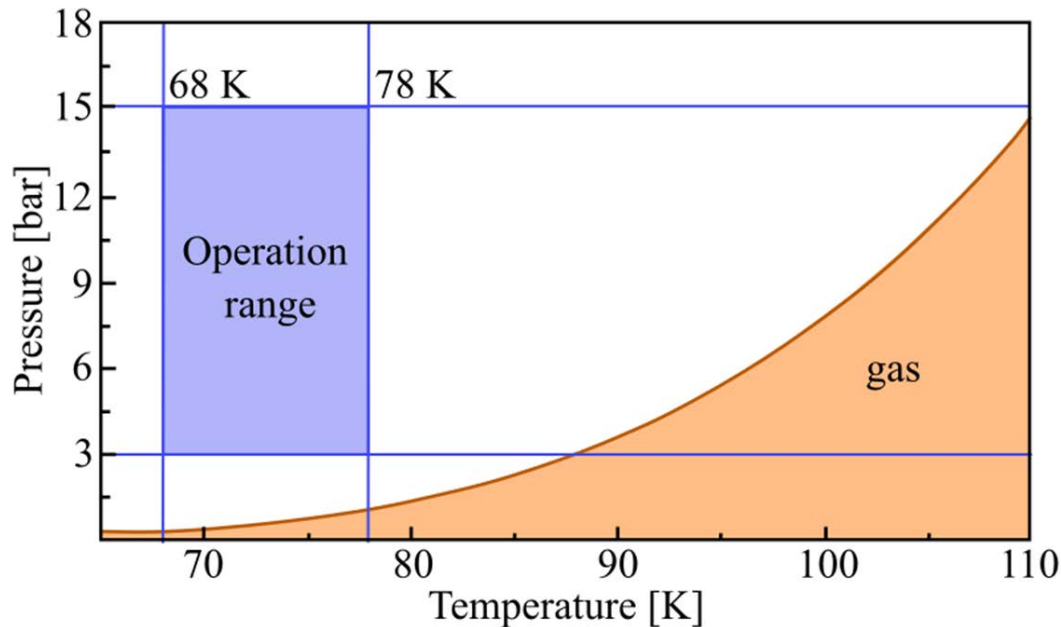
## One-sided closed cooling system



Adapted from [1] D. Kottonau et al., Bewertung des einsetzes supraleitender 380-kV-Kabel, vol. 26. KIT Scientific Publishing, 2019.


# HVAC HTS power cable system

Operation range of a LN2-cooled HTS cable



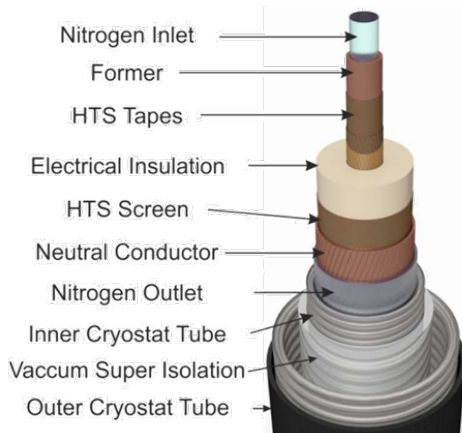
[1] C. Martin-Sanz Garrido, "Efforts towards the standardization of superconducting cables," Trabajo fin de grado, Comillas Pontifical University, ICAI, Spain, 2021.

# Other options...




## Cable Types

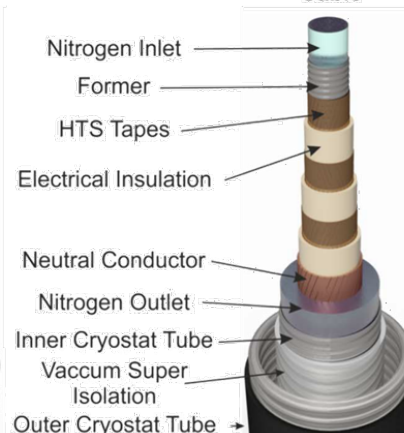
**Single Core Cable**



**Three Core Cable**



**Three-Phase Concentric Cable**



	Three single phases	Three phase in one cryostat	Three phase concentric
<b>Voltage level</b>	High voltage > 110 kV	30-110 kV	10-50 kV
<b>Amount of superconductor</b>	higher	higher	smaller
<b>Cryostat loss</b>	higher	smaller	smaller

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M. Noe, EUCAS Short Course Power Applications, Superconducting Cables
KIT-Zentrum Energie

[1] M. Noe, "Superconducting Cables," EUCAS Short Course Power Applications, Geneva, Switzerland, Sept. 2017.


# Other options...

## Cooling Options

Cold 68 K
  Warm < 78 K
 

▶ LN<sub>2</sub> in (<15 bar)

◀ LN<sub>2</sub> return (>3 bar)

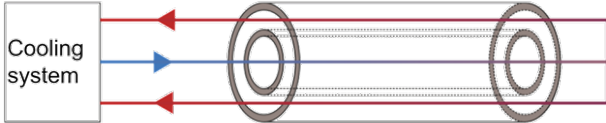


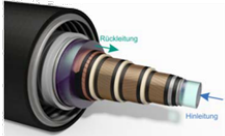
Karlsruher Institut für Technologie

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Option 1:

+ no external feedback line

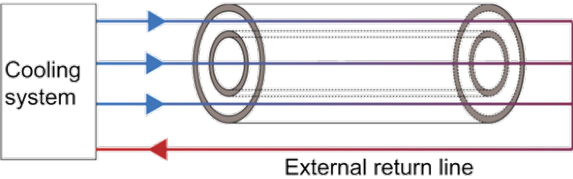




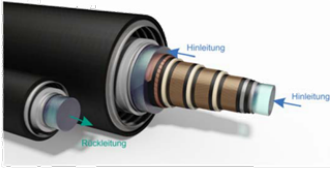
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Option 2:

+ longer cable length



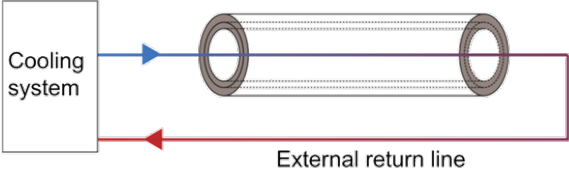
External return line



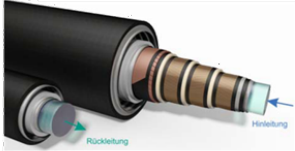
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Option 3:

+ smallest cable diameter




External return line




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Option 4:

+ longer cable length  
+ no external feedback line





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M. Noe, EUCAS Short Course Power Applications, Superconducting Cables
KIT-Zentrum Energie

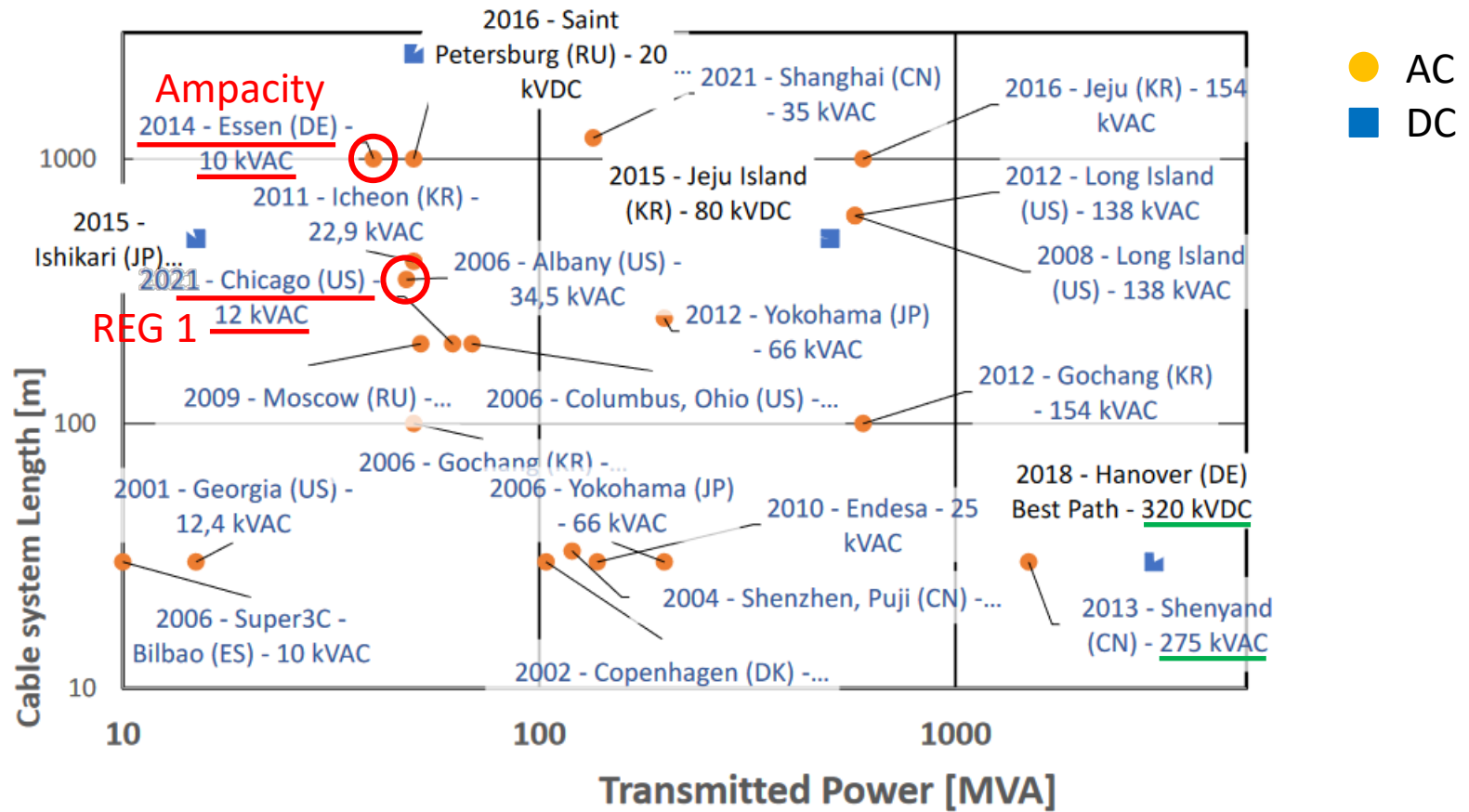
[1] M. Noe, "Superconducting Cables," EUCAS Short Course Power Applications, Geneva, Switzerland, Sept. 2017.

## II. Today



# State of the art

2001 - 2021



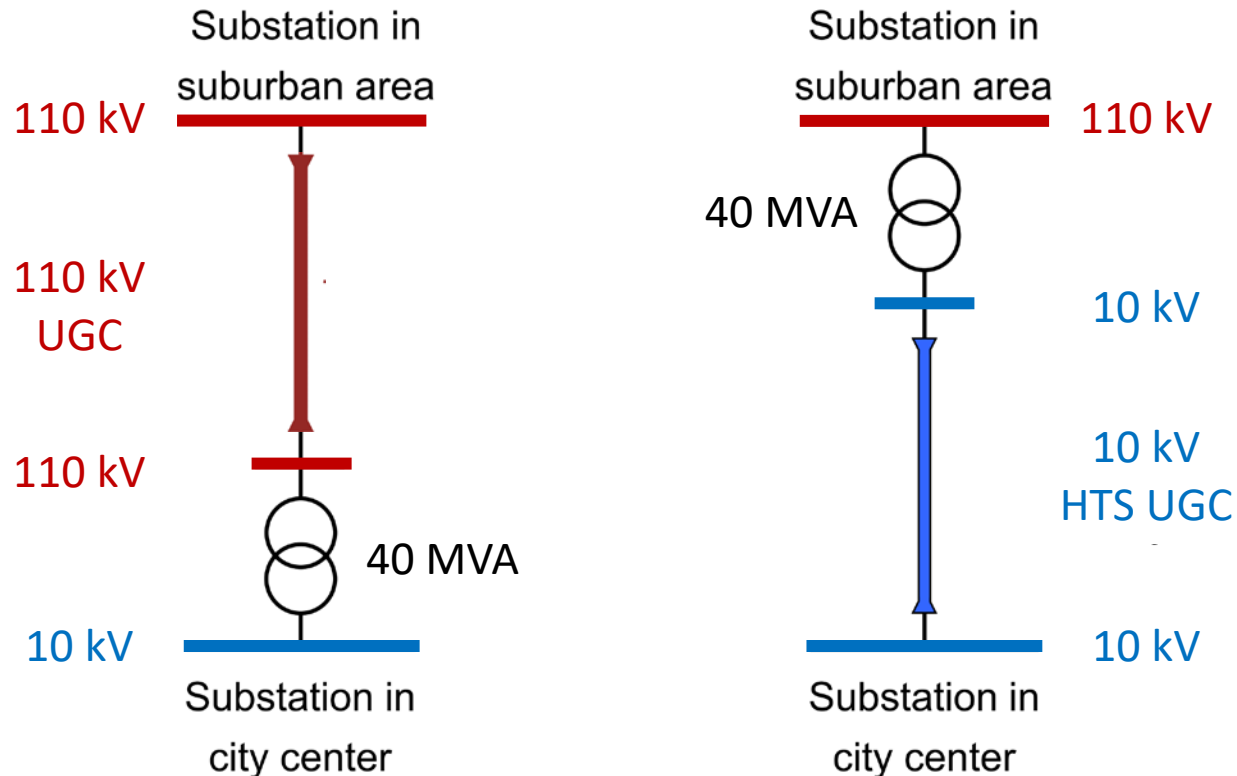
[1] A. Allais, "Nexans is paving the way for a superconducting electric world," 8th International Workshop on Numerical Modelling of High Temperature Superconductors, Nancy, France, Jun. 2022.

## **II. Today**

# **Ampacity**

# Ampacity

Essen, Germany



Adapted from [1] M. Stemmler, K. Allweins, F. Merschel, T. Kugel, F. Herzog, T. Kutz, J.-M. Saugrain, "Three years operation experience of the AmpaCity system installation in Essen, Germany," European Conference on Applied Superconductivity (EUCAS 2017), Geneva, Sept. 2017.

# Ampacity

Essen, Germany

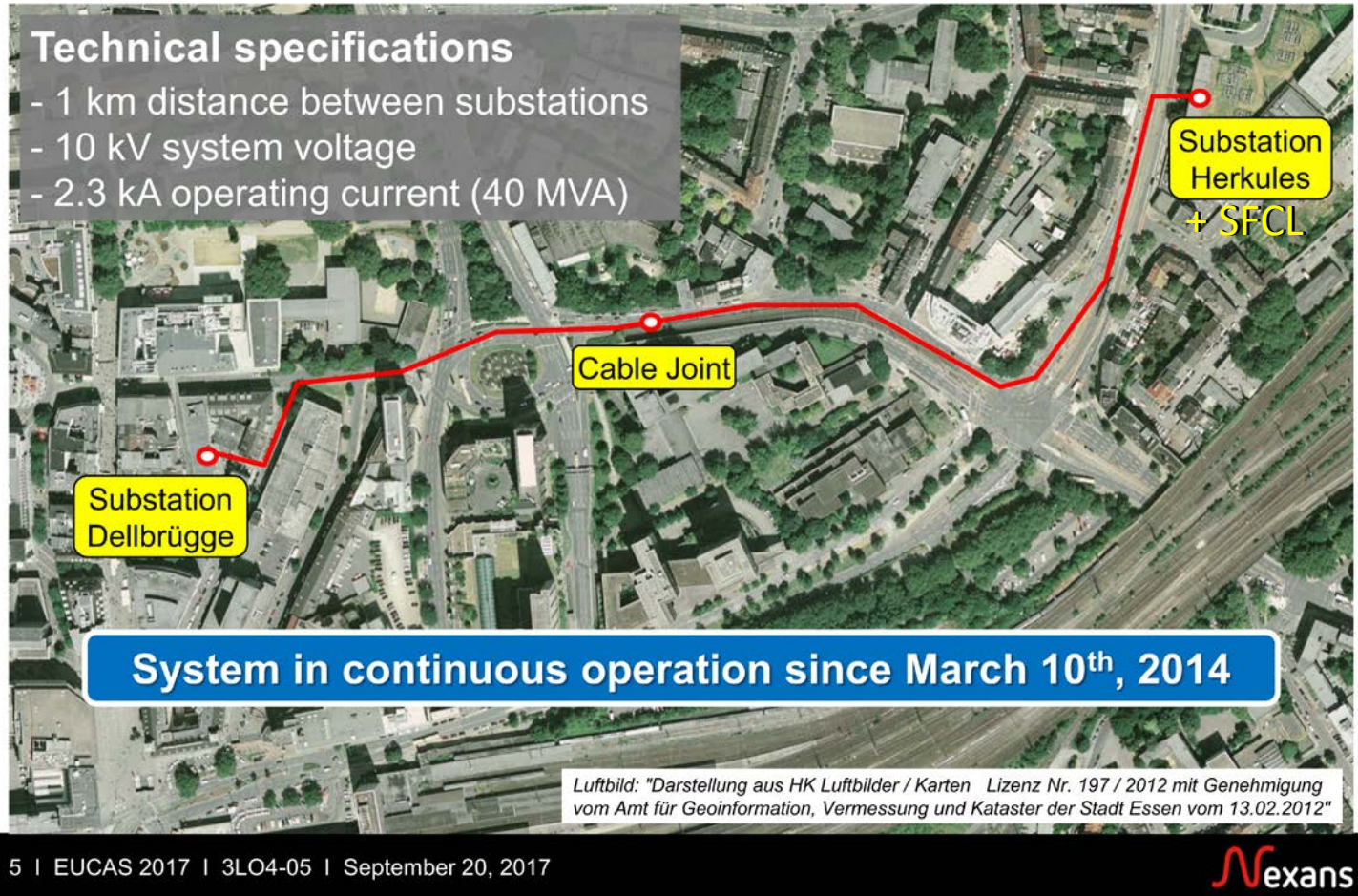
- 1 km long
- 10 kV
- 2.3 kA
- 40 MVA
- In service 2014

**RWEG**

**Nexans**

**KIT**  
Karlsruhe Institute of Technology

## AmpaCity installation in Essen, Germany



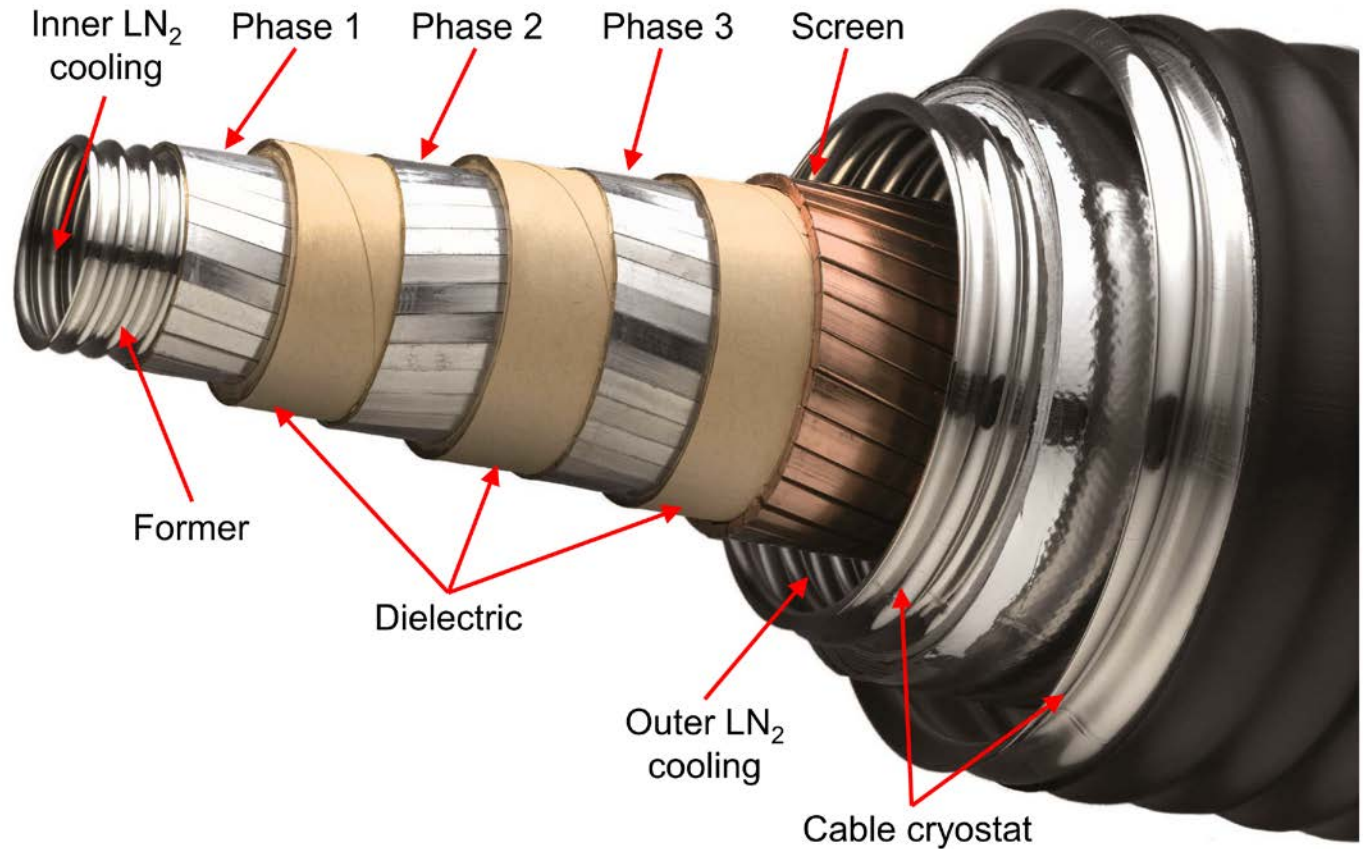
[1] M. Stemmler, K. Allweins, F. Merschel, T. Kugel, F. Herzog, T. Kutz, J.-M. Saugrain, "Three years operation experience of the AmpaCity system installation in Essen, Germany," European Conference on Applied Superconductivity (EUCAS 2017), Geneva, Sept. 2017.

# Ampacity

Essen, Germany

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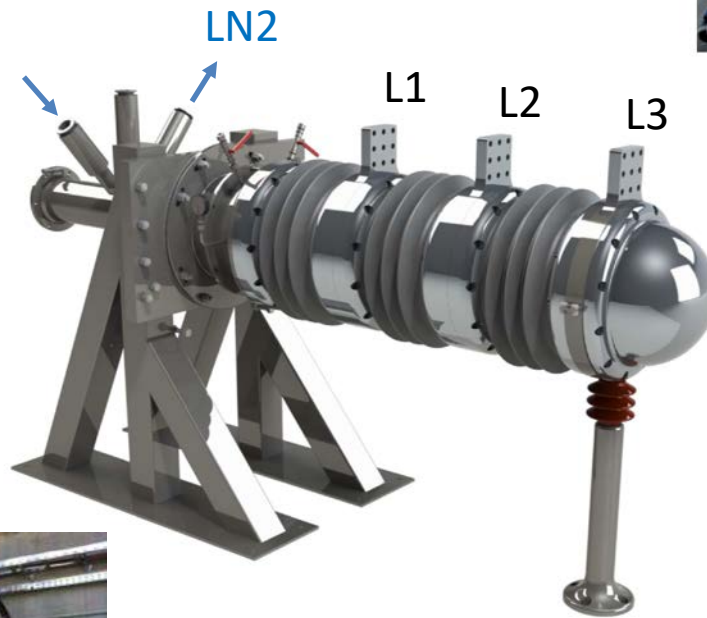
## Concentric cable design for MV applications



6 | EUCAS 2017 | 3LO4-05 | September 20, 2017

# Ampacity

Essen, Germany



[1] M. Stemmler, K. Allweins, F. Merschel, T. Kugel, F. Herzog, T. Kutz, J.-M. Saugrain, "Three years operation experience of the AmpaCity system installation in Essen, Germany," European Conference on Applied Superconductivity (EUCAS 2017), Geneva, Sept. 2017.

[2] F. Merschel, "AmpaCity, Energieverteilung von Morgen mit Hochtemperatur-Supraleiterkabeln und Strombegrenzern für Zentren mit hoher Lastdichte," VDE / IHK Forum Technische Innovationen, Köln, Germany, Sept. 2015.

## **II. Today**

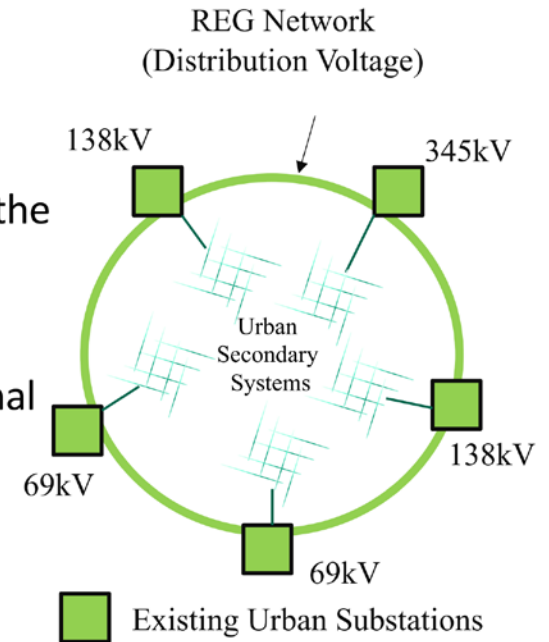
### **REG 1**

# REG 1

Chicago, USA

## REG Networks Utilize High Temperature Superconductor (HTS) Cables

- ✓ REG Networks provide **resiliency** by creating grid **redundancy**
- ✓ REG Networks **connect** urban substations on the **distribution side**, effectively **reinforcing** the transmission system
- ✓ REG Networks provide **high capacity, distribution voltage connections** with minimal footprint, civil work and permitting
- ✓ Approach is independent of **transmission voltage levels**, but compliments the existing transmission system



-8-





# REG 1

Chicago, USA

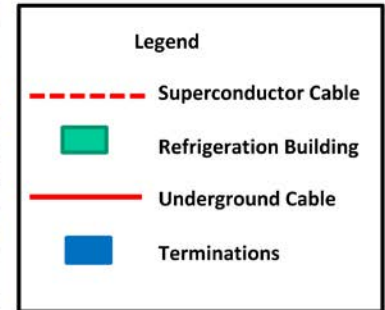
- 200 m long
- 12 kV
- 3 kA
- 62 MVA
- In service 2021

**ComEd**



**nexans**

## Superconductor Cable – Initial Project



← North



-14-

**ComEd**  
An Exelon Company

56th Annual Minnesota Power Systems Conference

[1] D. Brozman, M. Ross, "Chicago superconductor cable project and vision for the technology," 56th Annual Minnesota Power Systems Conference, [online], Nov. 2020.

# REG 1

Chicago, USA

- 200 m long
- 12 kV
- 3 kA
- 62 MVA
- In service 2021



[1] M. Ross, "Resilient electric grid networks: achieving enhanced resiliency in today's grid," Superconductors for power transmission webinar, [online], Jul. 2022.

## II. Today

**@ research laboratories**

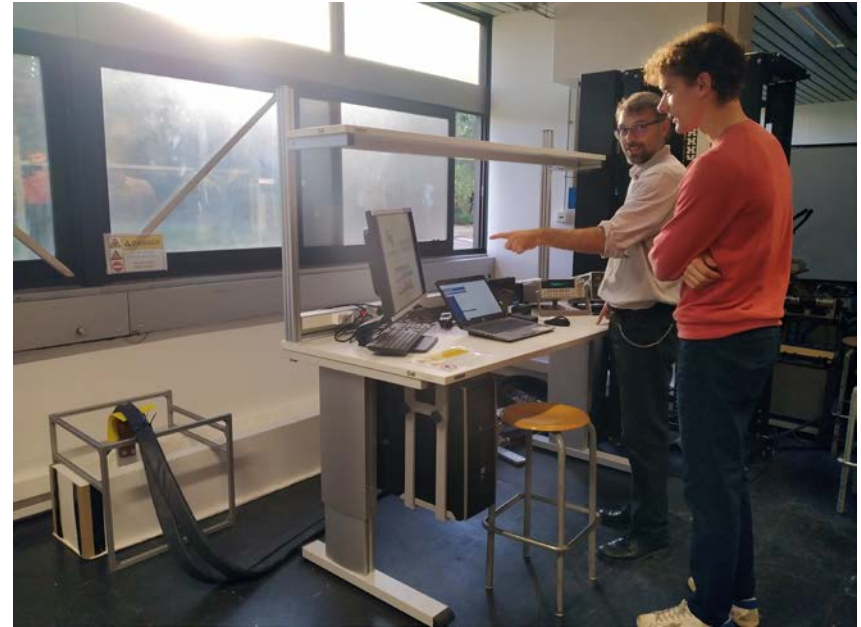
# Gargantua

GeePs' HTS cable DC test station:

- DC power supply (4x SGX1200)
- Open LN2 bath (2m long)
- Nanovoltmeter & thermometer

## Test capabilities

- 2m-long cables
- 4800 A at 10 V DC
- at  $\sim 77$  K under atmospheric pressure
- Measure nV voltage drop

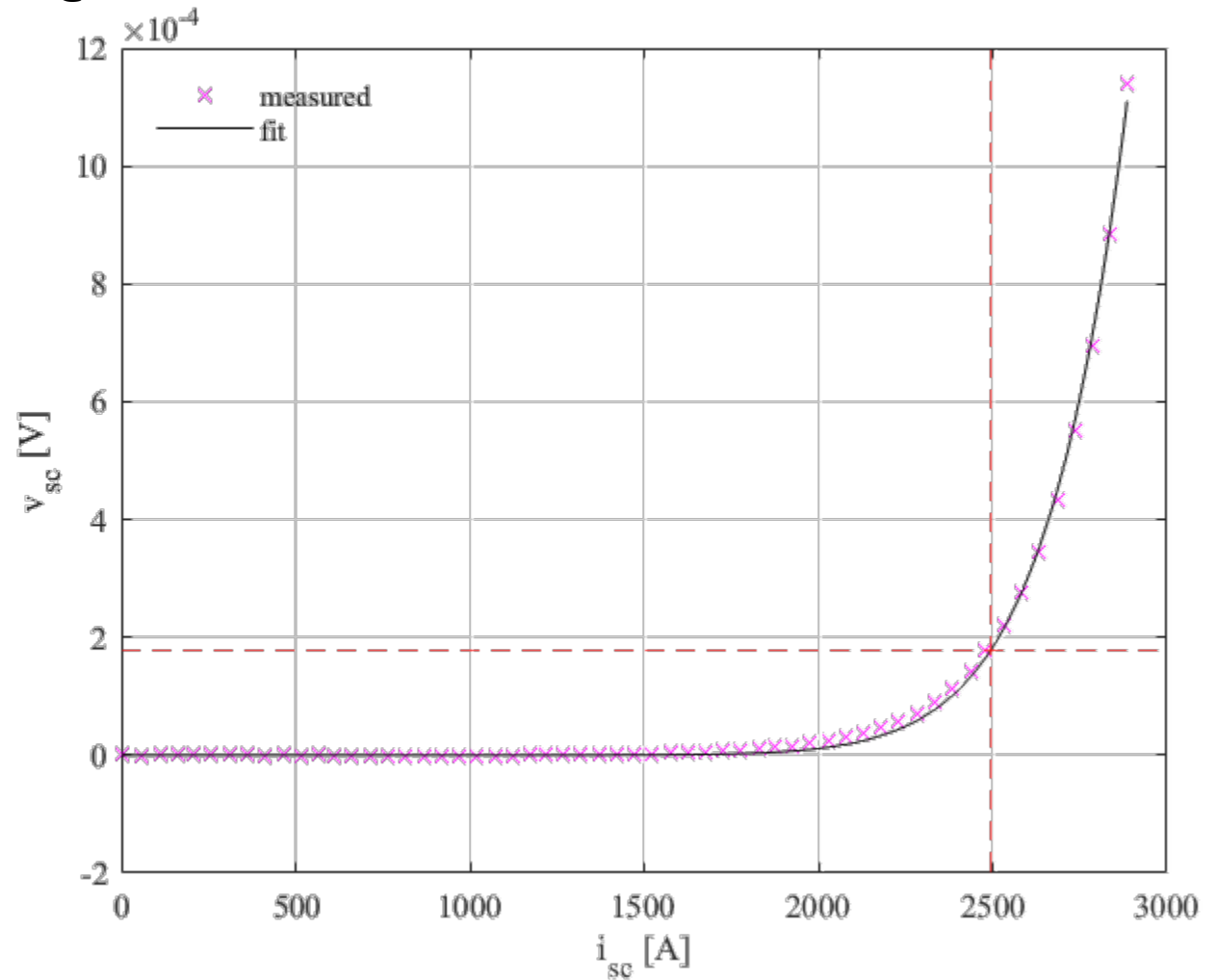


# Some results

Measured V-I characteristic @77 K

$$I_c = 2487 \text{ A}$$

$$n = 12$$



## **III. Tomorrow**

# **SuperLink**

# SuperLink

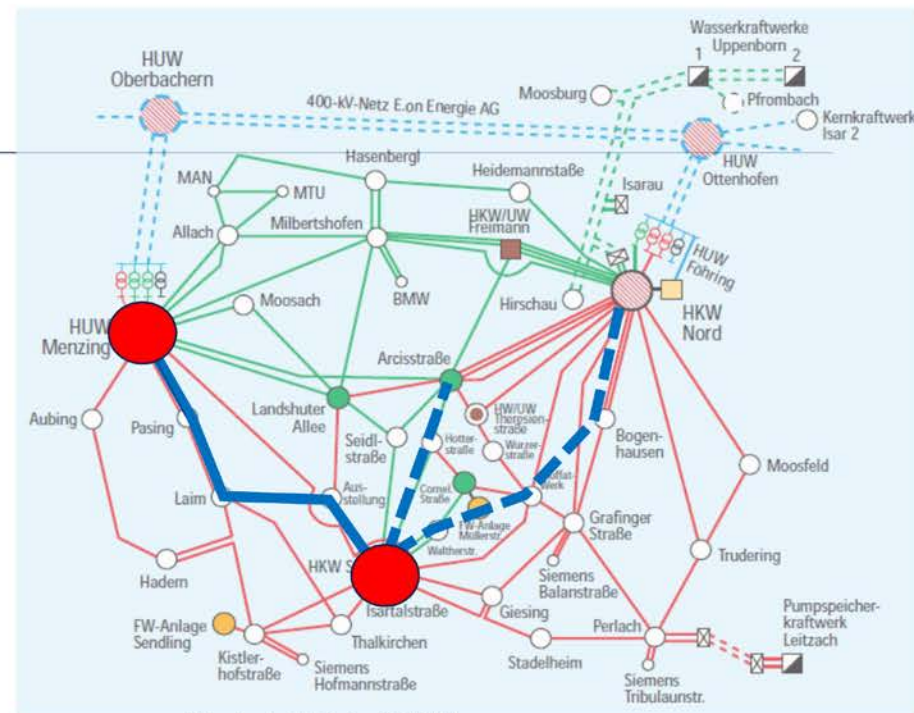
Chicago, USA



## Task Description

### High-density load area Munich

- Connect Kraftwerk Süd to the OH lines north of Munich
- Power rating 500 MVA
- Operation voltage 110 kV
- Length ~12 km
- Routed through the center of Munich



Werkstatt Kabel 2020

[1] D. Willén, "NKT HTS cable technology," *Superconductors for power transmission webinar*, [online], Jul. 2022.

# SuperLink

Chicago, USA



## Most Important requirements - Overview

The SuperLink must provide these advantages:

Criteria	Background
Save space	Very limited room for construction, Influence of other services, Routes and Right-of-way
Acceptance	Electromagnetic fields, Ground heating, Building sites
Economic	Cost of building and operating
Technically mature	Electric networks are critical infrastructure
Power Rating	Deliver 500 MVA or more in smallest space
Energy efficient	Reducing CO <sub>2</sub> Emissions

Werkstatt Kabel 2020

[1] D. Willén, "NKT HTS cable technology," *Superconductors for power transmission webinar*, [online], Jul. 2022.



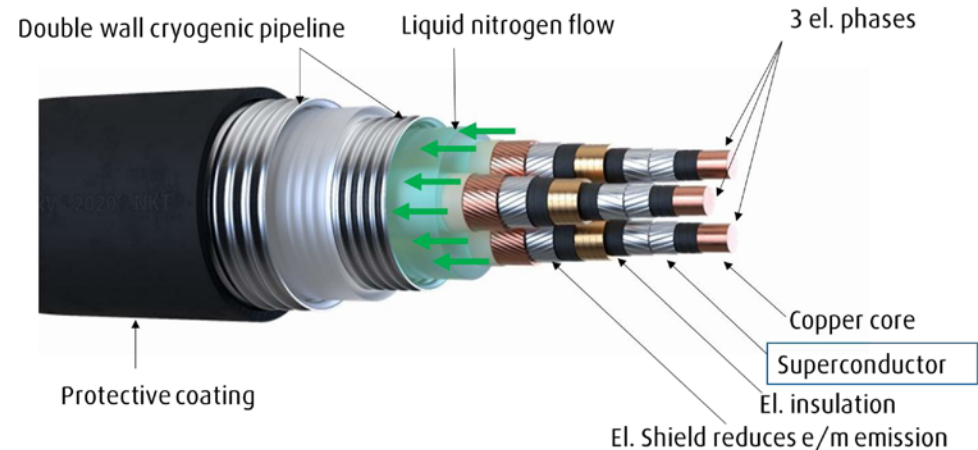
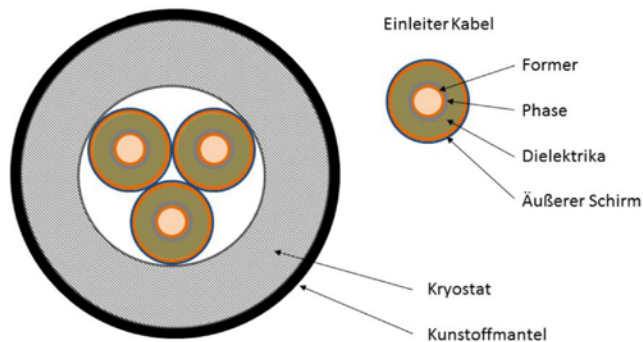
# SuperLink

Chicago, USA



## Development of the Cable System

- Three single-phase cables
- Terminations and joints
- Common Cryostat
- Ultra compact (Option to Retrofit)



### 110 kV SuperLink Kabel

- Three-phase cable with High-Temperature Superconductor (HTS)
- One cable in one trench replaces 5 conventional 110 kV cables in separate trenches

Werkstatt Kabel 2020

NKT HTS 21.06.202

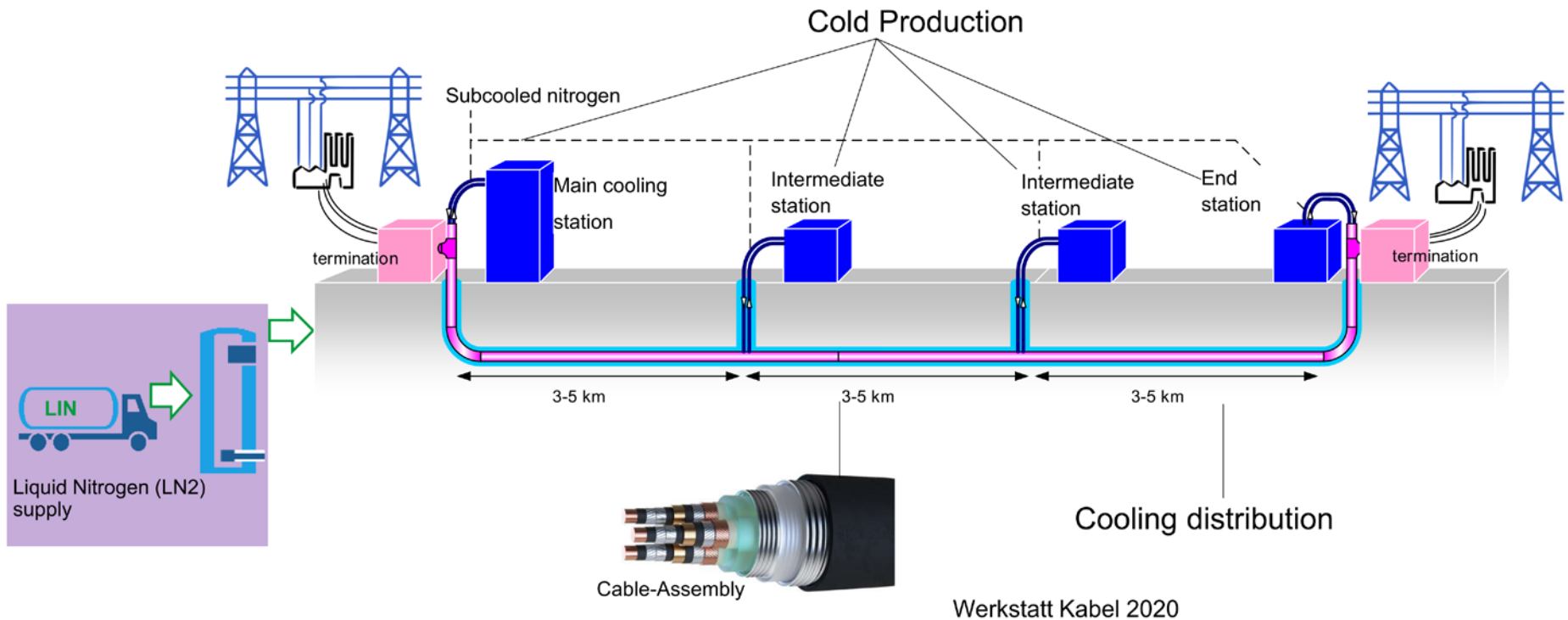
[1] D. Willén, "NKT HTS cable technology," *Superconductors for power transmission webinar*, [online], Jul. 2022.

# SuperLink

Chicago, USA



## Development of a distributed cooling system (Concept)



[1] D. Willén, "NKT HTS cable technology," *Superconductors for power transmission webinar*, [online], Jul. 2022.

## **III. Tomorrow**

# **SuperRail**

# SuperRail

Paris, France

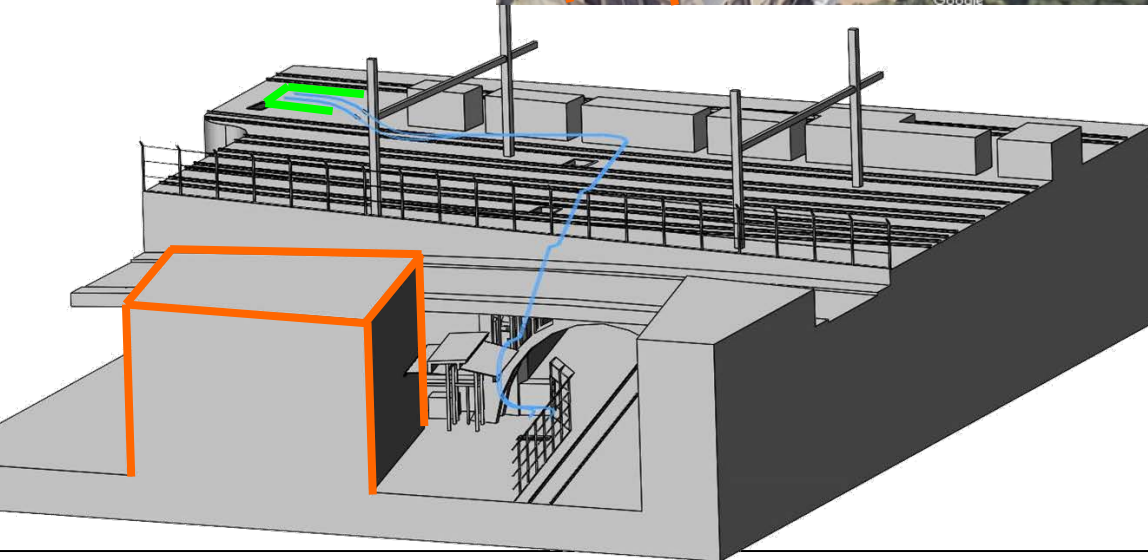
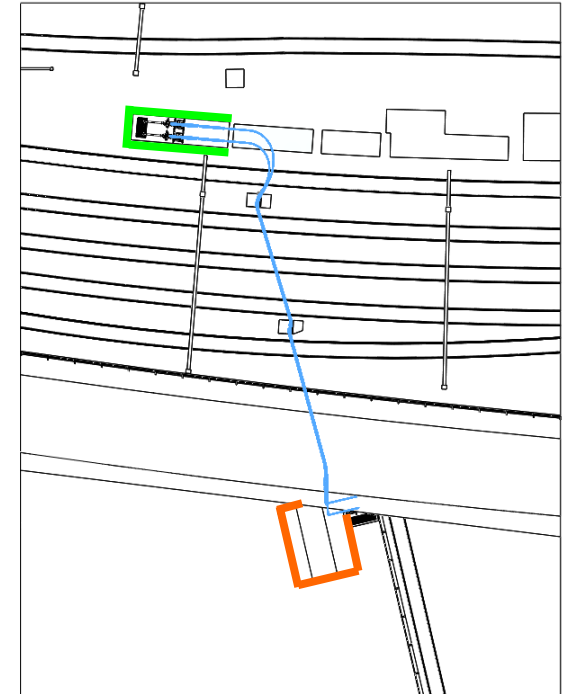


# SuperRail

Railway AC/DC  
substation

HTS cables

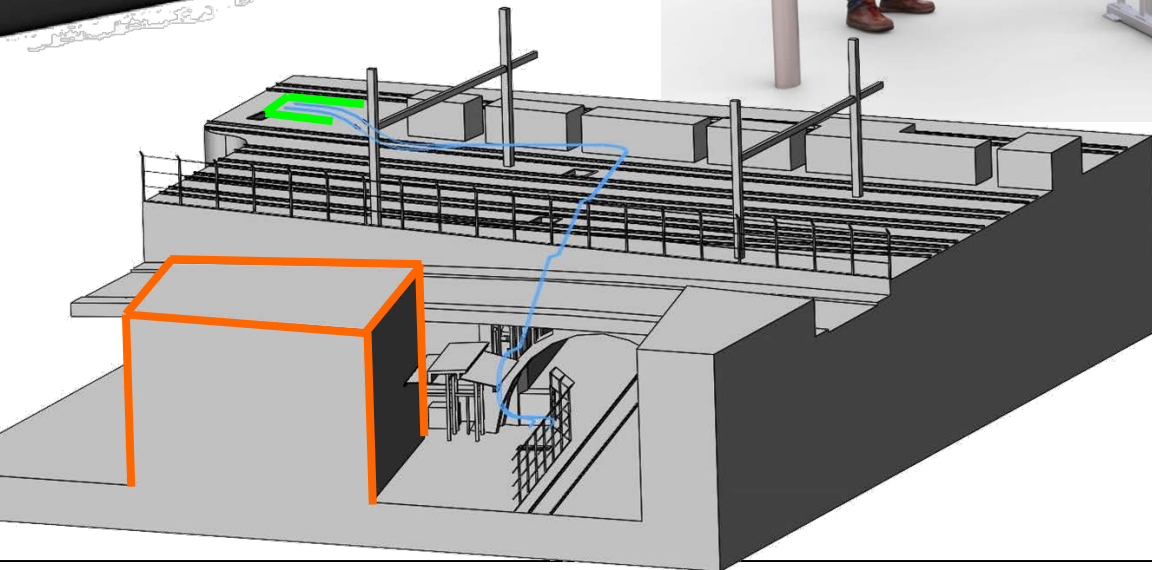
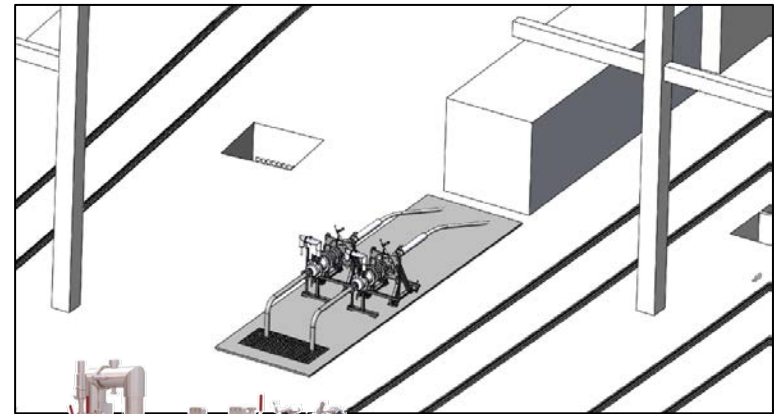
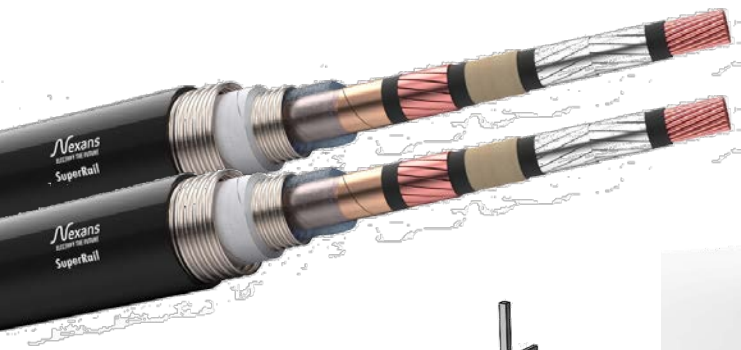
Platform



Length	2 x 80 m
Voltage	1500 V DC
Current	3500 A
Power	2 x 5 MW

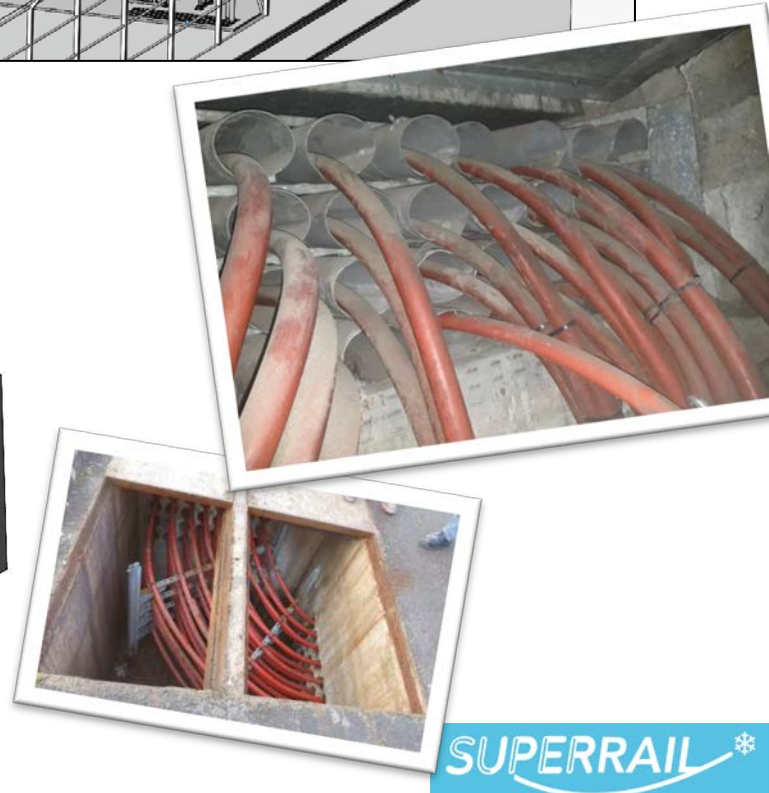
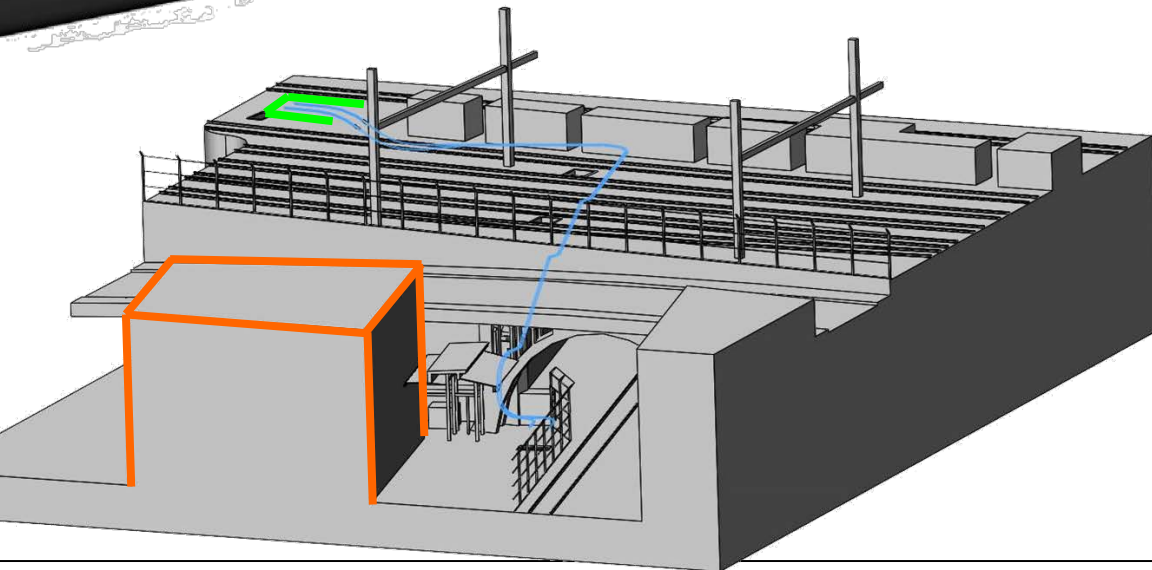
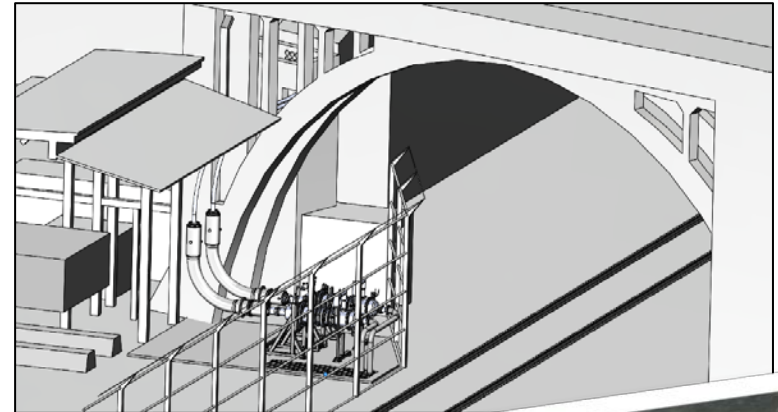
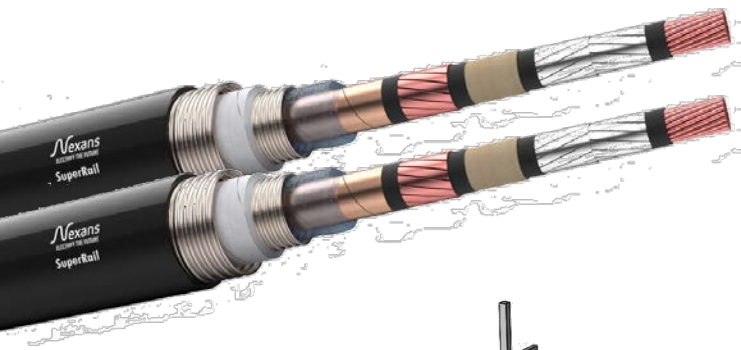
# SuperRail

- Railway application
- Continuous operation



# SuperRail

- Installation in existing pipes
- Sharp gradient and turns



**SUPERRAIL** \*

# V. Conclusion



## Conclusion

- The HTS power cable is an innovative device with potential to improve grids.
- HTS power cables are out of the laboratory development phase.
- Currently midway between pilot projects and industrial deployment. AC cable systems TRL 7-8. DC cable system TRL 5-6.
- First commercial products now available for LV, MV, and HV grids.
- More communication needed regarding successful field test experiences. Grid designers should be aware of this new device.
- Cryogenics does not pose a particular issue. Need to overcome psychological fears related to cryogenics.
- More long-term testing required to alleviate utility fears.
- Room for improvement in terms of conductor and cryostat costs and in terms of cryogenic processes.

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# Geeps

Electrical Engineering - Paris

**Merci !**

**université**  
**PARIS-SACLAY**



  
CentraleSupélec

 **SORBONNE**  
**UNIVERSITÉ**  
CRÉATEURS DE FUTURS  
DEPUIS 1257



# Technology Readiness Levels

- TRL 0: Idea.** Unproven concept, no testing has been performed.
- TRL 1: Basic research.** Principles postulated and observed but no experimental proof available.
- TRL 2: Technology formulation.** Concept and application have been formulated.
- TRL 3: Applied research.** First laboratory tests completed; proof of concept.
- TRL 4: Small scale prototype** built in a laboratory environment ("ugly" prototype).
- TRL 5: Large scale prototype** tested in intended environment.
- TRL 6: Prototype system** tested in intended environment close to expected performance.
- TRL 7: Demonstration system** operating in operational environment at pre-commercial scale.
- TRL 8: First of a kind commercial system.** Manufacturing issues solved.
- TRL 9: Full commercial application,** technology available for consumers.