IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), January, 2023.
This plenary presentation was given at the virtual EUCAS 2021, September 5-10, 2021.

Karlsruher Institut für Technologie

EUCAS 2021
SEPTEMBER, 5-9
MOSCOW

Superconductivity for Green Energy

EUCAS 2021, September 06, virtual conference

Tabea Arndt, Mathias Noe

KIT – Die Forschungsuniversität in der Helmholtz-Gemeinschaft

www.kit.edu

Hello Ladies and Gentlemen.
Welcome to the talk "Superconductivity for Green Energy"
Thanks to the organizers for the invitation to provide this plenary in the name of Mathias Noe and me. It's an honor and pleasure to contribute.

Acknowledgements

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We are grateful to all partners and colleagues that contributed to the development in applied superconductivity and that supported this presentation

Special thanks to:

- Wolfgang Reiser, Stefan Huwer and Claus Hanebeck from VESC
- Friedhelm Herzog from Messer
- Veit Grosse and Werner Prusseit from Theva
- Robert Nagel and Peter Michalek from SWM
- René Steinhorst from Thüringer Energienetze
- Robert Bach and Patrick Mansheim from University of Applied Science Südwestfalen
- Dag Willén from NKT Cables
- Alexander Alexeev from Linde
- The "AppLHy!" partners by Amprion, Daimler, Linde, HTW Dresden, IFW Dresden, TU Dresden, SciDre, Theva, KIT ETI, KIT IAM-WK, KIT ITES
- The former colleagues by Siemens
- Yingshen Liu, today at Harbin Institute of Technology, China

and to all colleagues from our Institute of Technical Physics

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- First some general aspects on fossil energy and sustainability.
- Then we will look into the history and see what changed in power generation in the past and into the actual shape of the electric grids.
- Following that, Mathias Noe will describe what implications and opportunities arise from the situation for power grid devices.
- He will elaborate on the worldwide fusion activities a bit.
- Then I will take over to describe the key performance values in generator types and opportunities for HTS
- The popularity of the “game changer hydrogen” leads to some new opportunities for HTS in the combination with LH2
- Finally, we will conclude.

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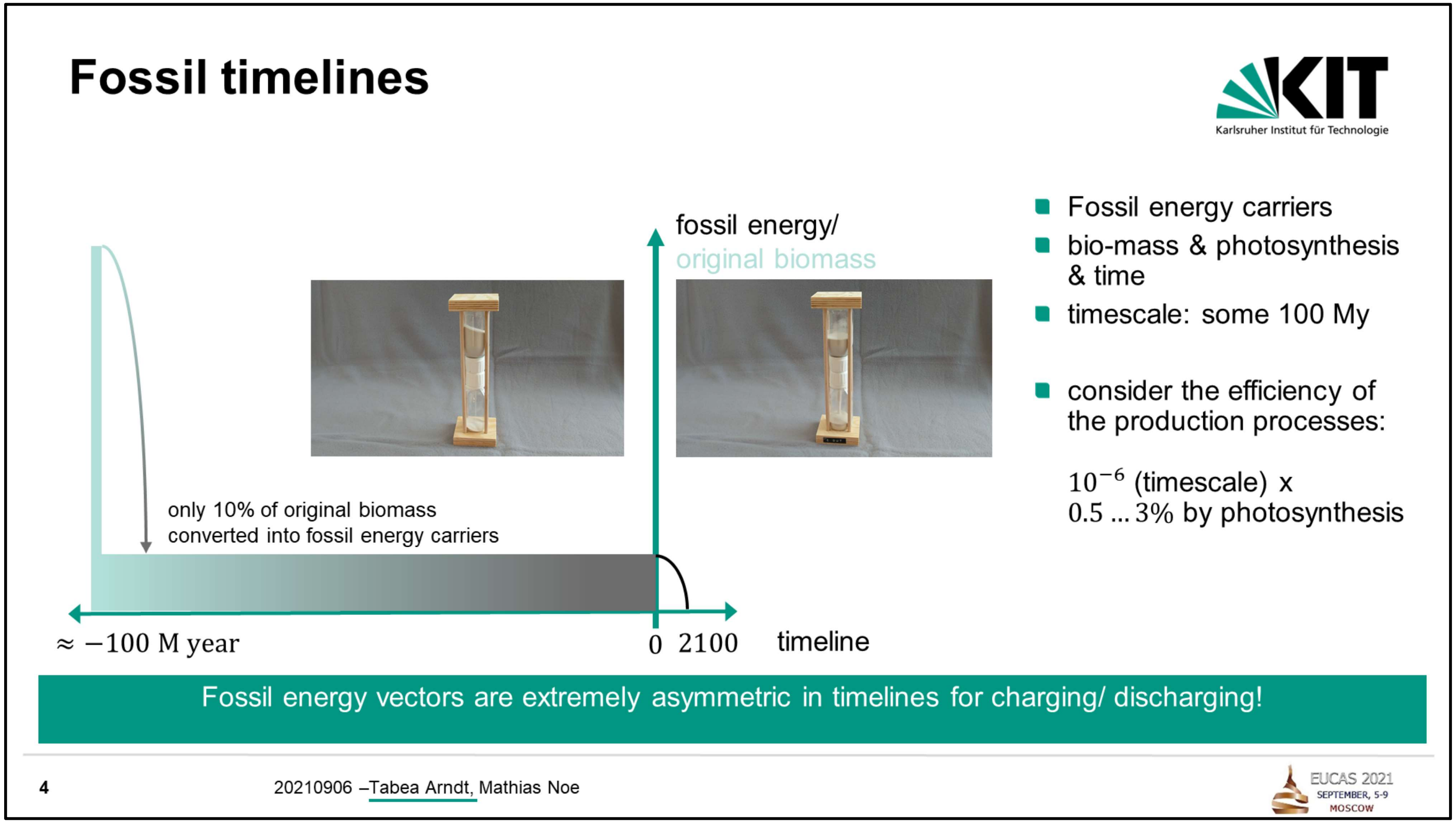

- The earth had 100 My time to convert 10% of original biomass into fossil energy carriers.
- Nature build a considerable energy deposit for us – with extremely low efficiency on long timescales = like the hourglass to the left.
- However, we are living from this energy deposits for abt. 200 years =like the hourglass to the right.
- These are extremely asymmetric charging/ discharging processes!
- What means “Green Energy”?
- In other words “sustainability”?

Green Energy – Symmetric Cycling

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- timescale of processes (charging/ discharging) should be similar.
- timescale should be similar to human lifetime or even shorter.
- Energy content might be small (locally)
- Either cycling like nature with
  - low efficiency
  - high number/ widespread
- or sophisticated cycling with
  - high efficiency
  - selected spots

Green Energy means cycling smaller energy content on much shorter times!

Contents

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- Now we will look into the history and see what changed in power generation in the past and into the actual shape of the electric grids.

Evolution of the Energy System

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Courtesy: Hermans,J. – „Energy Survival Guide“

Pictures: T.Arndt

17th century:
Consumption moves to Generation
(windmill, watermill, Al-works, wheat milling)
easy transportation of peat

Rheinfall Schaffhausen
(Germany/ Switzerland)

Industrial use

- 11th century:
  small mill
- lateron:
  workshops (grinding, forging)
- 16th century:
  iron ore smelting
- 19th century:
  Swiss Wagon Fab
  Aluminum Industry AG
  Hydro Power Plant

Fact source:
https://rheinfall.ch/de/informieren/informieren/geschichte/wirtschaftliche-nutzung.html

**Consumption moved to selected Locations of Generation.
“Localized Generation”**

- Nice example on the evolution of energy use is by the Rheinfall in Schaffhausen
- The very first local use of energy was at selected locations:
  - windmills
  - watermills
- Industry was founded at selected locations (river hydro energy) and evolved from that over the centuries.
- The first transport of high-density energy was in the form peat (first fossil)

Power Generation in Germany inaugurated 1941...1960 in total: 1040 MW

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Data by German Ministry for Environment „Database Power-Plants in Germany“

- Hydro Power

< 200 MW
≈ 500 MW
≈ 1000 MW

Up to 1960, Hydro Power was erected at selected spots in Germany.
“Localized Generation”

Example: Germany
“Localized Generation” (Erection of Hydro)

Power Generation in Germany inaugurated 1961...1980 in total: 15738 MW

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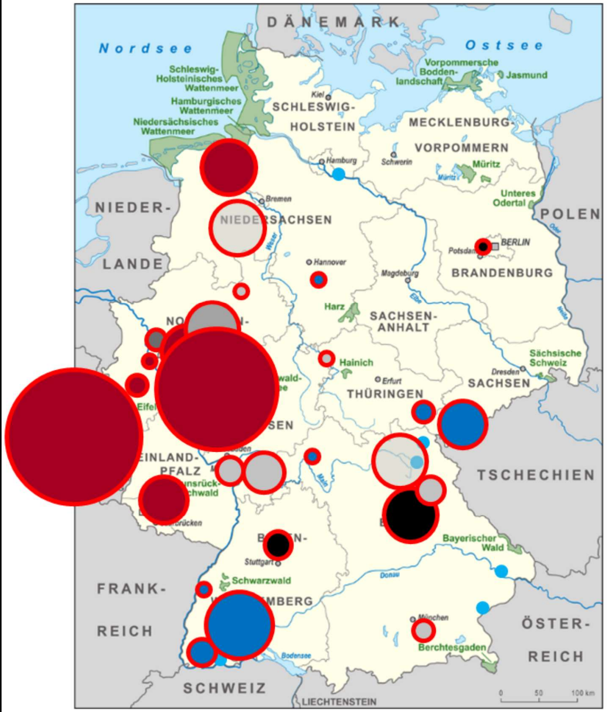

Data by German Ministry for Environment „Database Power-Plants in Germany"

- hydro
- blast furnace gas
- petrol
- natural gas
- coal

- < 200 MW
- ≈ 500 MW
- ≈ 1000 MW

1961-1980 Fossil Generation was placed at high-consumption Areas.
"Tailored Fossil Generation"

The next two decades may be called "tailored fossil power generation." In decreasing capacity:

- mainly coal
- some natural gas
- some petrol
- some hydro

Power Generation in Germany inaugurated 1981...2000 in total: 24229 MW

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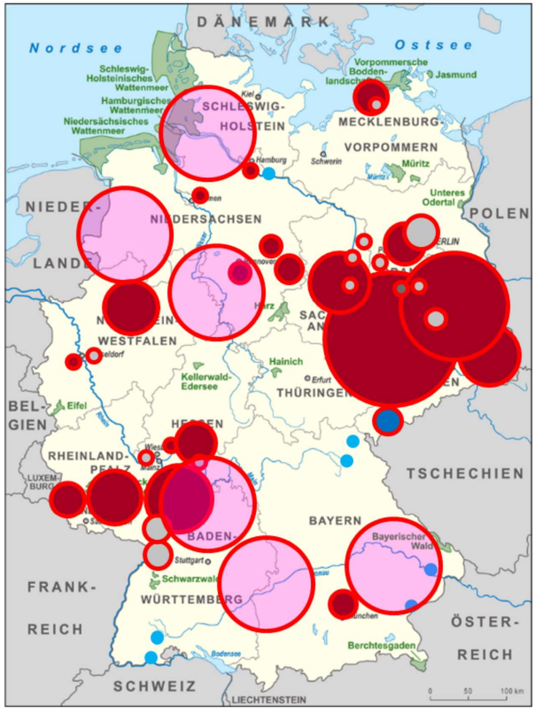

Data by German Ministry for Environment „Database Power-Plants in Germany"

- hydro
- blast furnace gas
- petrol
- natural gas
- coal
- uranium

< 200 MW
≈ 500 MW
≈ 1000 MW

1981-2000: Nuclear & Fossil placed at high-consumption areas and filling the gaps.
"Coal & Uranium Power Generation"

This timeframe may be called the "coal & uranium power generation"

Coal and Nuclear used to create full coverage of generation – filling the gaps.

What happened in the next/last 20 years?

Presently installed Electric Power Generation Germany

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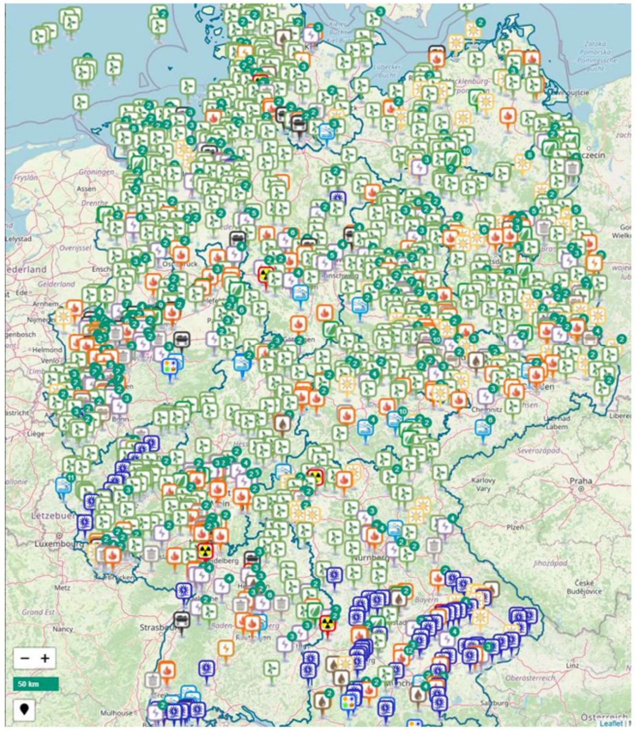


- Wind Onshore
- PV
- River Hydro
- Biomass
- Pumped Hydro
- Wind Offshore
- Gas
- Dark Coal
- Waste
- Petrol
- Brown Coal
- misc.
- Nuclear

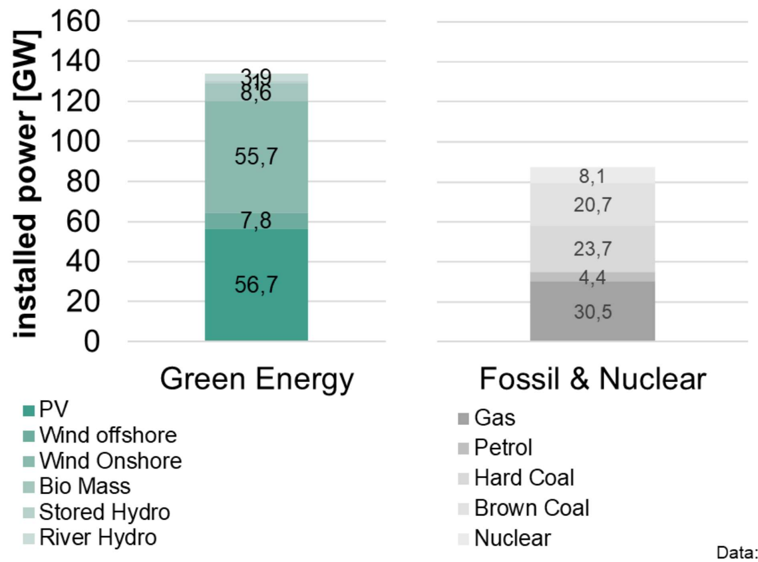
- Renewable:
  Green and Blue Symbols
- Conventional/ Fossil, Nuclear:
  Grey, Red, Brown

source: Fraunhofer ISE

Distributed Renewables dominate the Power Generation Landscape

Distributed Renwables dominate the power generation landscape – at least in numbers.

Installed Electric Power Generation 2021 (Germany)



Data: Fraunhofer ISE

- The installed Fossil & Nuclear Power Generation sticks to the “millennium value” of ≈ 80 GW.
- The installed “Green Energy” is much larger, nearly double that value.

The Power Generation by Fossil (mainly Coal) has to fill the gaps (in time) of the “Green Energy”.

The REN outnumbers the conventional power generation by far in capacity.
Changed role for Fossil Power Generation: from base load to “peaker.”
(Nuclear is somewhat special and more or less still base load).

→ How about the situation in Europe as a bigger picture?

Green Energy on European Level – Share on full Energy Needs[1)].

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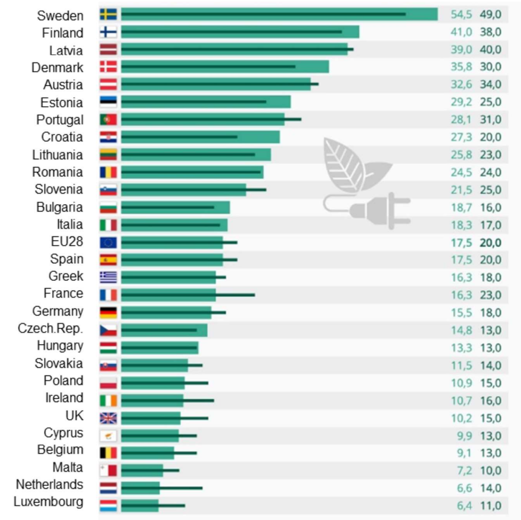

[1)] Energy Needs: electricity, heating, fuel, gas, etc. by private households, commerce, trade, service, industry, traffic

- Energy Needs is more than Electricity.
- Still a considerable way to go for all countries.

The European Energy Systems are by far NOT Green Today!

- Full Energy Need is more than Electricity!
- The European Energy Systems are by far NOT green today!
- A long way to go, but electrification is a must.
- The "Green Energy Generation“ is a beginning.
- First time situation: widespread generation of REN
- Need in improved electric grids in transmission & distribution
- Opportunities for Superconductivity and HTS

→ Mathias Noe will address these opportunities on Superconductivity and HTS in the next minutes.

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Opportunities for fault current limiters

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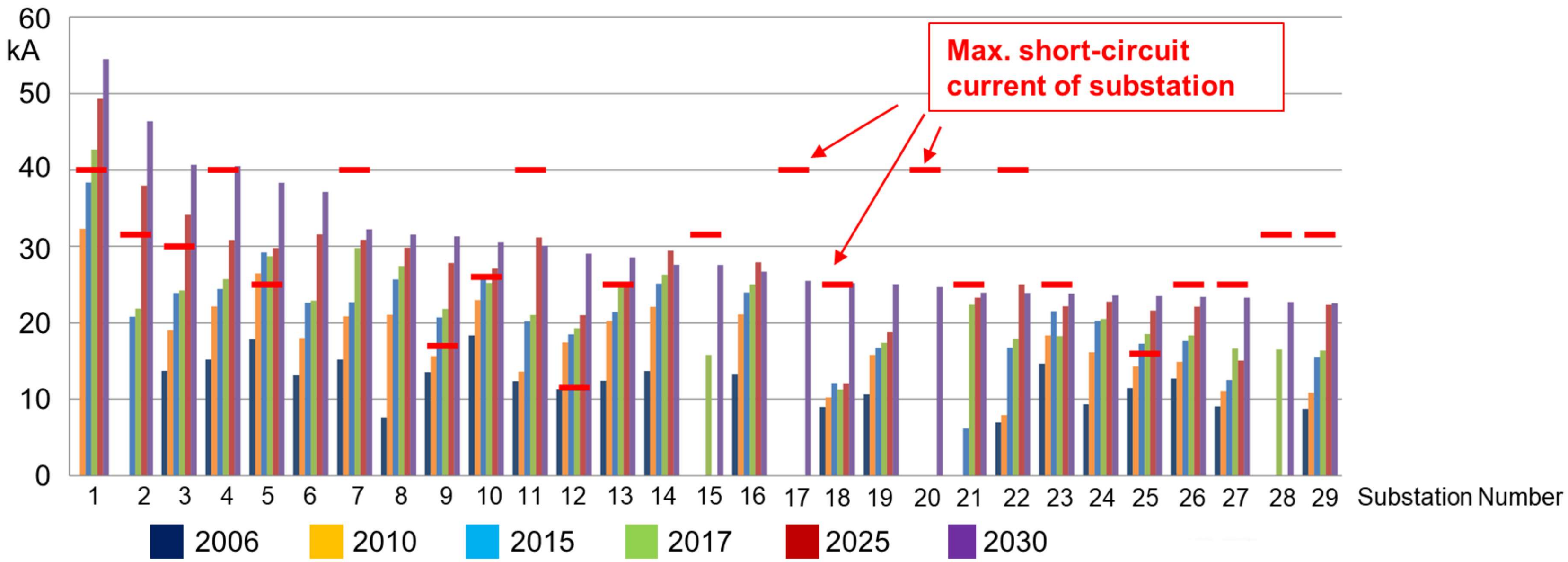
Development of highest short-circuit current of high-voltage to medium voltage substations of a German distribution system operator



In some locations a new substation has to be built with higher short-circuit ratings

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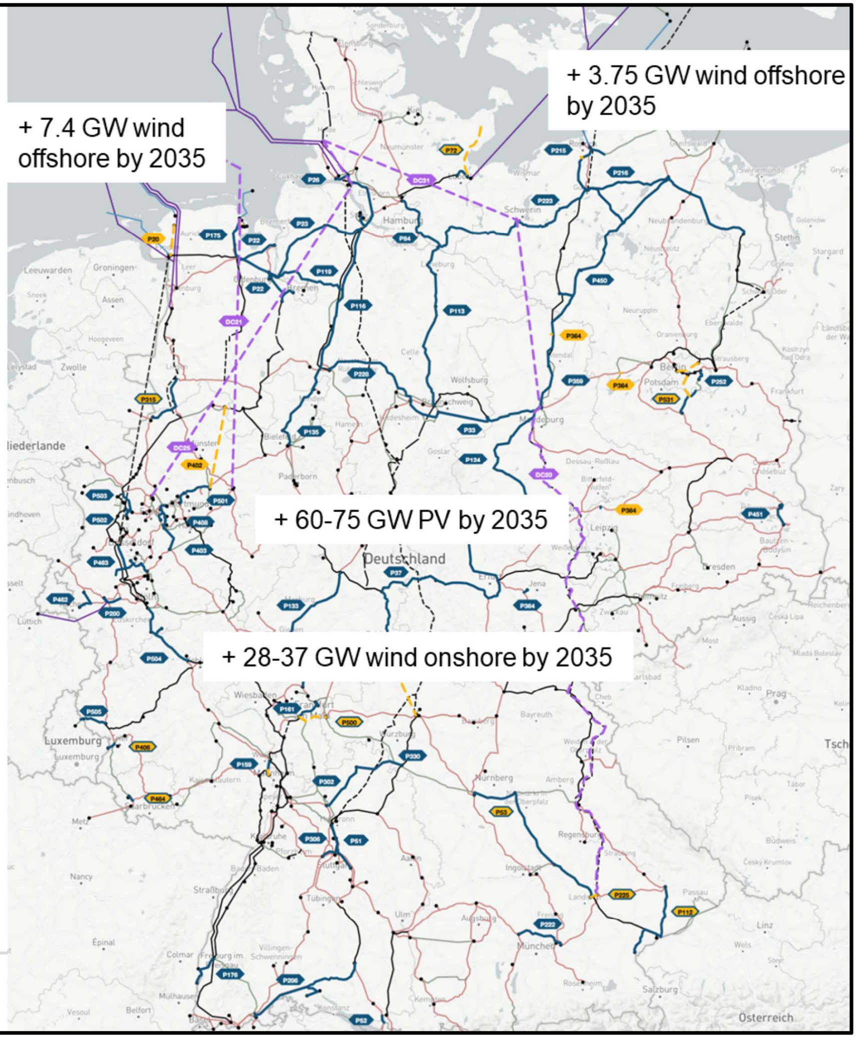
Opportunities for fault current limiters

Installation of many new transmission and distribution lines

Scenario	AC upgrade	DC upgrade	AC New	DC New
A	3365	540	380	1310
B	3365	540	380	1310
C	3490	540	380	1835
D	3775	540	520	1835

All values in km

By 2035 an investment of up to 80 Mrd. Euro is expected for the high voltage transmission grid only in Germany



Source and picture: Netzentwicklungsplan Strom 2035, Version 2021

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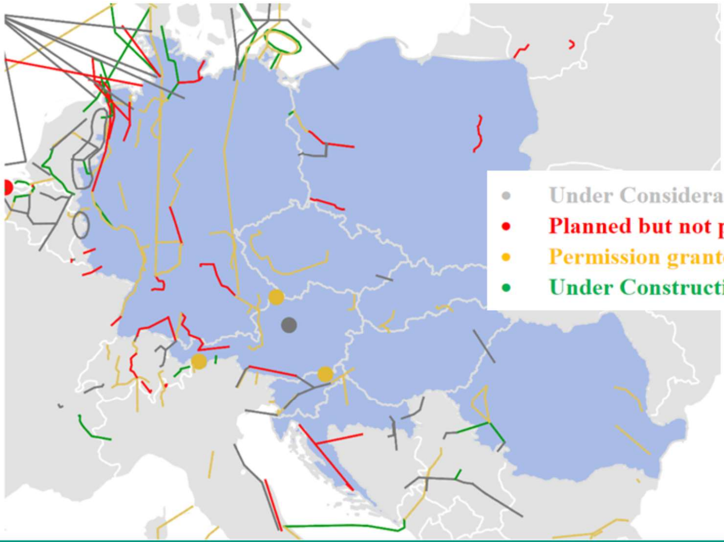
Opportunities for fault current limiters

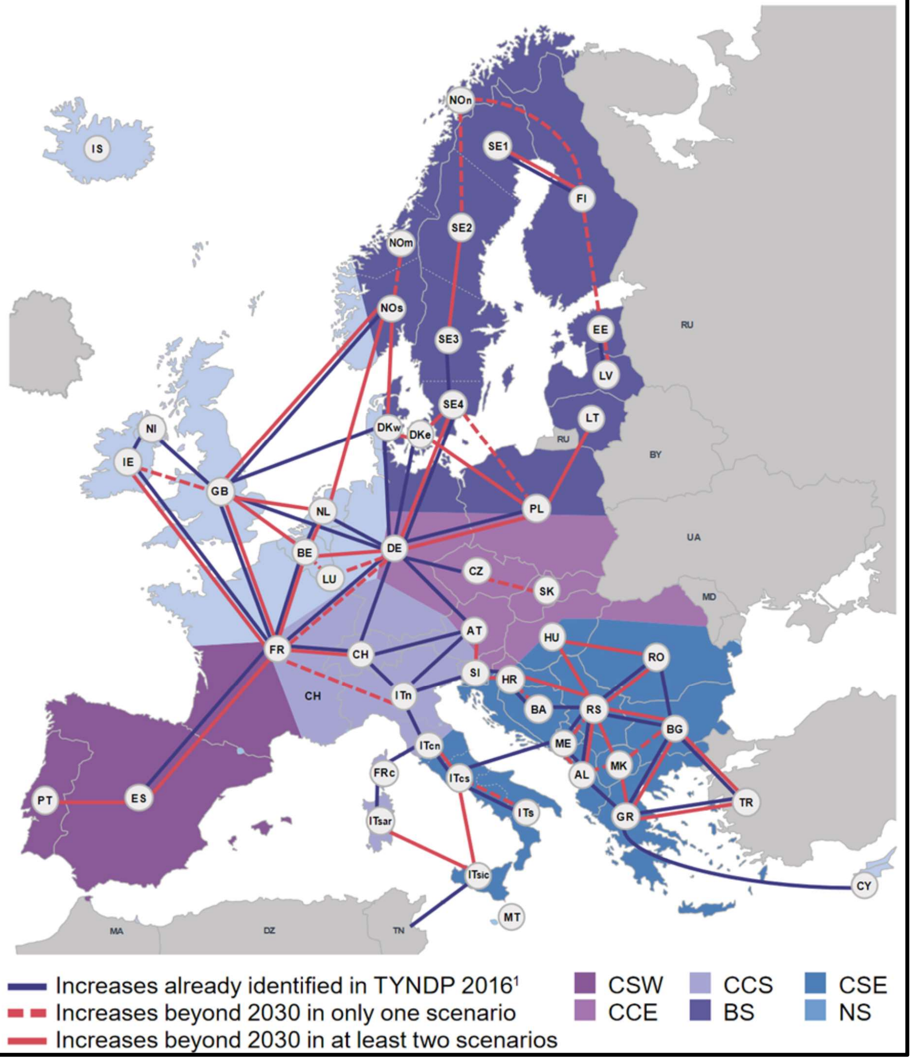
Installation of many new transmission and distribution lines



Cross border capacities in Europe will increase

Source and pictures: ENTSOE Regional investment plan 2017, Continental Central East, Final Version October 2019

Summary of capacity increases from 2020 to 2040



Opportunities for fault current limiters

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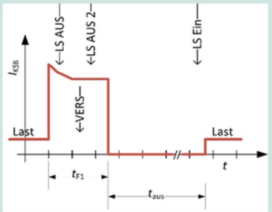
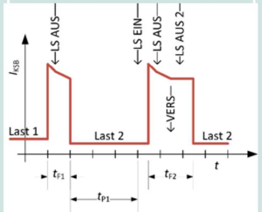
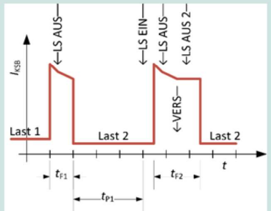
Typical specification of a German DSO

	Busbar Coupling (A+B)		Transformer Feeder C
Nominal Voltage	110 kV	110 kV	110 kV
Nominal Current	3.15 kA (rms)	3.15 kA (rms)	2.1 kA (rms)
Max. short-circuit current w/o limiter	50 kA (rms)	50 kA (rms)	13 kA (rms)
Max. limited current with FCL	6.5 kA (rms)	6.5 kA (rms)	4.5 kA (rms)
Fault duration	t_{F1} = 0.25 s 	t_{F1} = 0.10 s t_{P1} = 0.30 s t_{F2} = 0.20 s 	t_{F1} = 0.55 s t_{P1} = 0.30 s t_{F2} = 0.20 s 

Fault ride trough capability or recovery under load is mandatory for the transformer feeder location

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Opportunities for fault current limiters

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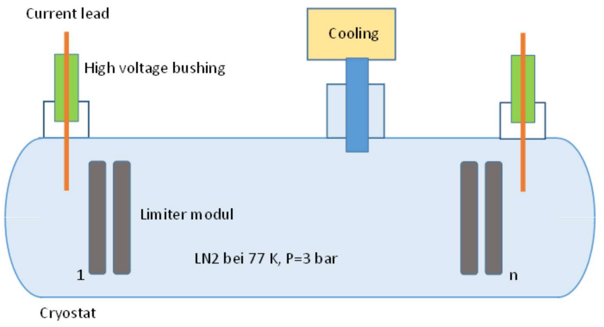
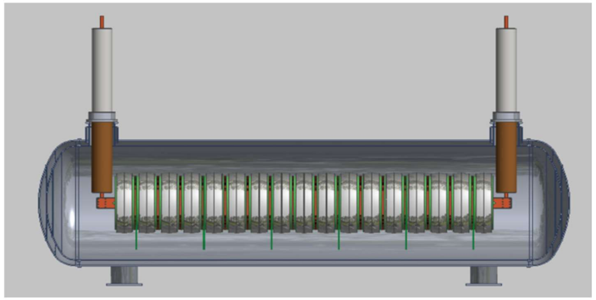
Conceptual design parameters

Parameter	Busbar coupling A without shunt	Transformer feeder C with shunt
Nominal Voltage	110 kV	110 kV
Nominal Current	3.15 kA	2.1 kA
LN2 pressure	3 bar	3 bar
Operating temperature	77 K	77 K
Cryostat dimension (LixDi)	~ 7.2 m x 1.8 m	~ 5.7 m x 1.8 m
Superconductor length	57.9 km (12 mm)	19.90 km (12 mm)
Cooling power at I_n	11 kW	4.120 kW
Number of limiter modules	84 (42 in Series)	40 (20 in Series)

Sketch of one phase





 20210906 –Tabea Arndt, Mathias Noe

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Opportunities for fault current limiters

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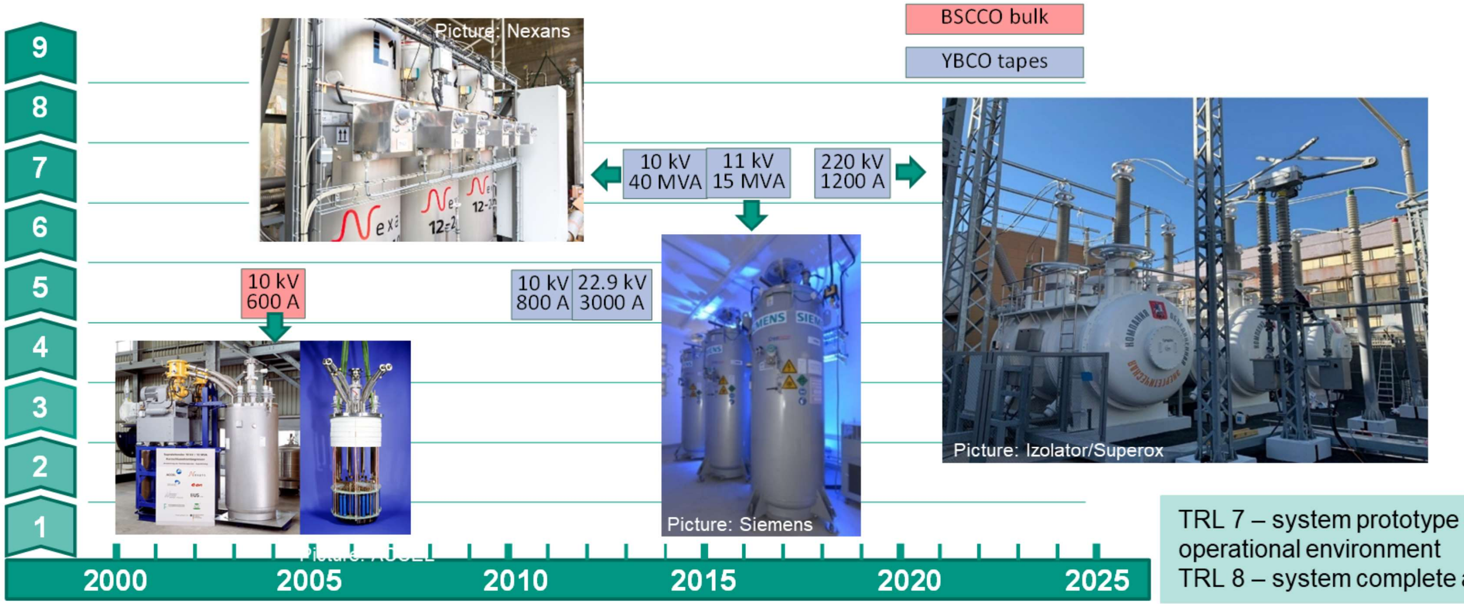
Development of technology readiness level of resistive type SFCLs



TRL 7 – system prototype demonstration in operational environment
TRL 8 – system complete and qualified

In the past 15 years resistive type SFCLs have reached a high TRL and are commercially available even at HV

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Opportunities for AC cables

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Overview on Superconducting Cable Applications

	Typical Length	TRL 1	TRL2	TRL 3	TRL 4	TRL 5	TRL 6	TRL 7	TRL 8	TRL 9
AC										
Inner city medium voltage (6-30 kV)	few km							X		
Inner city high voltage (110-220 kV)	few km						X			
High voltage transmission (380 kV)	few 100 km		X							
High voltage partial in ground cables (380 kV)	few km		X							
Generator feeder (6-30 kV)			X							
DC										
Elektrolysis industry (einige 10 kA)	few 10 m					X				
Aluminium industry (> 100 kA)	few 100 m		X			X				
Data Center	few 10 m				X					
Connection of renewable energies	few km					X				
Railway feeder	few km						X			
Medium voltage DC transmission	~ 100 km		X							
High voltage DC transmission	~ 100-1000 km		X							
Elektric aircraft power supply	~ 10-100 m			X						
Degaussing of ships									X	

Low TRL (TRL 1–3) | Medium TRL (TRL 4–6) | High TRL (TRL 7–9)

Opportunities for AC cables

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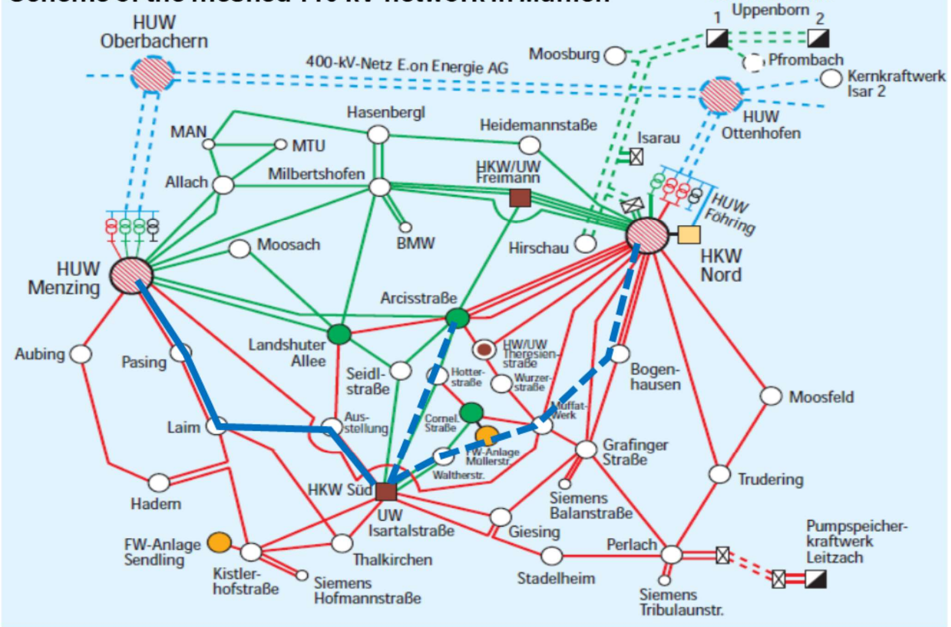
Example of a 110 kV, 500 MVA SuperLink cable in Munich

Scheme of the meshed 110 kV network in Munich



- Necessary change in cable technology
- Mainly gas pressure cable network with age between 25-55 years
- Non-availability of gas pressure cables, terminations, joints and transition joints
- Strong renewal pressure in the cable network (enormous volume > 90 cable sections)
- Avoidance of another 400/110 kV main substation (space requirement, costs)

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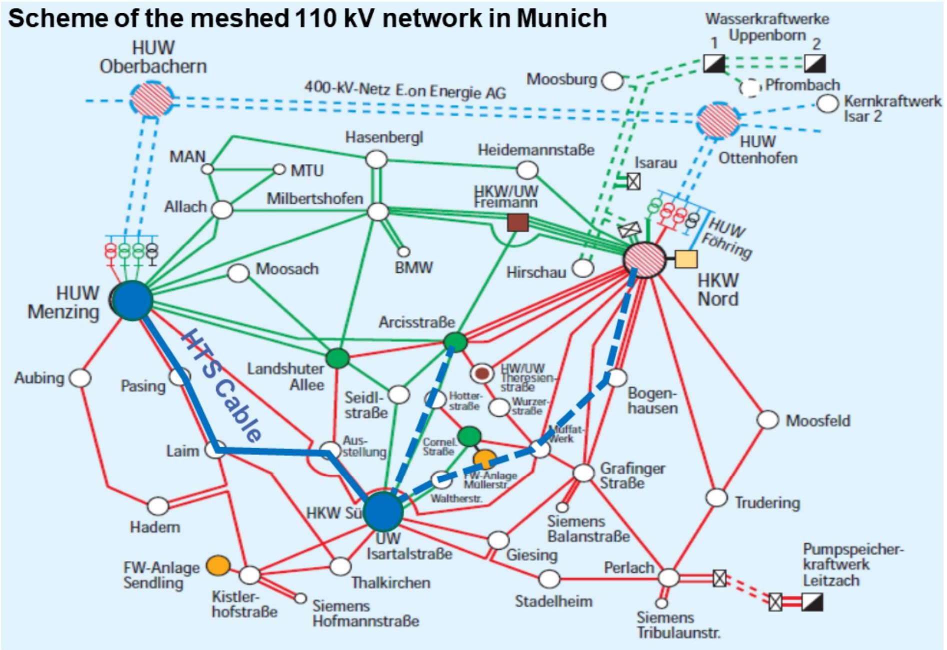
Opportunities for AC cables

Example of a 110 kV, 500 MVA SuperLink cable in Munich



- Necessary change in cable technology
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- Strong renewal pressure in the cable network (enormous volume > 90 cable sections)
- Avoidance of another 400/110 kV main substation (space requirement, costs)

SWM needs a high power line between Menzing and Kraftwerk Süd with 500 MW and appr. 12 km.

Opportunities for AC cables

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110 kV, 500 MVA SuperLink cable in Munich – Technical alternatives

400 kV XLPE cable system

E.g. tunnel solution, as in Berlin

400 kV overhead line

Not feasible in the city
Even in the surrounding countryside almost unfeasible today

Multiple 110 kV XLPE cable systems

Several systems necessary for 500 MVA
Limited bending radii for laying in inner cities

110 kV HTS cable system

New technology

Folie 24

NM(1 Noe, Mathias (ITEP); 02.08.2021

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Opportunities for AC cables

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110 kV, 500 MVA SuperLink cable in Munich – Evaluation criteria from power system operator

Criteria	Background
Minimum space	Challenges with routing and influence on other media
Acceptance	Electromagnetic fieds, ground heating, construction side
Economic feasible	Low total cost of ownership (investment and operation)
Technical maturity	Network is a critical infrastructure
High power and power density	500 MVA with minimim space
Low losses	Saving of losses and CO_2

Opportunities for AC cables

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110 kV, 500 MVA SuperLink cable in Munich – Evaluation criteria from power system operator

Criteria	OHL (400 kV)	Several 110-kV-VPE-Cable	400-kV-Cable	110-kV-HTS-Cable
Minimum space	☹	☹	☹	☺
Acceptance	☹	😐	☹	☺
Economic feasible	☺	☹	☹	😐
Technical maturity	☺	☺	☺	😐
High power and power density	☺	☹	☺	☺
Low losses	😐	☹	☹	☺

HTS cables have major advantages but also a need for further development. At present, a 500 MVA, 110 kV, 12 km long HTS cable is not available.

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Opportunities for AC cables

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110 kV, 500 MVA SuperLink cable in Munich – Evaluation Criteria from power system operator

Criteria	OHL (400 kV)	Several 110-kV-VPE-Cable	400-kV-Cable	110-kV-HTS-Cable
Minimum space	☹	☹	☹	☺
Acceptance	☹	😐	☹	☺
Economic feasible	☺	☹	☹	😐
Technical maturity	☺	☺	☺	😐
High power and power density	☺	☹	☺	☺
Low losses	😐	☹	☹	☺

HTS cables have major advantages but also a need for further development. At present, a 500 MVA, 110 kV, 12 km long HTS cable is not available.

Opportunities for AC cables

110 kV, 500 MVA SuperLink cable in Munich – Motivation for a new project and project partners

SWM	**Stadtwerke Munich**	Utility for 400 V – 400 kV urban infrastructure
NKT	**NKT Cables Group**	High voltage HTS cable manufacturer
THE LINDE GROUP	**Linde Group**	Technical gas, cryogenics and cryogenic systems
THEVA	**Theva**	HTS tape manufacturer
Fachhochschule Südwestfalen University of Applied Sciences	**FH SWF, Soest**	High voltage and cable testing
KIT Karlsruhe Institute of Technology	**Karlsruhe Institute of Technology**	Power system, electromagnetic and thermal modelling

The project is funded under FKZ 03EN2036

Bundesministerium für Wirtschaft und Technologie

Projektträger Jülich Forschungszentrum Jülich

Opportunities for AC cables

SuperLink

110 kV, 500 MVA SuperLink cable in Munich – Project objective and status

Duration
1.10.2020 - 31.3.2023

Objective
Development of the technology for a 500 MVA, 110 kV cable and field test of a 200 m cable section

Status
Cable design fixed, project within planned time

The project is funded under FKZ 03EN2036

Bundesministerium für Wirtschaft und Technologie

PtJ Projektträger Jülich Forschungszentrum Jülich

Opportunities for AC cables

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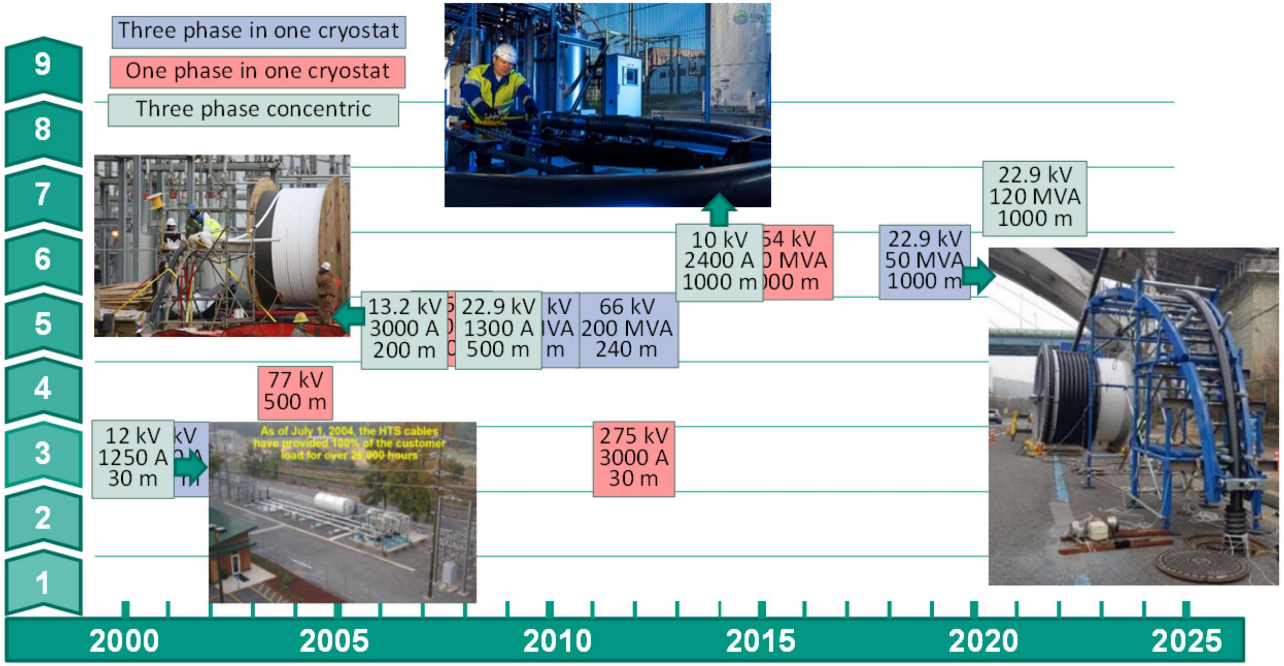
Development of technology readiness level of AC HTS cables



TRL 1 - Basic principles observed
TRL 2 - Technology concept formulated
TRL 3 – Experimental proof of concept
TRL 4 - Technology validated in lab
TRL 5 - Technology validated in relevant environment
TRL 6 - Technology demonstrated in relevant environment
TRL 7 – system prototype demonstration in operational environment
TRL 8 – system complete and qualified
TRL 9 - Actual system proven in operational environment

A clear progress can be seen in the past 20 years since the first field test of a HTS superconducting cable

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Opportunities for DC cables

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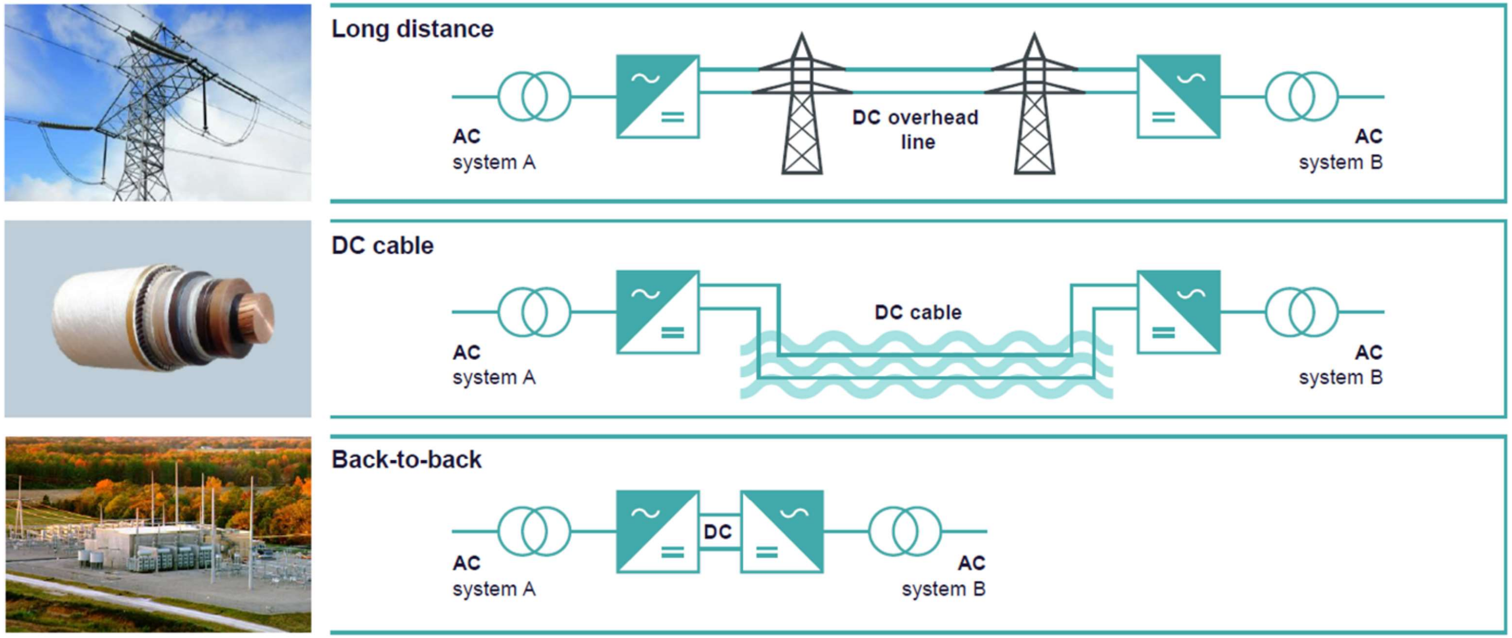
High voltage high power DC connection



German Kuhn | SE T SO PLM-FACTS 3

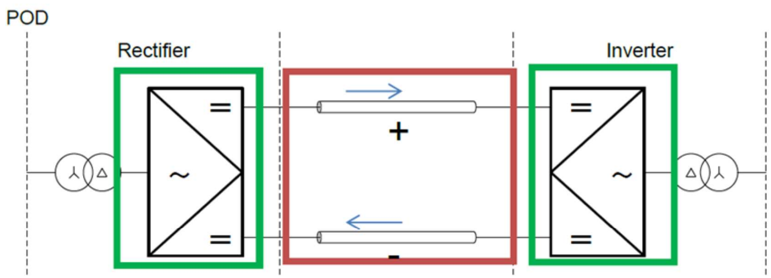
2020-11-12

Siemens Energy, 2020

In Germany several 525 kV DC cable connections are planned from north to south

Opportunities for DC cables

Medium voltage high power DC solutions



Types from Siemens Energy	Var. 1	Var. 2	Var. 3
DC voltage converter	± 24 kV	± 30 kV	± 50 kV
Real power converter cos φ 0.9	30-70 MW	up to 90 MW	up to 150 MVA
Max. spec. DC Phase resistance	0.01 Ω /km		

Transmission power and length of MVDC is limited by the parameters of conventional cables.
Is it possible to achieve a GW transmission power with MVDC technology and HTS cables?

Opportunities for DC cables

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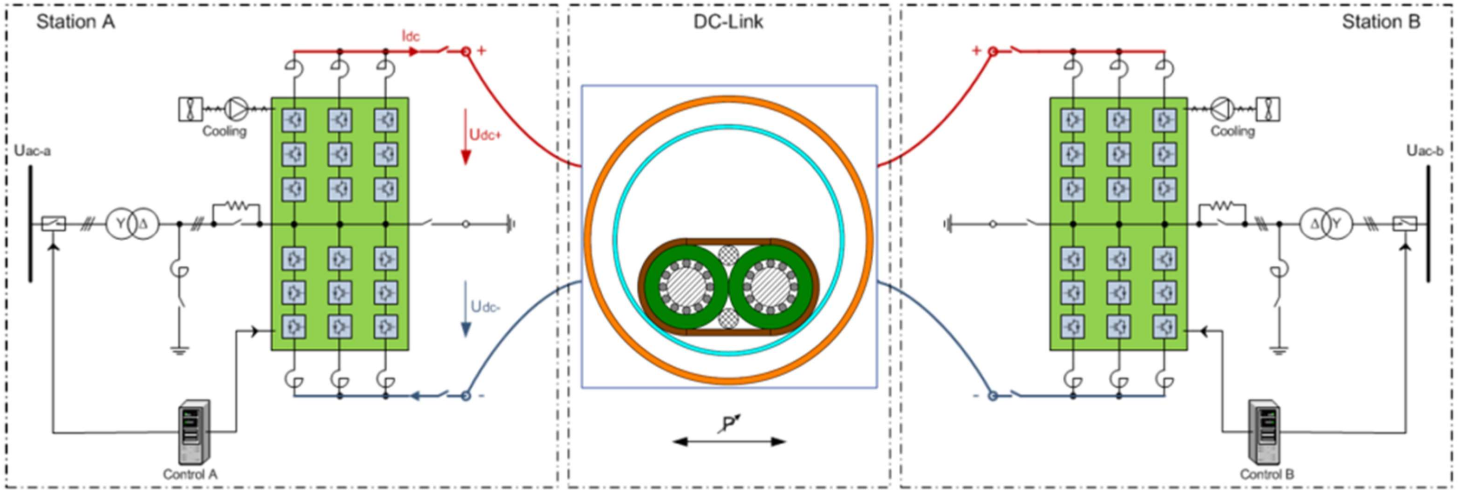
Medium voltage high power DC solutions with HTS DC cable



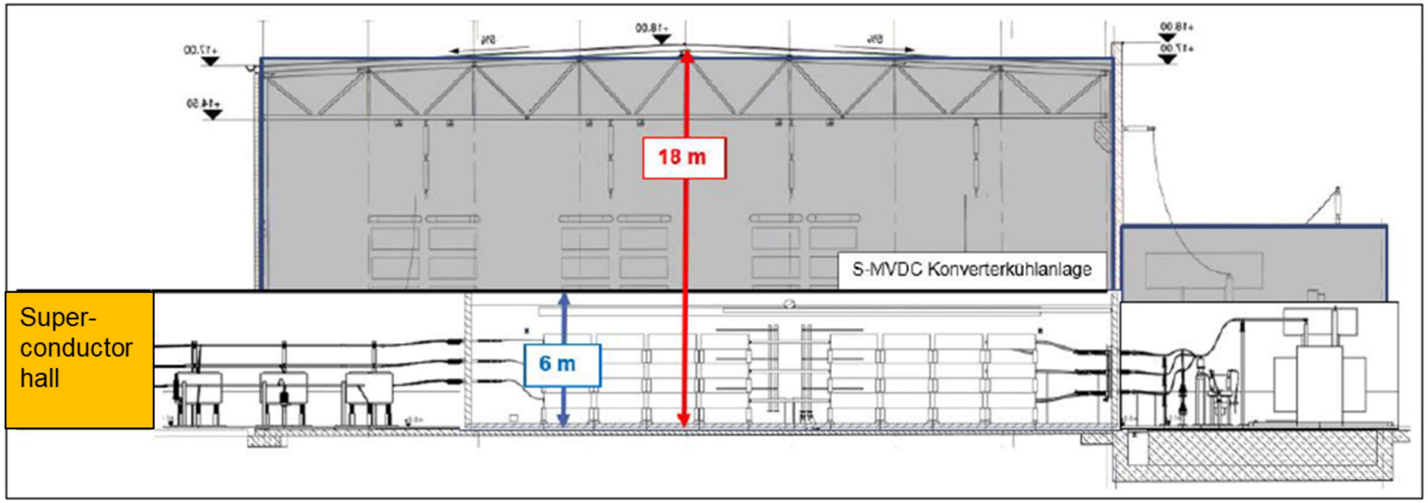
Main advantages
- GW transmission power with several MVDC stations in parallel
- Smaller line width and higher transmission power
- Lower permission effort

Opportunities for DC cables

HTS MVDC high power transmission

Application study with Utility, Vision Electric Super Conductors, Messer, Siemens Energy and KIT

Comparison of size of converter buildings



Opportunities for DC cables

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HTS MVDC high power transmission

Application study with Utility, Vision Electric Super Conductors, Messer, Siemens Energy and KIT

Comparison of size of converter buildings

	HVDC – 1 GW – S-MVDC	
DC voltage	± 320 kV	± 50 kV
Hall space	4800 m²	3300 m²
Outdoor space	1000 m²	1000 m²
Total space	**5800 m²**	**4300 m²**
	100 %	**75 %**
Building height (converter)	18 m	6 m
Building volume	**90.000 m³**	**22.500 m³**
	100 %	**25 %**

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This plenary presentation was given at the virtual EUCAS 2021, September 5-10, 2021.

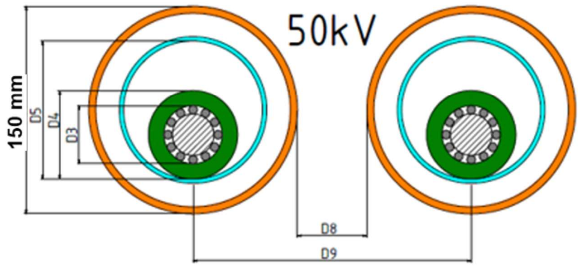
Opportunities for DC cables

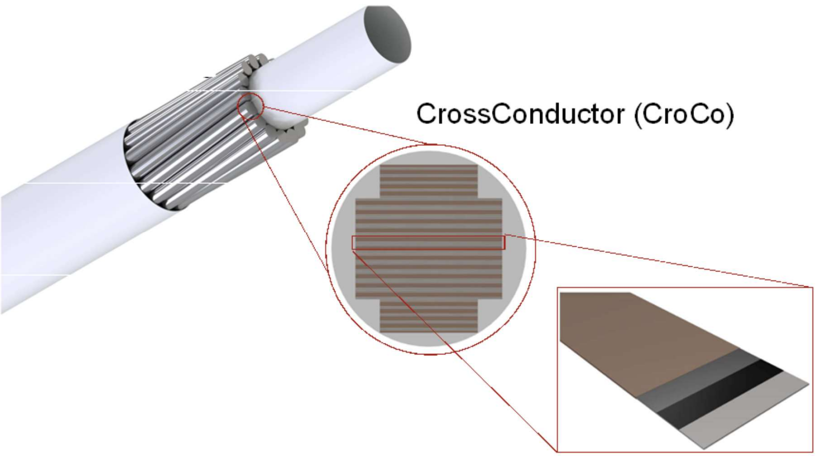
HTS MVDC high power transmission

Application study with Utility, Vision Electric Super Conductors, Messer, Siemens Energy and KIT

S-MVDC Cables for 1 GW

One pole in one cryostat





Opportunities for DC cables

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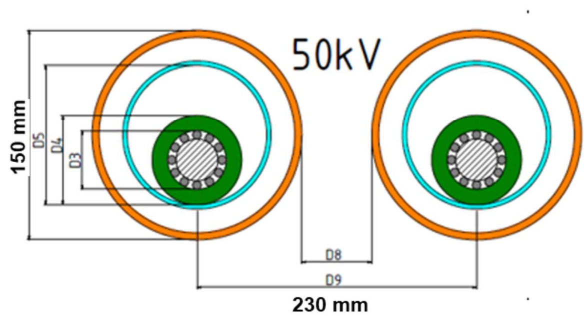
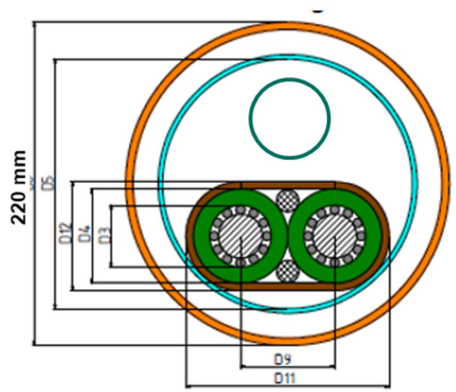


Two poles in one cryostat



a) With integrated LN2 return
b) Separate LN2 return

Cryostat

- Laying similar to pipeline
- Corrugated tube up to 500 m
- Plain tube length up to 16 m
- on-site welding L = appr. 1 km

HTS Phase conductor

- Transport length L = 1 - 5 km
- Incl. electr. insulation, and mech. protection
- Optional with HTS-shield

Electromagnetic design that fulfills short-circuit specification with maximum temperature and forces

Opportunities for DC cables

Karlsruher Institut für Technologie

HTS MVDC high power transmission

Application study with Utility, Vision Electric Super Conductors, Messer, Siemens Energy and KIT

Summary of main characteristic

Cable routing

- ☺ Highest acceptance
- ☺ Lowest impact on environment
- ☺ Lowest realisation time
- ☺ Less effort with cable laying

Converter stations

- ☺ Full HVDC functionality
- ☺ Smaller footprint 75 %
- ☺ Smaller converter buildings 25 %

Investment cost

- ☺ 10 % savings at converter
- ☹ HTS cable more expensive
- ☹ Additional cooling
- ☺ Less effort for laying

Operation cost

- ☹ Little higher maintenance
- ☺ Lower losses

Superconducting DC cables enable a 1 GW MVDC power transmission.

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Opportunities for DC cables

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Overview on Superconducting Cable Applications

	Typical Length	TRL 1	TRL2	TRL 3	TRL 4	TRL 5	TRL 6	TRL 7	TRL 8	TRL 9
AC										
Inner city medium voltage (6-30 kV)	few km							X		
Inner city high voltage (110-220 kV)	few km						X			
High voltage transmission (380 kV)	few 100 km		X							
High voltage partial in ground cables (380 kV)	few km		X							
Generator feeder (6-30 kV)			X							
DC										
Elektrolysis industry (einige 10 kA)	few 10 m					X				
Aluminium industry (> 100 kA)	few 100 m		X			X				
Data Center	few 10 m				X					
Connection of renewable energies	few km					X				
Railway feeder	few km						X			
Medium voltage DC transmission	~ 100 km		X							
High voltage DC transmission	~ 100-1000 km		X							
Elektric aircraft power supply	~ 10-100 m			X						
Degaussing of ships									X	
			Low TRL			Medium TRL			High TRL	

Many applications for DC cables exist ranging from a few kA to several 100 kA and from kV to more than 100 kV.

Contents

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- Fossil Energy – Storage and Usage
- Evolution of Electric Power Generation
- Opportunities in Transmission and Distribution
  - SFCL
  - AC-Cables
  - DC-Cables
- **Opportunities in Generation**
  - **Fusion**
  - Turbo, Wind Power, Hydro Power
- Liquid Hydrogen and Opportunities for HTS
- Conclusions

Fusion

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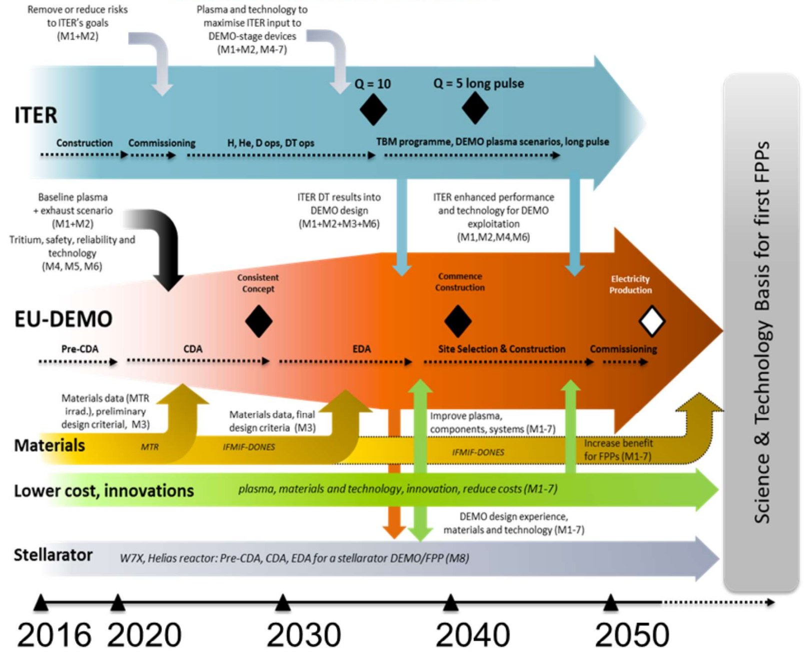
Timeline of ITER and DEMO

EU Fusion Roadmap to Fusion Electricity (v2.0) , under discussion, dates indicative



Item	DEMO	ITER
Fusion power	2 GW	0,5 GW
Plasma volume	2580 m³	816 m³
Major radius	9.1 m	6.2 m
Minor radius	2.9 m	2 m
Toroidal field on axis	5.3 T	5.3 T
Max. toroidal field	12 T	11.8 T
Number TF coils	16	18
TF overall height	~ 19 m	~ 13.5 m
TF system stored energy	150 GJ	41 GJ
Fast discharge time const.	35 s	11 s
Centring force per TF	850 MN	400 MN
Vertical force on half TF	520 MN	200 MN

Neil Mitchell et al 2021 Supercond. Sci. Technol. in press https://doi.org/10.1088/1361-6668/ac0992

Fusion

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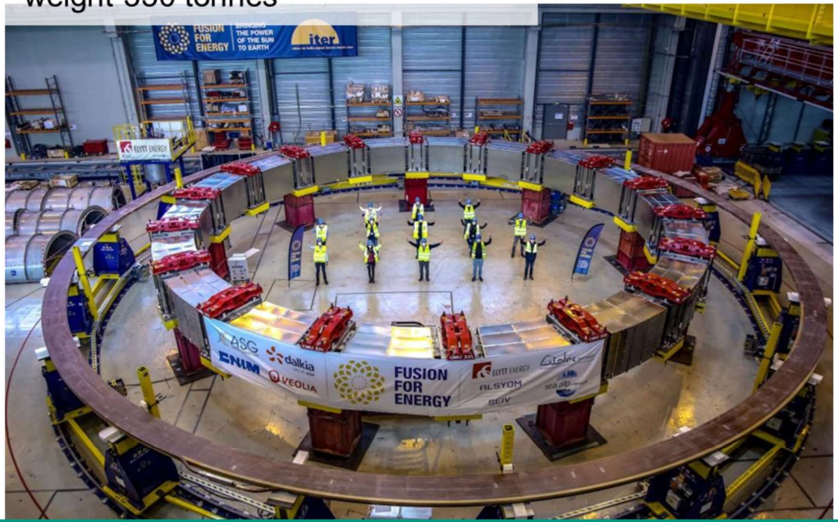
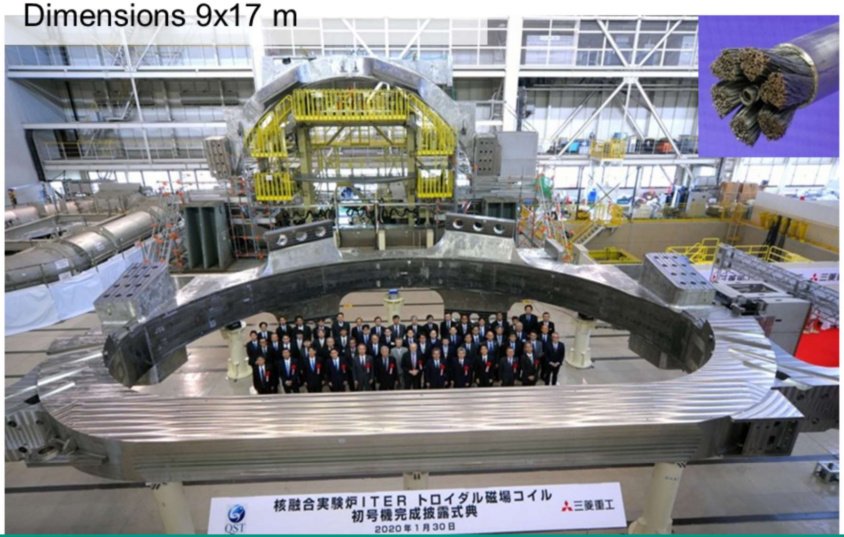
ITER Magnets state of the art

April 2021
PF5 coil leaves manufacturing
Outer diameter 17 m
weight 330 tonnes



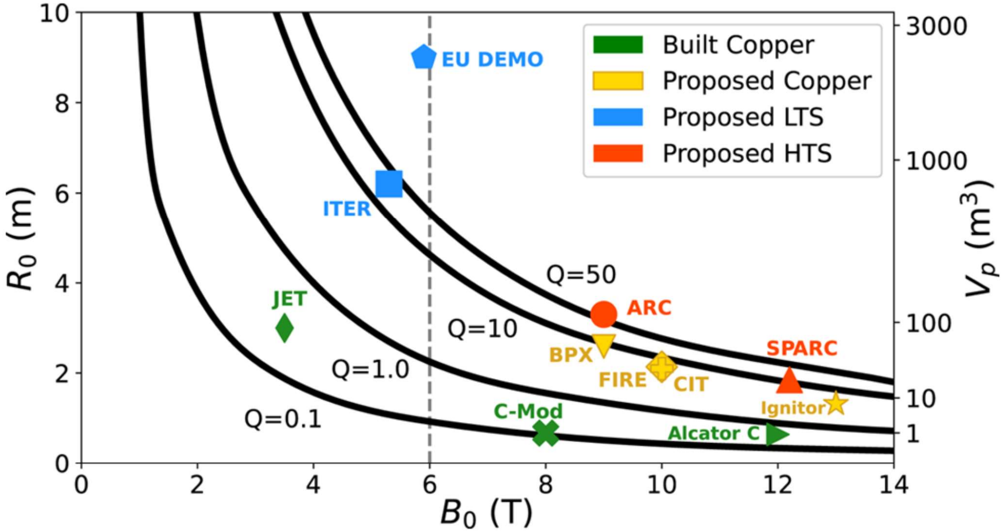
Feb 2020
First Japanese Toroidal Field Coil completed
Magnetic field 11.8 tesla
Stored energy 41 gigajoules
Weight 360 tonnes
Dimensions 9x17 m

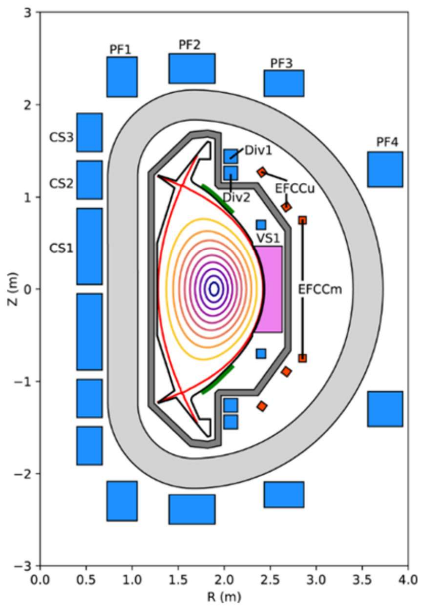


Tremendous progress in the development of the ITER magnets

Fusion

Compact HTS Fusion magnets – Commonwealth Fusion Systems (US)





Timeline
Building HTS magnet in progress
Start SPARC Fusion Energy Denonstration in 2021

Source: A.J. Greely, et.al. Overview on the SPARC Tokamak, Published online by Cambridge University Press: 29 September 2020

Fusion

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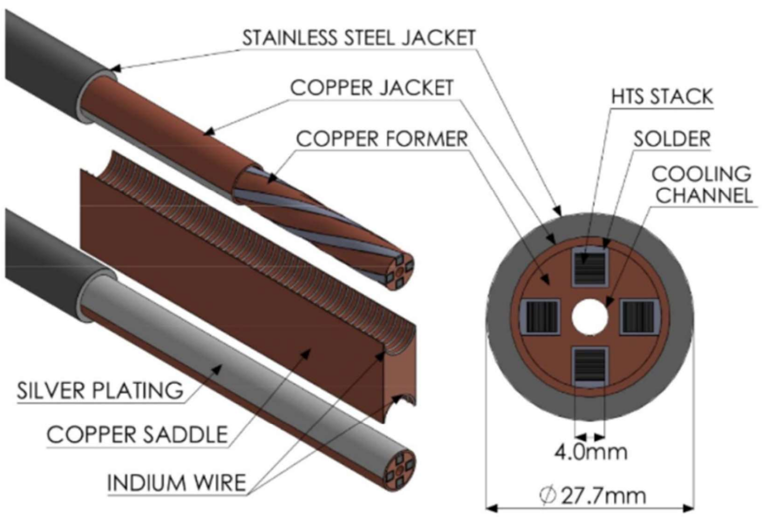
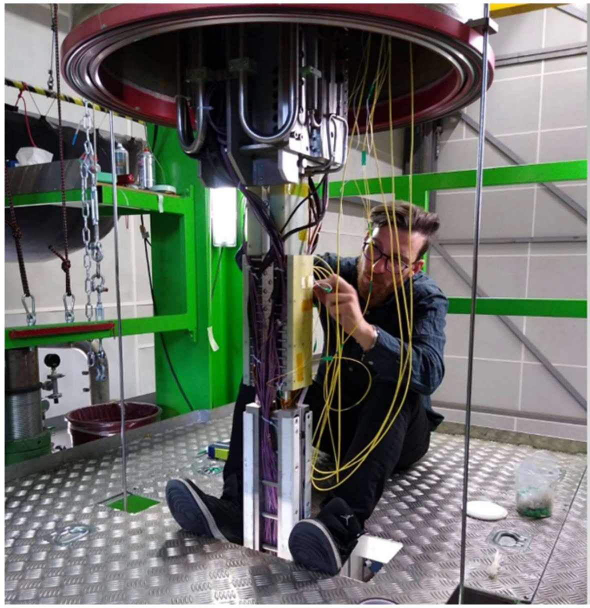
Compact HTS Fusion magnets – Commonwealth Fusion Systems (US)





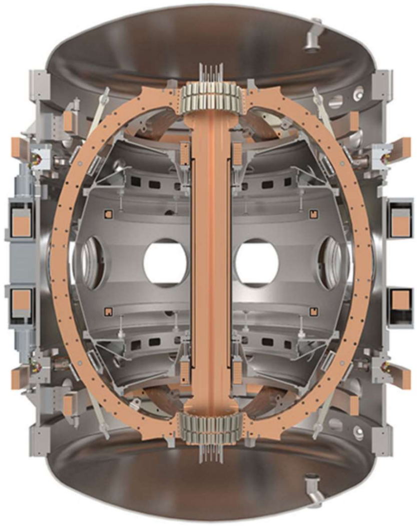
July 2020
Critical Current: 45.5 kA at B=10.9 T and T=10 K

Source: Zachary S Hartwig et al 2020 Supercond. Sci. Technol.33 11LT01

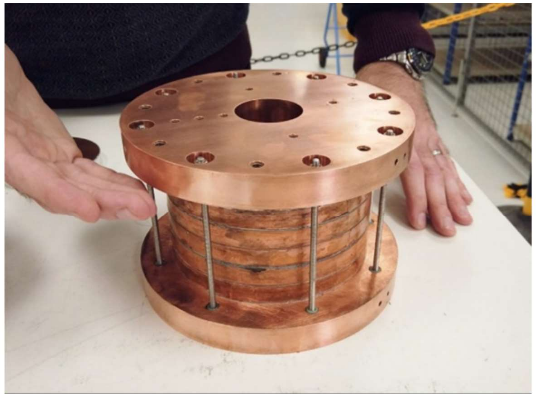
Fusion

Compact HTS Fusion magnets – Tokamak Energy (UK)

Tokamak ST40 is with copper and power supply from Supercapacitors



Non insulated HTS magnet has achieved magnetic field of 24.4 T at a temperature of 21 K in 2019



Conceptual design of ST 135

P_{fus} = 200 MW
Q_{fus} = 5
R_0 = 1.35 m
B_{HTS} = 20,2 T
I_{plasma}=7.2 MA

There is a strong mismatch in timelines of ITER and DEMO development in comparison to compact HTS Fusion Magnet development

Source: picture and data from https://www.tokamakenergy.co.uk/

Fusion – Status und Trends

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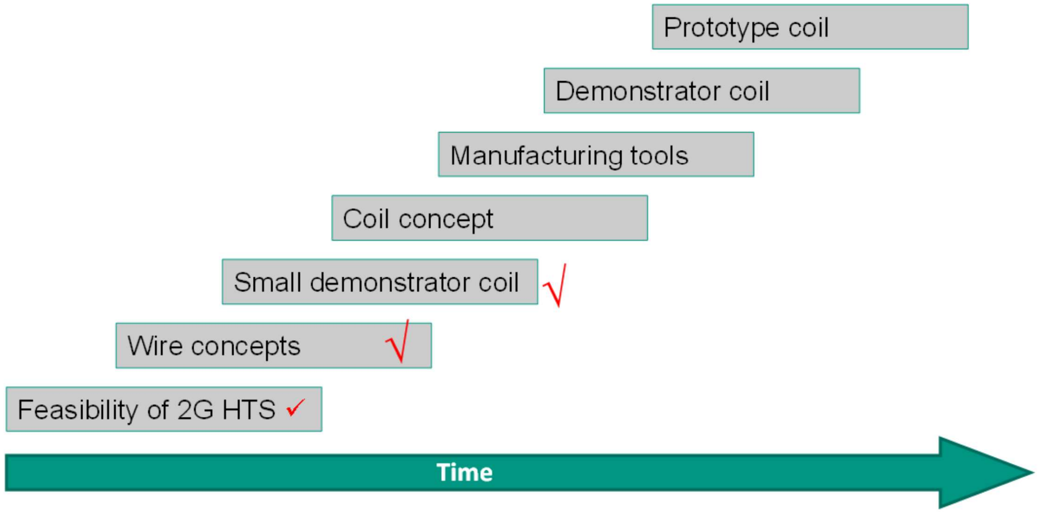
According to present planning ITER will reach TRL 5 by 2035 and DEMO TRL 7 beyond 2050

Compact HTS Fusion Magnets are presently at low TRL



Fusion – Status und Trends

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According to present planning ITER will reach TRL 5 by 2035 and DEMO TRL 7 beyond 2050

Compact HTS Fusion Magnets are presently at low TRL

GOALS	SOLUTIONS	CHALLENGES
Successful coil manufacturing and test	Cable tests Coil demonstrators	Degradation with cycling
		Quench stability and current distribution in partly non-insulated coils
		Demountable joints
		Magnet protection
Complete HTS Tokamak at relevant scale	See ST135 and SPARC approach	Funding
		Material availability in cost targets

Contents

Challenges for Turbo, Hydro, Wind Power

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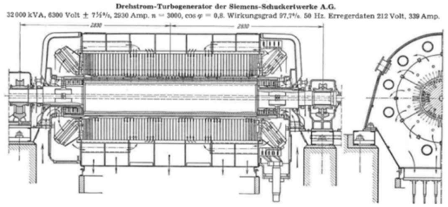
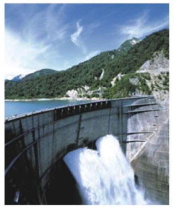




Turbo Generators (≈200-2000 MW)
- high rotational speed (up to 3600 rpm)
- large diameter, long length
- low pole number
- low electric frequency
- high efficiency (>95%)
- flexible operation („peaker“)
- CO_2-less/ CO_2-free fuel

Hydro Power (≈20-1000 MW)
- medium rotational speed (≈300 rpm)
- huge diameter, medium length
- high pole number
- low electric frequency
- high efficiency
- robust assembly
- long MV-power link

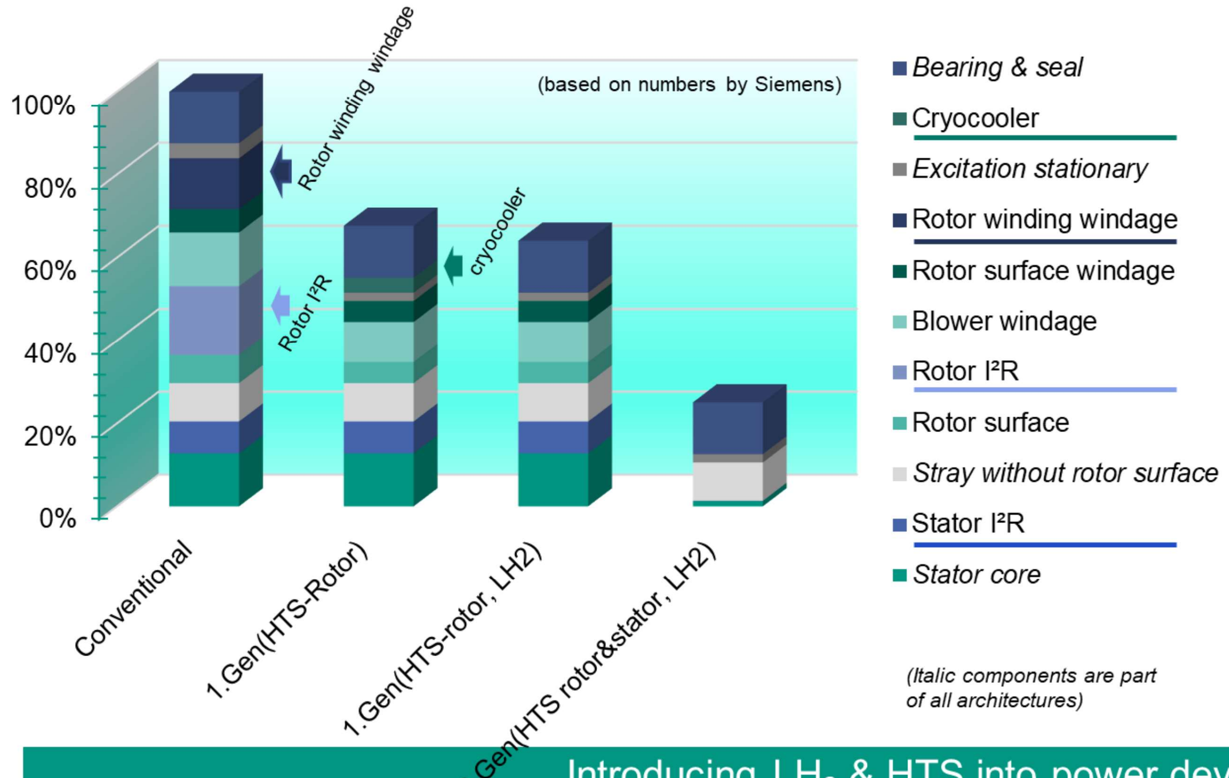
Wind Power (<12 MW)
- low rotational speed (≈10 rpm)
- large diameter, short length
- high pole number
- low electric frequency
- high efficiency
- low service needs
- LCOE

For the specific Types of Power Generation, the Key Requirements are quite different.

- The situation is special for the different rotating machines of power generation.
- Turbo:
  - high rotational speed
  - high efficiency
  - need for CO2-free fuel
- Hydro Power:
  - medium rotational speed
  - high pole number
  - high efficiency – depending on type
  - robust assembly
  - long MV power link
- Wind Power:
  - high pole number
  - high efficiency (85...95%)
  - LCOE

- Let’s look at the General aspects, benefits and prospects for HTS machines...

Example: Loss Reduction in Rotating Machines (motors, generators)



Description of columns:

- Using the loss in conventional Cu-based machines as a reference (100%).
- A HTS-Rotor will reduce the loss to ≈ 65%
- LH_2 "for-free cooling" reduces the loss further ≈ 65%.
- Introducing HTS-stators will yield a loss fraction of ≈ 20%
- In addition, the power-to-mass ratio may be increased from 5 kW/kg to >20 kW/kg

Introducing LH_2 & HTS into power devices will deliver a quantum leap in efficiency and power density!

Here: not only for Generation, but for drive applications, too.

- describe columns
- LH2 is already mentioned, lateron in detai

1. Introducing HTS into e-machinery (rotor) will reduce the loss by abt. 37% (depending on specific application)
2. Using the for-free cold of LH2 will yield a loss-reduction of >40%.
3. Using HTS in the stator, too, (today, only viable without cooling penalty), will reduce the loss by abt. 80%.

→ But let us first consider a Wind Power and perform a back of an envelope check on options and restrictions...

Wind Power – estimation of boundary conditions (from efficiency)

KIT
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10 MW turbine:

- considering 1%-pt. of loss, e.g. 100 kW
- assuming an energy cost of 0.05 €/kWh
- estimating efficient full-load time: 6000 h/year
- so 1 %-pt. of losses corresponds to: 600000 kWh
- converted to budget: 30000 €
- over 10 years: 300000€
- assuming pure wire cost: 40 €/m
- yields: 7.5 km HTS

- Conclusion:
  per 1%-pt. of efficiency gain, a maximum of 7.5 km HTS can be financed.
  (w/o considering additional technology components)

A high-efficiency HTS Wind Turbine will need **Clever Designs** to be competitive!
Is there something around the Corner which might be helpful for HTS Machines?

- follow slide

This might be addressed with LTS (but high effort of cooling below Tc and stable operation). Conclusion: Clever Designs are needed!

→ However: is there something around the corner which might be helpful for such HTS-machines? (DUDA)

New Winding Options with HTS
The Disk-Up-Down-Assembly (DUDA)

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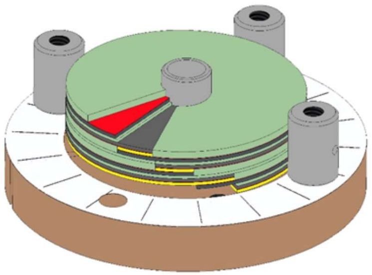

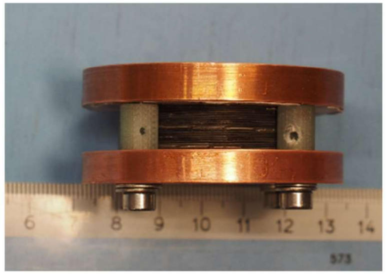

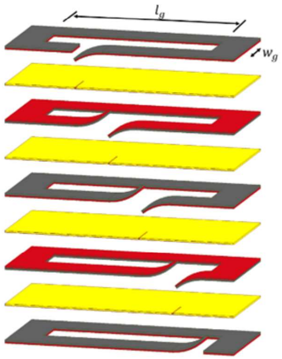

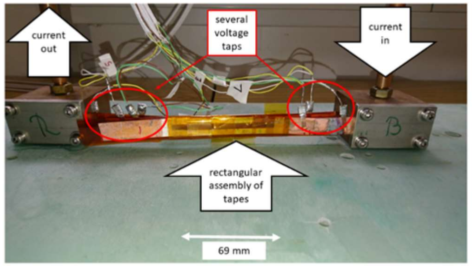

(Arndt et al., SUST 02.08.2021, https://doi.org/10.1088/1361-6668/ac19f4)

Principle:

- Stacking sheets of 2G-HTS with alternating orientation
- Preparing (low resistance) intersheet contacts (either in efficient current path or in outer joint areas)

Pros:

- No limitation on miniaturization (e.g. winding heads)
- Short unit length (impact on wire cost!?!)
- Homogeneity in planar structures
- Good „radial heat conduction“
- High pole numbers feasible
- Magnet configurations (Halbach-arrays)

Cons:

- resistive contacts → local heating (but may be removed at designated locations)

Compact DUDA windings may be beneficial in rotating machines.

- We followed a “stacked 2G-HTS sheet approach”.
- Kind of Single-turn windings.
- Change of paradigm: move away from fully superconducting current trajectory →compact engineering current path with manageable small contact loss.
- follow slide...

- compact magnet configurations

→ How could that influence a Wind Power Generator, for example? (wound-tape vs. DUDA)

Out-of-the box prospects on 2G-HTS Windpower Generators of 10 MW class

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Wound tape machine
(rotor & stator 2G-HTS, airteeth-stator)

Parameter	Value	Unit
Power	**10.6**	**MW**
Rotation	10	rpm
Length	0.885	m
Radius of Airgap	**2.500**	**m**
Number of pole pairs	**32**	n.a.
Field Current (at ≈30 K)	274	A
Number of slots	**384**	n.a.
Armature current (at ≈65 K)	73	A

DUDA windings machine
(rotor & stator DUDA, airteeth-stator)

Parameter	Value	Unit
Power	**10.5**	**MW**
Rotation	10	rpm
Length	0.885	m
Radius of Airgap	**1.250**	**m**
Number of pole pairs	**160**	n.a.
Field Current (at ≈20 K)	800	A
Number of slots	**1920**	n.a.
Armature current (at ≈20 K)	160	A

Volume of a DUDA Windpower Generator may be drastically reduced by (/4).
Detailed design still to be done.

 20210906 –Tabea Arndt, Mathias Noe

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- left: wound tape airteeth stator (optimized)
- right: DUDA high-pole-number/ high slot number machine (and 20K) – not optimized, simple emag-approximation
- eliminating the space consuming winding heads
- Miniaturization by DUDA
- might be used for other applications/ machines with even greater benefit.

Conclusion: There is the need for clever design – DUDA might be among them.

→ next section: back to energy and energy carriers...

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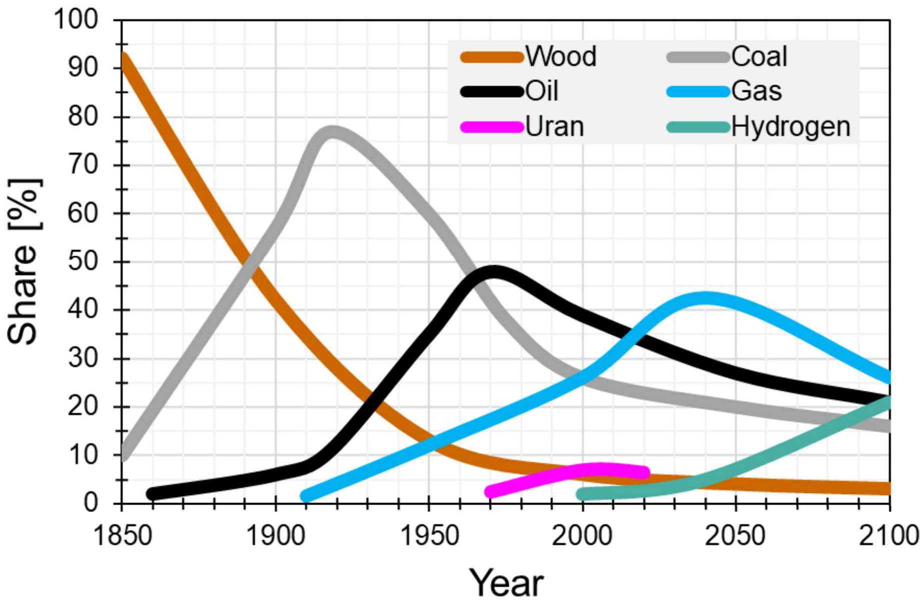
- **Liquid Hydrogen and Opportunities for HTS**
- Conclusions

→ development of Energy Vectors...

Development of Energy Vectors



- General trend:

  Wood → Peat → Coal → Oil → Gas → Uranium → Hydrogen

  →high-energy density vectors replace the lower density ones!

- H_2 as vector interplaying with REN?

see: Gerling und Wellmer, Chem. Unserer Zeit, 39(2005)236

For centuries there is a replacement by energy vectors of increasingly higher energy density. H_2 seems to be on the Radar.

- follow slide

→ H2 has a higher energy density than fossil – it depends?

LH_2 – outstanding in non-fossil energy density

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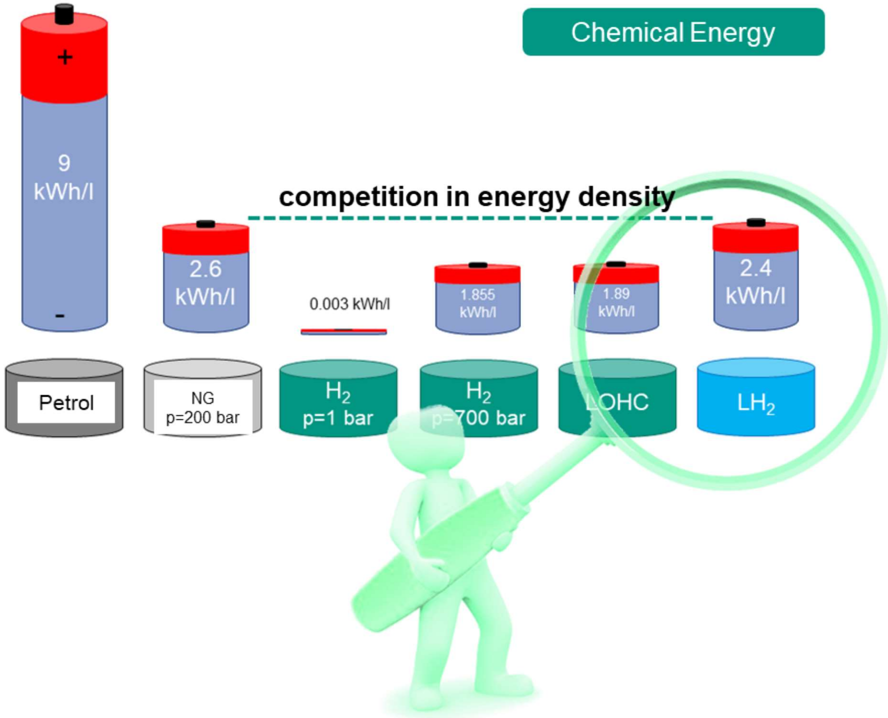

LH_2 is

- of high energy density (in volume and even more in weight) (Hero values of Batteries: 0.9 kWh/l; 0.6 kWh/kg[1)])
- pure (no reforming needs),
- non-toxic
- reactive (in presence of O_2) and needs careful material choice
- less reactive (and insulated from O_2) when liquid

High energy density & purity!
How about energy efficiency in chain?→

[1)] Fraunhofer ICT, 2021

- Fossil energy carriers (C-Atom) are „benchmark“ – mainly liquid, if gaseous: compression needed!
- H2 as pressurized gas not bad, but when at same pressure as NG (co-mixing) reducing the energy content of the pipeline/ gas-grid
- H2 under high pressure is not bad, but a lot of drawbacks
- LOHC very similar to H2-hi-pressure, makes sense in niches, but high needs in energy for storage/ release.

- LH2 competitive to compressed Natural Gas – meets "benchmark“!
- Furthermore: the for-free high-value cold may be used in devices/ applications down the energy chain...

→ How about the energy chain efficiency of LH2?

(L)H_2 energy chain efficiency – e.g. sustainable wind to mechanical power

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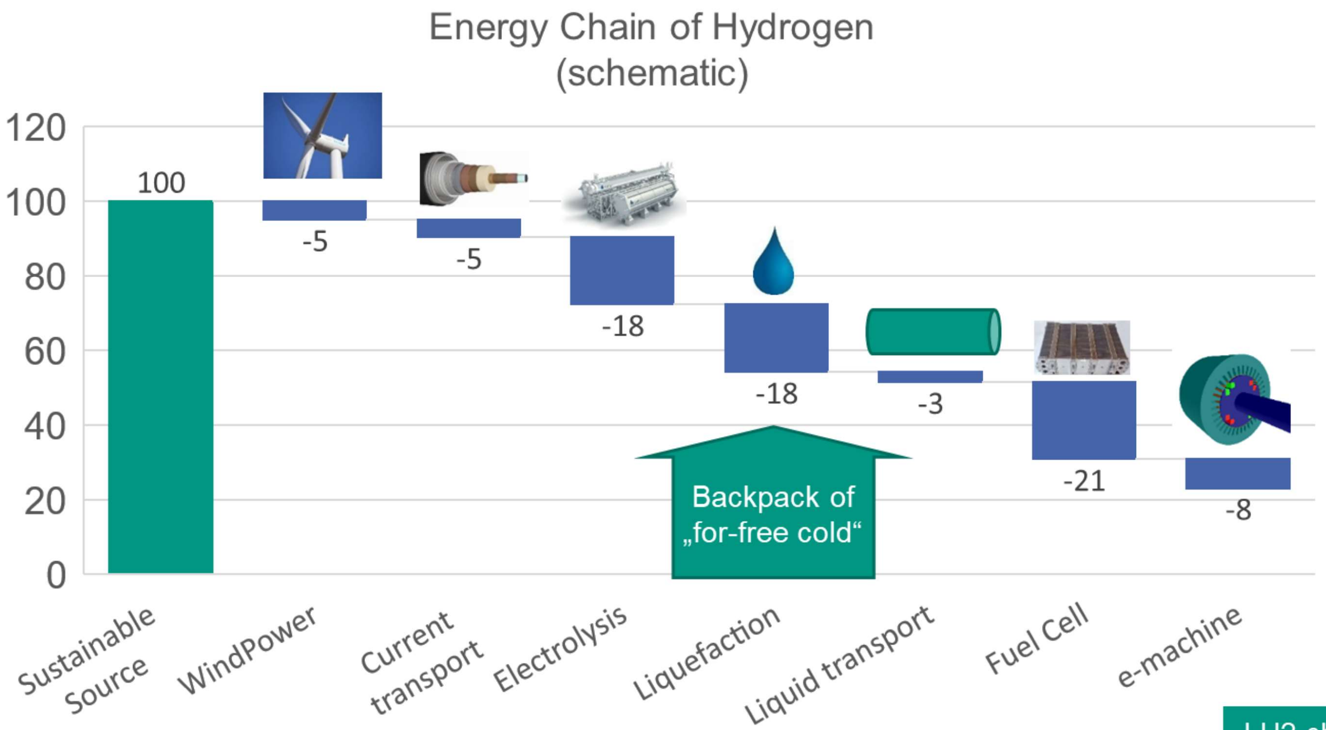

- There is substantial loss along the energy chain
- Research is conducted in selected parts:
  - transportation
  - power engineering

24% at shaft

LH2-chain may be used as a **giant heat-pump**
Basic approach in transportation...

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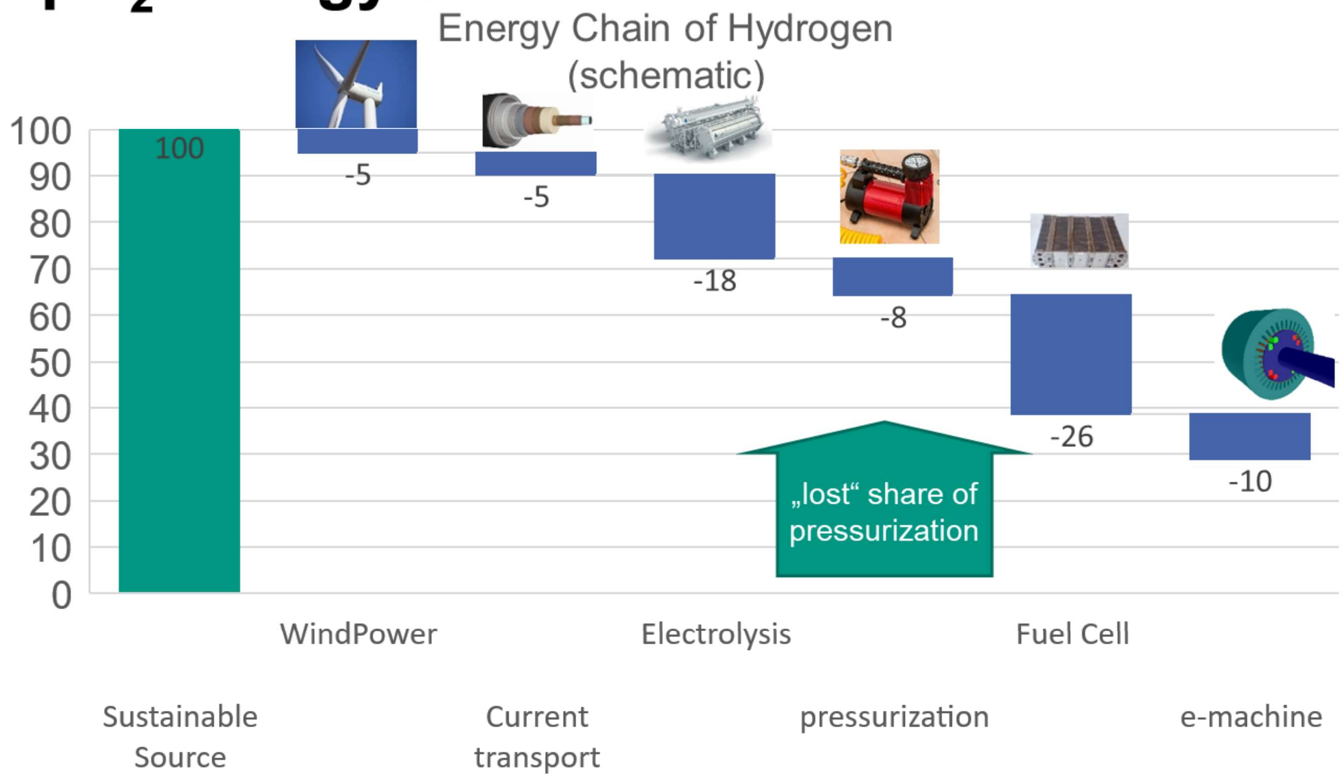
- Describe the chain (for vehicles)
- highlight 24% at shaft

(WP:
97%:

95%: Xu, Y., et al. (2015). "Operating Temperature Influence on Performance of 10 MW Wind Turbine HTS Generators." IEEE Transactions on Applied Superconductivity **25**(3): 1-5.)

→ energy chain of pH2...

pH_2 energy chain



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- loss in transport is not considered: abt. 1 bar/km
- remember: LH_2: 24% at shaft

28% at shaft
(w/o pressure drop)

pressurization according HSR, Fachhochschule Ostschweiz; picture: pixabay/stevepb

pH_2-chain is less effective than LH_2 when „cold backpack“ is used.

- follow slide:
- energy share for pressurization is “lost”
- remember 28%

→ compare to petrol energy chain...

Petrol Energy Chain

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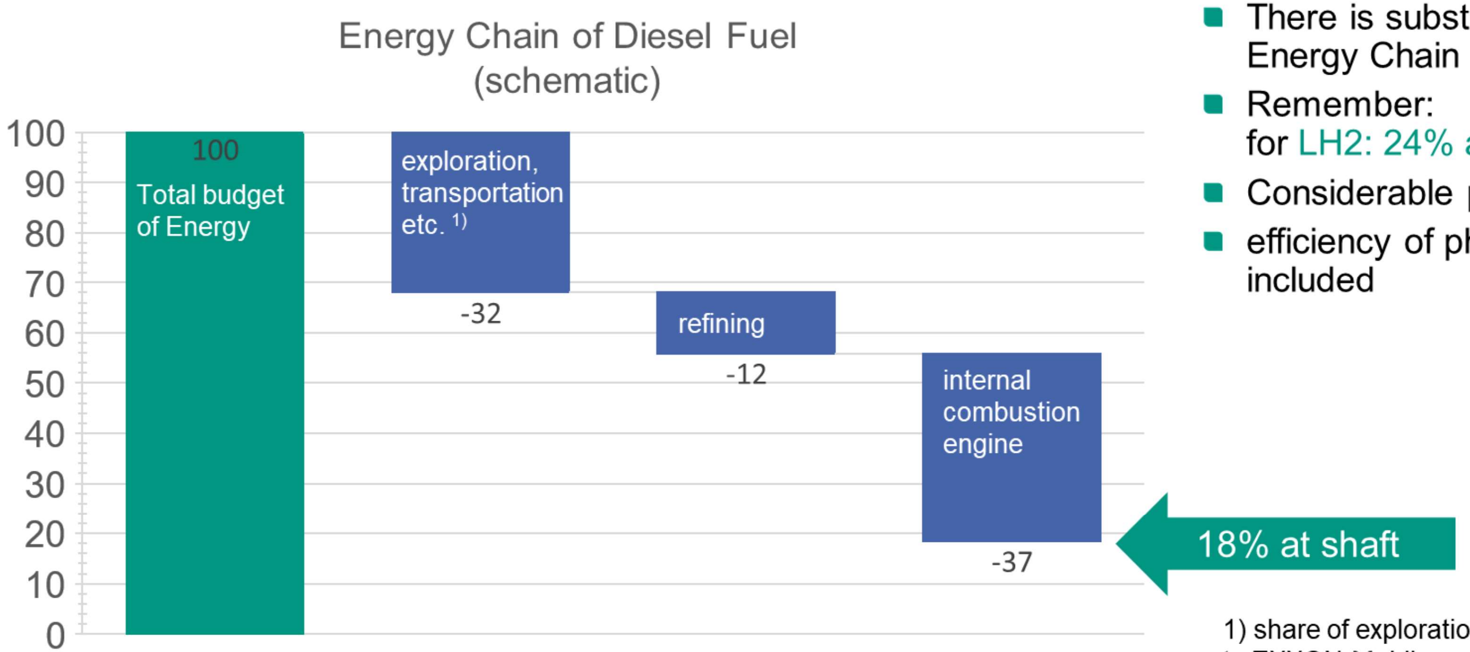

- There is substantial loss in the Energy Chain of Petrol Use
- Remember: for LH2: 24% at shaft
- Considerable production of CO_2
- efficiency of photosynthesis not included

1) share of exploration etc. is 7 kWh/l according to EXXON Mobile

Considering the overall energy budget, petrol (savings from the past) is less efficient than sustainable LH_2 by REN.

- follow slide:
- When considering the “availability efforts,” the petrol energy chain is even less efficient than hydrogen!
- So we had 24%, 28% and 18%.

And we the chance to use the “for free energy backpack” of LH2...

→LH2 provides high-value cold...

LH2 provides high-value cold & excellent cooling properties

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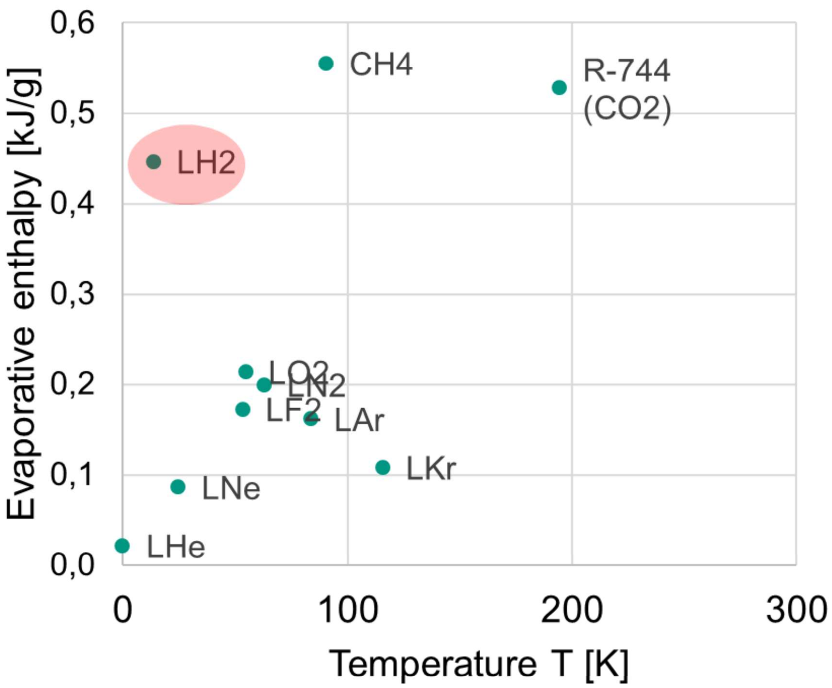

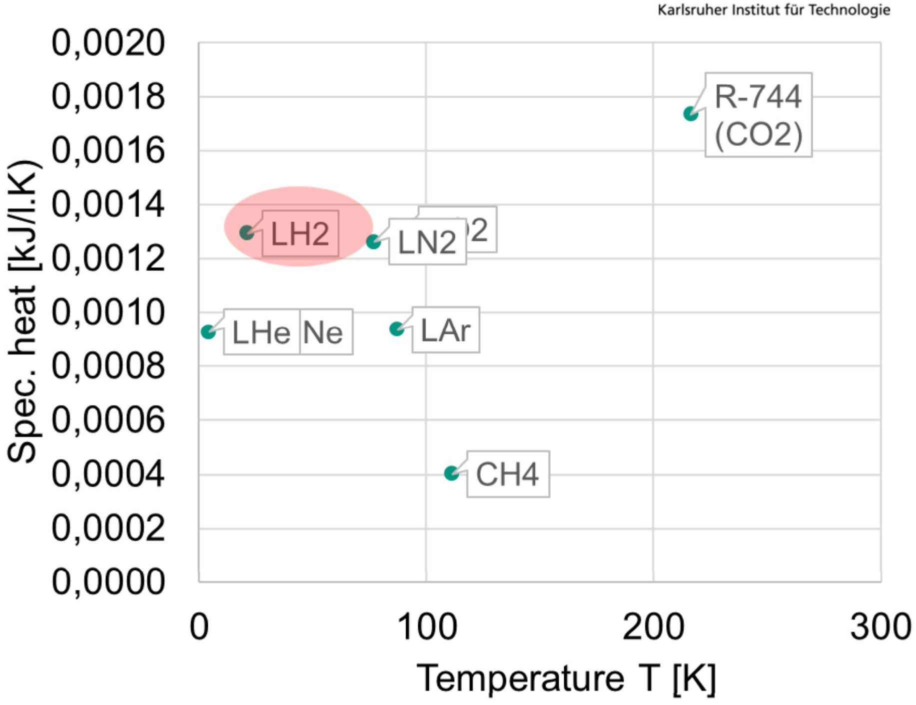

Evaporation Enthalpy & specific heat of LH2 underpin relevance as a coolant.
Using these two features in application will raise the efficiency of the LH_2-chain to >28%.

- When evaporating, LH2 is one of the “stars” of cooling media (taking away a lot of heat)
- When warming up, due to the high specific heat of LH2, it is an excellent cooling media above boiling temperature, too.
- This is the motivation to include that in rotating machines as a coolant (for free!, see previous slide)
- Using these features will raise efficiency to (at least) pH2!!!

→ So, how to address LH2 in the Energy System...example Germany: AppLHy!...

The German National H_2-Strategy – the Project „AppLHy!“

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National Hydrogen Strategy

Call for ideas „Wasserstoffrepublik Deutschland“ (BMBF)

H2Mare

H2Giga

TransHyDE

AppLHy! Transport & Application of LH_2

- The lead project AppLHy! is part of the national strategic research.

Liquid Hydrogen is part of the German National H_2-Strategy.

- 3 projects within the range of 140 M€ each all partly research, partly implementation
- addressing H2-production near-shore
- addressing GW-electrolyzers
- addressing transport

→ work packages in AppLHy!...

Project "AppLHy!"

Duration: 01.04.2021-30.03.2025 (plus 2x 3 years, hopefully)
Volume: >15 M€
Lead: KIT ITEP

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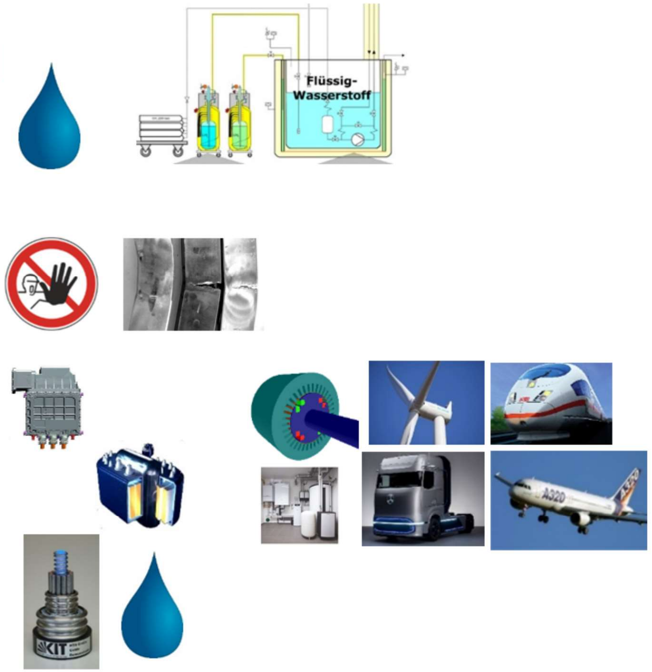
Workpackage	Tasks	Contributors
WP1- Energy Efficient Liquefaction, Storage and Transport	- Techno-economic studies - Systems & Components for Storage/ Transport - Erection of liquefaction facility at KIT	Amprion Daimler Linde HTW Dresden IFW Dresden TU Dresden KIT ITEP KIT ETI KIT ITES KIT IAM-WK SciDre THEVA VESC and open to other
WP2- Safety & Materials Aspects	- Selection and characterization of materials - Safety aspects and concepts for transport and equipment - Safe transfer protocols	
WP3- Concepts for LH_2 operated power devices	- Powertrains - Integration of terminations of transport pipelines - Inverters - Integration to multimodal energy system	
WP4- Synergies due to LH_2 transport	- Research platform on simultaneous transport of LH_2, cold and electric power - Utilization of LH_2-cold	



"AppLHy!" creates the Technology Bricks linking LH_2 via HTS to Power Engineering.

This project is not the first to address LH2 & superconductivity (first paper found of 1976 – even before HTS)!
Activities in Russia in the past (LH2+HTS flexible cable).
AppLHy! has unique research points:

- efficient liquefaction
- materials
- develop technology platform for bulk transport of LH2 (and electric power on-top) and integration into energy systems (KIT Energy Lab 2.0); hybrid energy transport
- researching in synergetic benefits of power devices using HTS and LH2

→ As an example: Is there some prospect for vehicle motors?

New Options with HTS in Vehicles (Trucks, Trains, Ships, Aircrafts)

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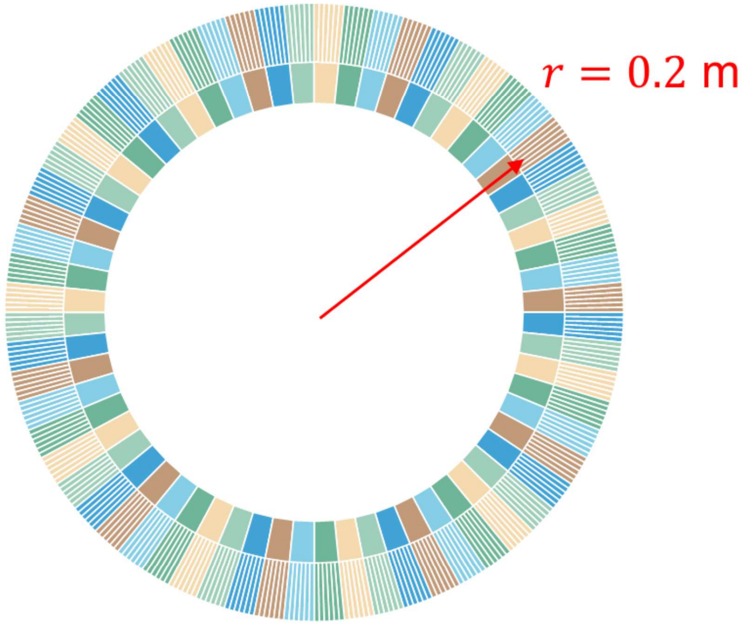

Symbolic Sketch (not to scale)

Example of vehicle machine
(rotor DUDA, airteeth-stator DUDA)

Parameter	Value	Unit
Power	**7.3**	**MW**
Rotation	3000	rpm
Length	0.300	m
Radius of Airgap	**0.200**	**m**
Number of pole pairs	**32**	n.a.
Field Current (at ≈20 K)	400	A
Number of slots	**384**	n.a.
Armature current (at ≈20 K)	80	A

High pole and slot numbers even in compact machines.
The Fuel LH_2 compensates I^2R loss in DUDA, AC-optimization in progress.

One rationale for addressing vehicles in the project AppLHy!:

- Combining compact HTS machines (perhaps by DUDA) with LH2-cooling will yield extremely compact motors e.g., for vehicles.

→ How about the transportation of energy?

Pointwise A→B Transport Efficiency of Energy

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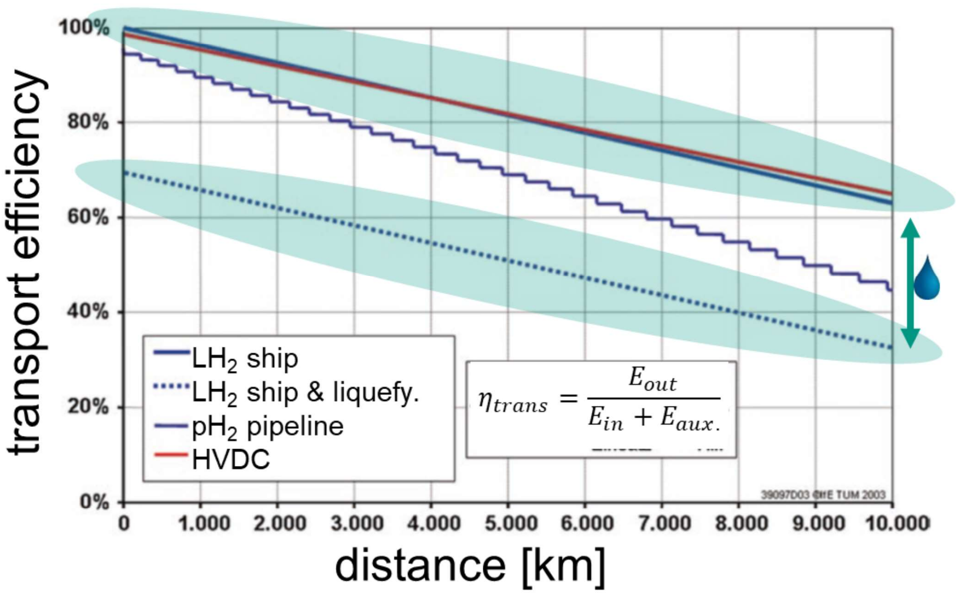

(T. Hamacher in „Wasserstoff und Brennstoffzelle“, J. Töpler, J. Lehmann (Eds.))

Efficiency (long distance):

- (-) Electrical transport is most efficient
- (-) Second efficient is LH_2 by ship, but
- (···) Liquefaction requires some upfront energy

Sophisticated approaches of AppLHy!:

→ decrease energy backpack of liquefaction (by increasing liquefaction efficiency)

→ improve storage & boil-off aspects

→ combine electrical & chemical (LH_2) transport for spearhead efficiency

→ use invested high-value cold backpack and get a reimbursement in power applications

Combine transport & liquefaction & electric power to convert cons to pros!

- Point-to-point (electrical) energy transport is most efficient when done by HVDC.
- However, the transport of (chemical) energy by LH2 is nearly as efficient – neglecting the "liquefaction energy backpack.“
- Combining chemical (LH2) & electrical (HTS) transport & power devices (cooling) will leverage synergies, turn cons into pros and increase the overall efficiency.
  (The first paper on that is from 1976 – even before the birth of HTS)
  Several proposals and some projects already done with LH2 and HTS

Hopefully we will be able to realize convincing demonstrators in the next 4 years in the project.

→ Coming to the conclusions...

Summary

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- „Green Energy" requires the closing the Energy Cycles in the short Timescale of Human Life.
- There is an increasing Need for limiting Fault Currents in Transmission and Distribution Electric Power Grids
  → Opportunity for SFCL.
- Huge investment in Transmission and Distribution Electric Power Grids is needed and planned.
  → Opportunity for compact and powerful AC-Cables.
  → Opportunity for GW HTS DC-Power Transmission.
- Contribution of HTS for Fusion is still under Evaluation.
- The Development shows a General Trend to High-Density Energy Vectors.
- (L)H_2 is valuable as an energy vector, in addition the cold backpack has to be used in systems.
- The LH_2 energy chain is more efficient than a priori perceived.
- Integrating LH_2 into electric power devices will cut the Gordian knot of cryo-cooling penalty.
- AC-loss reductions are beneficial, but mitigated by LH_2.
- New topologies of HTS windings allow strong compact magnet windings and new pole/slot-type electric machines.
- „Green Energy" (and LH2 in systems) is a groundbreaker for HTS.

Thank you for your attention!

Thank you

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