Superconducting wind turbine generators - Current status & perspectives

Loic Queval

ESAS'2023 School - Col de Porte, France

Superconducting wind turbine generators
Current status & perspectives

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Content

I. Resource and potential

World electricity generation

« What we need » following IEA Stated Policies Scenario

	2018	2040
Total generation [TWh_e / year]	26 603	**41 373**

Source: IEA (2019), World Energy Outlook 2019, IEA, Paris https://www.iea.org/reports/world-energy-outlook-2019

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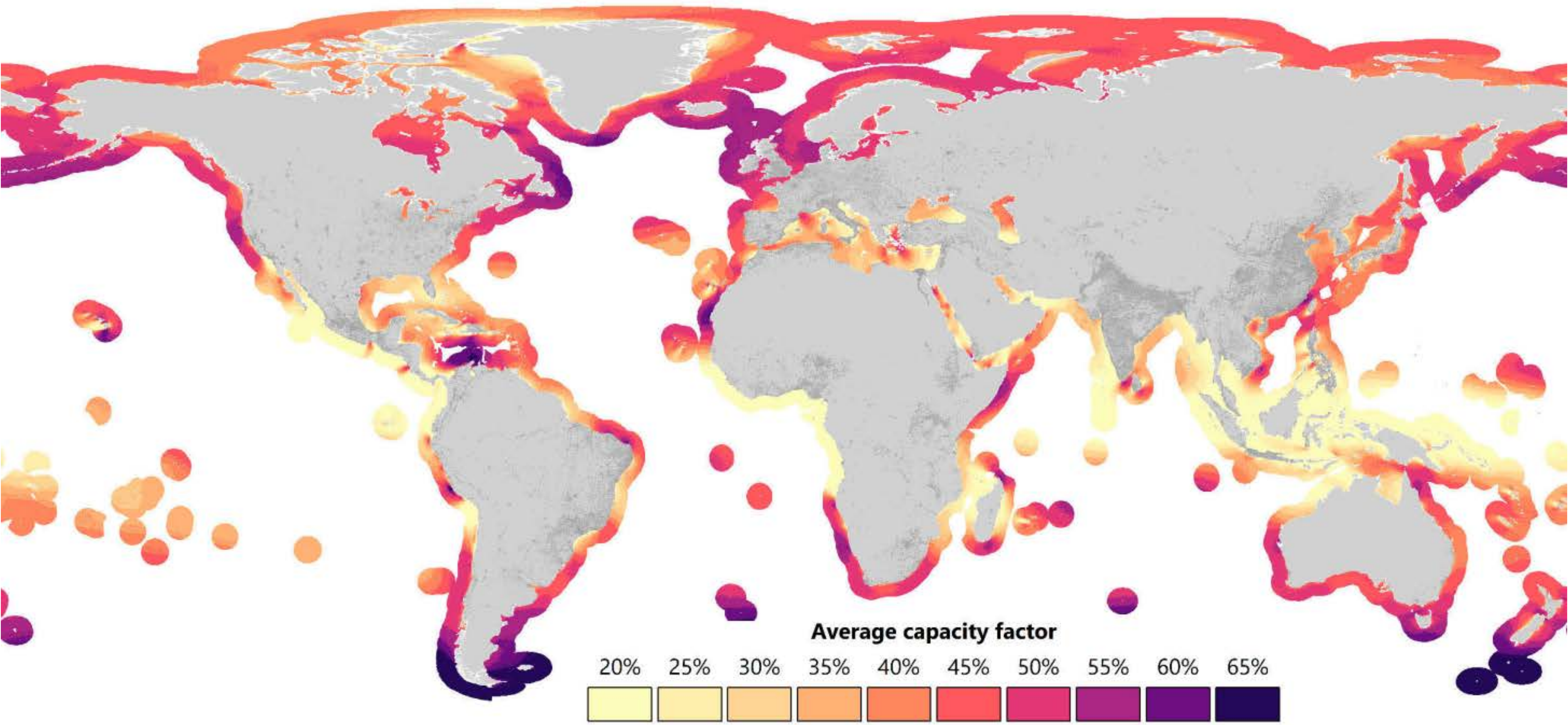
Resource and potential

Primary resource:
30 000 000 TWh_p / year

Technical potential:
420 000 TWh_e / year



Source: IEA (2019), Offshore Wind Outlook 2019, IEA, Paris https://www.iea.org/reports/offshore-wind-outlook-2019

Resource and potential

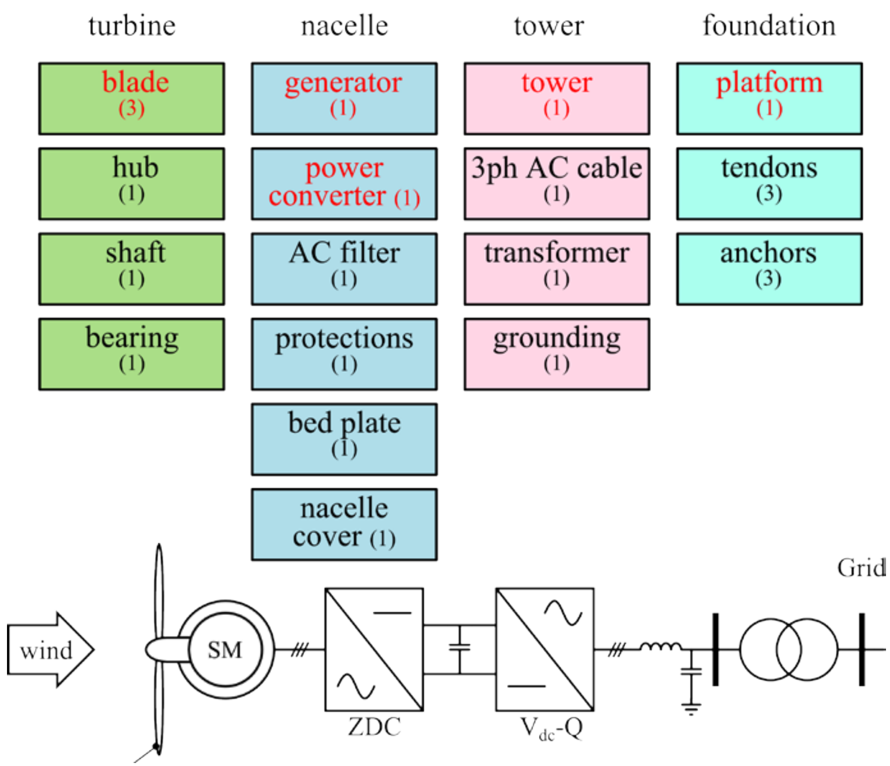
Dunkerk
44 €/MWh

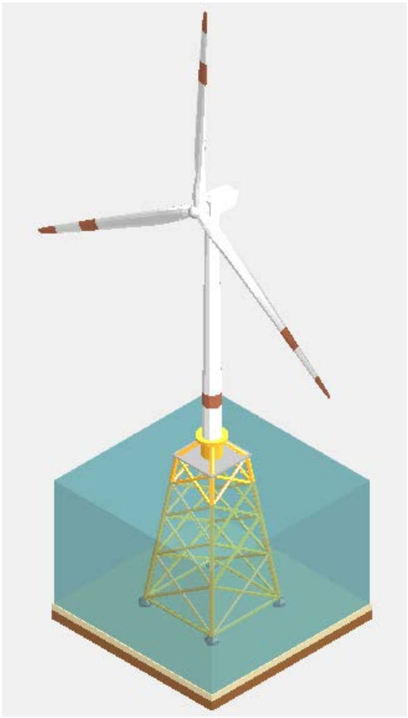
	Near to shore (20 - 60 km)	Far from shore (60 - 300 km)
Shallow water (< 60 m)	36 000 TWh_e / year	51 000 TWh_e / year
Deep water (60 - 2 000 m)	76 000 TWh_e / year	254 000 TWh_e / year

Source: IEA (2019), Offshore Wind Outlook 2019, IEA, Paris https://www.iea.org/reports/offshore-wind-outlook-2019

II. Wind Energy Conversion System (WECS)

Wind energy conversion system

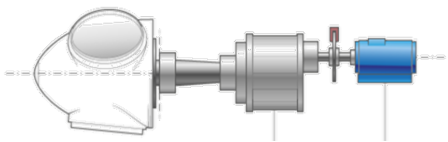


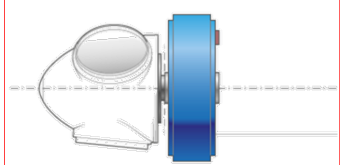


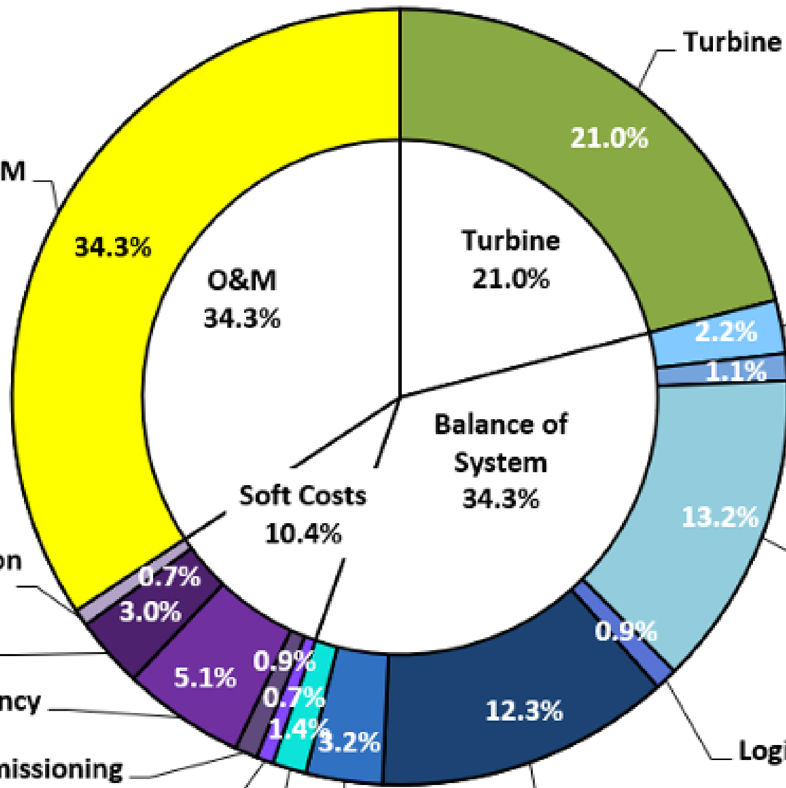
Source: Mulders, S. P., et al. "Wind turbine control: Open-source software for control education, standardization and compilation." *Journal of Physics: Conference Series*. Vol. 1452. No. 1. IOP Publishing, 2020.

LCOE breakdown of offshore windfarm

Costs of a reference fixed-bottom offshore wind farm







[1] T. Stehly, P. Beiter and P. Duffy, "2019 Cost of Wind Energy Review," National Renewable Energy Laboratory (NREL), 2020.

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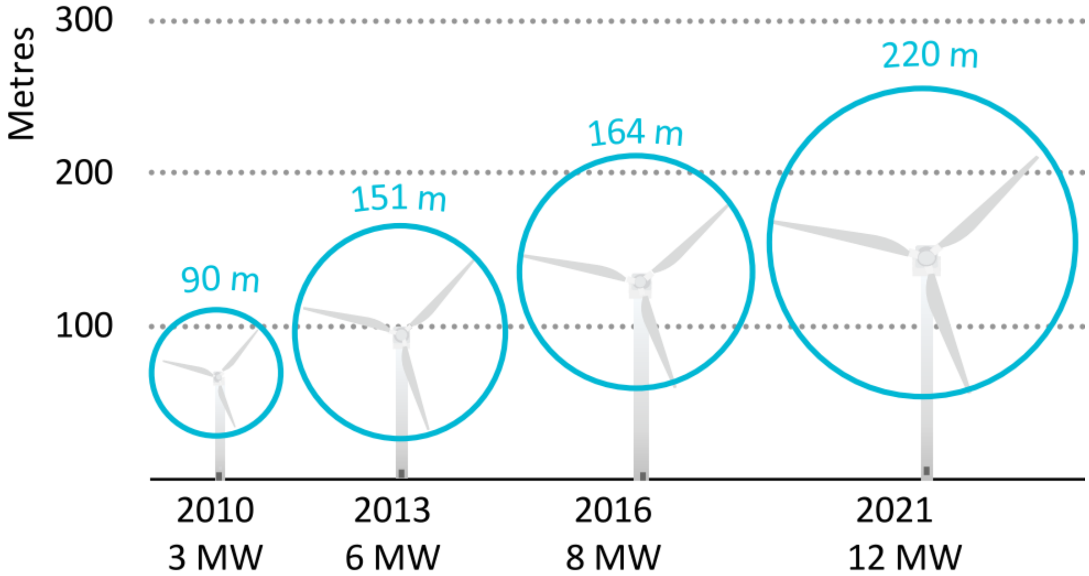
Unit power

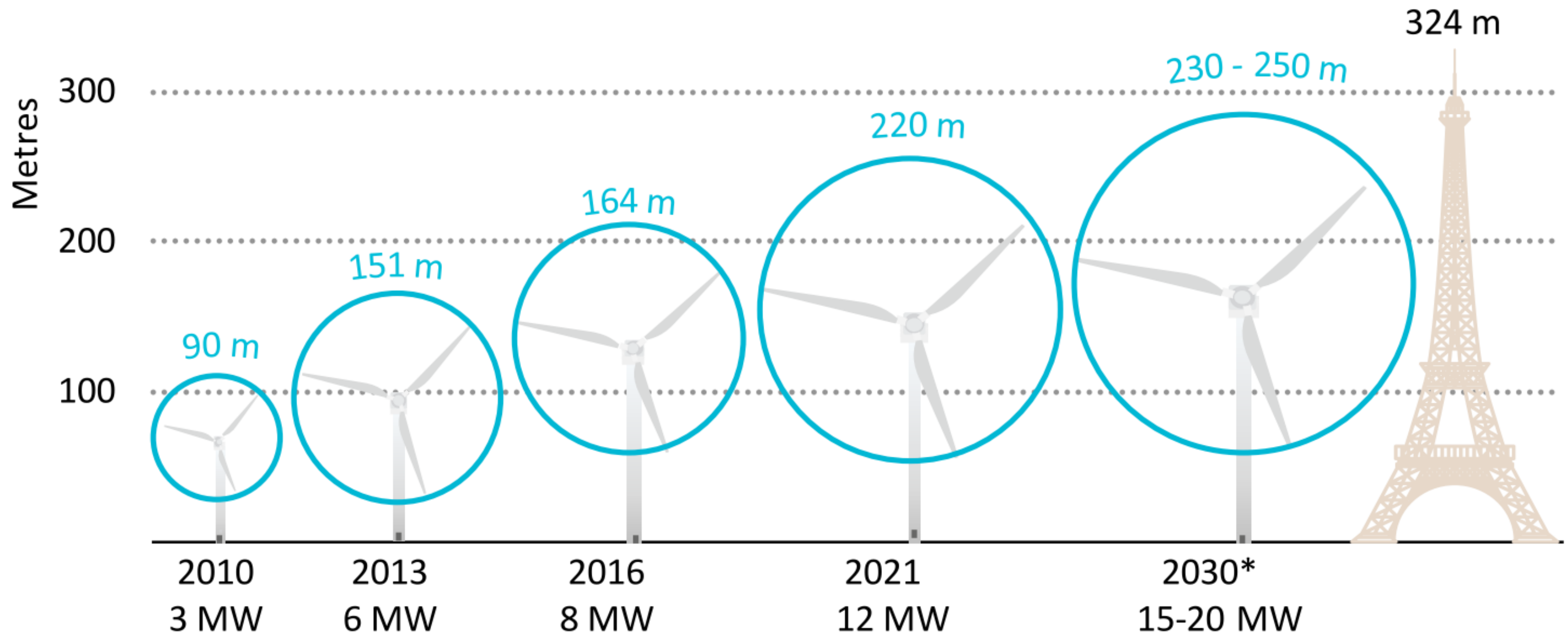


World's largest wind turbine generator

Vestas V236-15.0 MW ➡

Source: https://www.vestas.com/en/products/offshore/V236-15MW

Unit power



Towards 20 MW offshore wind turbines !

GE Haliade-X 18 MW

MingYang Smart Energy MySE 18.X-28X

CSSC Haizhuang H260-18MW

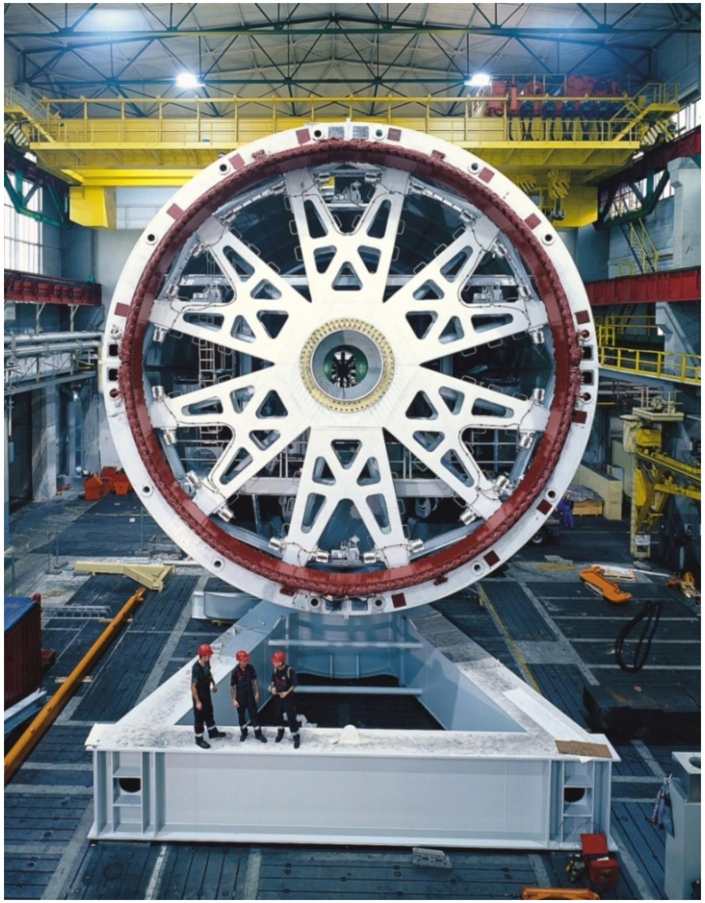
…

Source: IEA (2019), Offshore Wind Outlook 2019, IEA, Paris https://www.iea.org/reports/offshore-wind-outlook-2019

Wind turbine generator

Synchronous generator

EESG in Enercon
E-138 EP3 4.2 MW

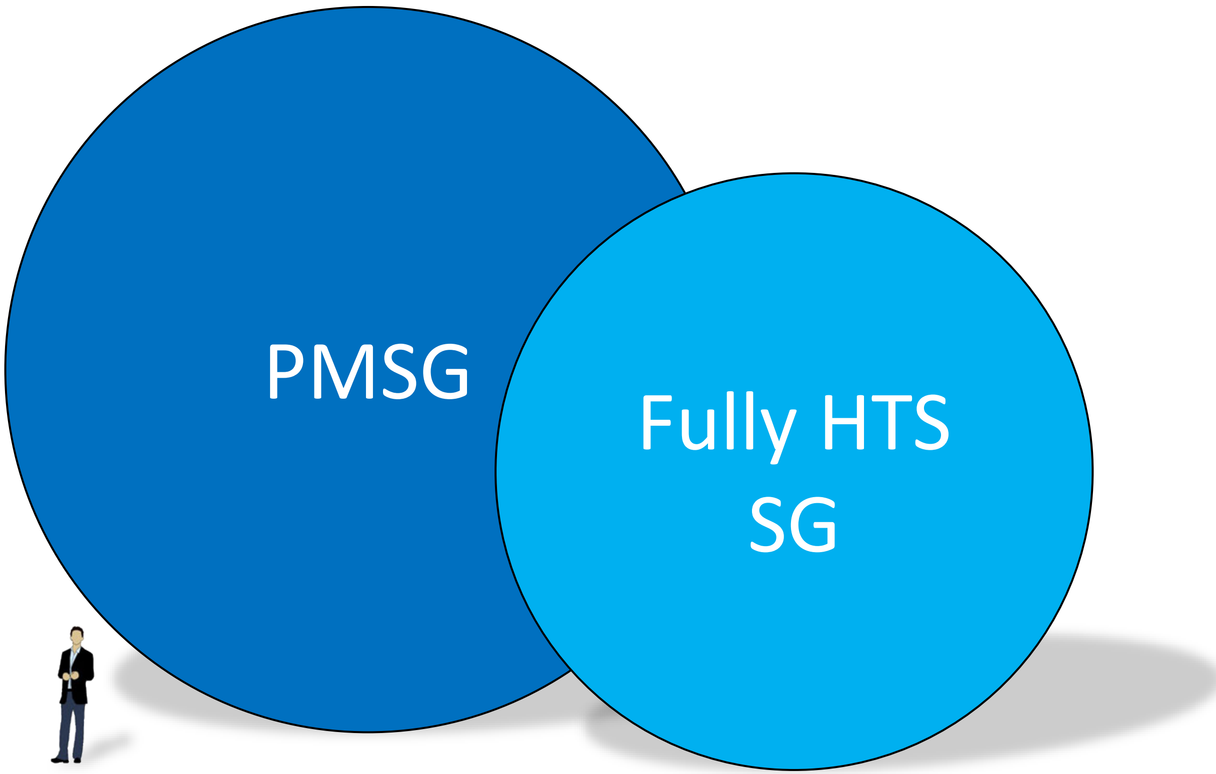


EESG in Enercon
E-126- 7.5 MW

Source: https://www.windpowermonthly.com/article/1487163/enercon-starts-ep3-tests & https://www.intechopen.com/chapters/38933

III. Superconducting wind turbine generator ?

Comparison 20 MW DD PMSG vs. Fully HTS SG

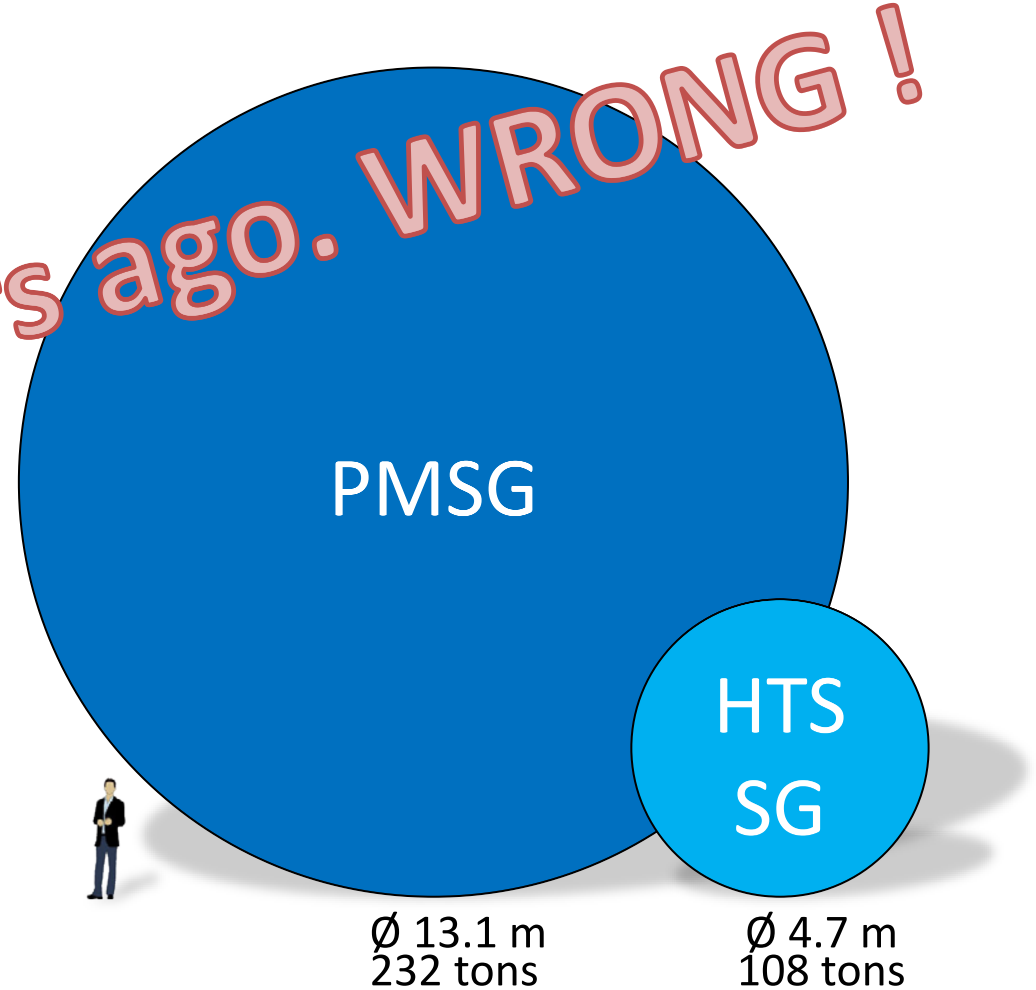


Ø 9.6 m
430 tons

Ø 7.9 m
145 tons

[1] T.-K. Hoang, L. Quéval, L. Vido, D.-Q. Nguyen, “Levelized cost of energy comparison between permanent magnet and superconducting wind generators for various nominal power,” *IEEE Transactions on Applied Superconductivity*, vol. 32, no. 7, id. 5202606, Oct. 2022.

Comparison 10 MW DD PMSG vs. HTS SG



[1] L. Quéval, "Modeling and simulation of grid-connected superconducting wind turbine generators," PhD thesis, The University of Tokyo, Tokyo, Japan, 2013. Online: www.lqueval.com

Superconducting wind turbine generators ?

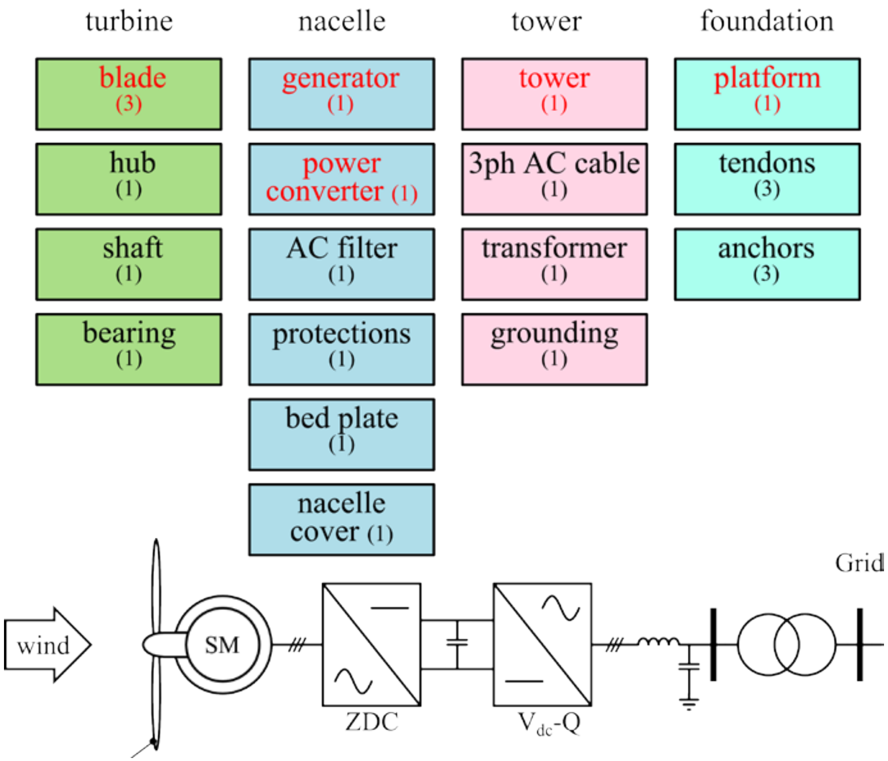
#1 - Technical reason

Conventional technologies do not meet the constraints of size and weight for the next generation >20 MW direct-drive wind turbine generators that will be installed on offshore floating platforms?

#2 - Techno-economic reason

WECS with superconducting machines have the potential to be more competitive than conventional machines?

Impact of a modification of the generator ?



Source: Mulders, S. P., et al. "Wind turbine control: Open-source software for control education, standardization and compilation." *Journal of Physics: Conference Series*. Vol. 1452. No. 1. IOP Publishing, 2020.

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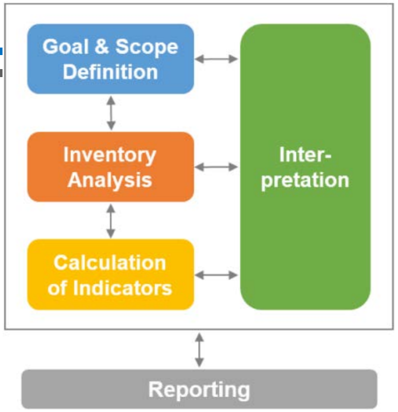
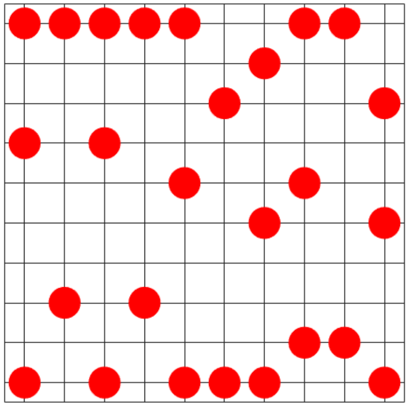
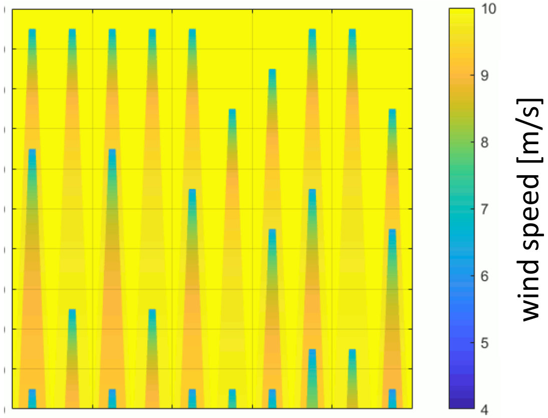
Techno-economic assessment

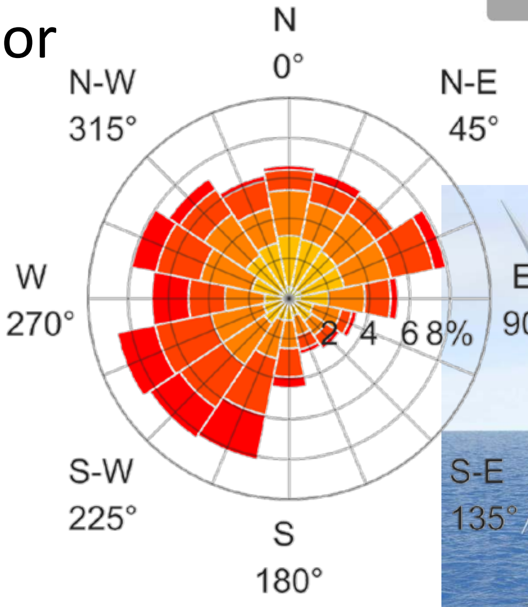


Goal: WECS PM generator **vs.** WECS HTS generator

Scenario:







Performance indicator: LCOE [€/MWh]

Superconducting wind turbine generators ?

#1 - Technical reason

Conventional technologies do not meet the constraints of size and weight for the next generation >20 MW direct-drive wind turbine generators that will be installed on offshore floating platforms?

#2 - Techno-economic reason

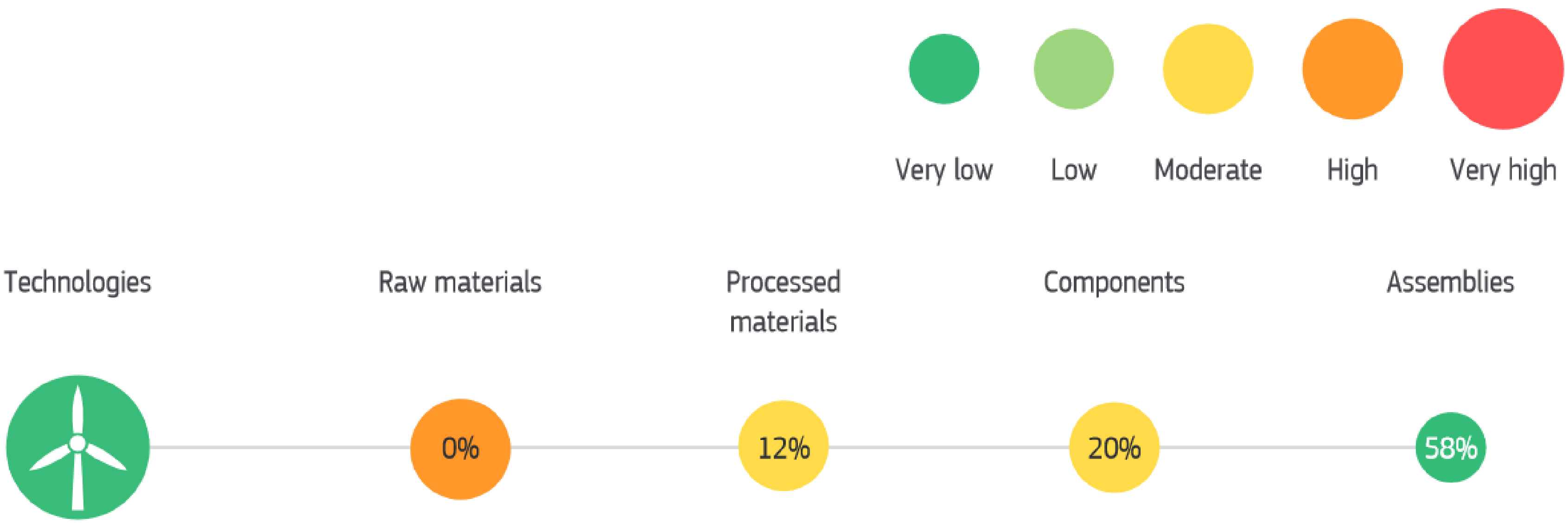
Superconducting wind turbines will be more competitive than conventional machines?

#3 - Geopolitical reason

Critical raw material act

Critical raw material act

European Commission, March 16th, 2023



Identified supply risks for the EU and EU shares of production

Source: European Commission, "Critical materials for strategic technologies and sectors in the EU - a foresight study," 2020

IV. Current status and perspectives

Founding article

IOP PUBLISHING SUPERCONDUCTOR SCIENCE AND TECHNOLOGY

Supercond. Sci. Technol. **23** (2010) 034019 (8pp) doi:10.1088/0953-2048/23/3/034019

Superconducting wind turbine generators

A B Abrahamsen[1], N Mijatovic[2], E Seiler[1], T Zirngibl[1], C Træholt[2], P B Nørgård[3], N F Pedersen[2], N H Andersen[1] and J Østergård[2]

[1] Materials Research Division, Risø-DTU, Frederiksborgvej 399, 4000 Roskilde, Denmark
[2] Department of Electrical Engineering, Technical University of Denmark, DK-2800 Lyngby, Denmark
[3] Wind Energy Division, Risø-DTU, Frederiksborgvej 399, 4000 Roskilde, Denmark

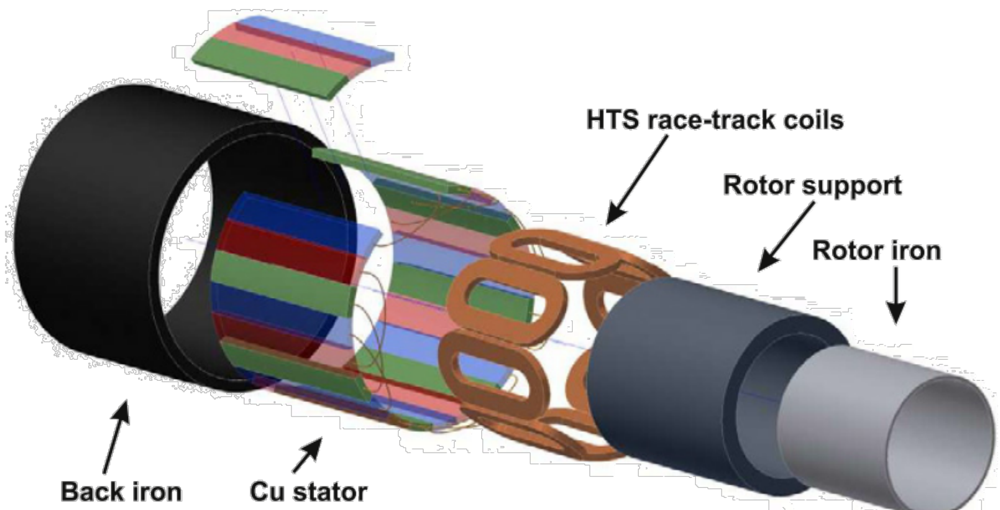
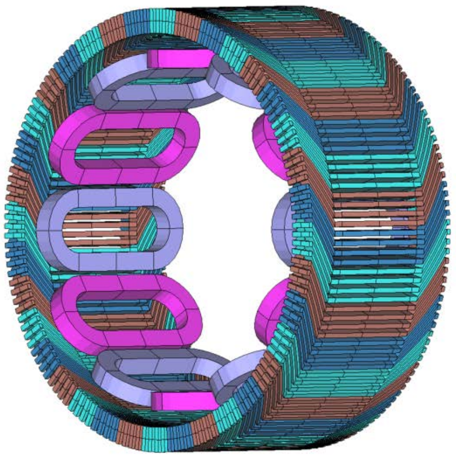
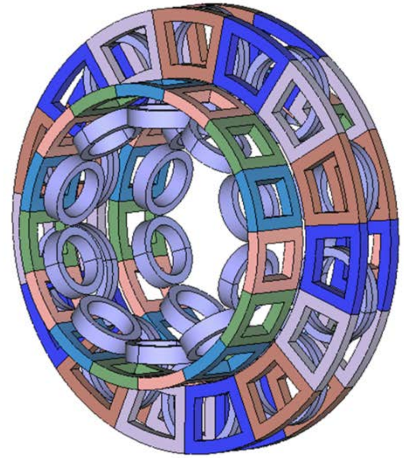
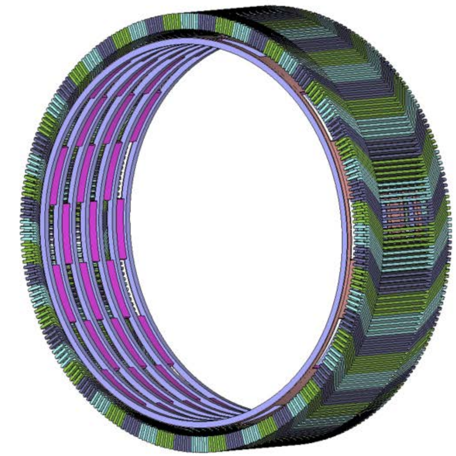
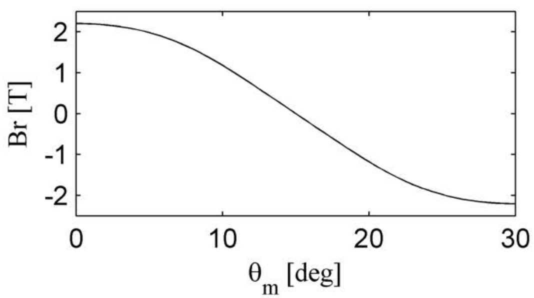


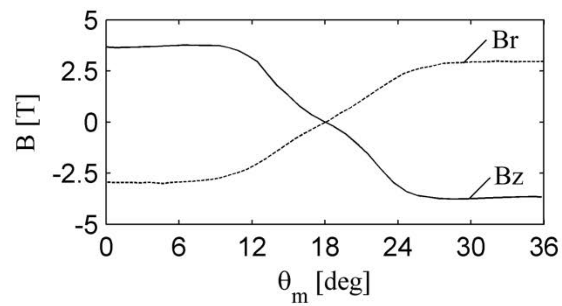
Table 2. Properties of an extreme 10 MW generator example.

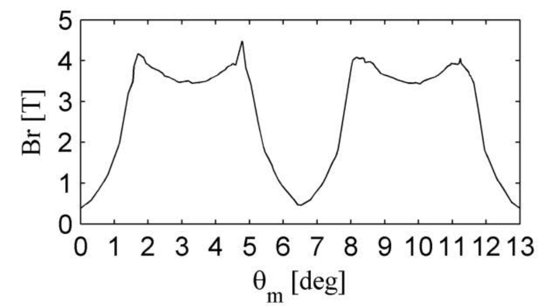
Rated power P_N (MW)	10
Poles	16
Diameter D_{gen} (m)	4.7
Length L_{gen} (m)	1.15
Rotation speed $\omega_{R,rpm}$ (rpm)	10
Shaft torque τ_T (10^6 N m)	9.7
Mass superconductor m_{sc} (ton)	22
Mass Cu m_{Cu} (ton)	14
Mass Fe m_{Fe} (ton)	32
Mass glass fiber m_{GF} (ton)	20
Mass total (ton)	88
Length of SC (km)	1450
Current density J_e (A m^{-2})	6.3×10^7
Temperature T (K)	20
Maximum field B_{max} (T)	9.1

Design of partially SC WT generators (ironless)

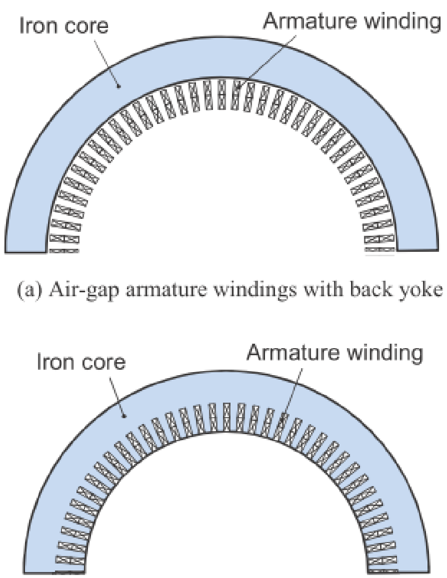






[1] H. Ohsaki, Y. Terao, R. M. Quddes, “Electromagnetic characteristics of 10 MW class superconducting wind turbine generators,” *Int. Conf. on Electrical Machines and Systems*, pp. 1303-1306, 10-13 Oct 2010.
[2] M. R. Quddes, M. Sekino, H. Ohsaki, N. Kashima, S. Nagaya, "Electromagnetic Design Study of Transverse Flux Enhanced Type Superconducting Wind Turbine Generators," *IEEE Transactions on Applied Superconductivity*, vol. 21, no. 3, pp. 1101-1104, June 2011.
[3] H. Ohsaki, Y. Terao, M. Sekino, “Wind turbine generator using superconducting coils and bulks,” *J. Phys.: Conf. Ser.*, vol. 234, part. 3, 2010.

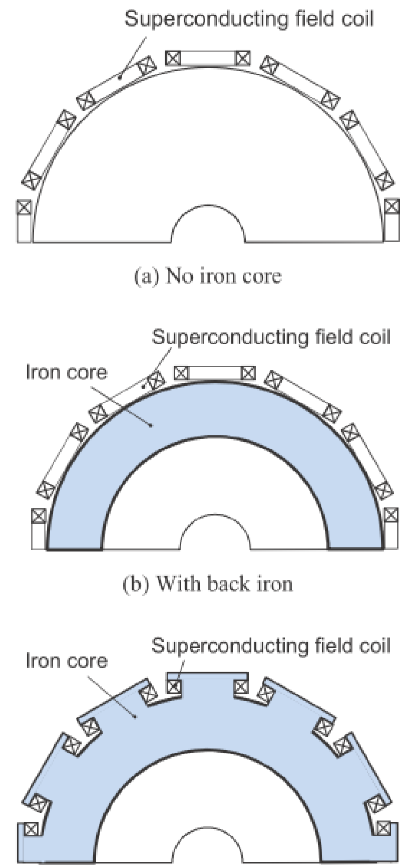
Design of partially SC WT generators (with iron)



(a) Air-gap armature windings with back yoke

(b) Armature windings in the slots of iron core

Fig. 4 Fundamental stator structures with armature windings.



(a) No iron core

(b) With back iron

(c) Salient pole type

Fig. 5 Fundamental rotor structures with superconducting field coils.

[1] H. Ohsaki, L. Quéval, Y. Terao, "Design and characteristic analysis of 10 MW class superconducting wind turbine generators with different types of stator and rotor configurations," *4th International Conference on Clean Electrical Power (ICCEP 2013)*, Alghero, Italy, June 2013.

Design of fully SC WT generators

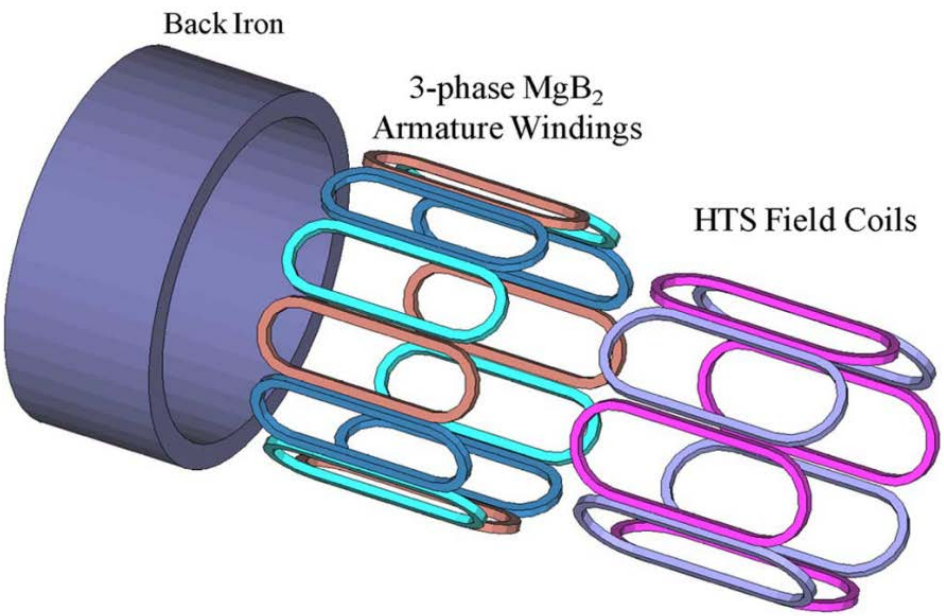


Fig. 1. Illustration of fully superconducting wind turbine generator [1]

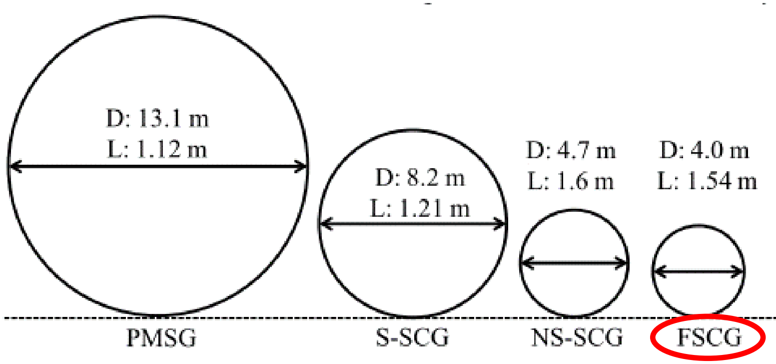
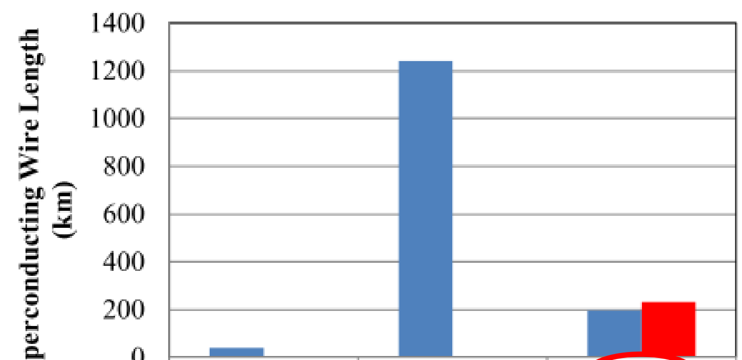


Fig. 7-1. Comparison of four wind turbine generator sizes [2]



	S-SCG	NS-SCG	FSCG
YBCO	36.9	1240	196
MgB2	0	0	231

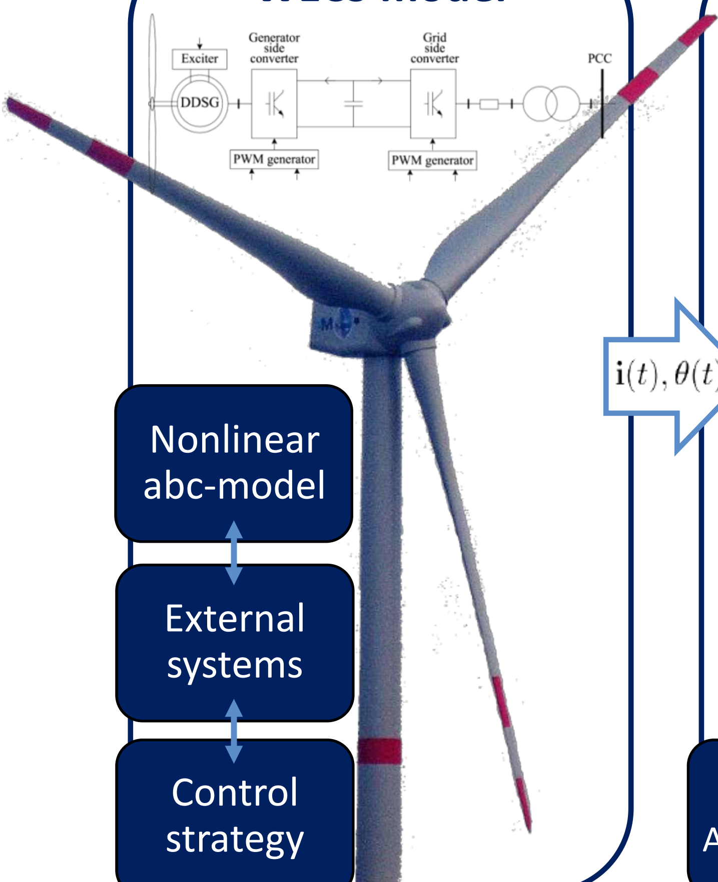
Fig. 7-2 Length of superconducting wires [2]

[1] Y. Terao, M. Sekino, H. Ohsaki, "Electromagnetic design of 10 MW class fully superconducting wind turbine generators," *IEEE Trans. on Applied Superconductivity*, vol. 22, no. 3, 2012.

[2] Y. Terao, "Electromagnetic design of light weight and high-power density superconducting synchronous machines for 10 MW class wind turbine generators," PhD thesis, The University of Tokyo, Tokyo, Japan, 2013.

Simulation of grid-connected SC WT generators

WECS model



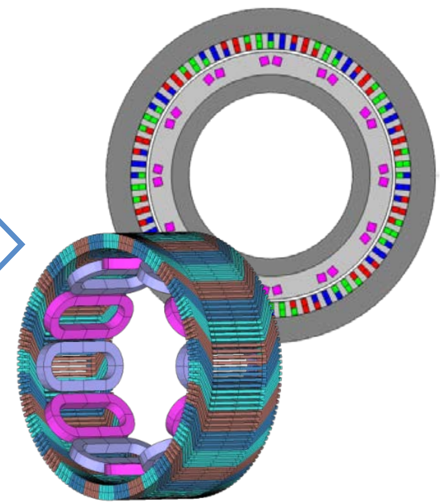
Nonlinear abc-model

External systems

Control strategy

$\mathbf{i}(t), \theta(t)$

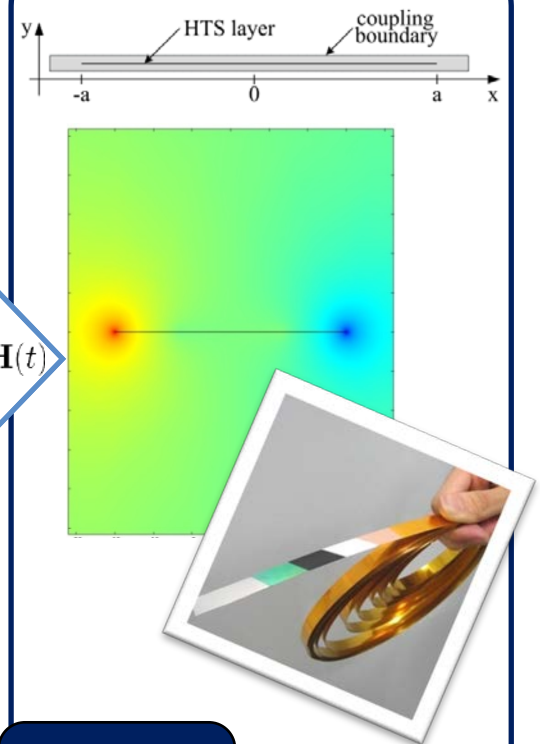
Machine model



FE model
A-formulation

$\mathbf{i}(t), \mathbf{H}(t)$

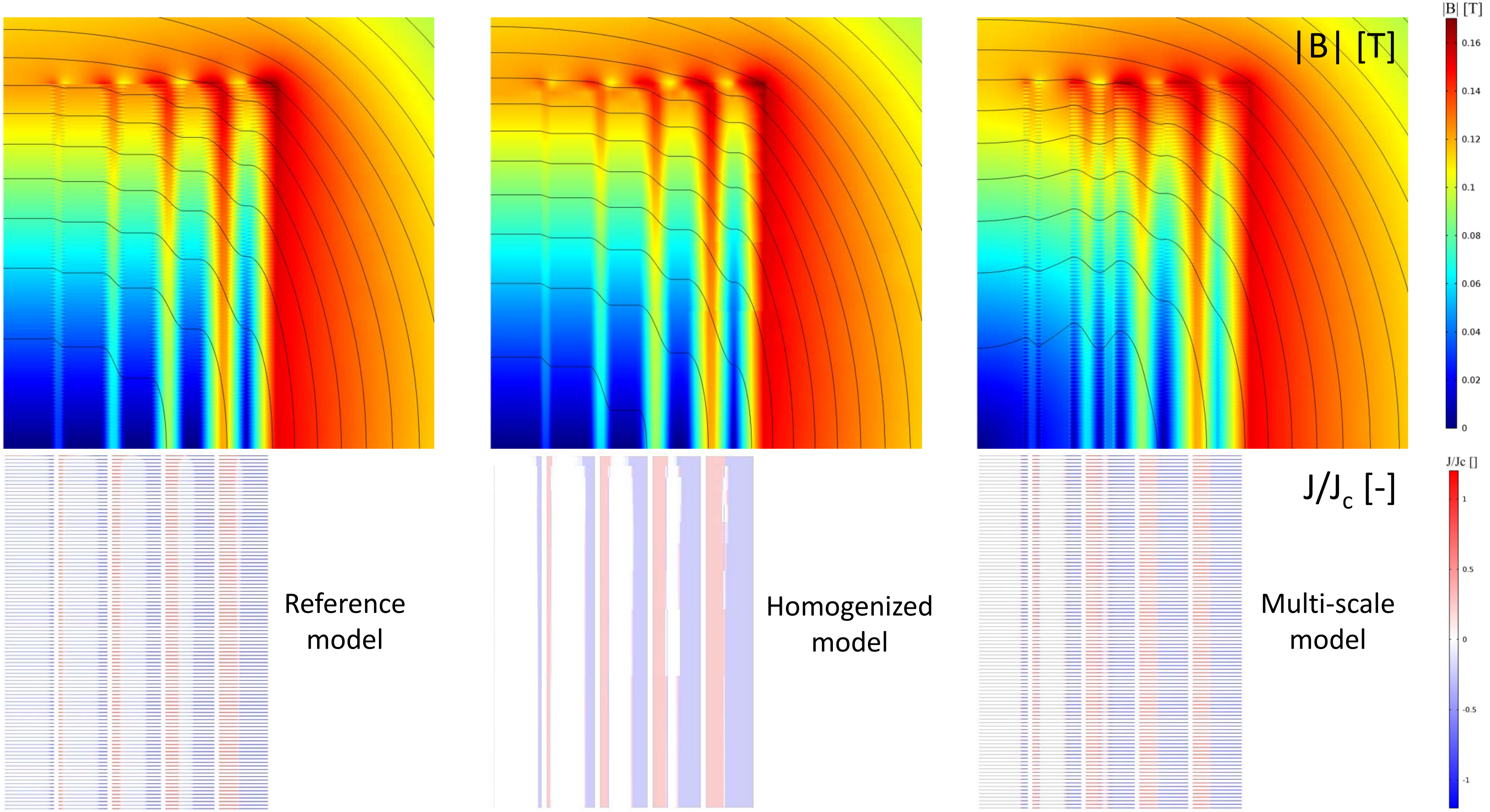
HTS Tape model



FE model
H-formulation

[1] L. Quéval, H. Ohsaki, "AC losses of a grid-connected superconducting wind turbine generator," *IEEE Trans. on Applied Superconductivity*, vol. 23, no. 3, pp. 5201905, 2013.
[2] L. Quéval, M. Sekino, H. Ohsaki, "A coupled FE phase-domain model for superconducting synchronous machine," *IEEE Trans. on Applied Superconductivity*, vol. 22, no. 3, pp. 5200804, 2012.

Numerical models for large superconducting coils



[1] L. Quéval, V.M.R. Zermeño, F. Grilli, "Numerical models for AC loss calculation in large-scale applications of HTS coated conductors," *Superconductor Science and Technology*, vol. 29, no. 2, Jan. 2016.

Development in USA

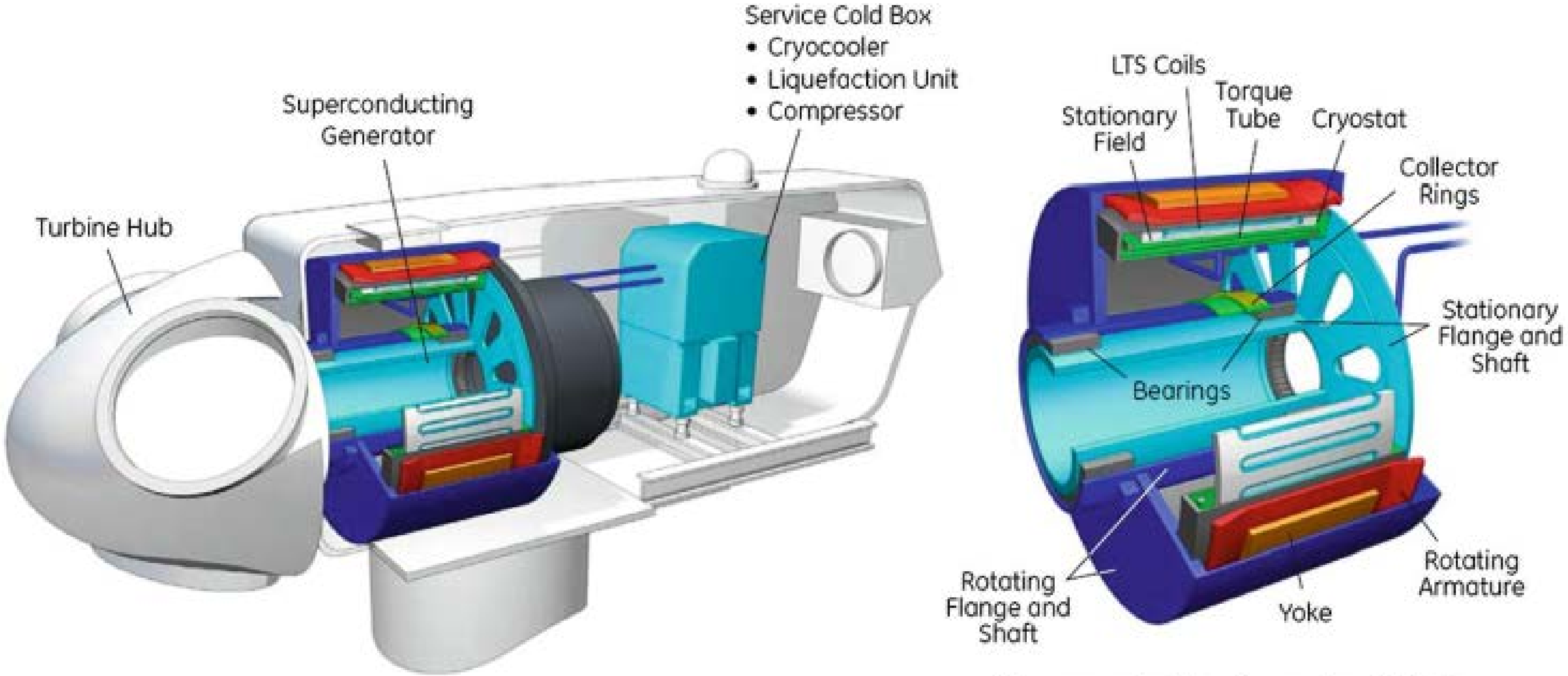
DOE funded project to “Develop High-Efficiency, Lightweight Wind Turbine Generators for Tall Wind and Offshore Applications”

- [July 2019] DOE selected projects
- Each of the selected projects received $500,000 to design a wind turbine generator that can be scaled up to at least 10 MW.
- 2 projects developed superconducting generators
  - AMSC develops HTS based concept – funding stopped
  - GE develops LTS based concept – 2nd phase started to develop a scaled demonstrator

- [Jan 2021] DOE selected GE to receive up to $20.3 million to build and test a scaled prototype of their generator on a wind turbine.
- GE plan to produce a working prototype of a superconducting wind turbine generator by 2023.

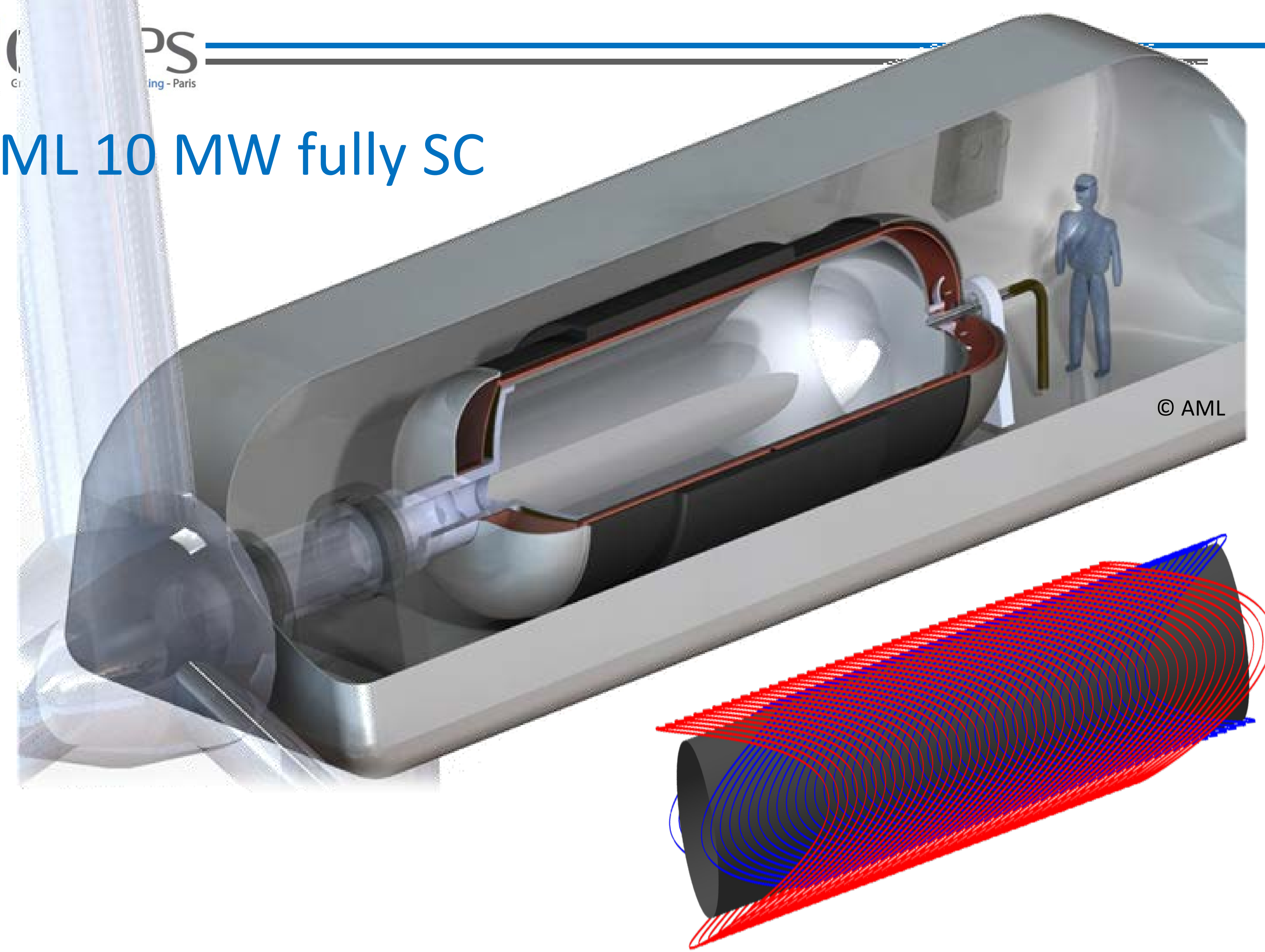
AMSC 10 MW DD SeaTitan

GE 10 MW Ecomagination



Superconducting Generator Details

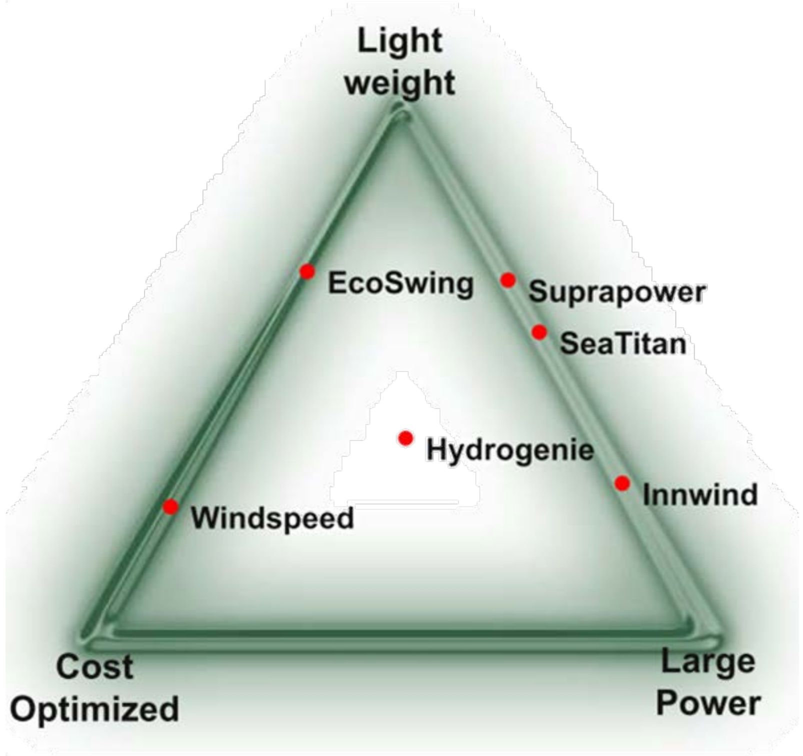
AML 10 MW fully SC



[1] L. Quéval, R. Gottkehaskamp, "Analytical field calculation of modulated double helical coils," *IEEE Transactions on Applied Superconductivity*, vol. 25, no. 6, pp. 4901307, Dec. 2015.

Development in EU

- Innwind 10 … 20 MW DD (Siemens)
  - Components demonstrated
  - LCOE: HTS vs. PM vs. magnetic gearbox
- SUPRApower (Tecnalia, ex. Acciona)
  - Design 10 MW DD, Hardware ?
- Windspeed (ECO 5)
  - Design 3.5 MW DD
- EcoSwing (Envision, Jeumont Elec.)
- EolSupra20 (Univ. Paris-Saclay)

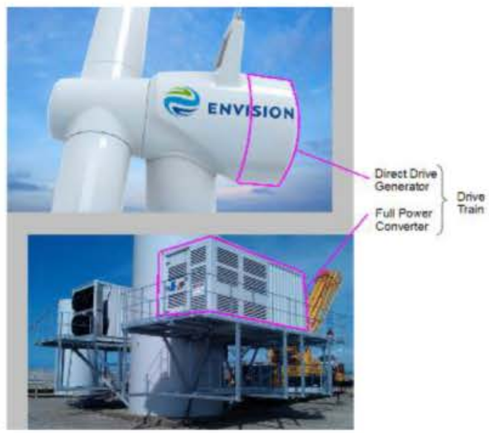


Adapted from [1] C. Bührer, "Attempting to shift a paradigm: HTS generators for cost-sensitive applications," DBU Seminar, Osnabrück, Apr, 2016.

EcoSwing

Our ambitions

ecoswing



ENVISION · ECO5 · JEUMONT Electric · DELTA Delta Energy Systems · THEVA · SHI Cryogenics Group · Fraunhofer · University of Twente. · DNV·GL

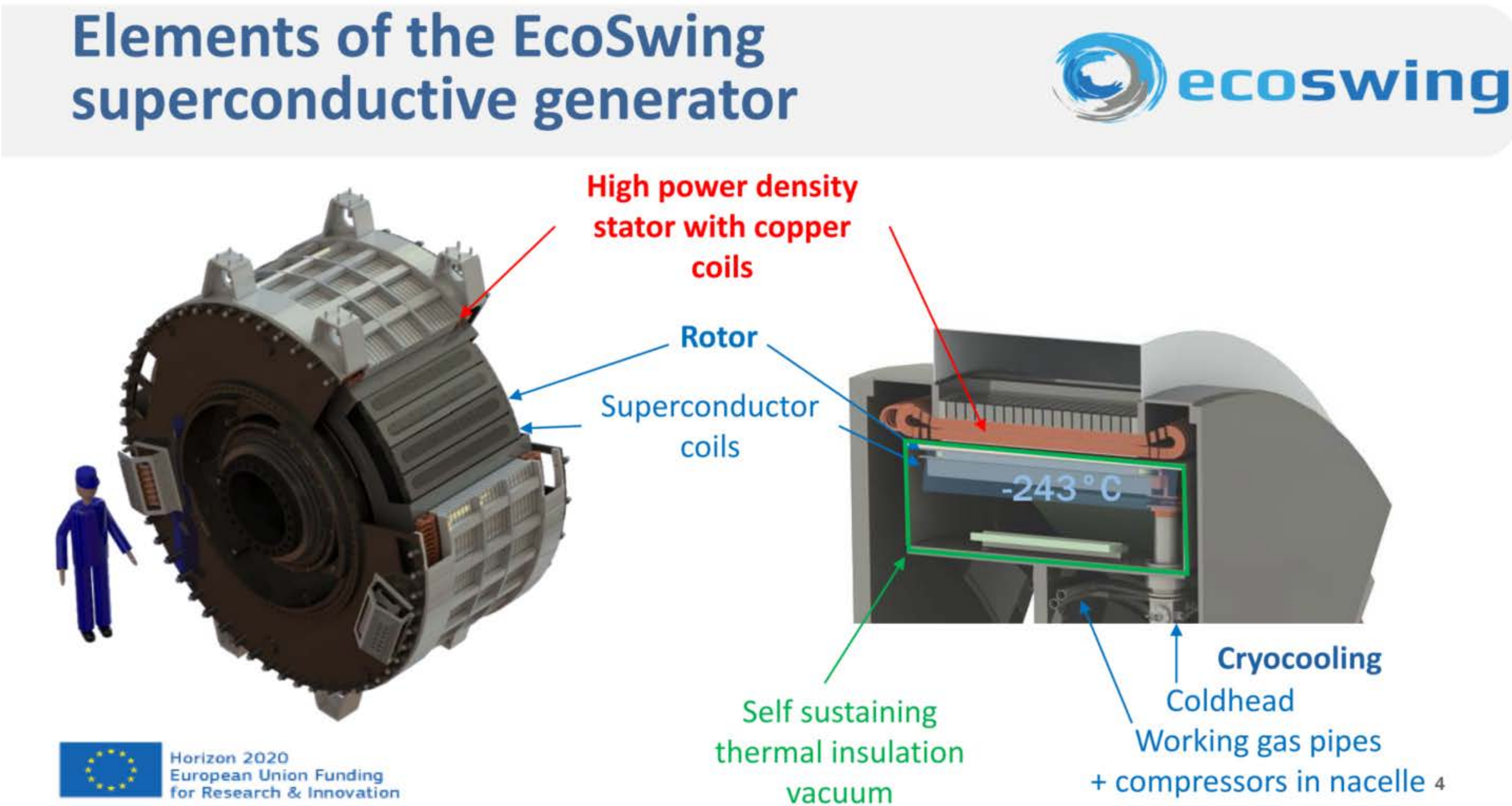
Horizon 2020
European Union Funding
for Research & Innovation

- Design, develop and manufacture a full scale multi-megawatt superconducting wind generator
- Install this superconducting drive train on an existing modern wind turbine in Thyborøn, Denmark, replace existing PM generator (3 MW Class, 14 rpm, 128 m rotor)
- Prove that a superconducting drive train is lighter, smaller and cost-competitive.
- Start Date: 2015-03-01
  End Date: 2019-04-30

3

Adapted from [1] M. Bauer, "Superconducting generators for wind power, EcoSwing generator and outlook," *COST ACTION 19108 Hi-Scale first joint WG3/4 industry-academia workshop on applications for HTS technologies in the electrical energy chain*, [online], Apr. 2021.

EcoSwing



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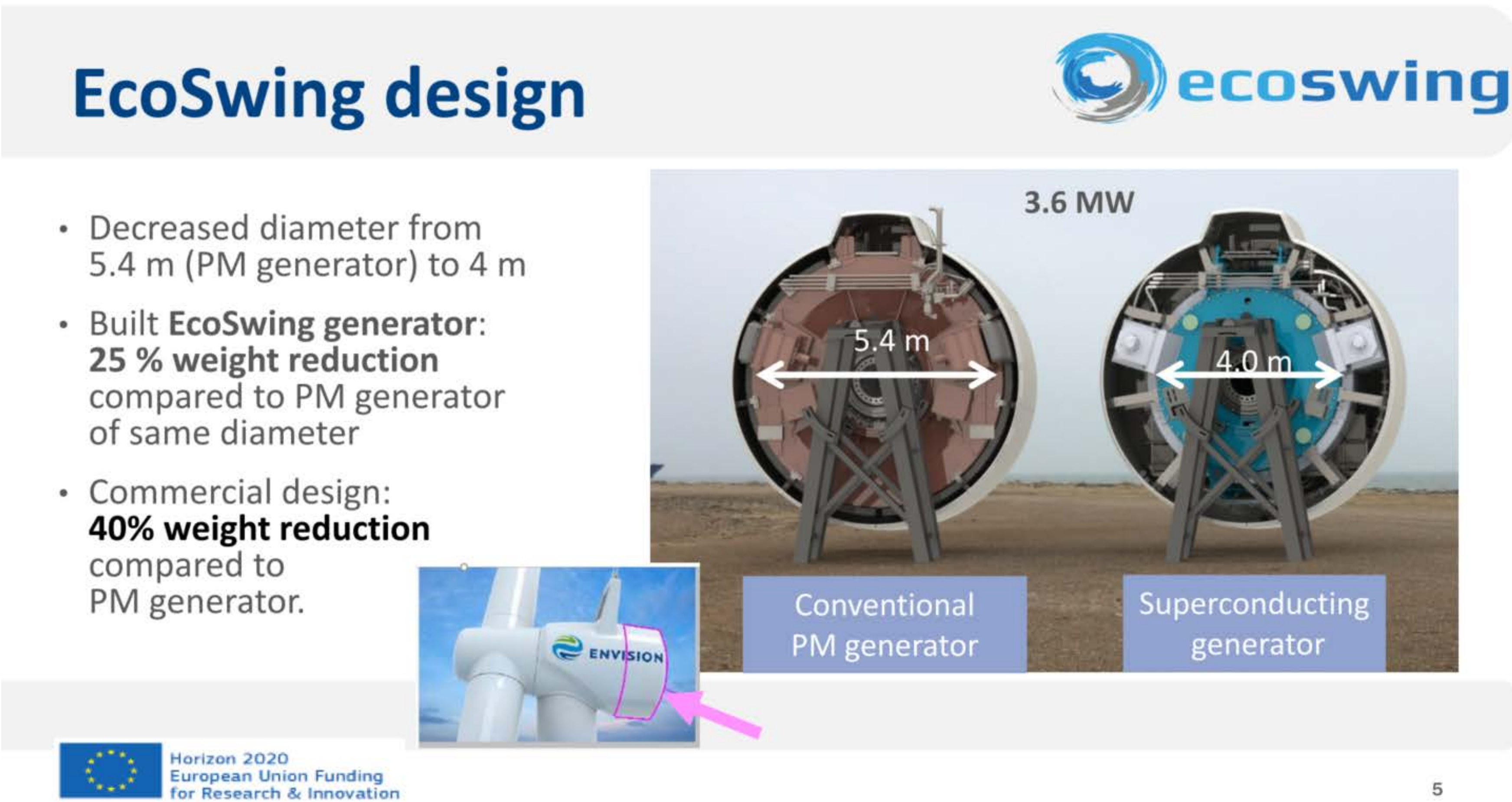
EcoSwing



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EcoSwing

Testing on ground and in turbine

ecoswing

At IWES, Bremerhaven for ground testing

Mounting on Envision wind turbine GC-1, Thyborøn, Denmark

Horizon 2020
European Union Funding
for Research & Innovation

12

[1] M. Bauer, "Superconducting generators for wind power, EcoSwing generator and outlook," *COST ACTION 19108 Hi-Scale first joint WG3/4 industry-academia workshop on applications for HTS technologies in the electrical energy chain*, [online], Apr. 2021.

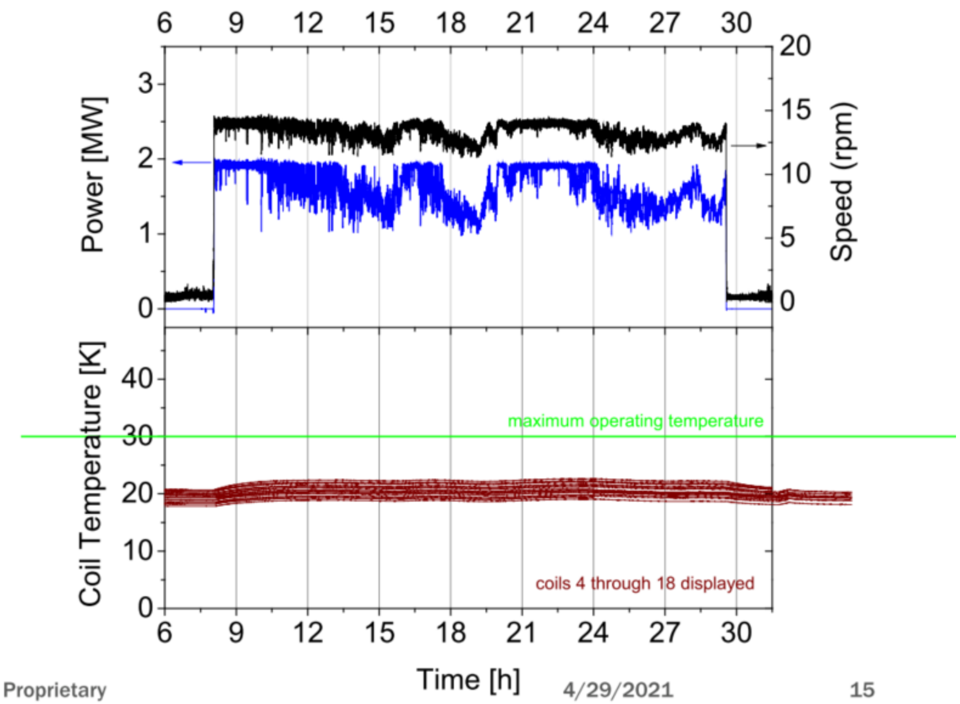
EcoSwing

Main project results

ecoswing

- EcoSwing generator reached +3 MW
- Converter limit exceeded
- 50 months EU project concluded on time
- +7 months stable reliable cryogenics
- +650 h producing power
- Superconducting coils showed great performance
- 25.4.2019 EcoSwing switched-off

Whats next?



Horizon 2020
European Union Funding
for Research & Innovation

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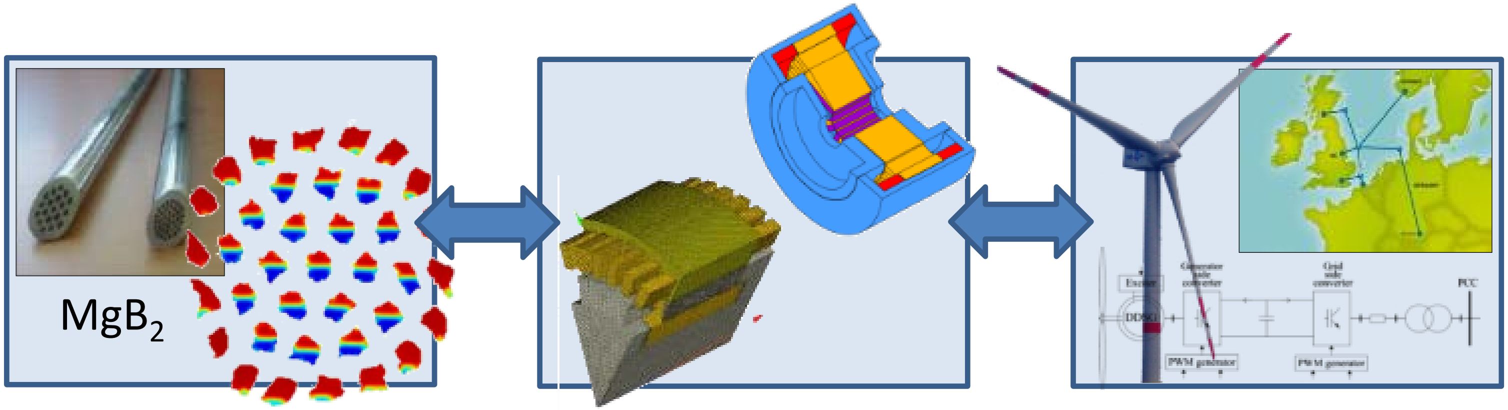
[1] M. Bauer, “Superconducting generators for wind power, EcoSwing generator and outlook,” *COST ACTION 19108 Hi-Scale first joint WG3/4 industry-academia workshop on applications for HTS technologies in the electrical energy chain*, [online], Apr. 2021.

EolSupra20

Feasibility study of a 20 MW superconducting wind turbine generator



EolSupra20

Design and optimization of the electromagnetic/cryogenic designs of a 20 MW fully SC wind turbine generator to minimize the LCOE

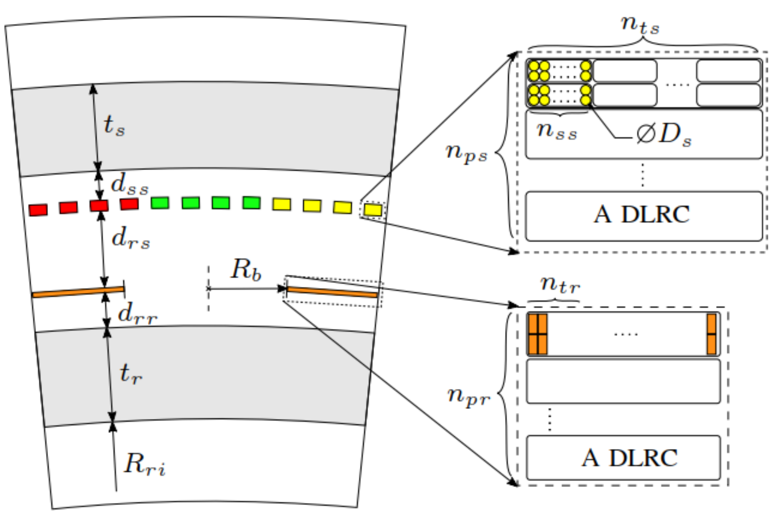


Fig. 1 - EolSupra20 electromagnetic design

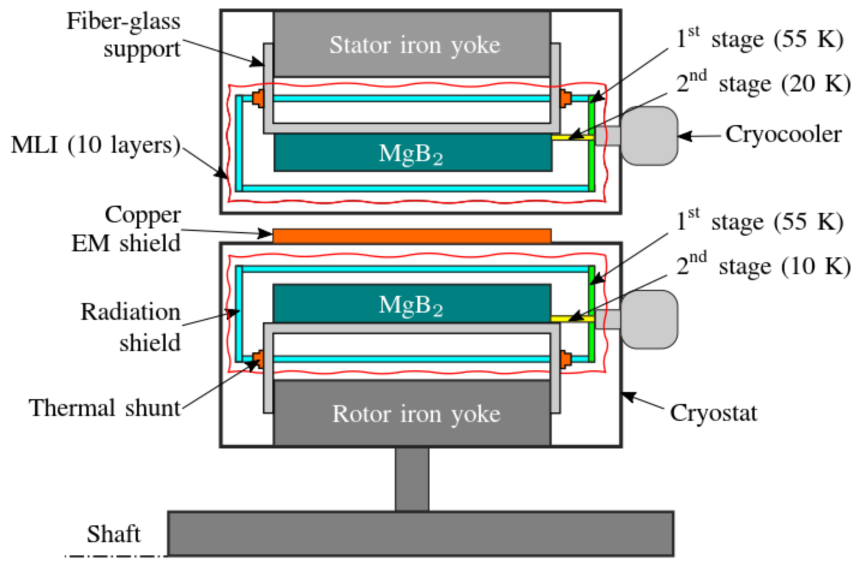


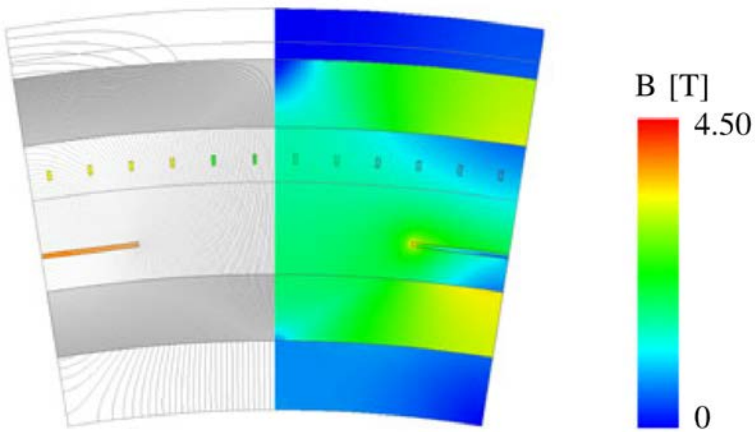
Fig. 2 - EolSupra20 cryogenic design

[1] T.-K. Hoang, L. Quéval, L. Vido, C. Berriaud, "Impact of the rotor blade technology on the levelized cost of energy of an offshore wind turbine," *Joint International Conference OPTIM-ACEMP*, Brasov, Romania, May 2017.

[2] T.-K. Hoang, L. Quéval, C. Berriaud, L. Vido, "Design of a 20 MW fully superconducting wind turbine generator to minimize the levelized cost of energy," *IEEE Transactions on Applied Superconductivity*, vol. 28, no. 4, pp. 1-4, June 2018.

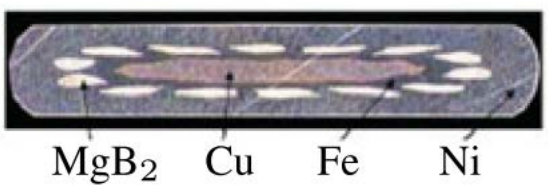
EolSupra20

EolSupra20 2018 base design

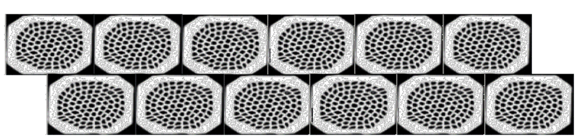


Description	Value
Rotor winding	
MgB2 conductor length [km]	37
Current density in filaments [A/mm^2]	2276/3294
Max. magnetic flux density [T]	4.01
First stage (55 K) losses [W]	268
Second stage (10 K) losses [W]	37
Nb of cryocoolers [-]	8
Stator winding	
MgB2 conductor length [km]	104
Current density in filaments [A/mm^2]	3165/4212
Max. magnetic flux density [T]	1.72
First stage (55 K) losses [W]	929
Second stage (20 K) losses [W]	1291
Nb of cryocoolers [-]	77
Machine geometry	
Phase-phase voltage [kV rms]	3.2
Output power [MW]	20
Outer stator yoke radius [m]	3.01
Active and inactive mass [kg]	167512
Economics	
Generator cost [$M]	5.81

Rotor:



Stator:

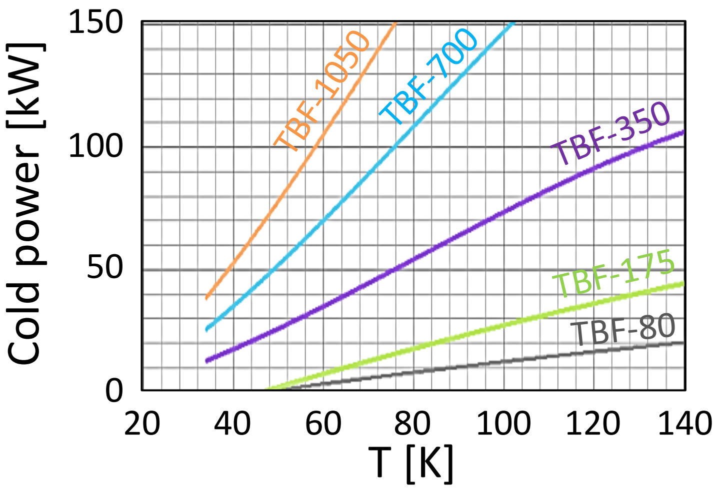


[1] T.-K. Hoang, L. Quéval, C. Berriaud, L. Vido, “Design of a 20 MW fully superconducting wind turbine generator to minimize the levelized cost of energy,” *IEEE Transactions on Applied Superconductivity*, vol. 28, no. 4, pp. 1-4, June 2018.

EolSupra20

EolSupra20 2018 base design

Air Liquide Turbo-Brayton TBF-80



Description	Value
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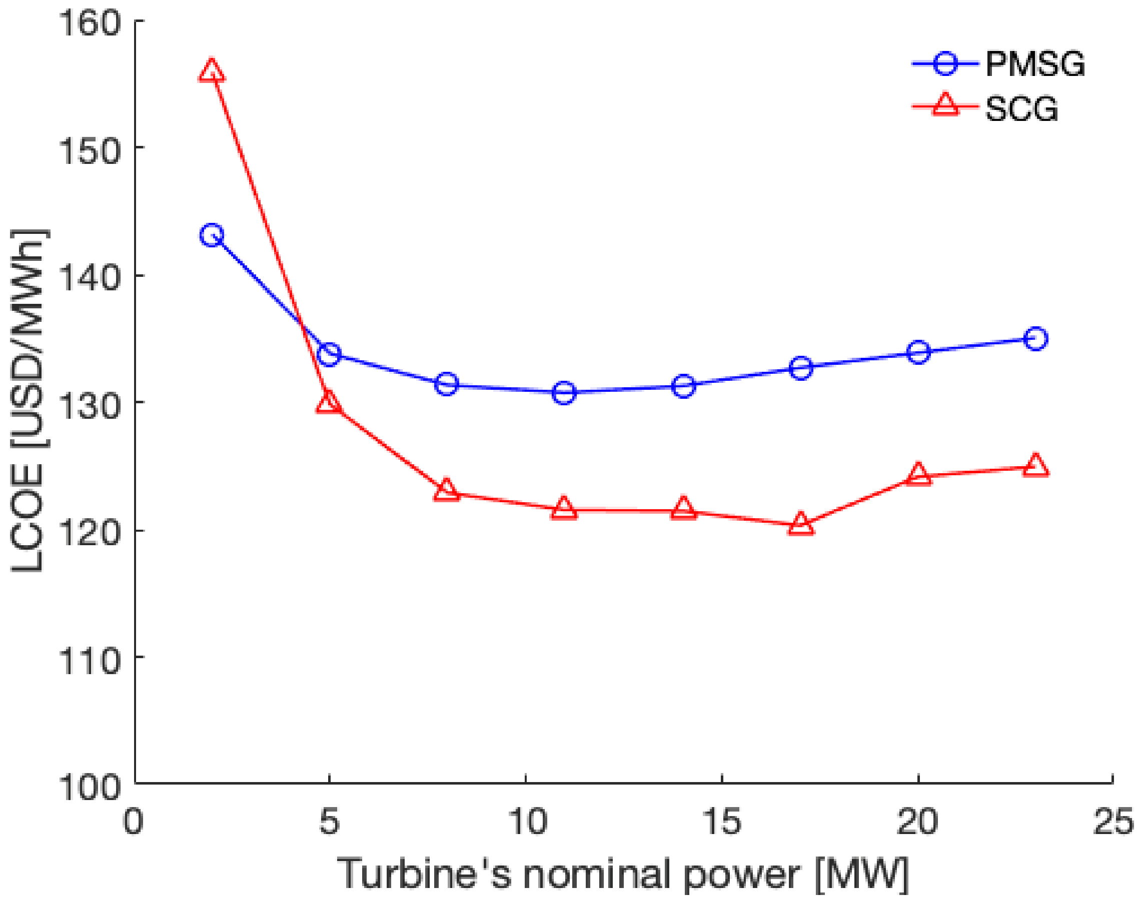
Generator cost [$M]	5.81

[1] C. Gondrand, “Turbo-Brayton cryogenic systems, An ideal solution for refrigeration,” *EASISchool2*, Oct. 2019.

EolSupra20

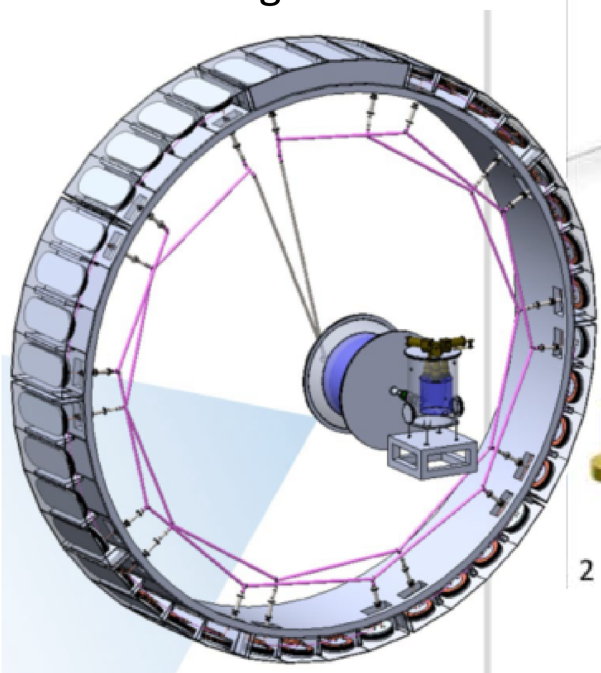
Some trends (offshore floating) …

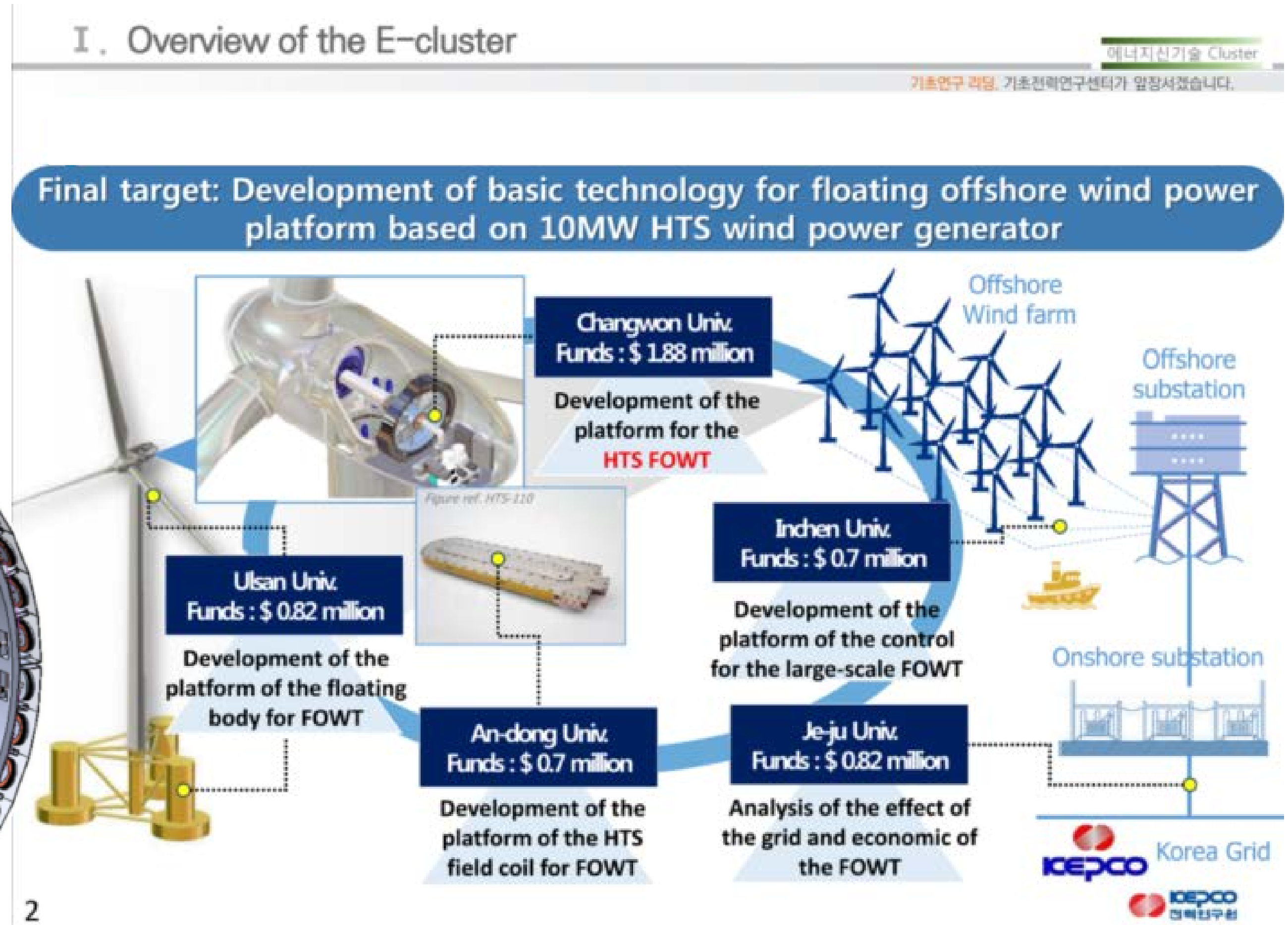


[1] T.-K. Hoang, L. Quéval, L. Vido, D.-Q. Nguyen, “Levelized cost of energy comparison between permanent magnet and superconducting wind generators for various nominal power,” *IEEE Transactions on Applied Superconductivity*, vol. 32, no. 7, id. 5202606, Oct. 2022.

Development in South Korea

10 MW generator





Adapted from [1] M. Bauer, “Superconducting generators for wind power, EcoSwing generator and outlook,” *COST ACTION 19108 Hi-Scale first joint WG3/4 industry-academia workshop on applications for HTS technologies in the electrical energy chain*, [online], Apr. 2021.

V. Conclusion

Conclusion

- Superconducting wind turbines are still in the laboratory development phase.
- EcoSwing: world's first HTS wind turbine in 2019.
- Currently no pilot projects nor industrial deployment. TRL 4-5.
- Today 16 MW conventional machines. Tomorrow 20 MW ? The business case needs to be re-examined …
  - Technical motivation: 30 MW ?
  - Techno-economic assessment: LCOE of the full system ?
  - Critical raw material act: rare earth materials.
- Fully HTS machines have potential for >20 MW floating offshore wind turbines. Bottlenecks identified in 2018 on the way to being resolved: Conductor length & Cooling system.

Merci !

European Commission

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.