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Superconducting wind turbine generators - Current status & perspectives

Loic Queval

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ESAS'2023 School - Col de Porte, France

Superconducting wind turbine generators

Current status & perspectives

Loïc Quéval

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

² Sorbonne University, CNRS, Group of electrical engineering - Paris, 75252, Paris, France

Content

- I. Resource and potential
- II. Wind energy conversion system
- III. Superconducting wind turbine generators ?
- IV. Current status and perspectives

I. Resource and potential

World electricity generation

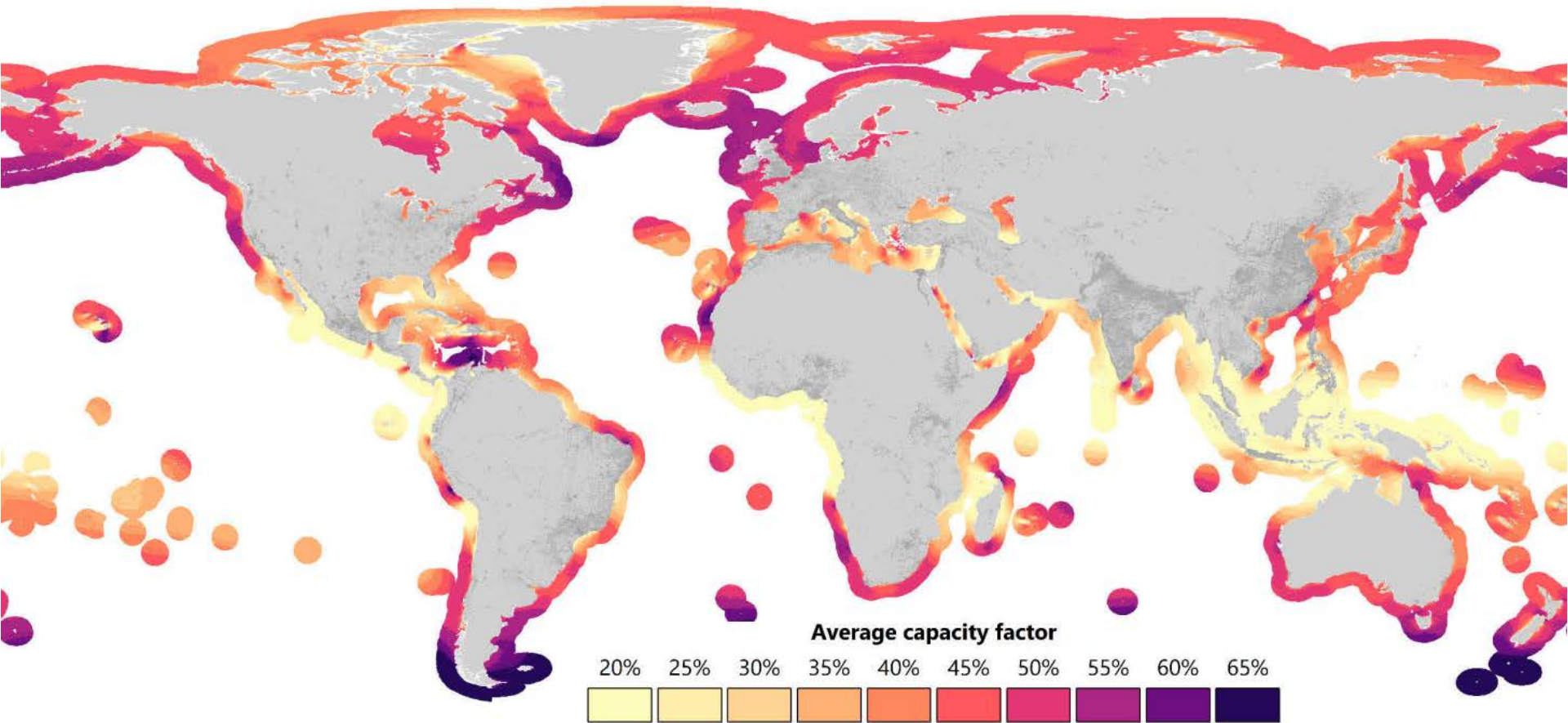
« What we need » following IEA Stated Policies Scenario

	2018	2040
Total generation [TWh _e / year]	26 603	41 373

Resource and potential

Primary resource:
30 000 000 TWh_p / year

Technical potential:
420 000 TWh_e / year



Resource and potential

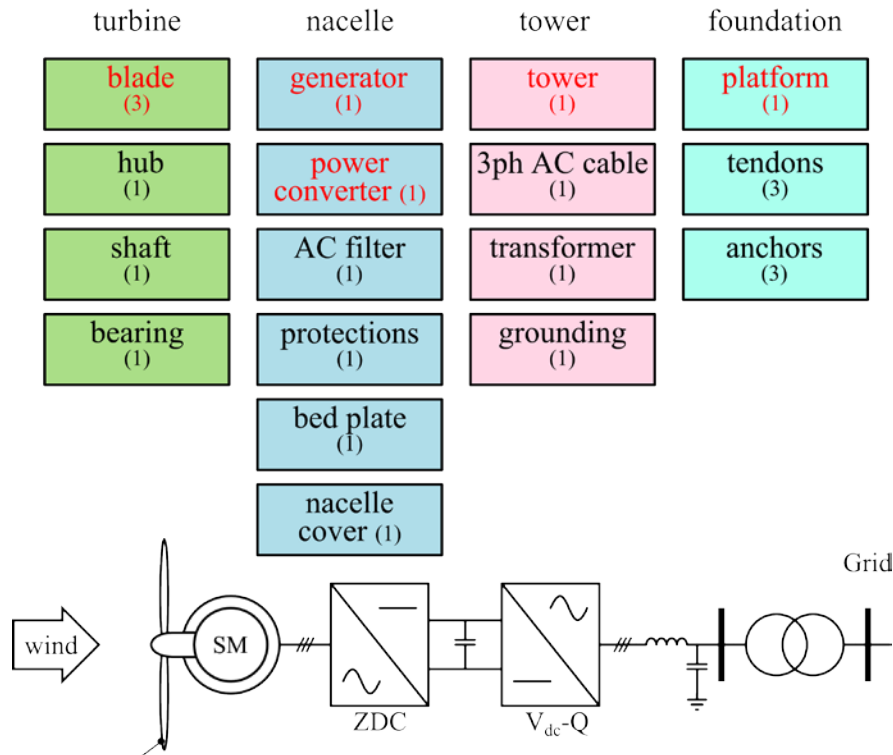
*Dunkerqk
44 €/MWh*



	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

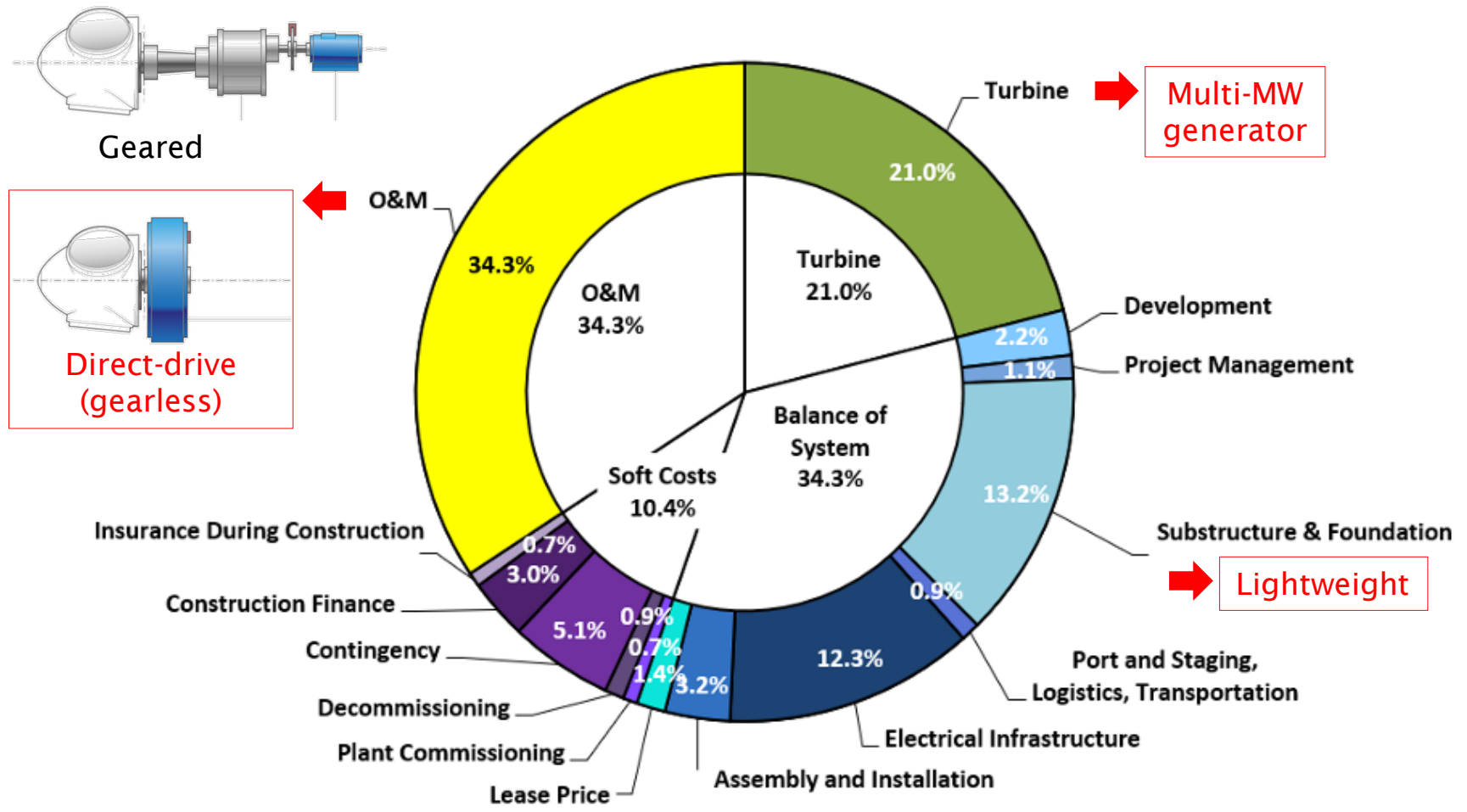
II. Wind Energy Conversion System (WECS)

Wind energy conversion system



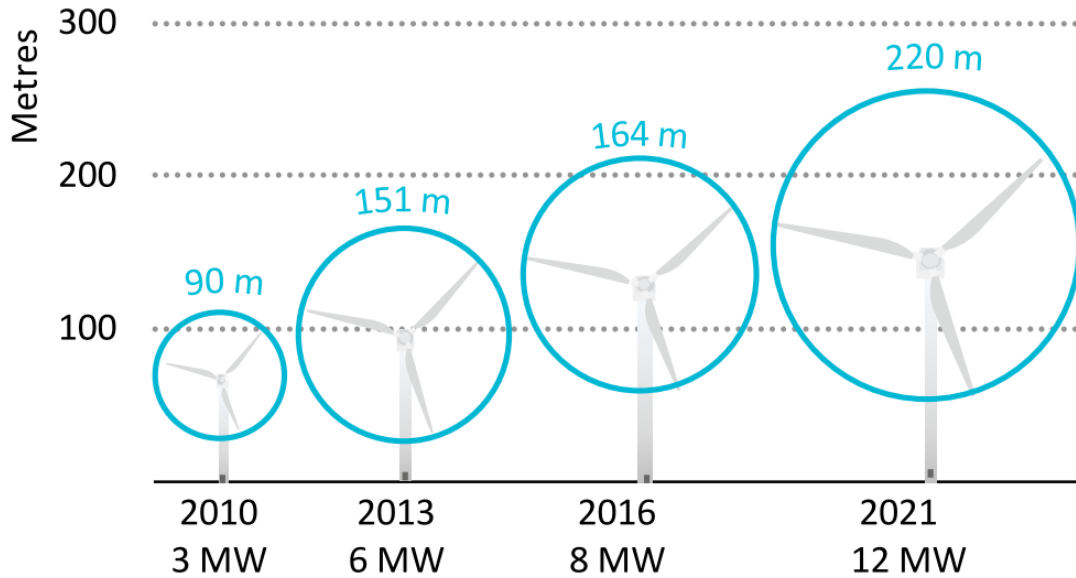
LCOE breakdown of offshore windfarm

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.

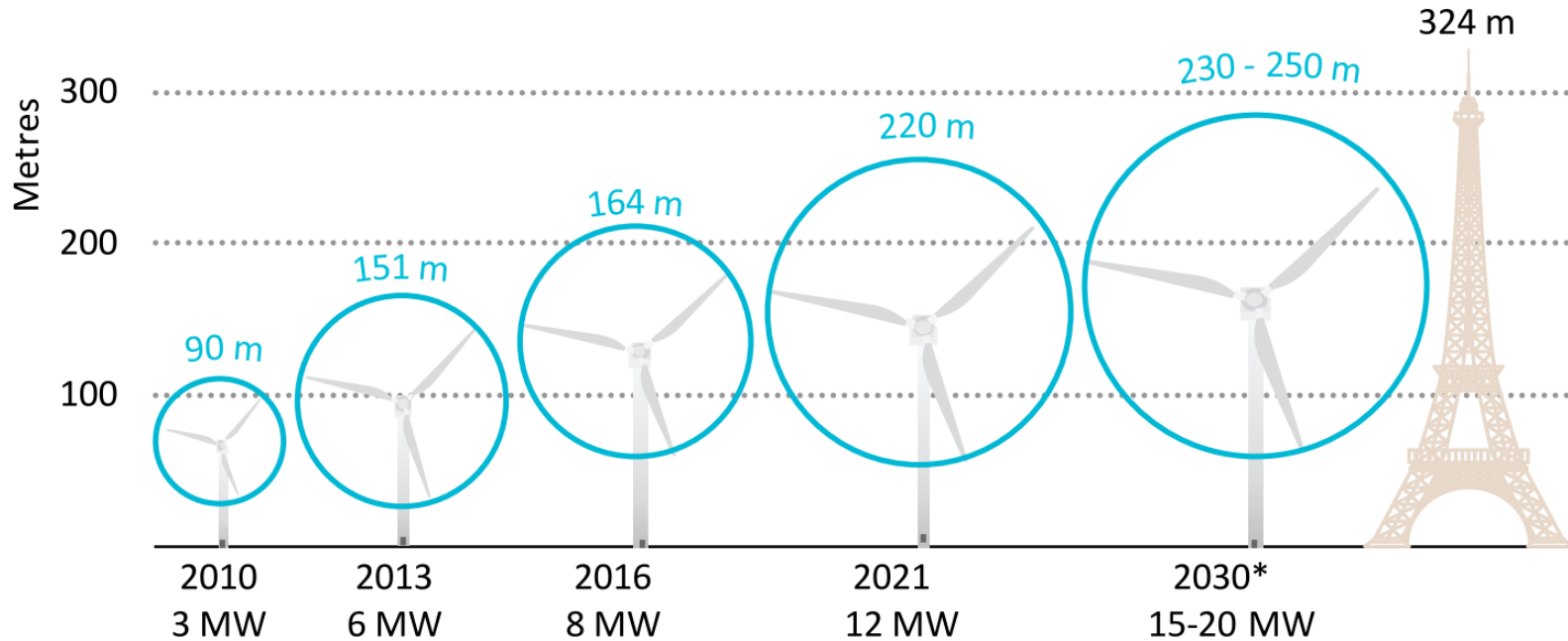
Unit power



World's largest wind turbine generator
Vestas V236-15.0 MW →



Unit power



Towards 20 MW offshore wind turbines !

GE Haliade-X 18 MW

MingYang Smart Energy MySE 18.X-28X

CSSC Haizhuang H260-18MW

...



Wind turbine generator

Synchronous generator



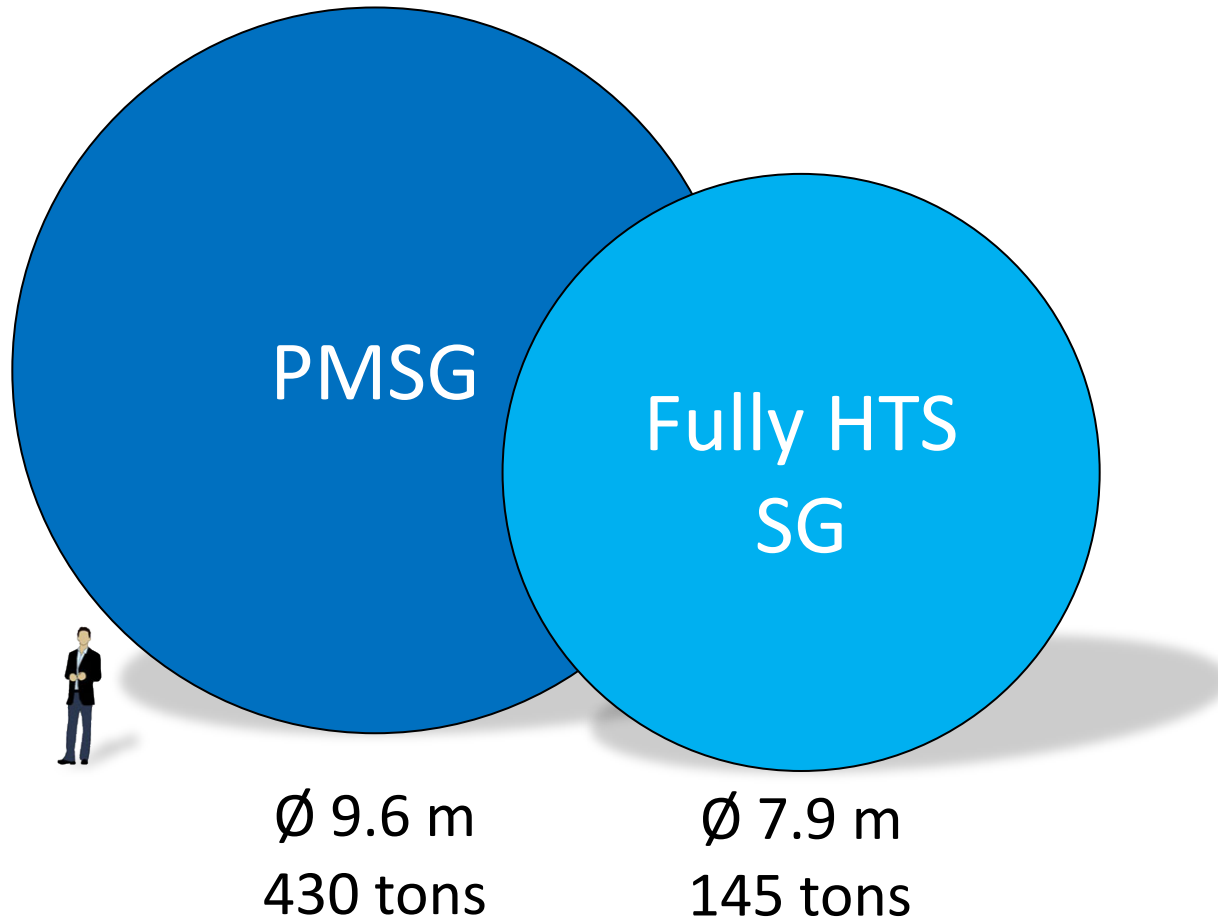
**EESG in Enercon
E-138 EP3 4.2 MW**



**EESG in Enercon
E-126- 7.5 MW**

III. Superconducting wind turbine generator ?

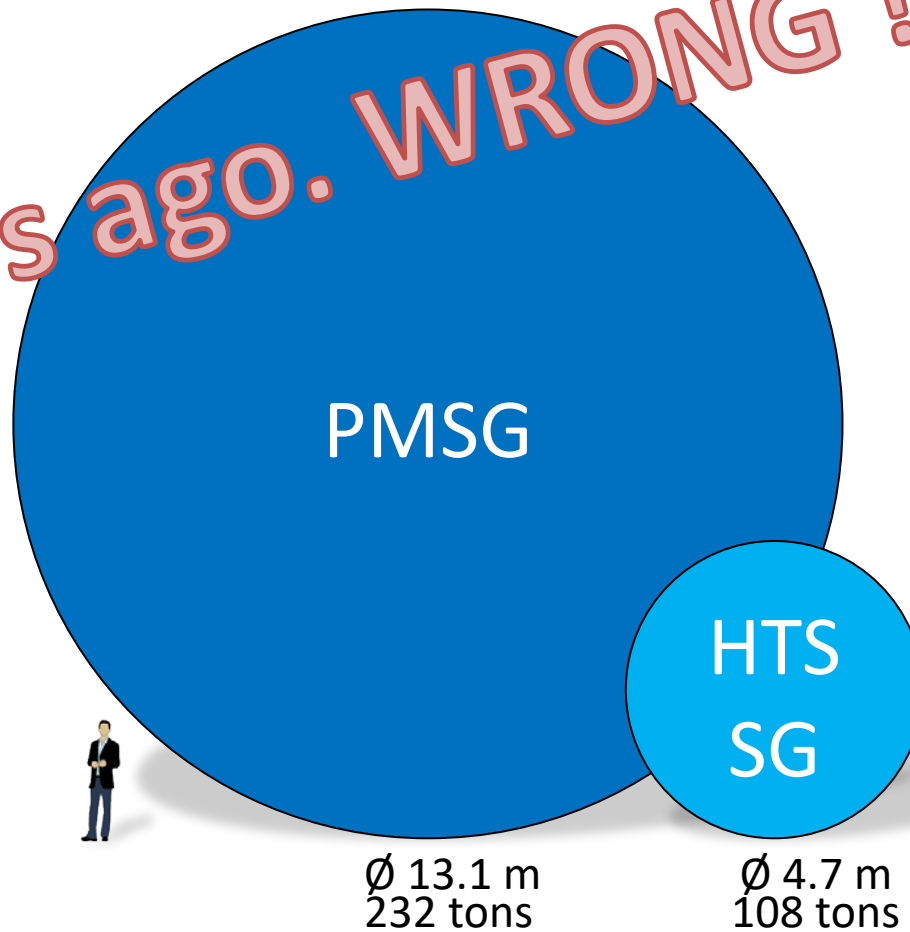
Comparison 20 MW DD PMSG vs. Fully HTS SG



[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

10 years ago. WRONG!



[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 ?

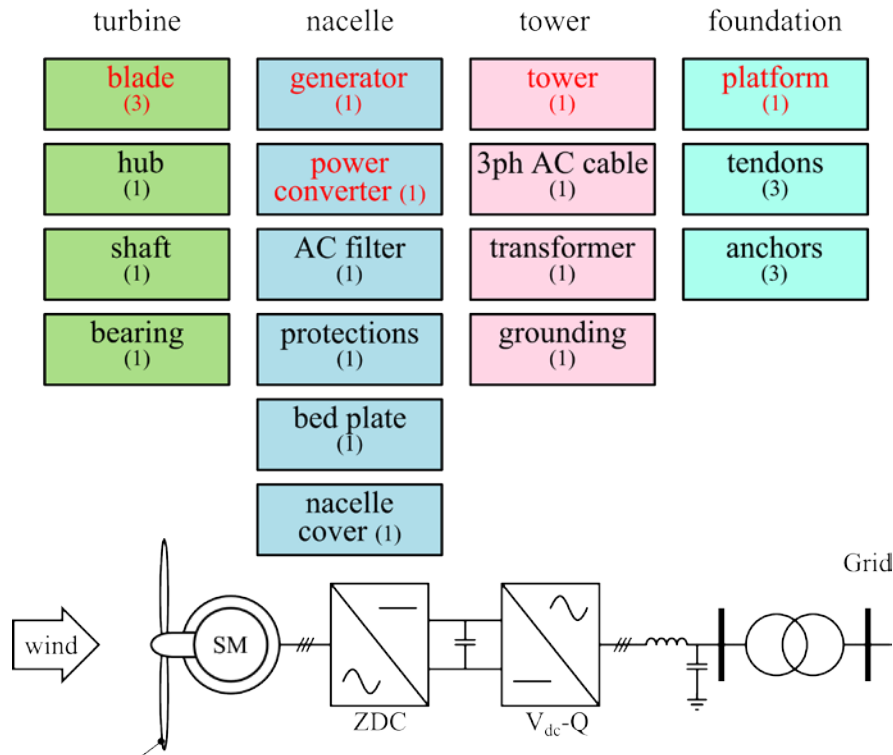
#1 - Technical reason

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?

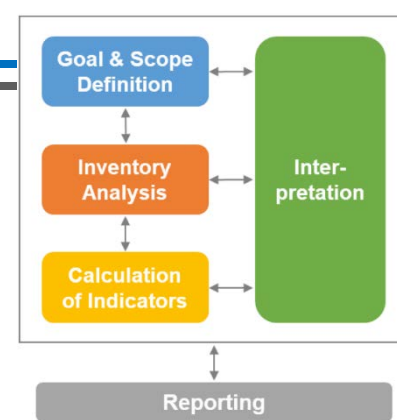
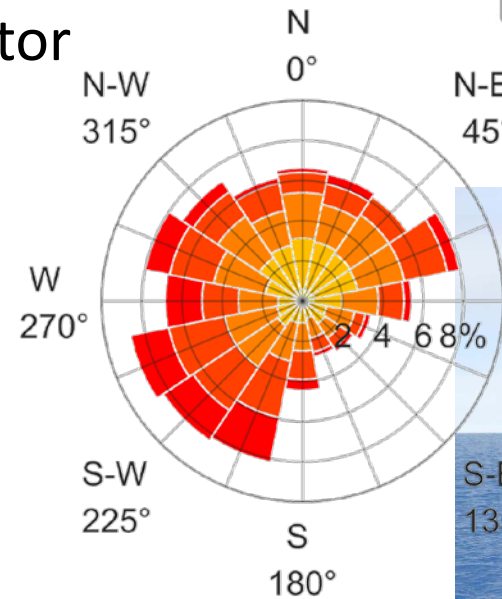
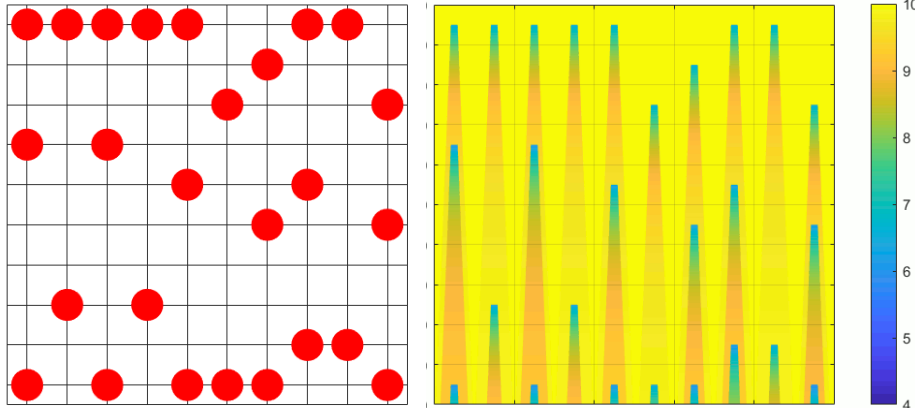
Impact of a modification of the generator ?



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

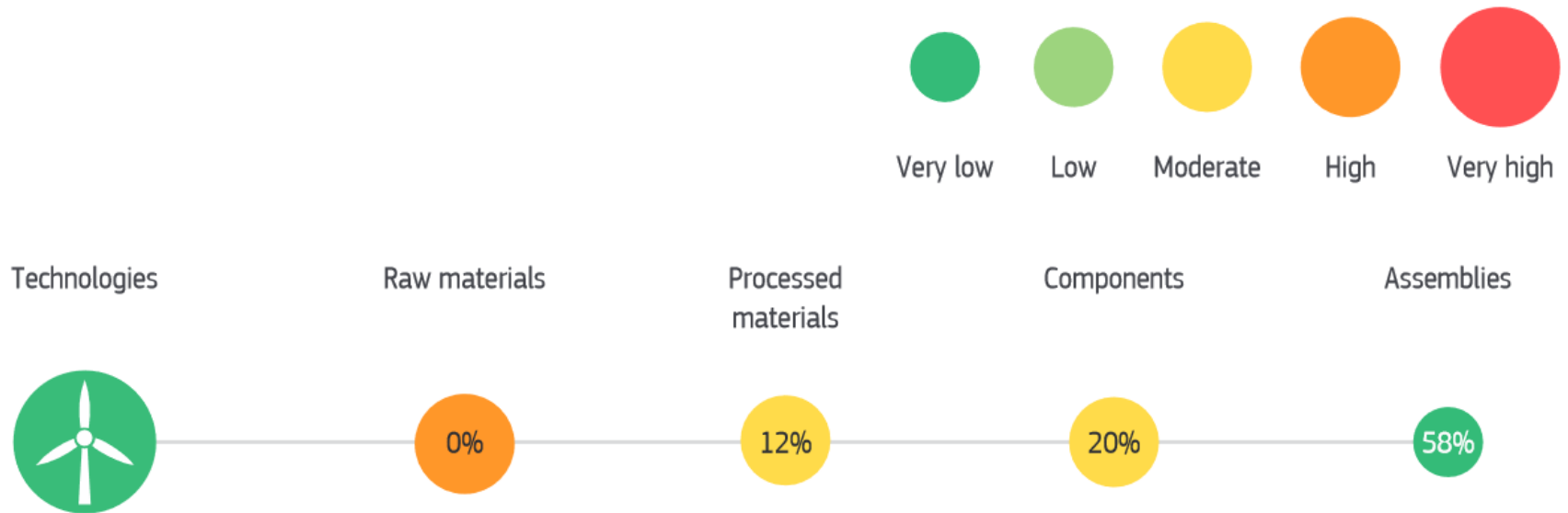
Superconducting wind turbines will be more competitive than conventional machines?

#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

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

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P B Nørgård³, N F Pedersen², N H Andersen¹ and J Østergård²

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² Department of Electrical Engineering, Technical University of Denmark, DK-2800 Lyngby, Denmark

³ Wind Energy Division, Risø-DTU, Frederiksborgvej 399, 4000 Roskilde, Denmark

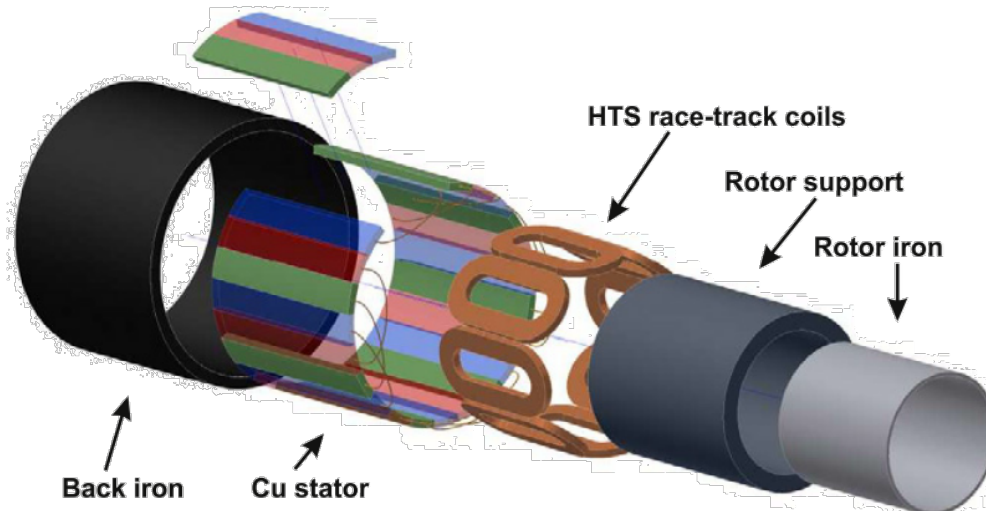
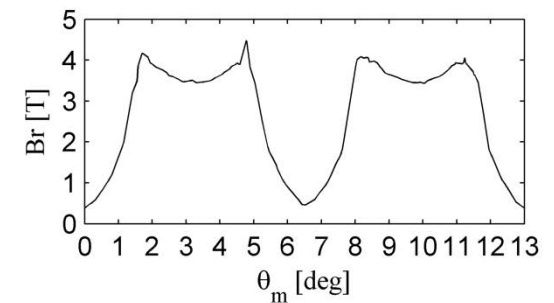
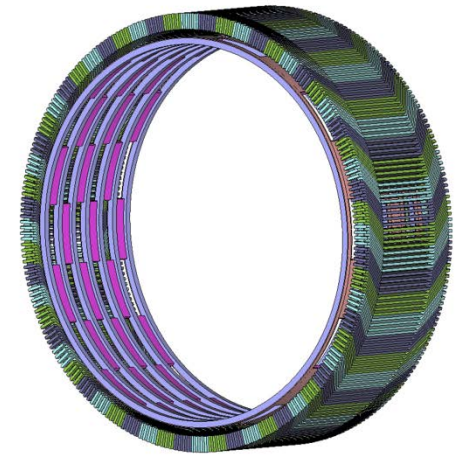
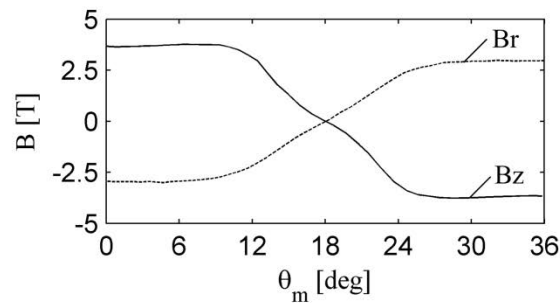
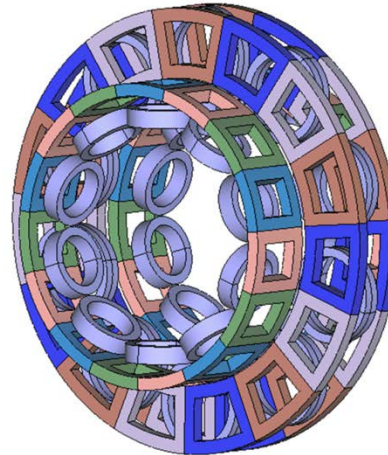
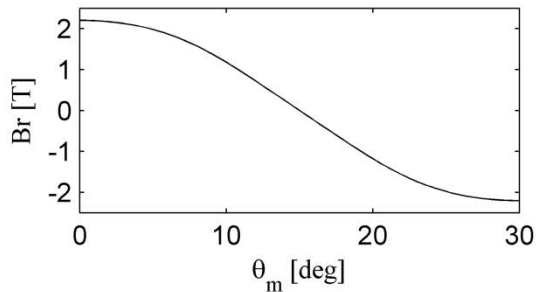
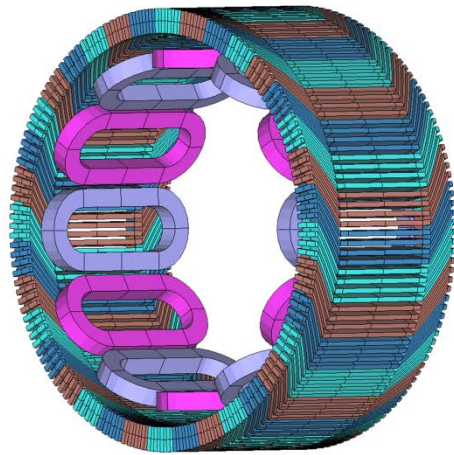


Table 2. Properties of an extreme 10 MW generator example.

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. Quides, "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. Quides, 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)

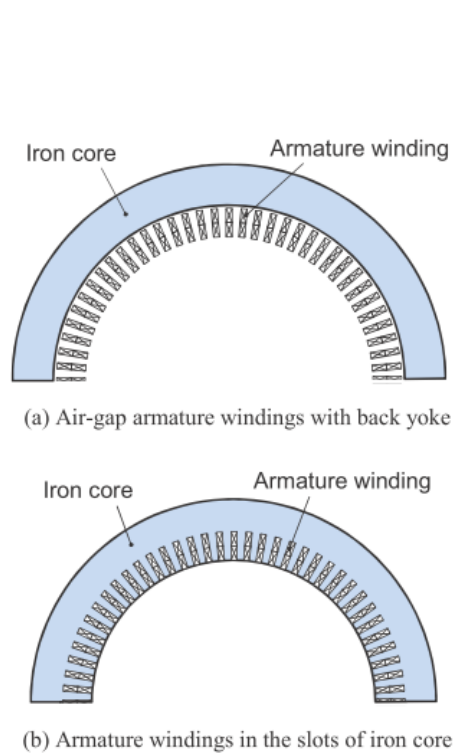


Fig. 4 Fundamental stator structures with armature windings.

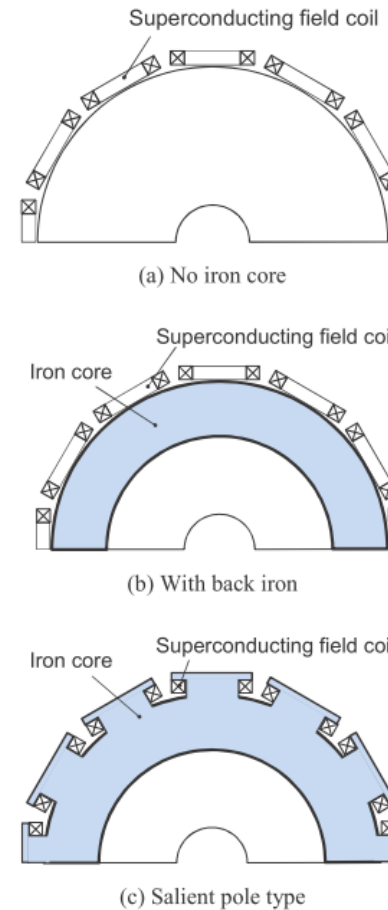


Fig. 5 Fundamental rotor structures with superconducting field coils.

[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

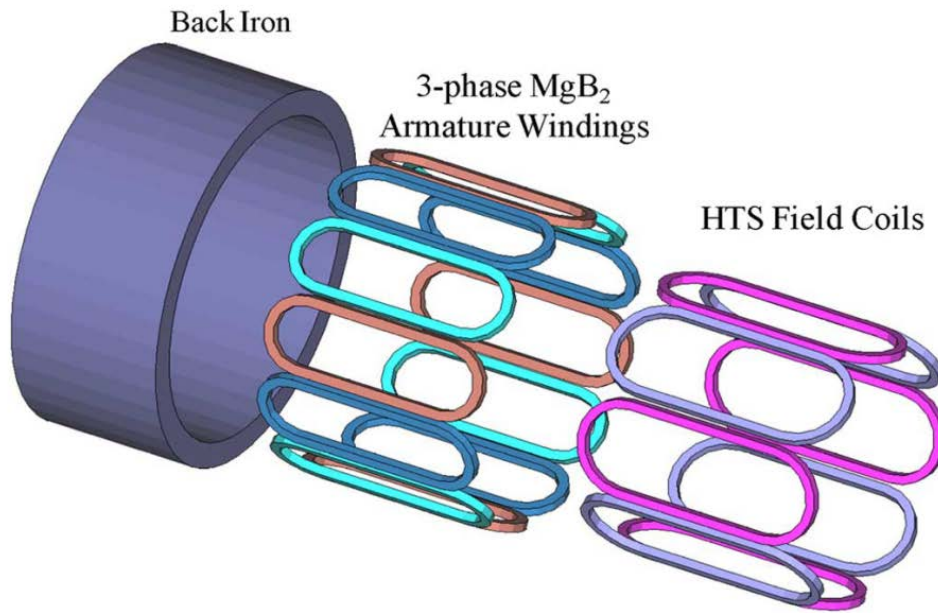


Fig. 1. Illustration of fully superconducting wind turbine generator [1]

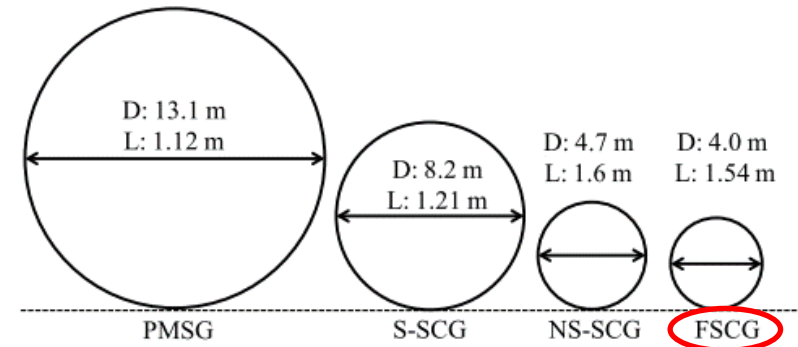


Fig. 7-1. Comparison of four wind turbine generator sizes [2]

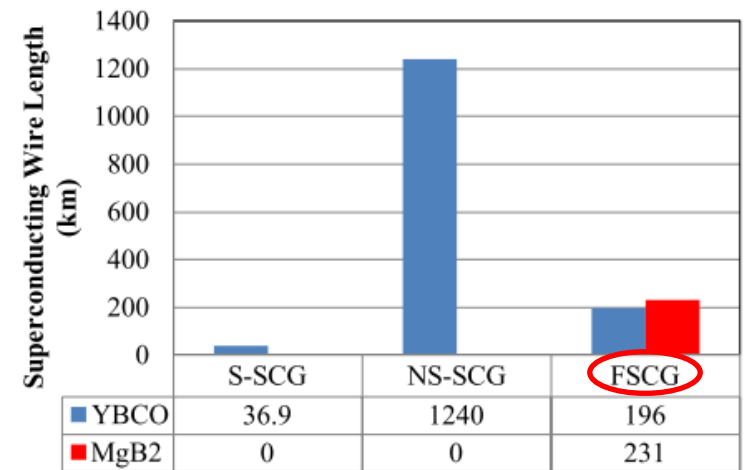
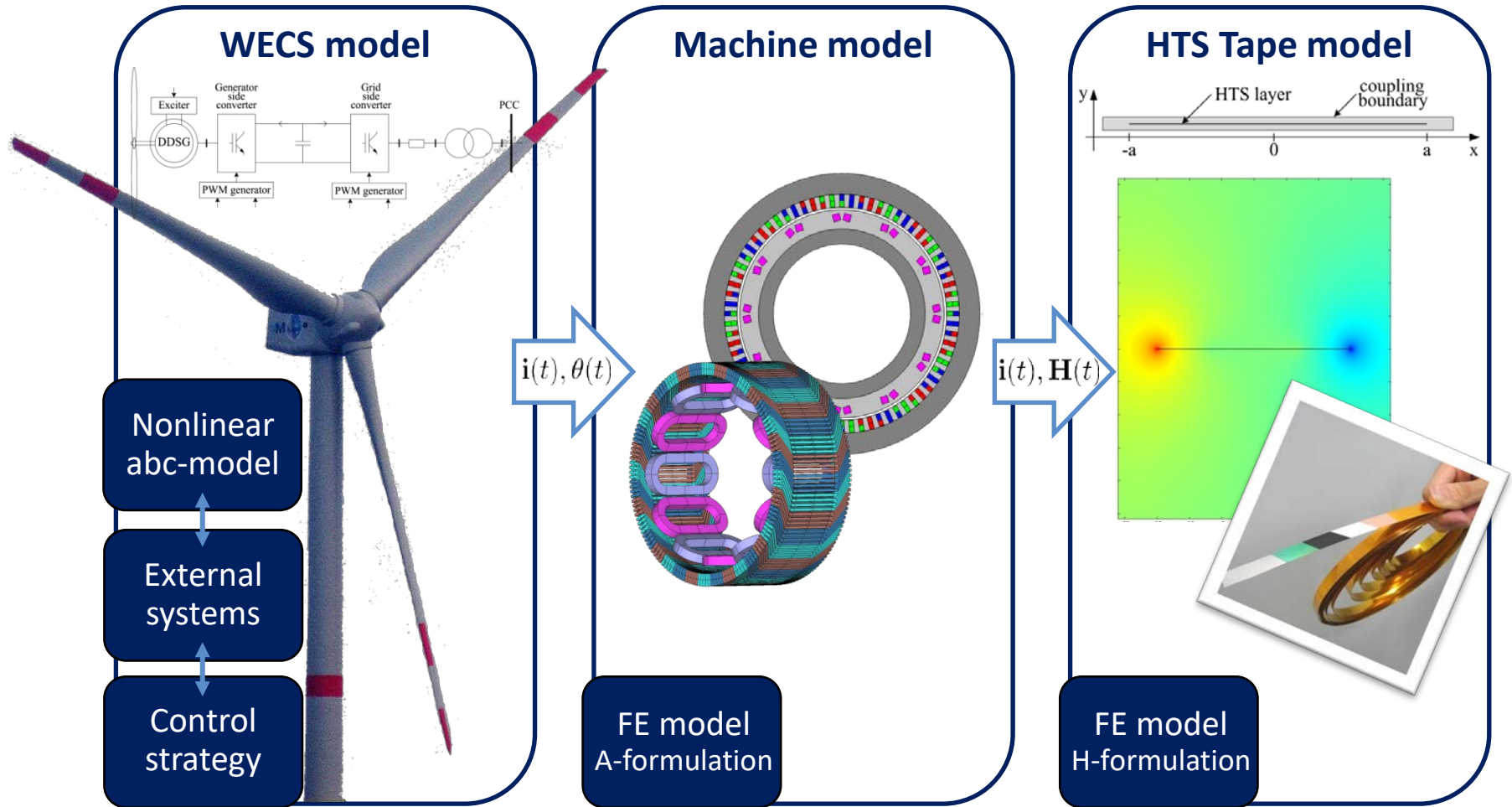


Fig. 7-2 Length of superconducting wires [2]

[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.

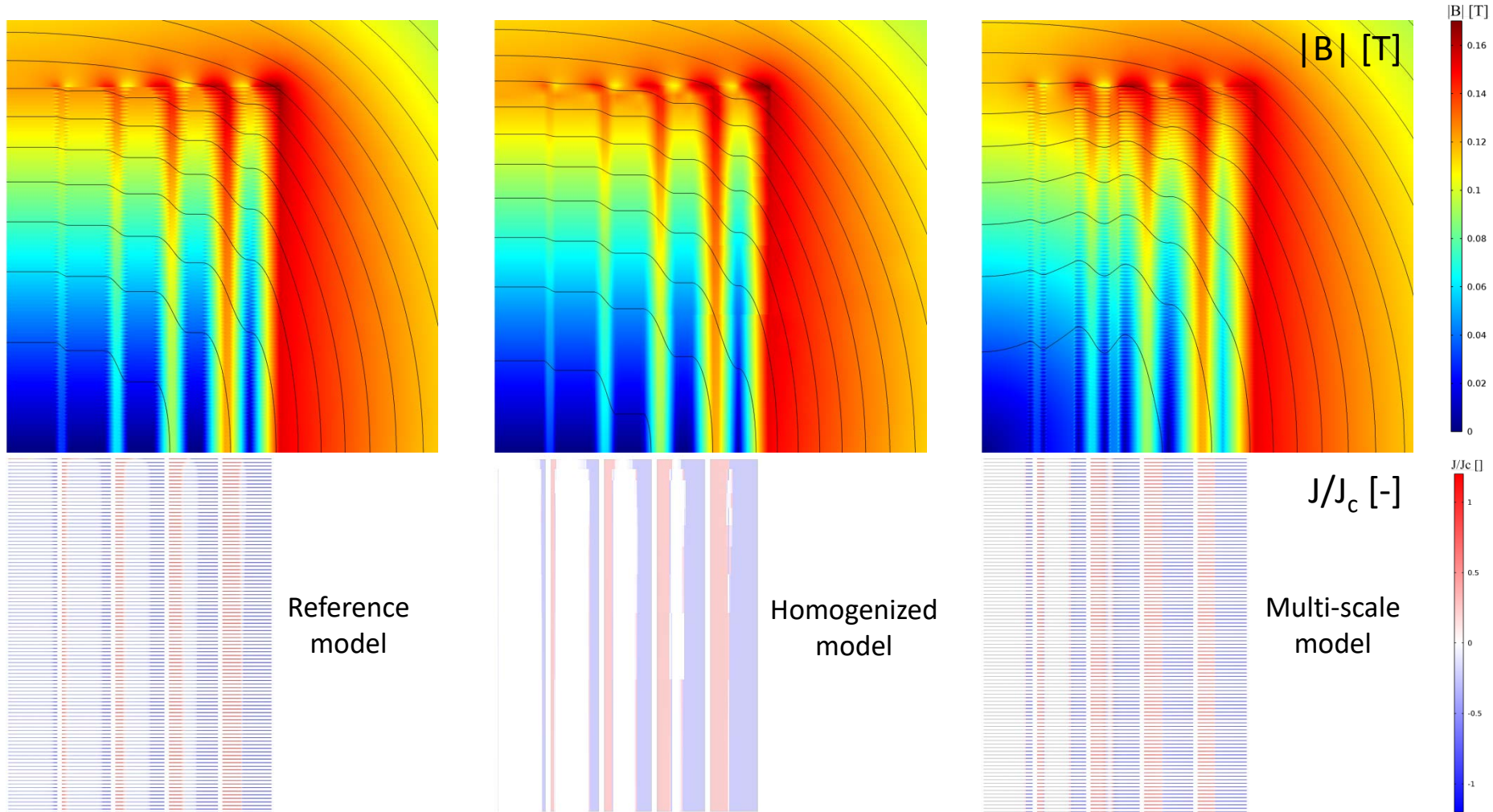
[2] Y. Terao, "Electromagnetic design of light weight and high-power density superconducting synchronous machines for 10 MW class wind turbine generators," PhD thesis, The University of Tokyo, Tokyo, Japan, 2013.

Simulation of grid-connected SC WT generators



- [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

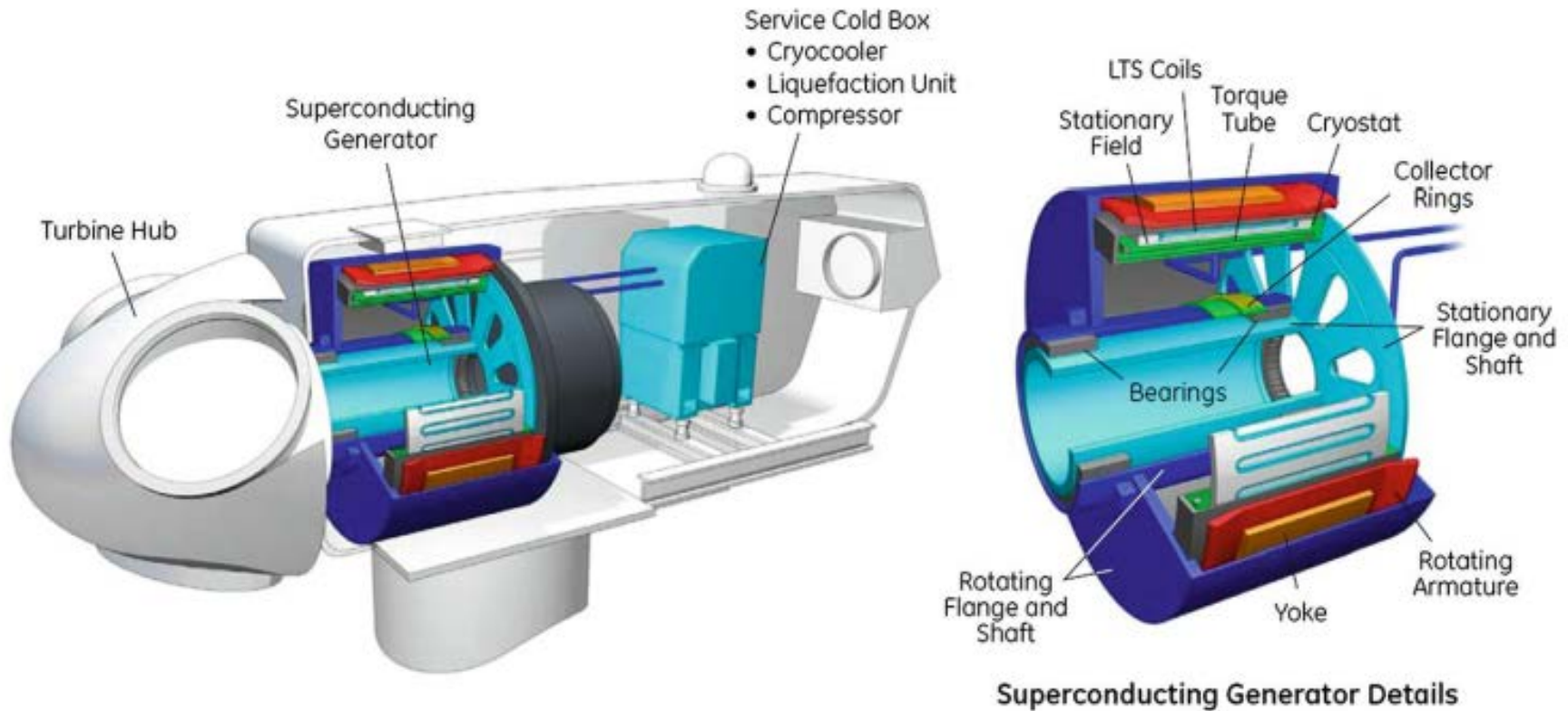
DOE funded project to “Develop High-Efficiency, Lightweight Wind Turbine Generators for Tall Wind and Offshore Applications”

- [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.

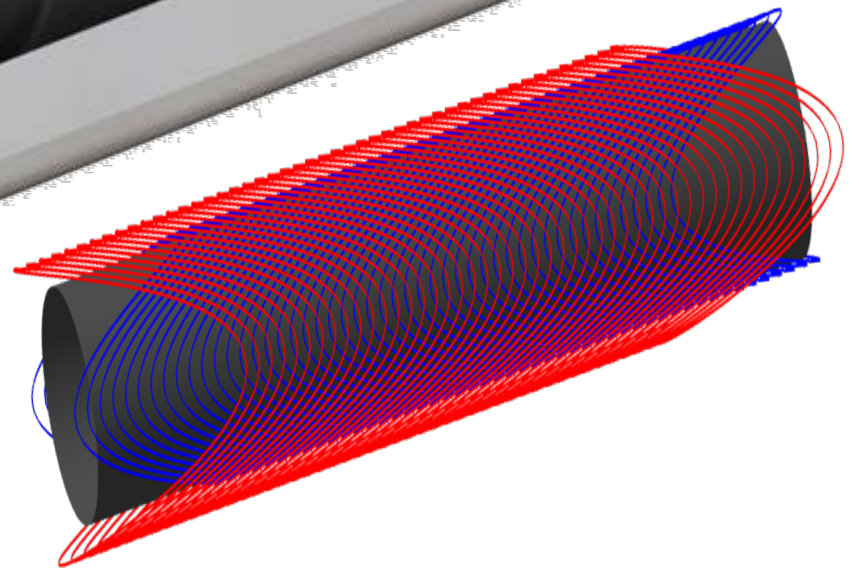
AMSC 10 MW DD SeaTitan



GE 10 MW Ecomagination



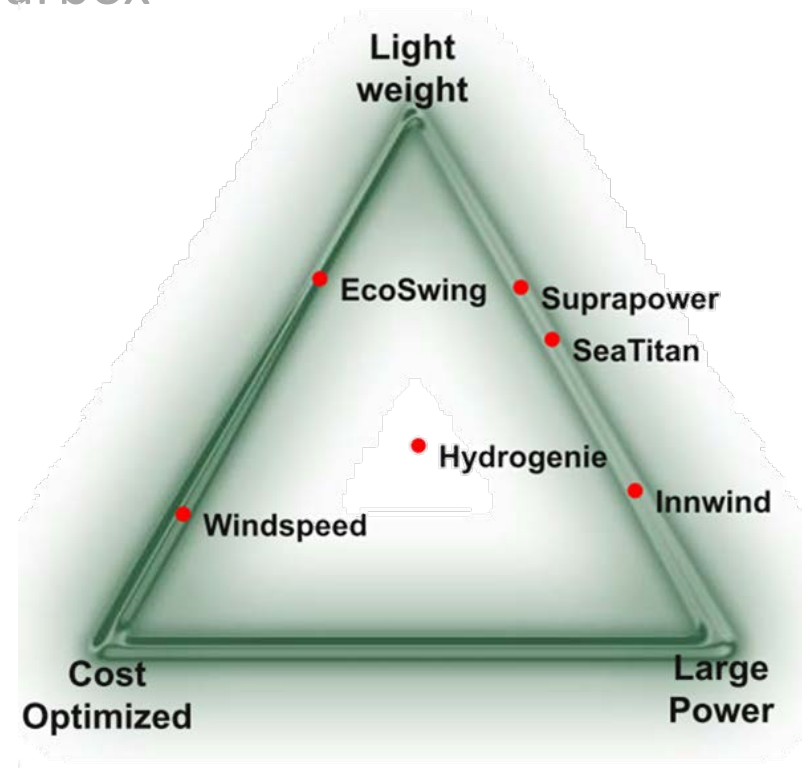
AML 10 MW fully SC



[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



- 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



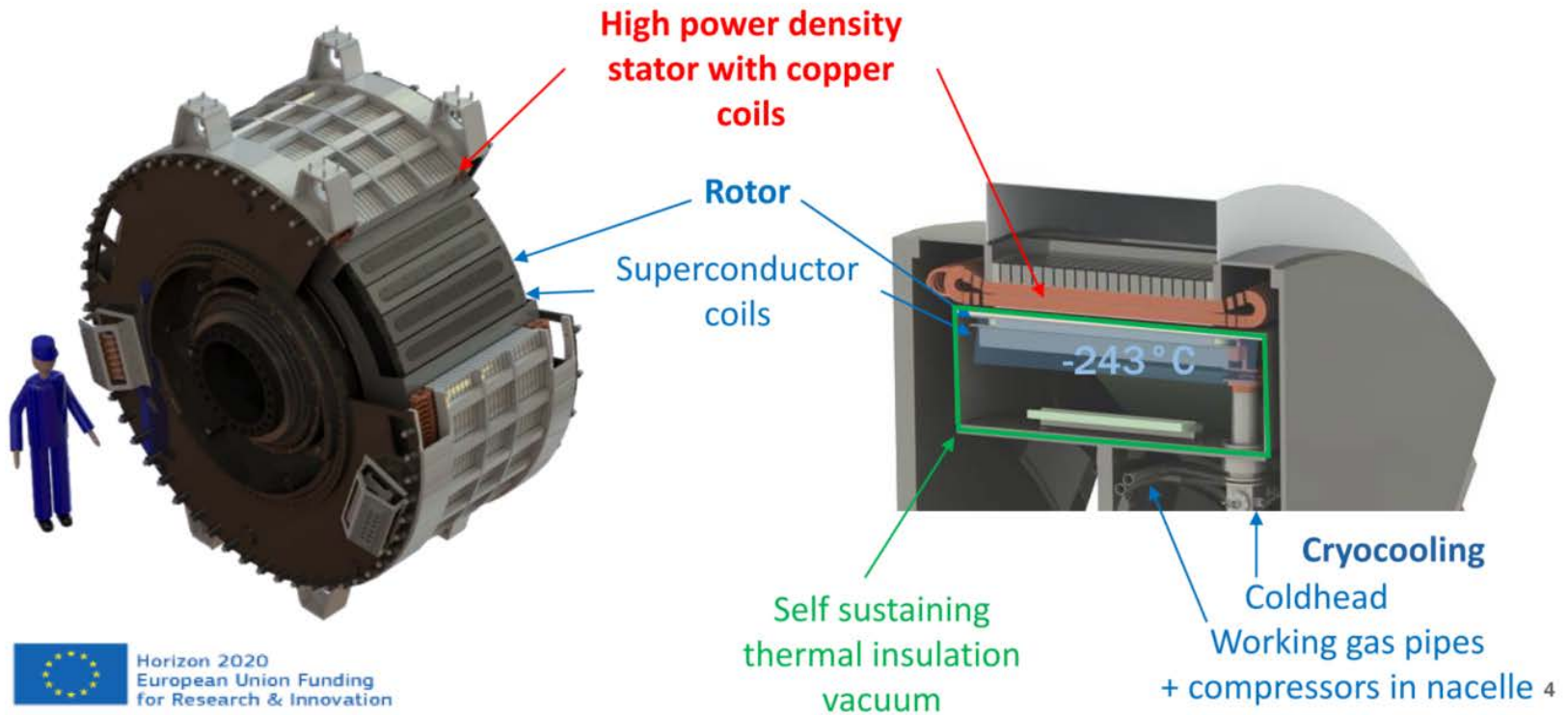
UNIVERSITY OF TWENTE.



Horizon 2020
European Union Funding
for Research & Innovation

EcoSwing

Elements of the EcoSwing superconductive generator



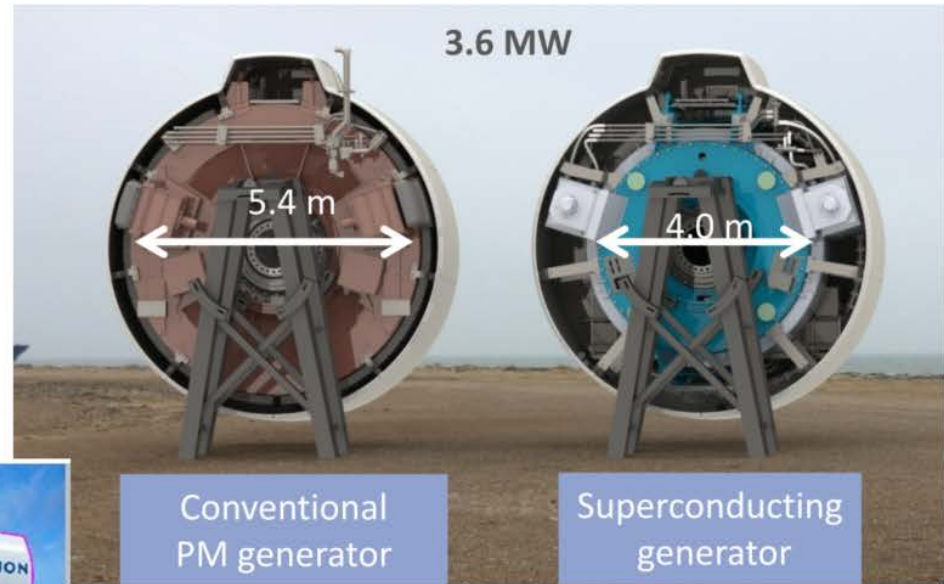
[1] M. Bauer, "Superconducting generators for wind power, EcoSwing generator and outlook," *COST ACTION 19108 Hi-Scale first joint WG3/4 industry-academia workshop on applications for HTS technologies in the electrical energy chain*, [online], Apr. 2021.

EcoSwing

EcoSwing design



- Decreased diameter from 5.4 m (PM generator) to 4 m
- Built **EcoSwing generator**: **25 % weight reduction** compared to PM generator of same diameter
- Commercial design: **40% weight reduction** compared to PM generator.



[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

Testing on ground and in turbine



At IWES,
Bremerhaven
for ground
testing



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



[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.

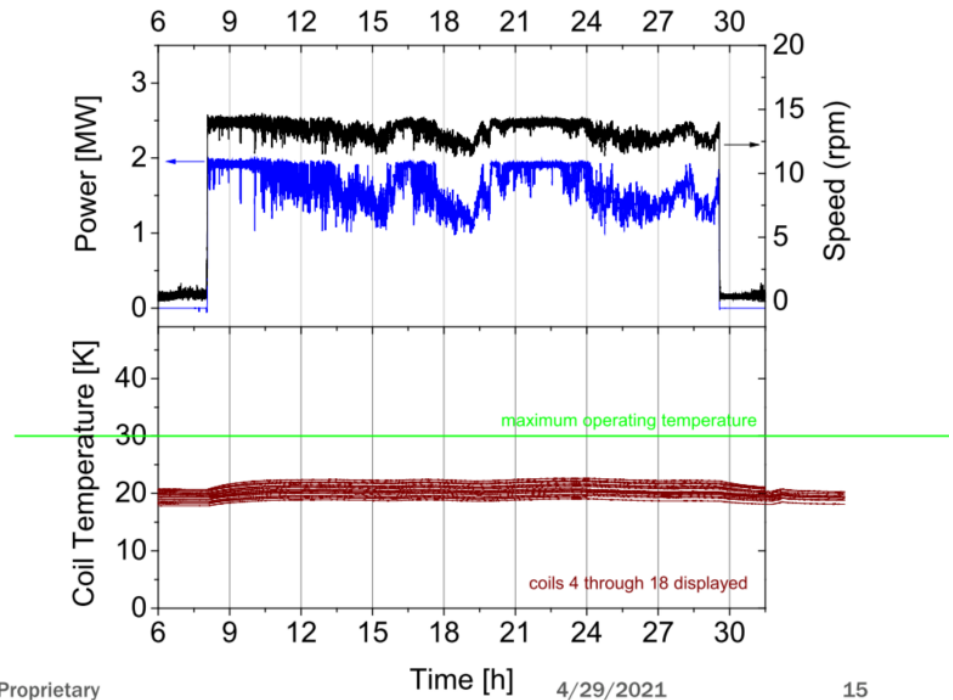
EcoSwing

Main project results



- EcoSwing 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?



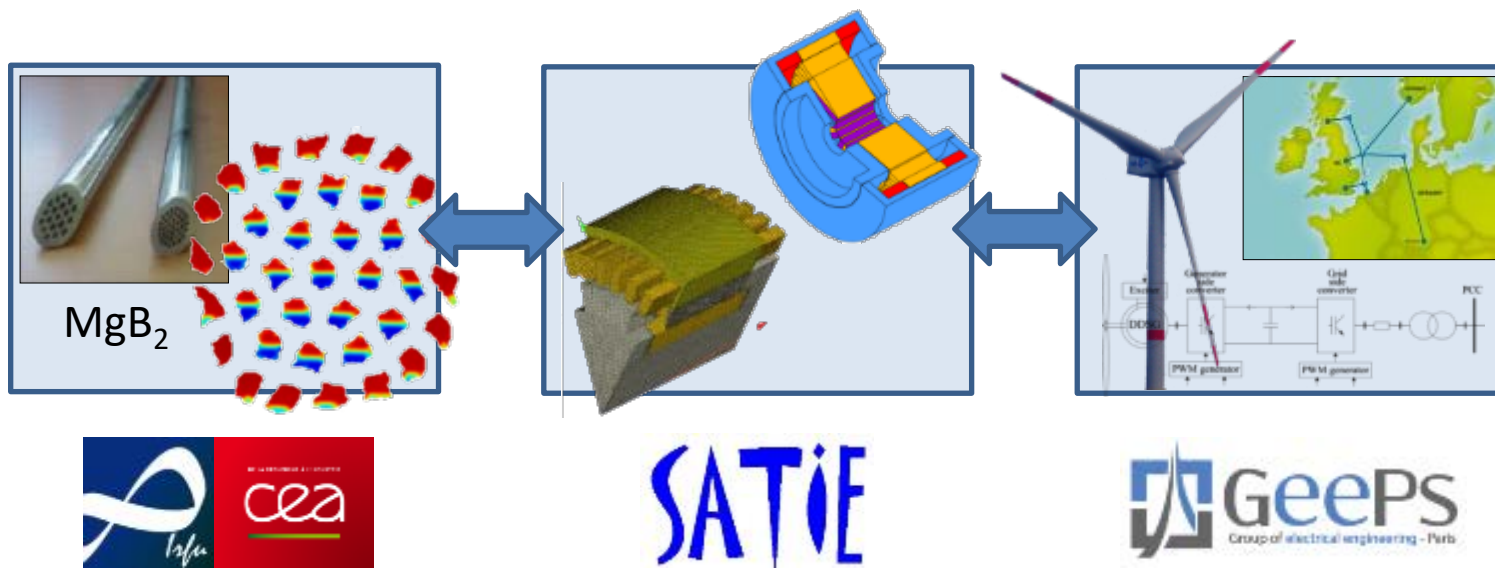
Confidential and Proprietary

15

[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

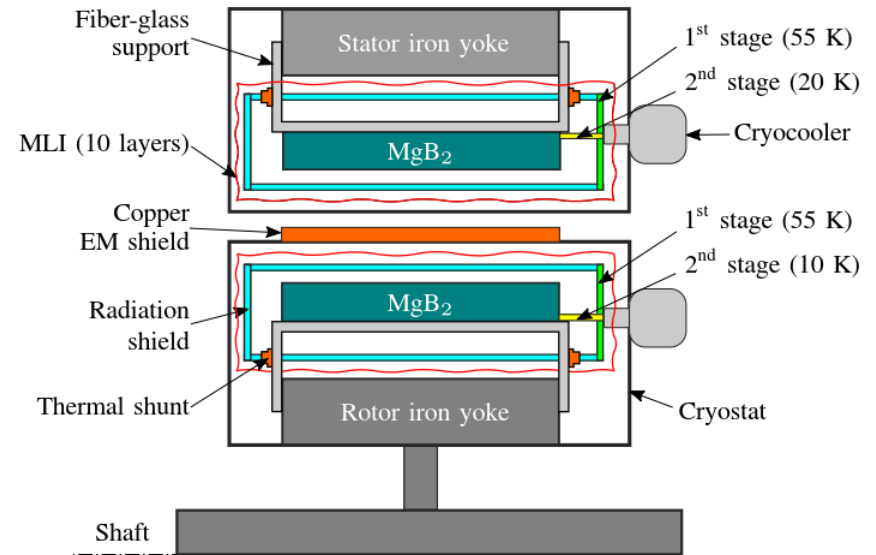
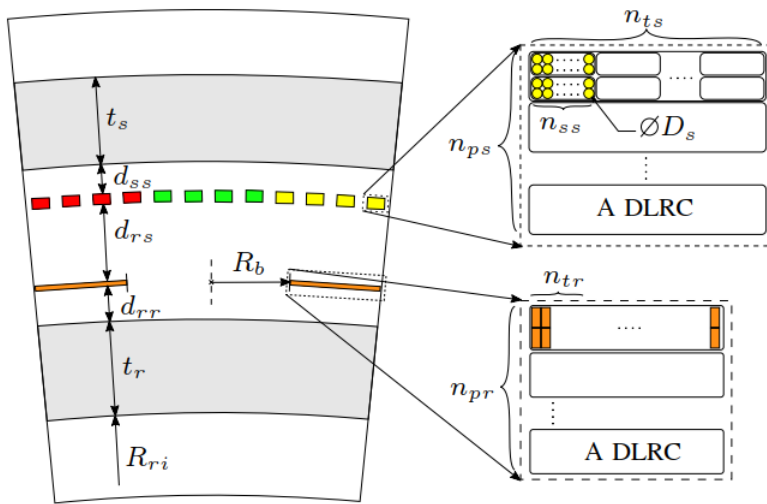


Fig. 1 - EolSupra20 electromagnetic design

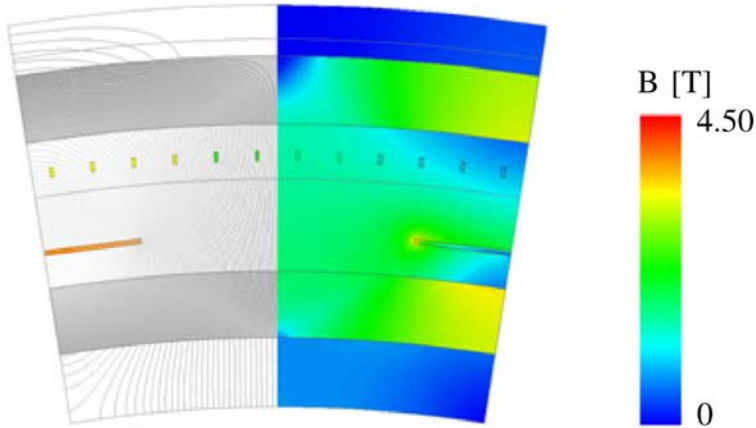
Fig. 2 - EolSupra20 cryogenic design

[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.

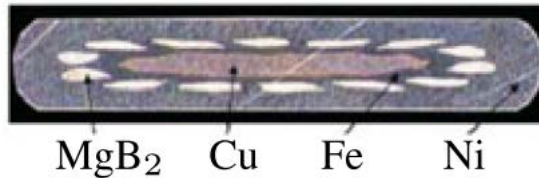
[2] T.-K. Hoang, L. Quéval, C. Berriaud, L. Vido, "Design of a 20 MW fully superconducting wind turbine generator to minimize the levelized cost of energy," *IEEE Transactions on Applied Superconductivity*, vol. 28, no. 4, pp. 1-4, June 2018.

EolSupra20

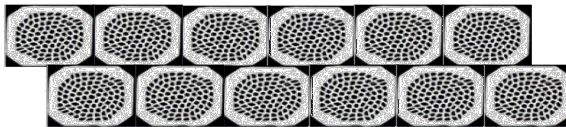
EolSupra20 2018 base design



Rotor:



Stator:



Description	Value
Rotor winding	
MgB ₂ 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	
MgB ₂ 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

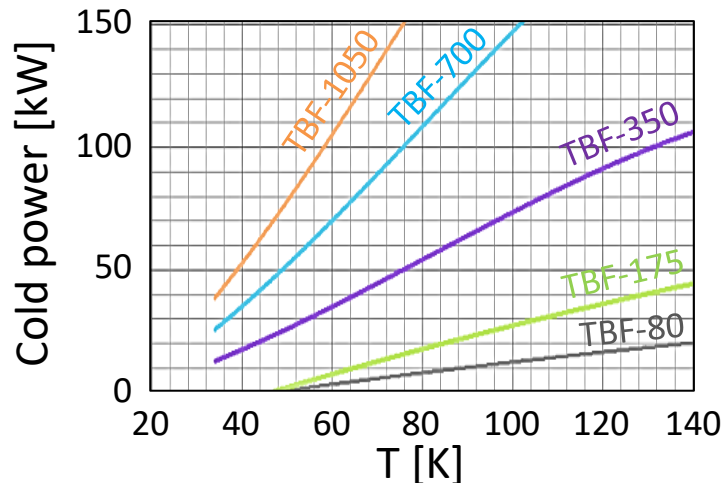
[1] T.-K. Hoang, L. Quéval, C. Berriaud, L. Vido, "Design of a 20 MW fully superconducting wind turbine generator to minimize the levelized cost of energy," *IEEE Transactions on Applied Superconductivity*, vol. 28, no. 4, pp. 1-4, June 2018.

EolSupra20

EolSupra20 2018 base design



Air Liquide Turbo-Brayton TBF-80

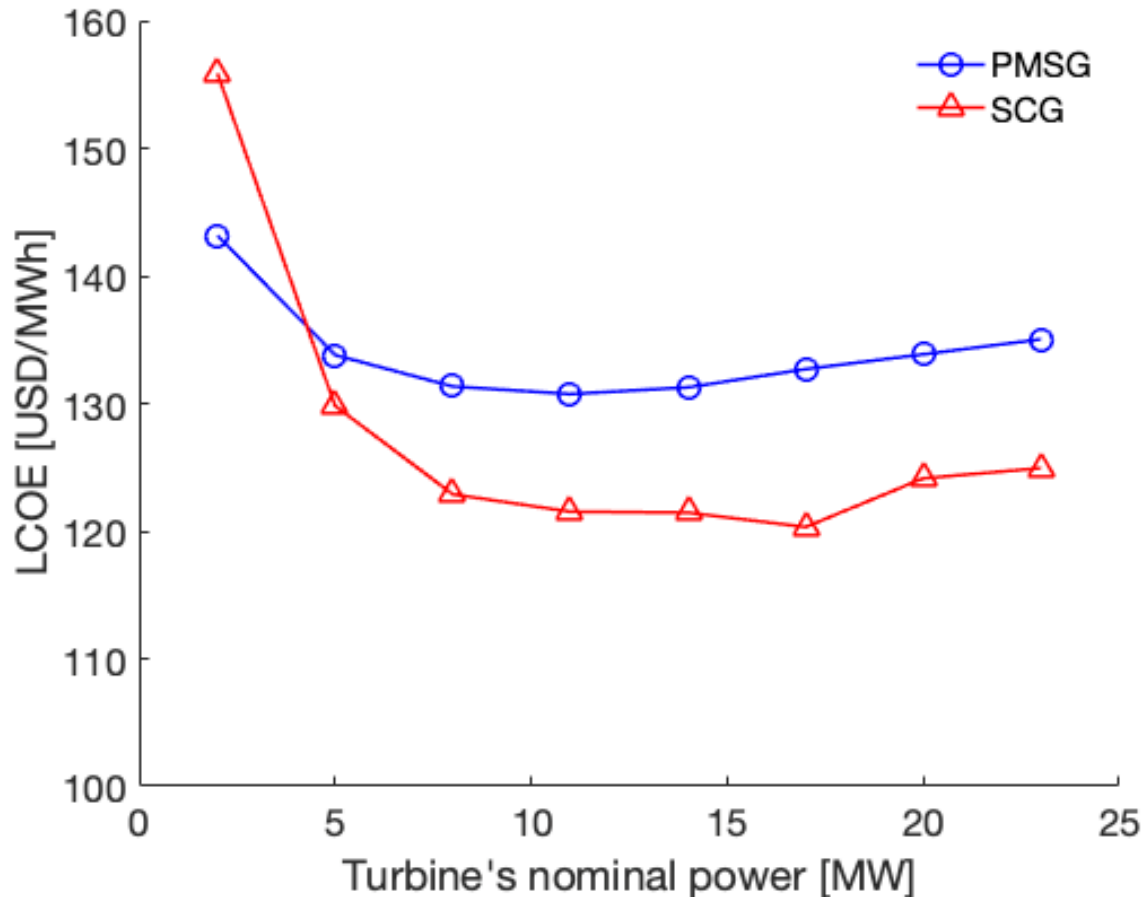


Description	Value
Rotor winding	
MgB2 conductor length [km]	37
Current density in filaments [A/mm ²]	2276/3294
Max. magnetic flux density [T]	4.01
First stage (55 K) losses [W]	268
Second stage (10 K) losses [W]	37
Nb of cryocoolers [-]	8
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Economics	
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

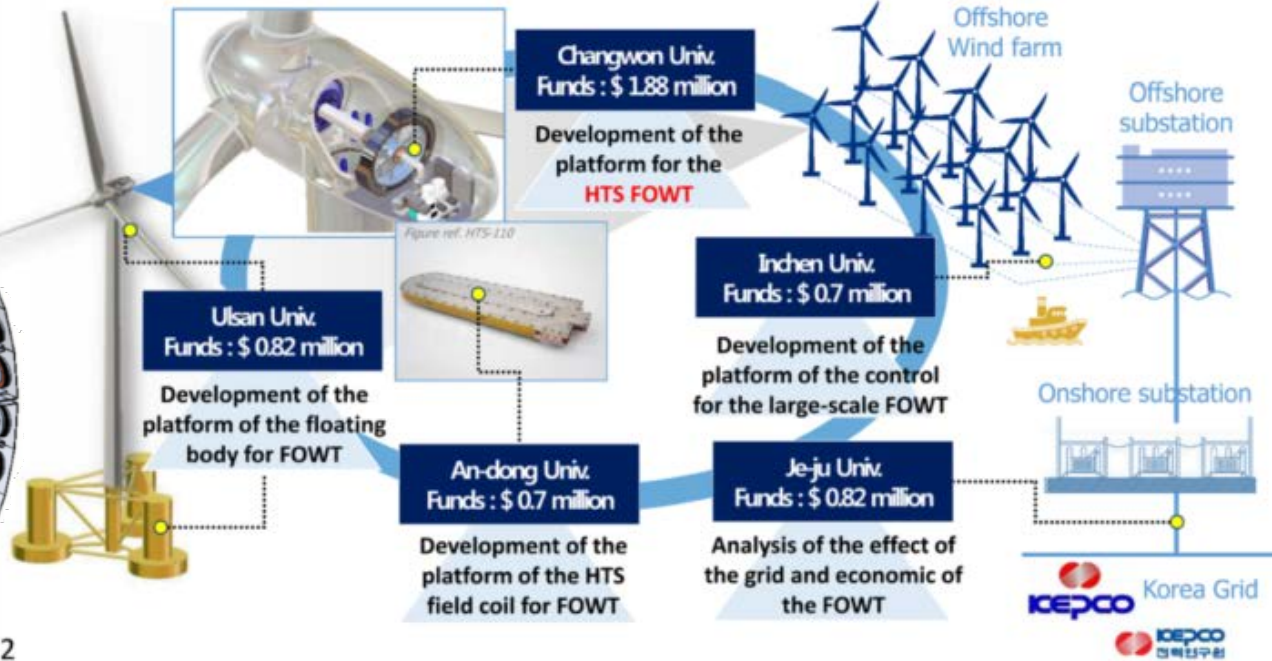
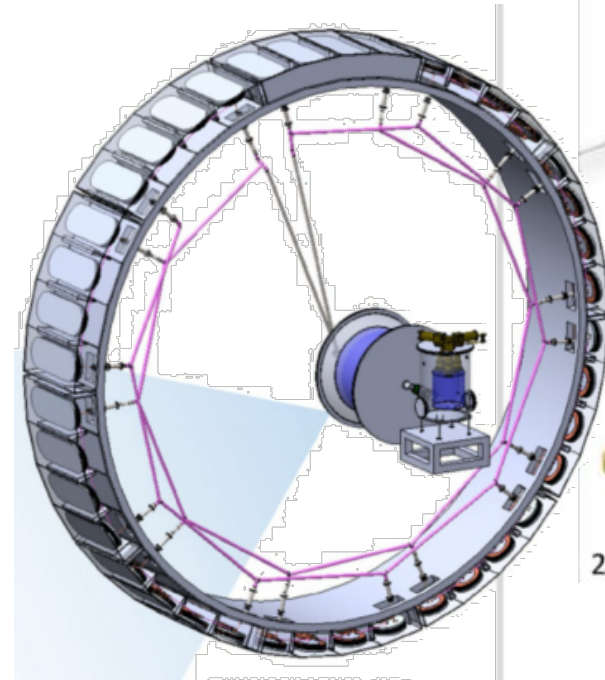
I. Overview of the E-cluster

에너지신기술 Cluster

기초연구 과업, 기초전략연구센터가 앞장서겠습니다.

Final target: Development of basic technology for floating offshore wind power platform based on 10MW HTS wind power generator

10 MW generator



2

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.



Geeps

Electrical Engineering - Paris

Merci !





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.