

# EolSupra20

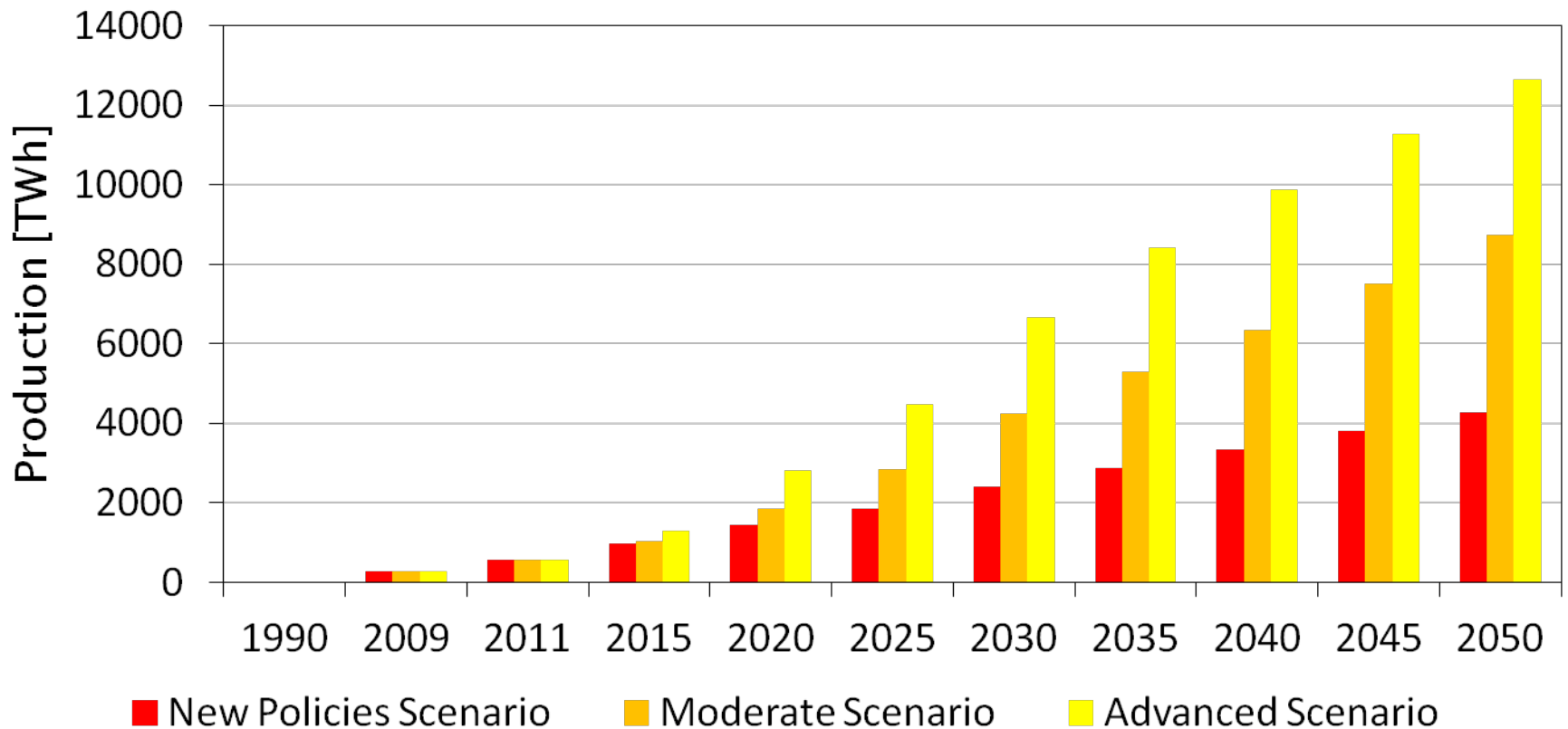
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## Current status & perspectives

L. Quéval, L. Vido, C. Berriaud

# I. Motivation

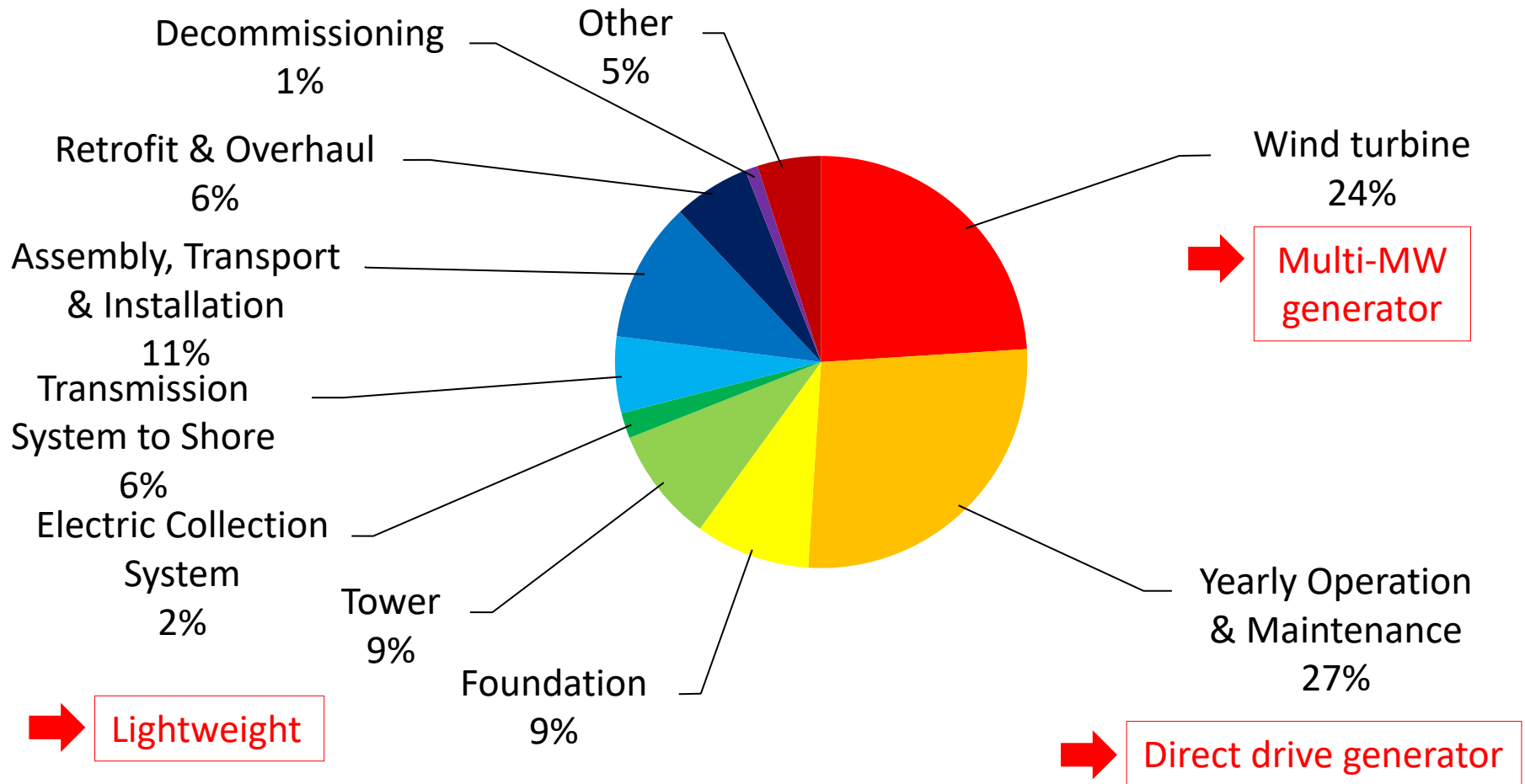
# Challenge: wind energy production



[1] adapted from "World energy outlook 2011," IEA, 2011.

[2] adapted from "Global wind energy outlook 2012," GWEC, 2012.

# Lifecycle cost breakdown of offshore windfarm



[1] adapted from S.A. Herman, "DOWEC cost model, Implementation, DOWEC-068," DOWEC project, 2003.

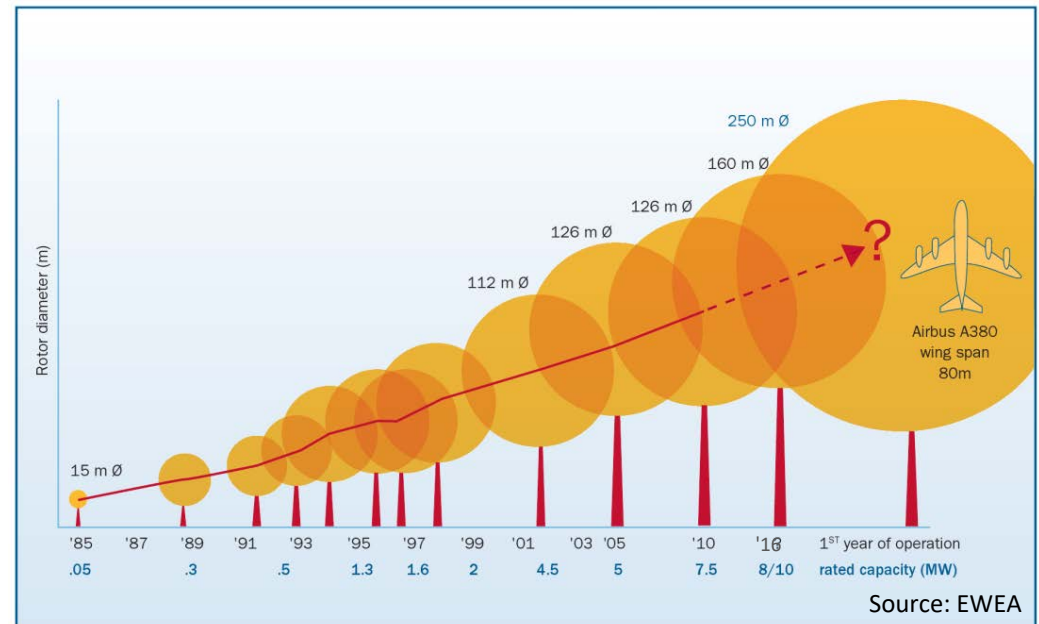


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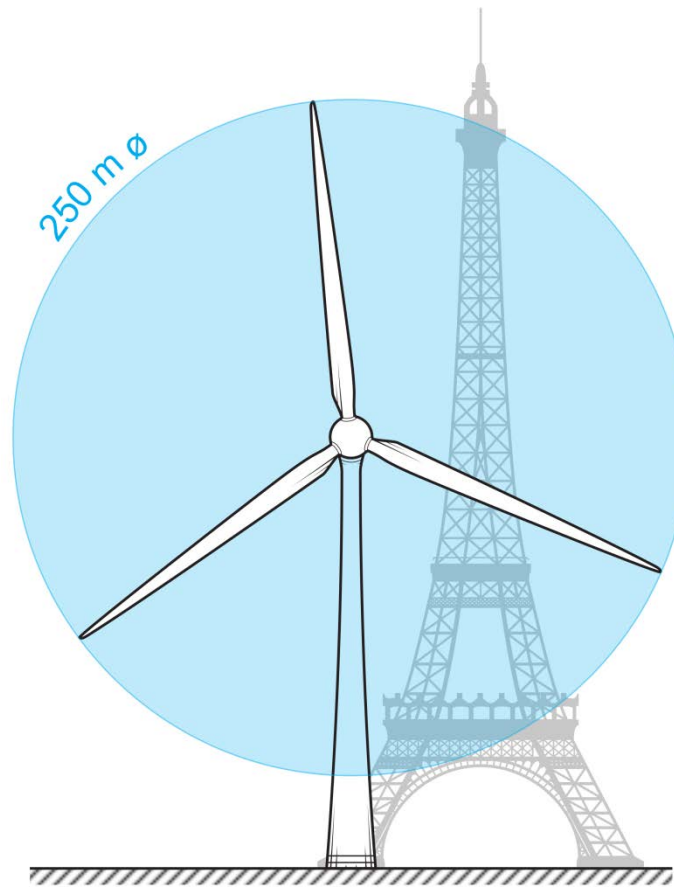


World's largest wind turbine generator

Haliade-X from GE  
12 MW

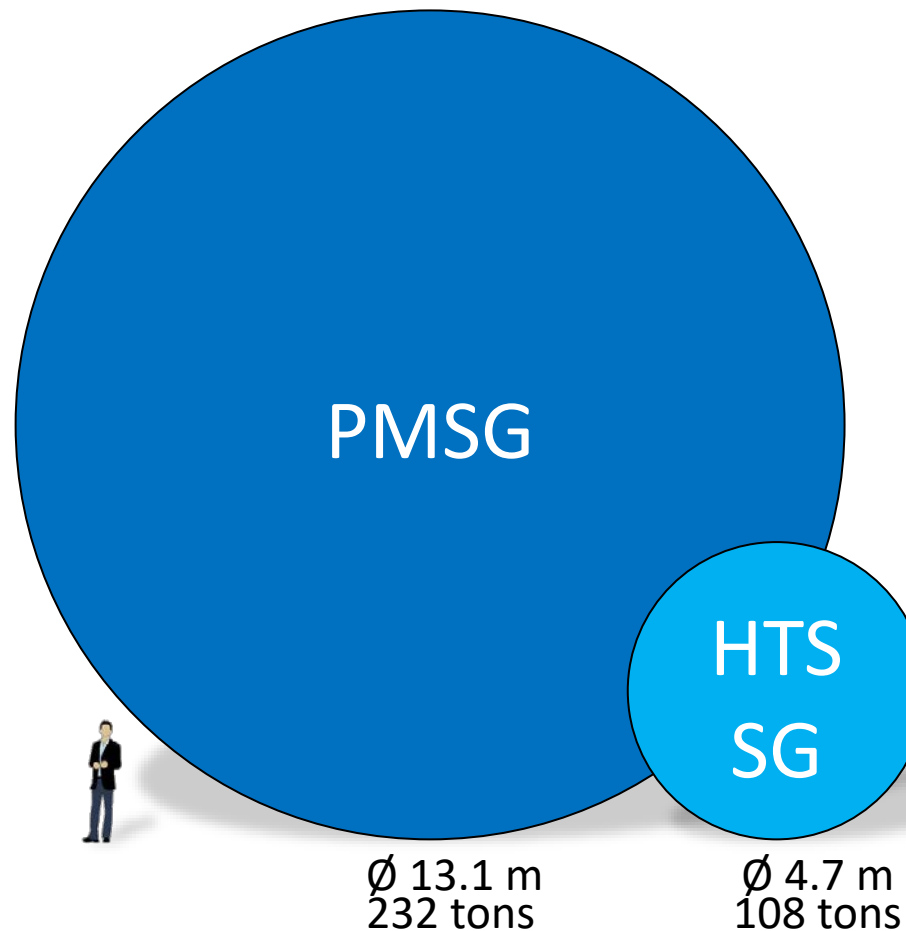


# Towards 20 MW offshore wind turbines



[1] R. Bos, W. Bierbooms, "Extreme gust loads for novel wind turbines," EAWC 9th seminar on Wind Energy, Delft University of Technology, 2013.

# Comparison 10 MW direct-drive 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](http://www.lqueval.com)

## III. Past projects



# Founding article

IOP PUBLISHING

SUPERCONDUCTOR SCIENCE AND TECHNOLOGY

Supercond. Sci. Technol. **23** (2010) 034019 (8pp)

doi:10.1088/0953-2048/23/3/034019

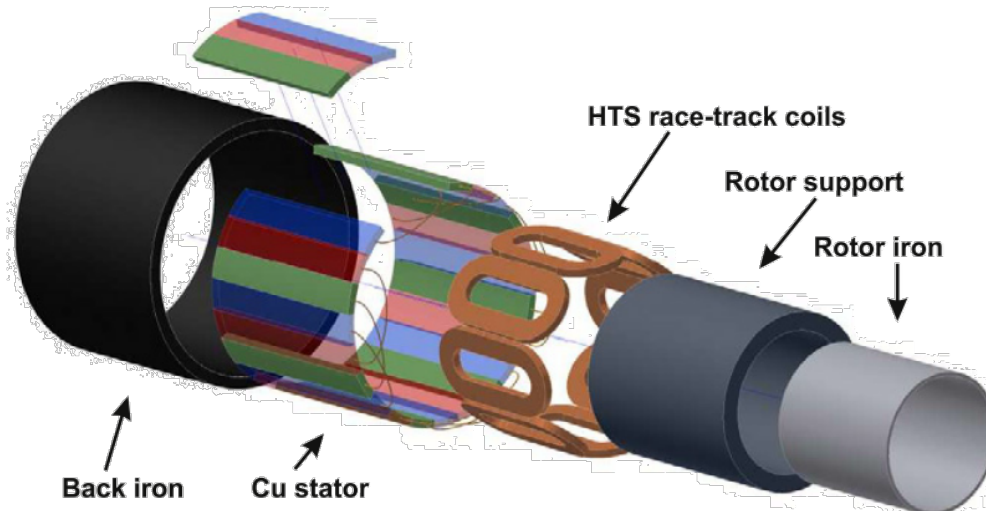
# Superconducting wind turbine generators

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

<sup>1</sup> Materials Research Division, Risø-DTU, Frederiksborgvej 399, 4000 Roskilde, Denmark

<sup>2</sup> Department of Electrical Engineering, Technical University of Denmark, DK-2800 Lyngby, Denmark

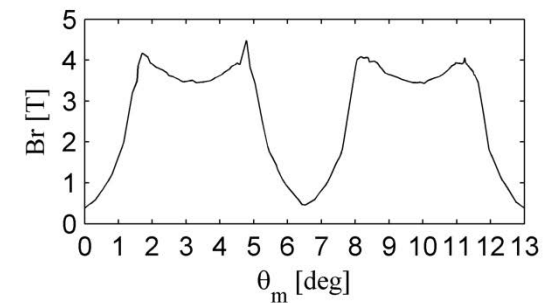
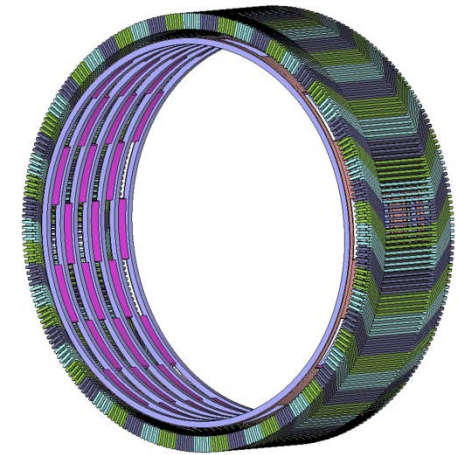
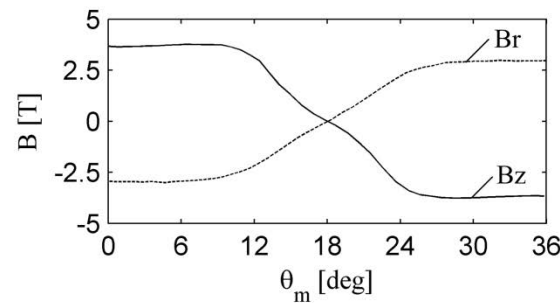
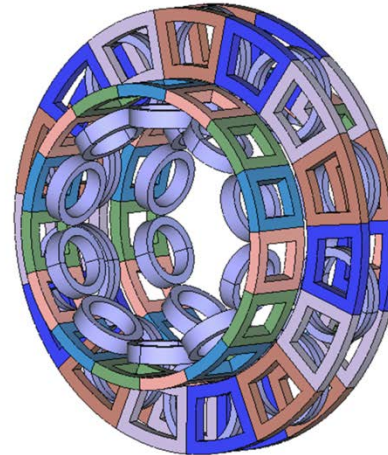
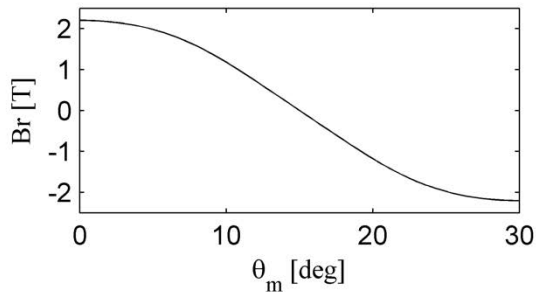
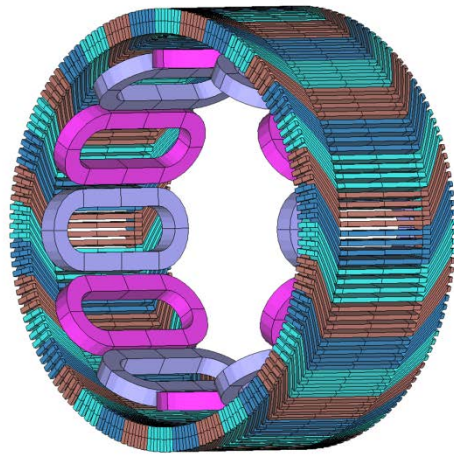
<sup>3</sup> Wind Energy Division, Risø-DTU, Frederiksborgvej 399, 4000 Roskilde, Denmark



**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 $\tau_T$ ( $10^6$ 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 $J_e$ ( $A\ m^{-2}$ )	$6.3 \times 10^7$
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)

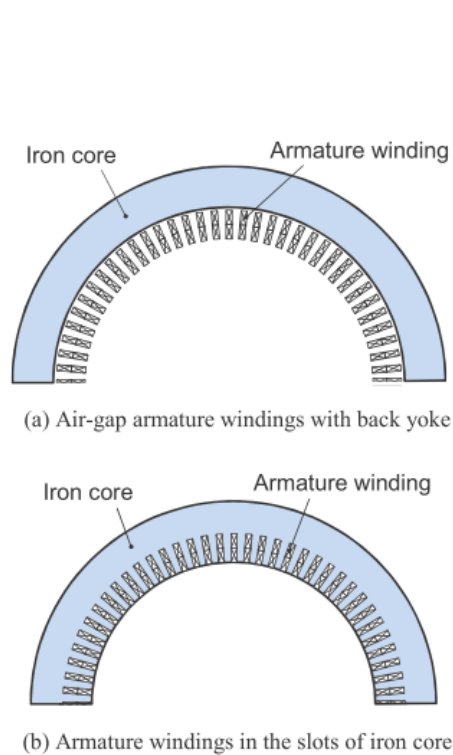


Fig. 4 Fundamental stator structures with armature windings.

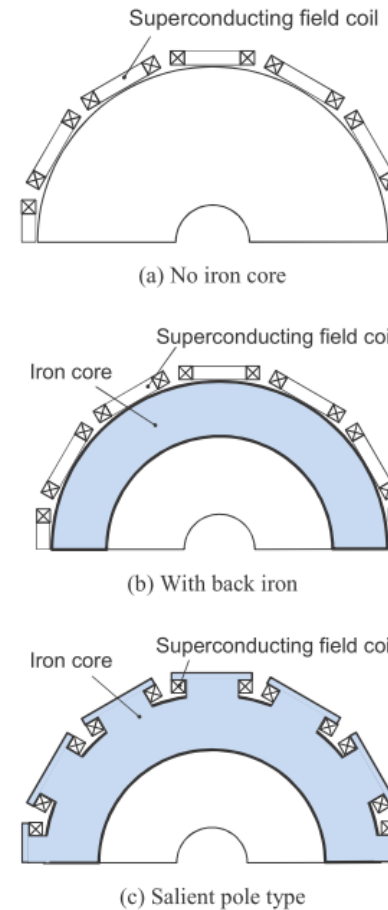


Fig. 5 Fundamental rotor structures with superconducting field coils.

[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

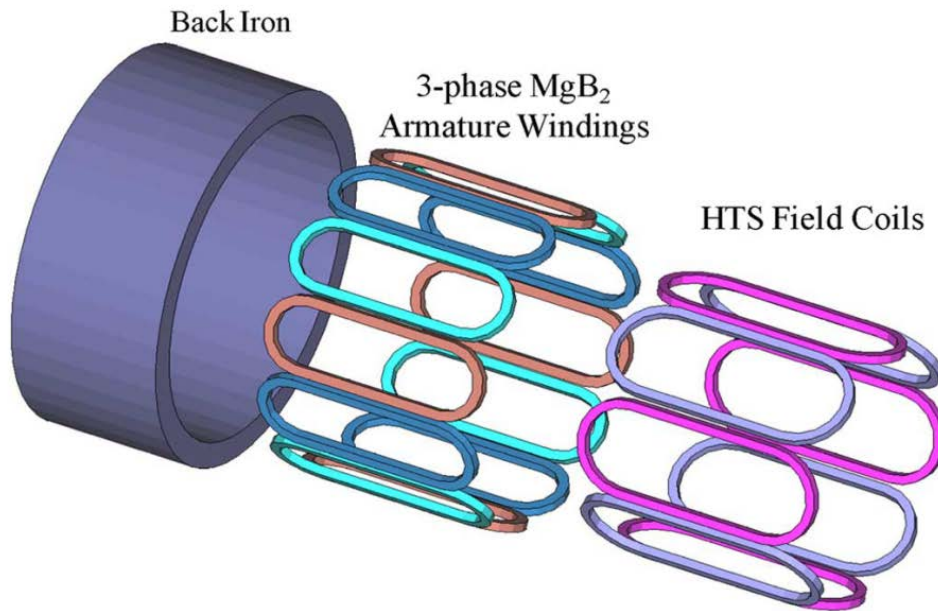


Fig. 1. Illustration of fully superconducting wind turbine generator.

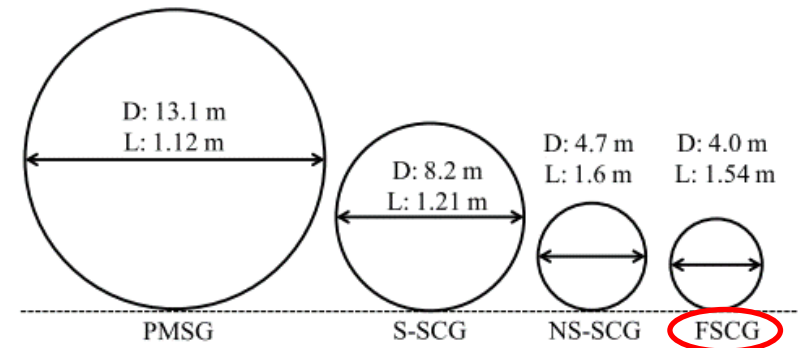


Fig. 7-1. Comparison of four wind turbine generator sizes

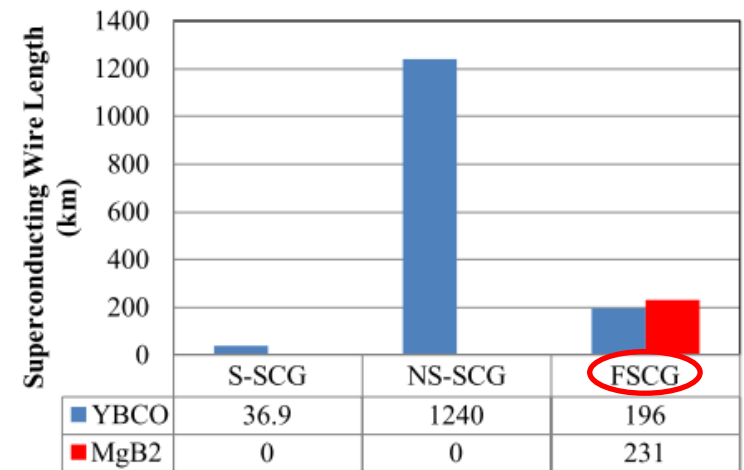


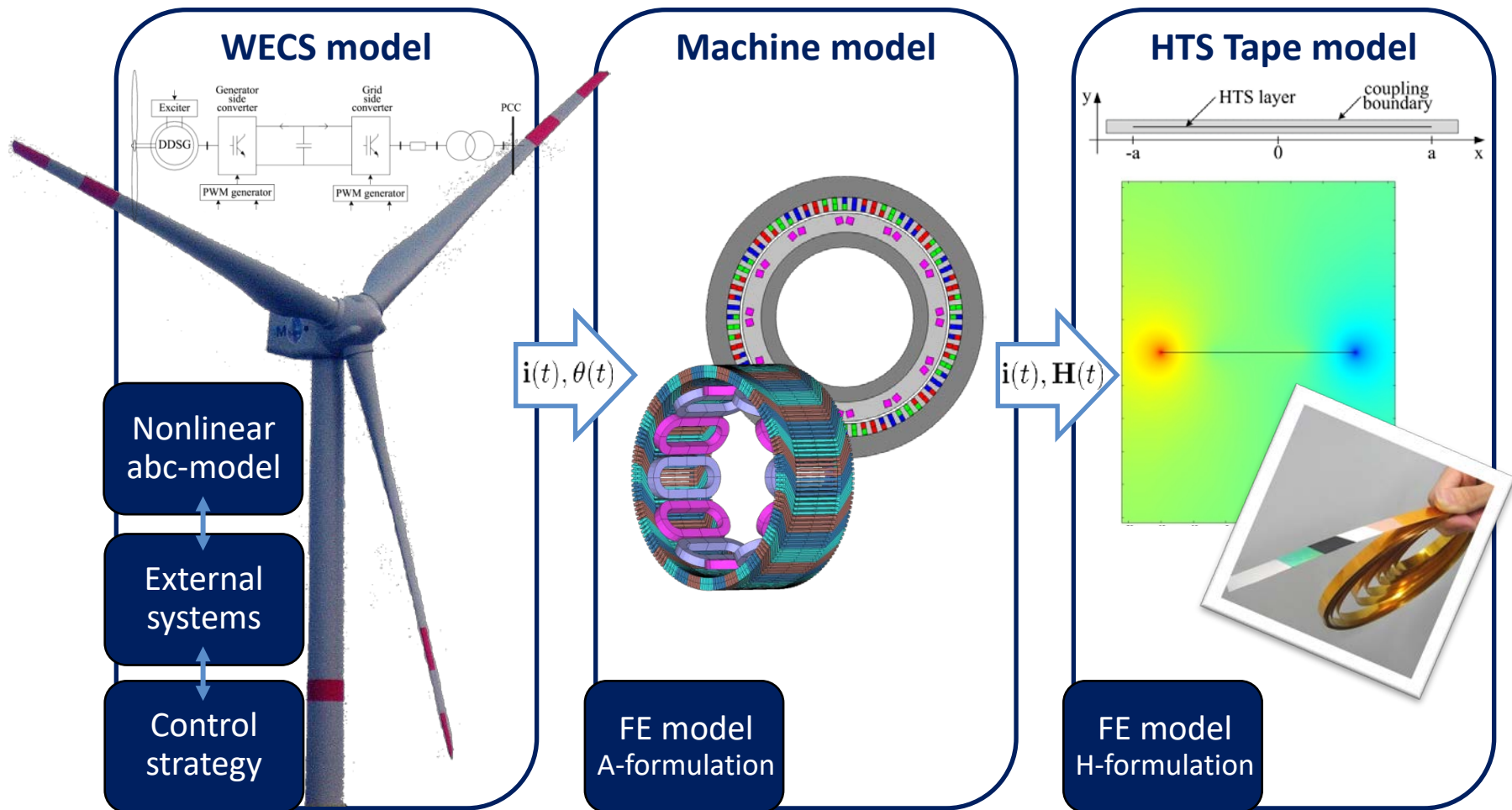
Fig. 7-2 Length of superconducting wires

[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.

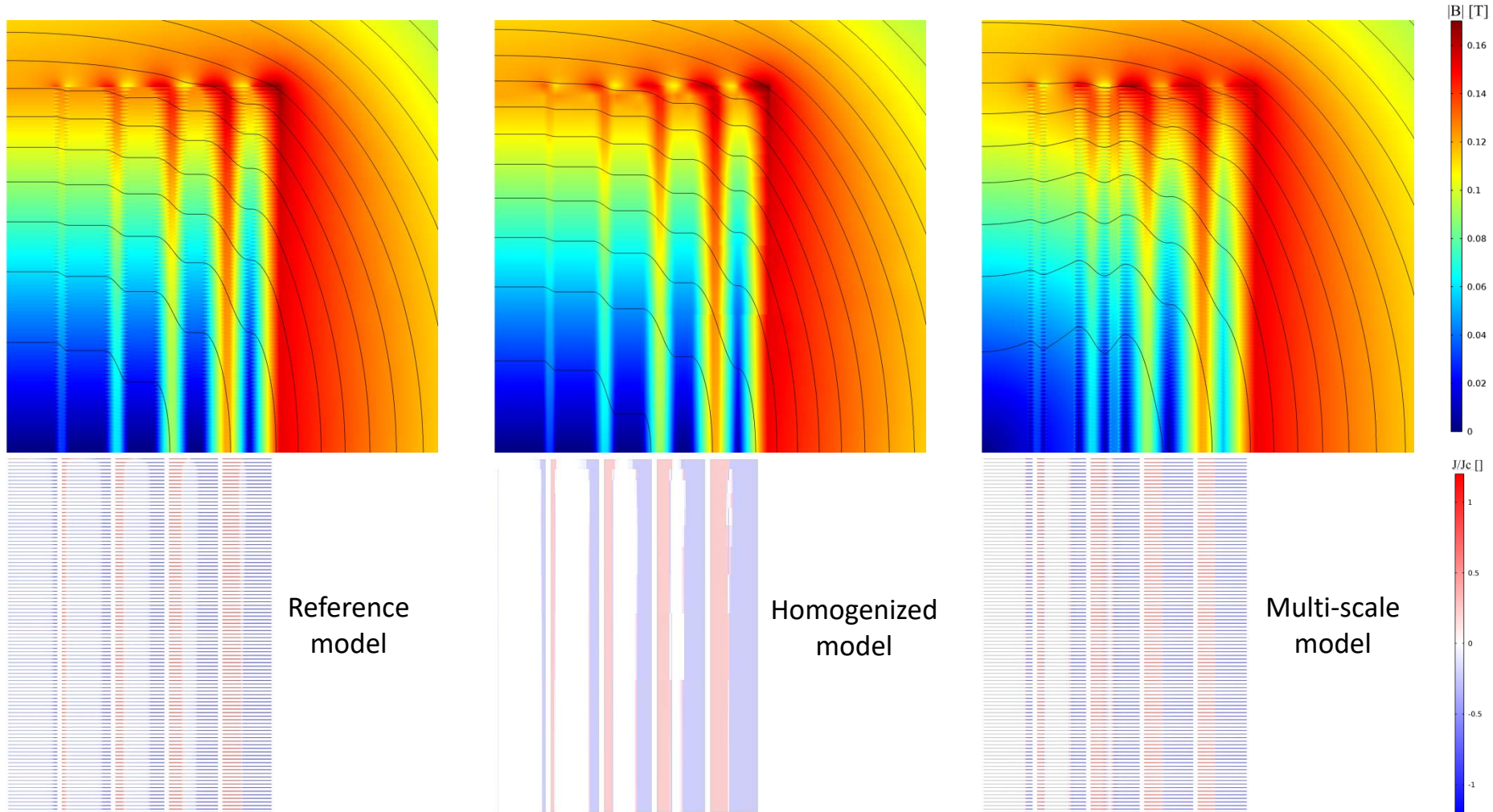


# Simulation of grid-connected SC WT generators



- [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.

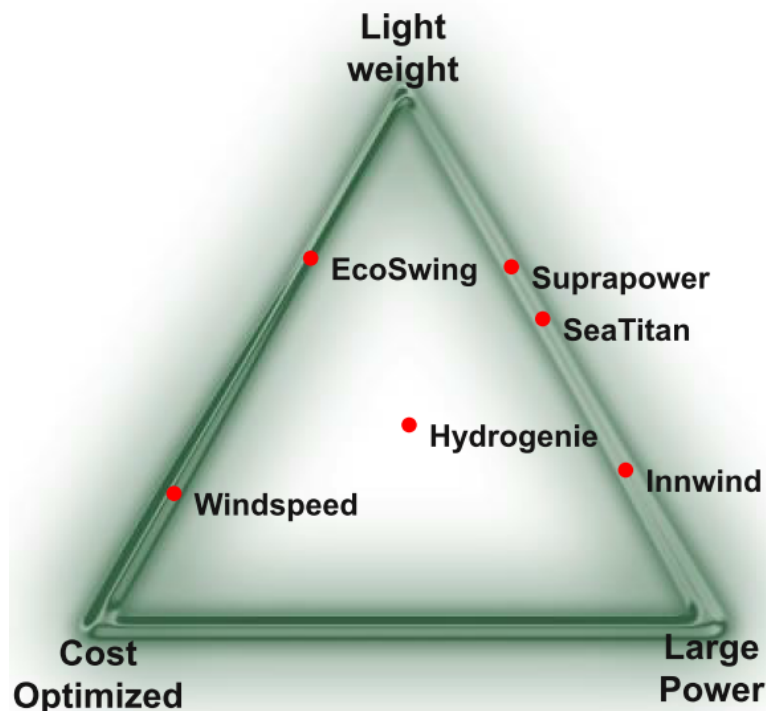
# Numerical models for large superconducting coils



[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.

## III. Commercial concepts (>1 MW)

## Review of Activities in Superconducting Generators



- Focus mostly on European activities and sort by ambition
  - *Hydrogenie* (Converteam/GE )
    - 2 MW fully tested, 8MW, 10 MW planned
  - *Innwind* 10...20 MW DD (Siemens)
    - Components demonstrated, CoE comparison @ EWEA
    - Comparing HTS to PM and to pseudo DD
  - *SeaTitan* 10 MW DD (AMSC)
    - Design complete, hardware de-risking complete
  - *Suprapower*, 10 MW DD (Tecnalia, ex Acciona)
    - Design complete, hardware in progress
- Trend is a bit towards *lower* power rating (as price of superconductors comes down).
  - *Windspeed*. 3.5 MW DD (ECO 5)
    - Design basics published
  - ***EcoSwing*, 3.6 MW DD**
    - Plans to be first on a turbine



## Development in USA

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

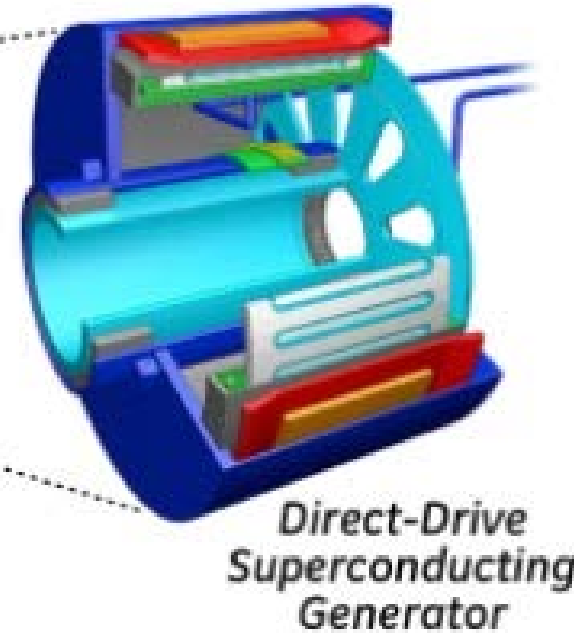
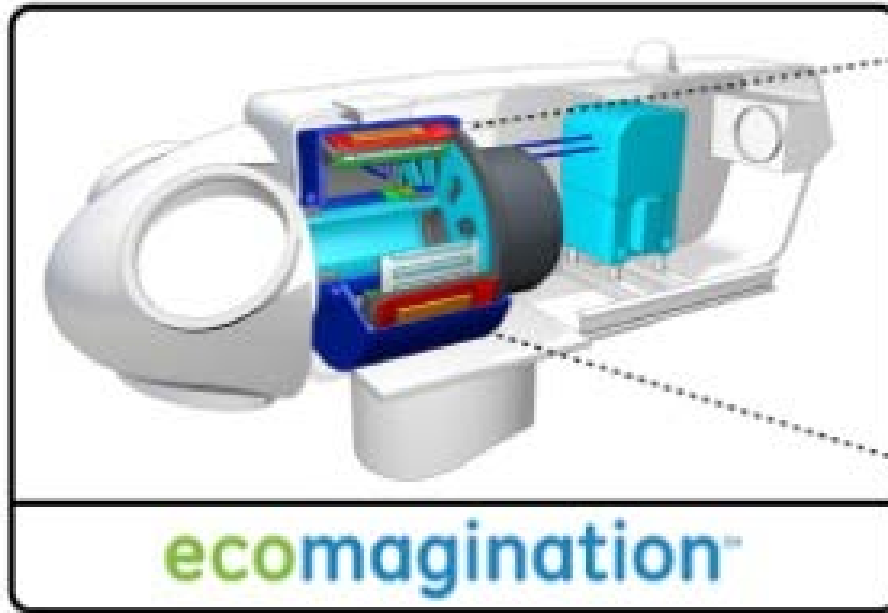
- [July 2019] DOE selected projects
- Each of the selected projects received \$500,000 to design a wind turbine generator that can be scaled up to at least 10 megawatts.
- 2 projects developed superconducting generators
  - AMSC develops HTS based concept – funding stopped
  - GE develops LTS based concept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

# AMSC 10 MW Seatitan

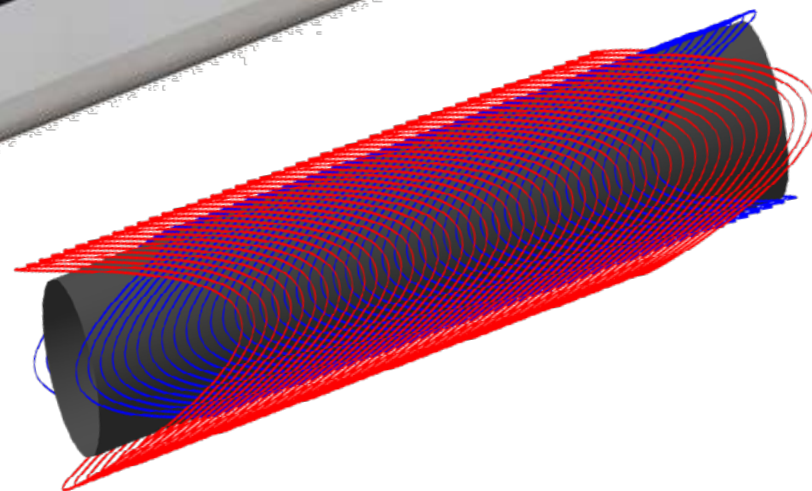


**Seatitan™**  
Powered by AMSC

# GE 10 MW Ecomagination



# AML 10 MW fully SC

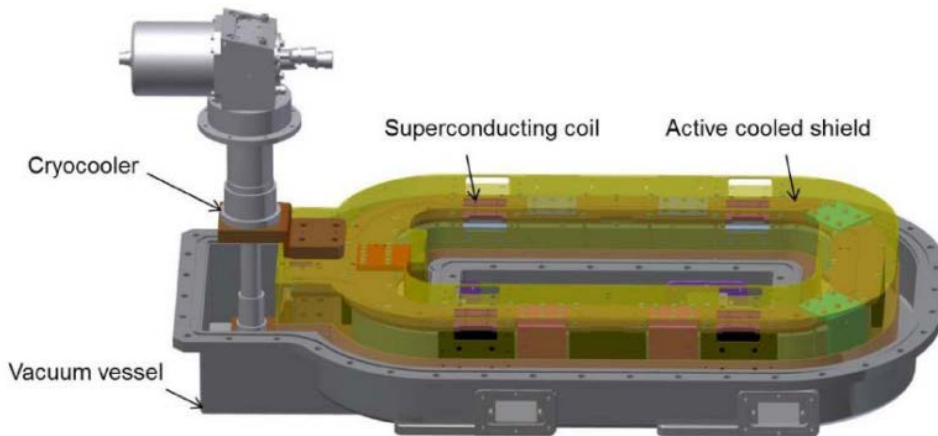


[1] L. Quéval, R. Gottkehaskamp, "Analytical field calculation of modulated double helical coils," *IEEE Transactions on Applied Superconductivity*, vol. 25, no. 6, pp. 4901307, Dec. 2015.

## Development in EU

- SUPRApower
- EcoSwing

# SUPRApower



## Project Information

### SUPRAPOWER

Grant agreement ID: 308793



Closed project

#### Start date

1 December 2012

#### End date

31 May 2017

Funded under  
FP7-ENERGY

Overall budget  
€ 5 152 069,37

EU contribution  
€ 3 891 058,46

Coordinated by  
FUNDACION TECNALIA RESEARCH & INNOVATION

Spain





# EcoSwing

## Our ambitions



Superconductivity has matured sufficiently that we can follow an ambitious plan:

- 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.

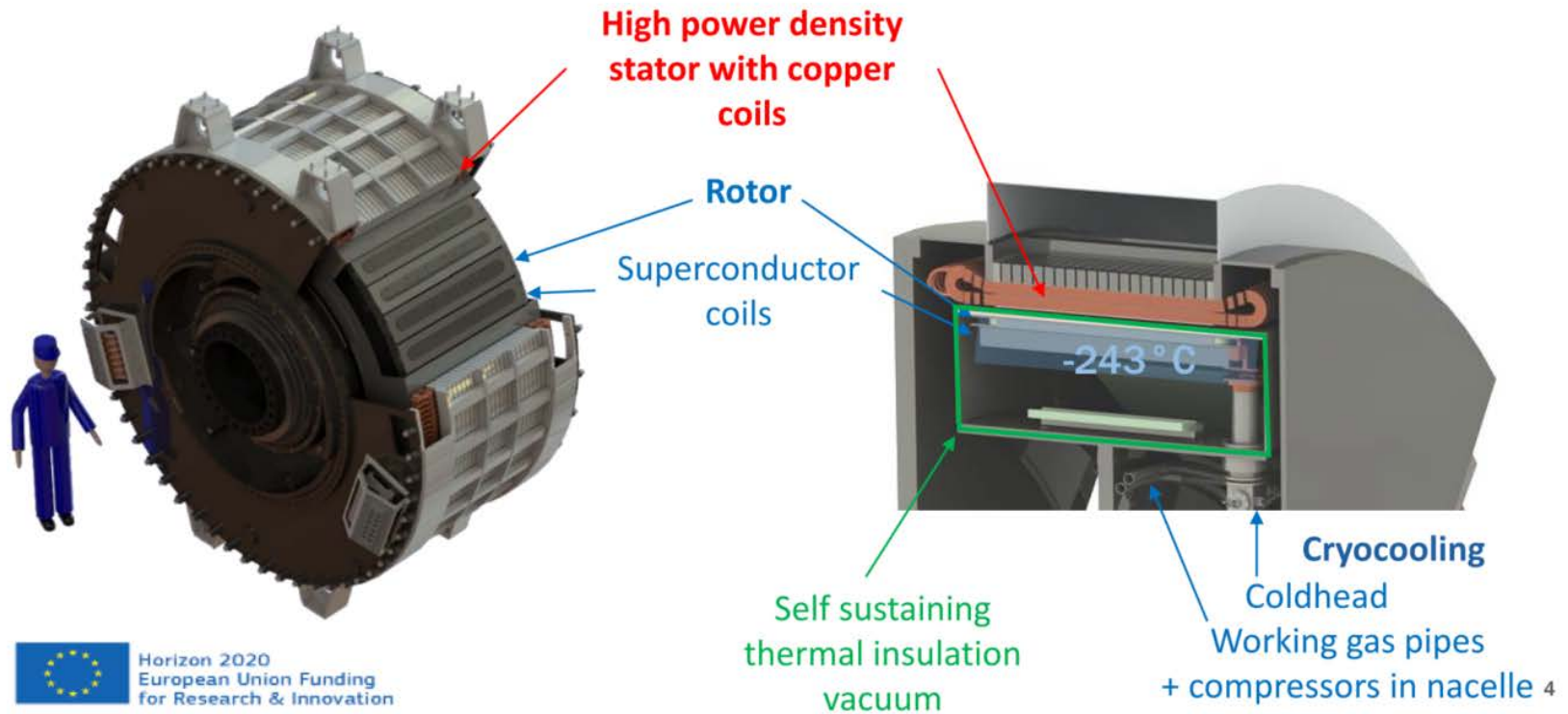
- Start Date: 2015-03-01
- End Date: 2019-04-30



[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

## 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.

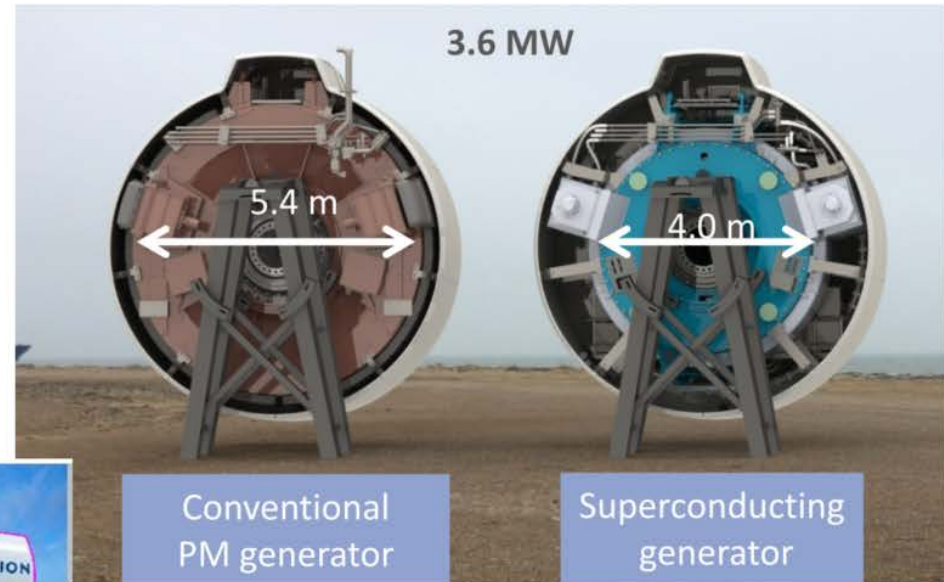


# EcoSwing

## 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.



# 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.

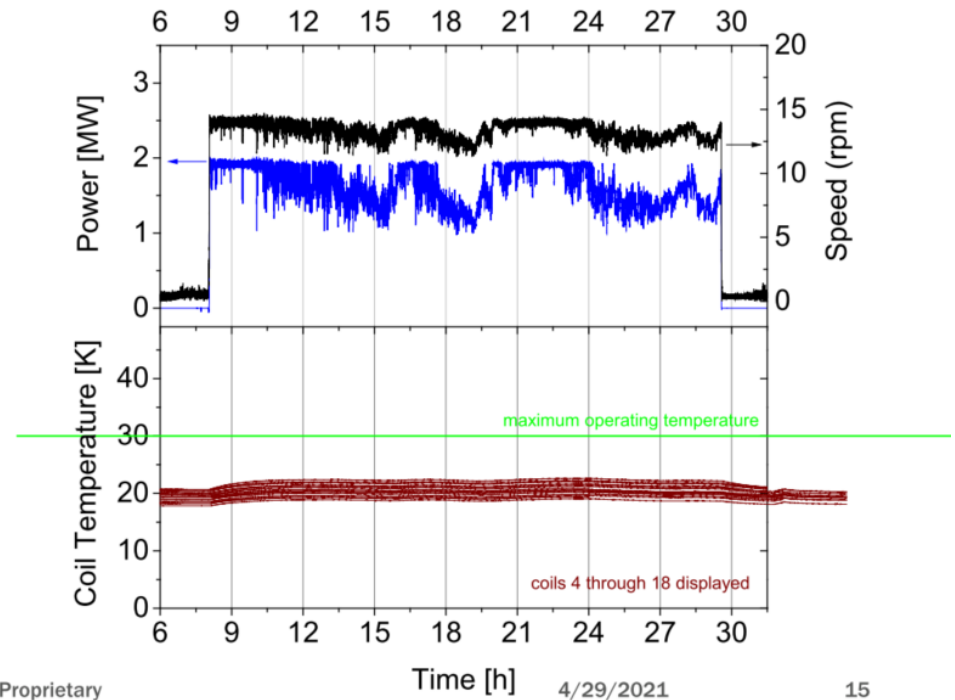
# EcoSwing

## 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?





# Development in South Korea

## I. Overview of the E-cluster

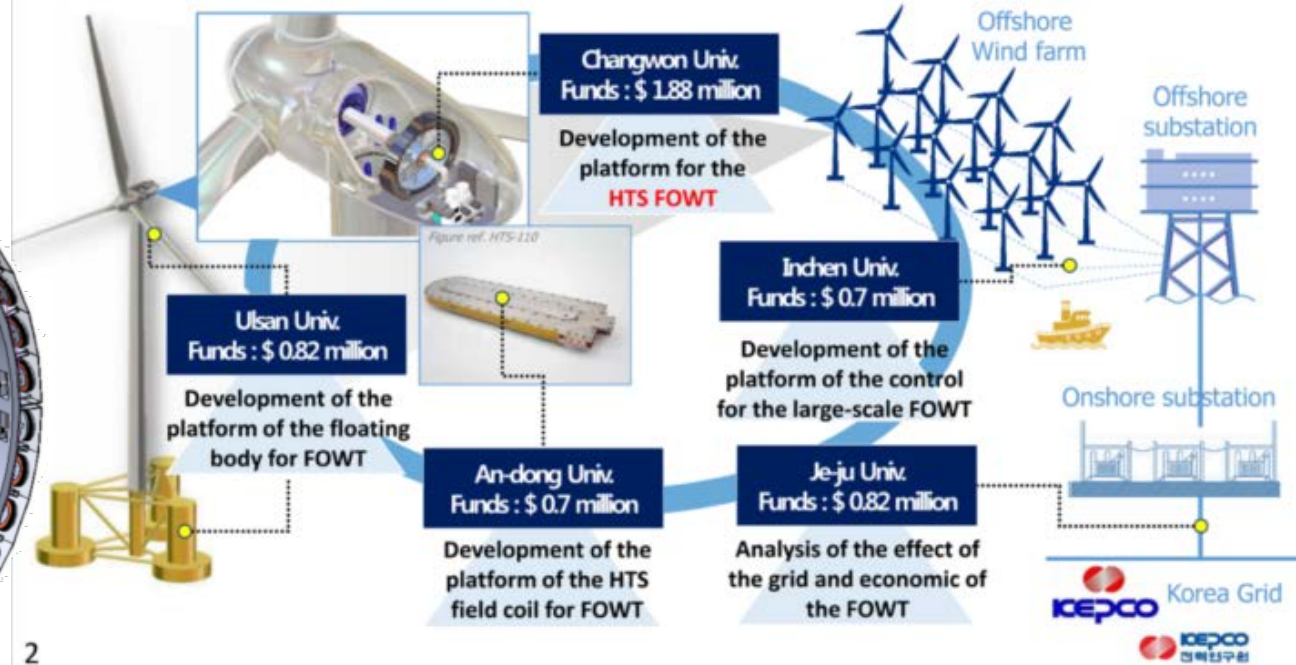
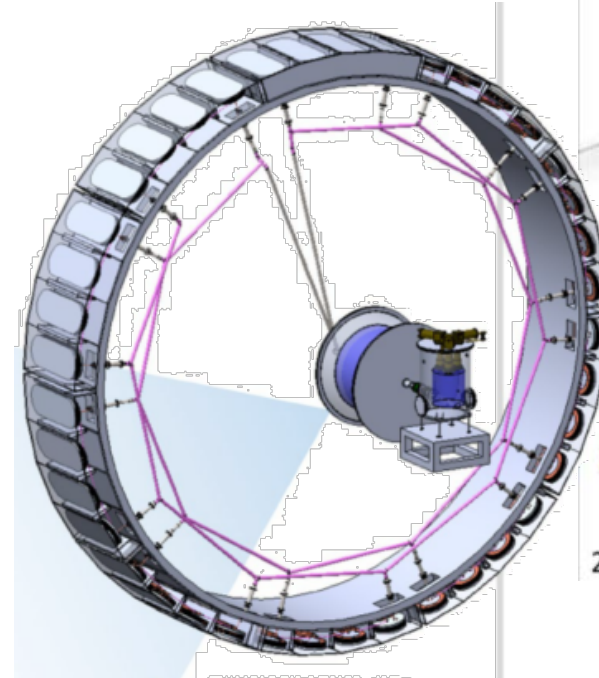
에너지신기술 Cluster

기초연구 러덤. 기초전략연구센터가 앞장서겠습니다.

Linkage of technology between participating institutions

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

10 MW generator



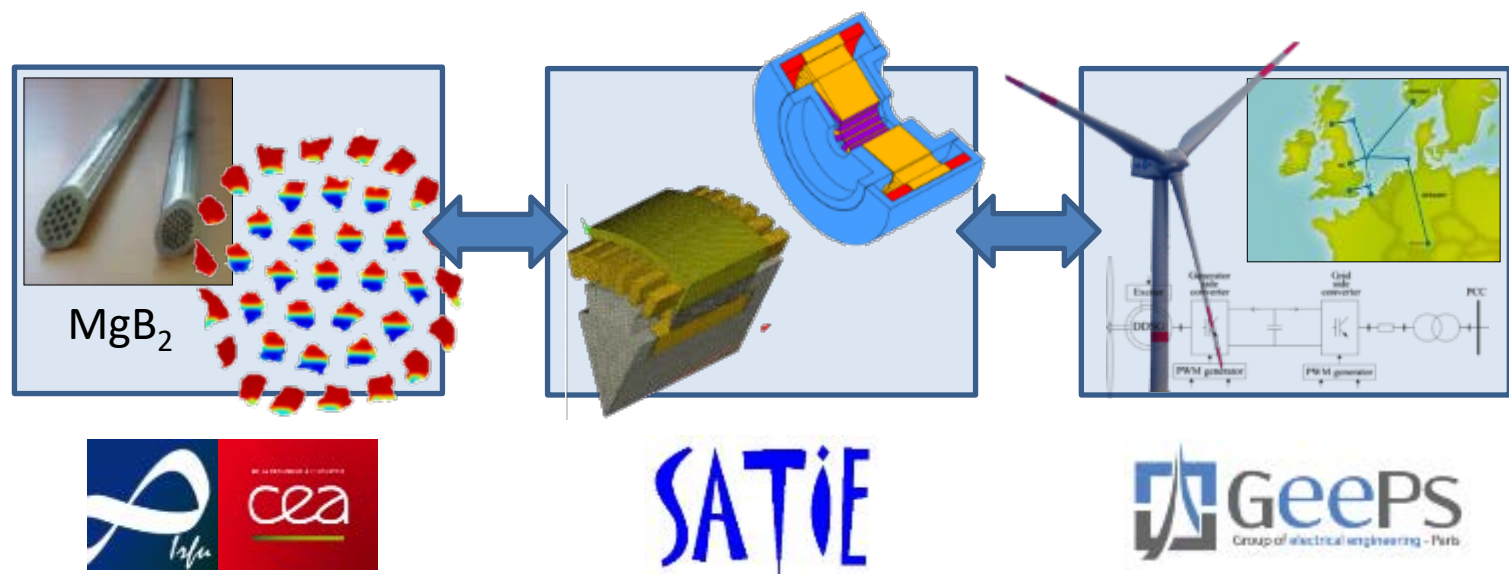
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[1] M. Bauer, "Superconducting generators for wind power, EcoSwing generator and outlook," *COST ACTION 19108 Hi-Scale first joint WG3/4 industry-academia workshop on applications for HTS technologies in the electrical energy chain*, [online], Apr.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

## IV. EolSupra20

# EolSupra20

Feasibility study of a 20 MW superconducting wind turbine generator



# IV. EolSupra20

## a) Around the generator

# EolSupra20

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

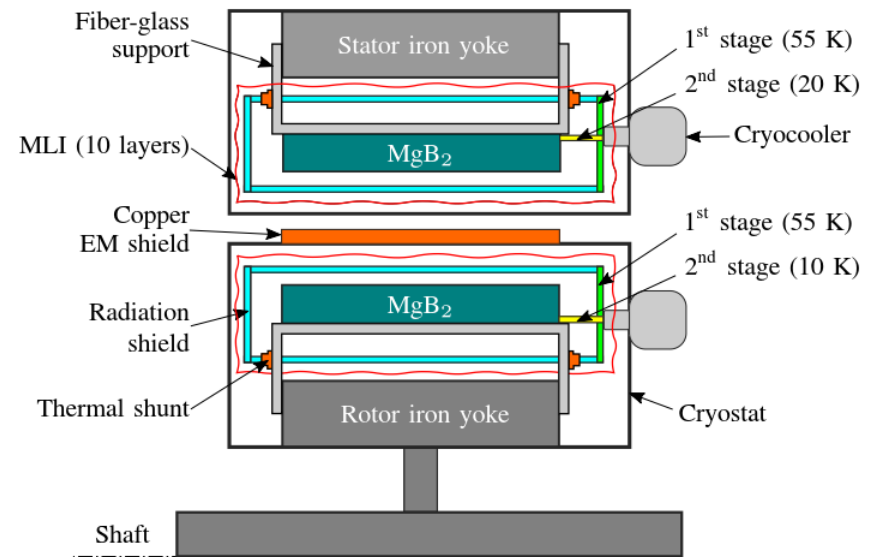
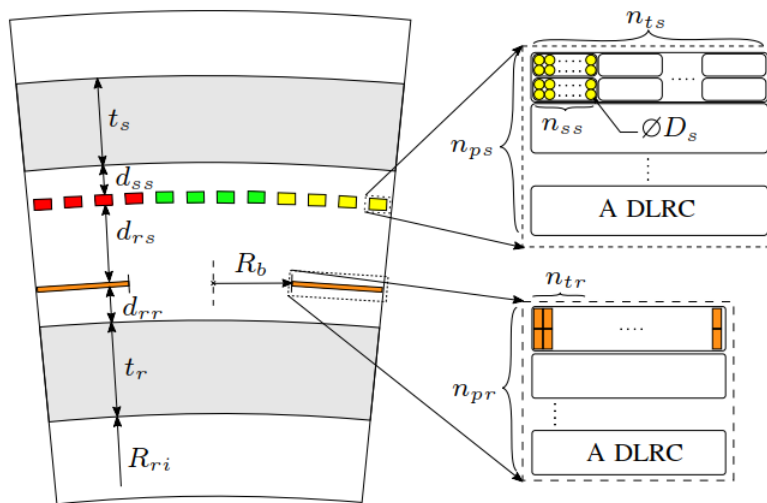


Fig. 1 - EolSupra20 electromagnetic design

Fig. 2 - EolSupra20 cryogenic design

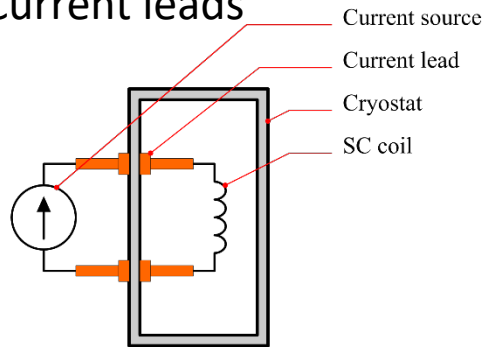
[1] T.-K. Hoang, L. Quéval, L. Vido, C. Berriaud, "Impact of the rotor blade technology on the levelized cost of energy of an offshore wind turbine," *Joint International Conference OPTIM-ACEMP*, Brasov, Romania, May 2017.

[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.

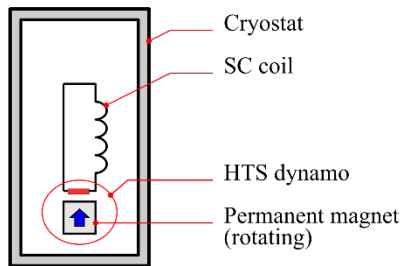


# HTS dynamo-type flux pump

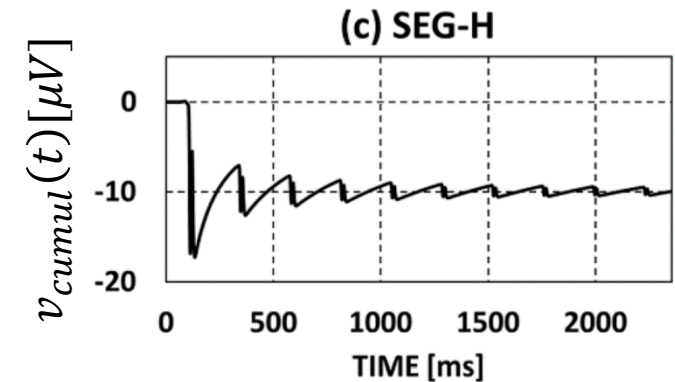
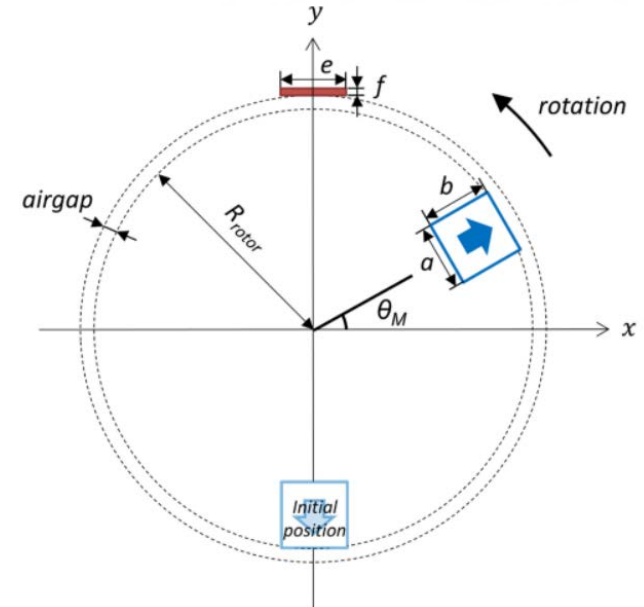
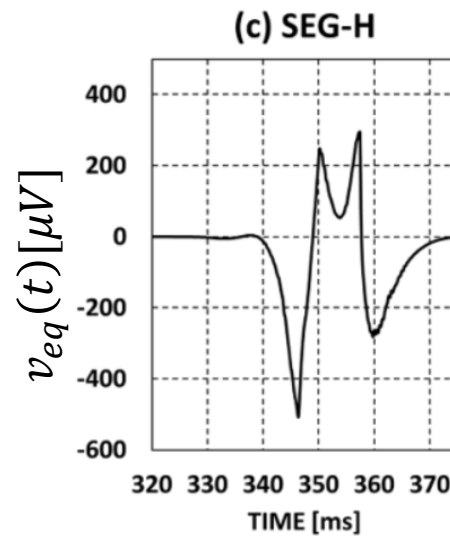
## Current leads



## Flux pump



## Benchmark & Results



- [1] M.D. Ainslie, F. Grilli, L. Quéval, E. Pardo, F. Perez-Mendez, R. Mataira, A. Morandi, A. Ghabeli, C. Bumby, R. Brambilla, "A new benchmark for electromagnetic modelling of superconductors: the high-Tc superconducting dynamo," *Superconductor Science and Technology*, vol. 33, no. 10, pp. 105009, Aug. 2020.
- [2] M.D. Ainslie, L. Quéval, R.C. Mataira, C.W. Bumby, "Modelling the frequency dependence of the open-circuit voltage of a high-Tc superconducting dynamo," *IEEE Transactions on Applied Superconductivity*, vol. 31, no. 5, pp. 1-7, Aug. 2021.
- [3] A. Ghabeli, M. Ainslie, E. Pardo, L. Quéval, R. Mataira, "Modeling the charging process of a coil by an HTS dynamo-type flux pump," accepted for publication in *Superconductor Science and Technology*, Apr. 2021.

# EolSupra20

Estimation of the LCOE of resistive vs. HTS generator

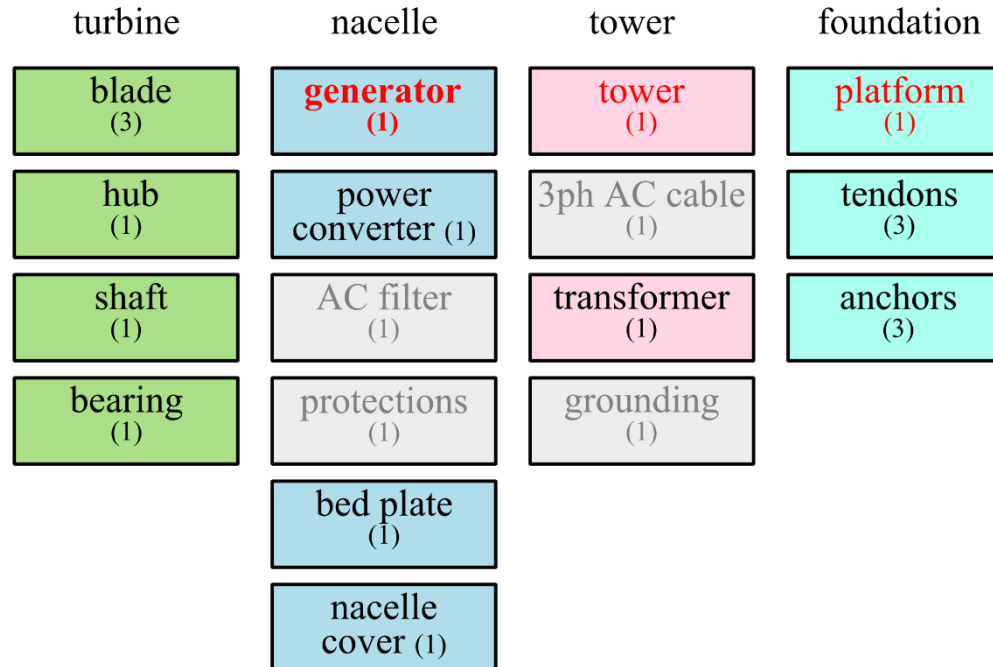


Fig. 1 – Components of a wind turbine and impact of modification of the generator

## **IV. EolSupra20**

### **b) Around the wind farm**

# EolSupra20

Design and optimization of the wind farm layout and its cabling to minimize the LCOE

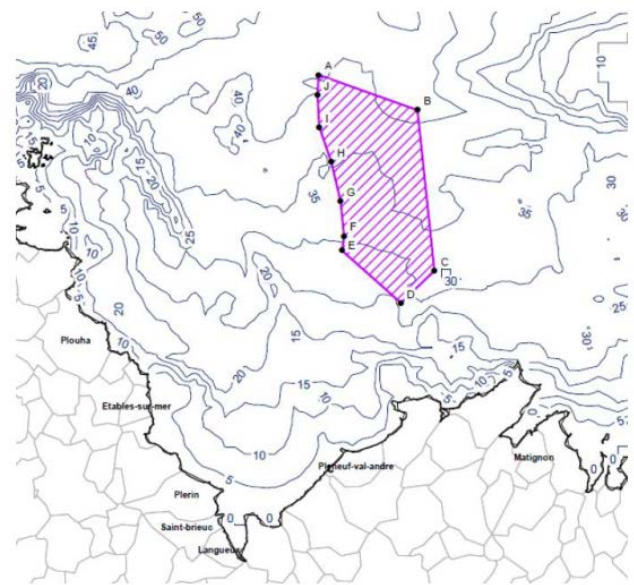


Fig. 1 – Bidding area

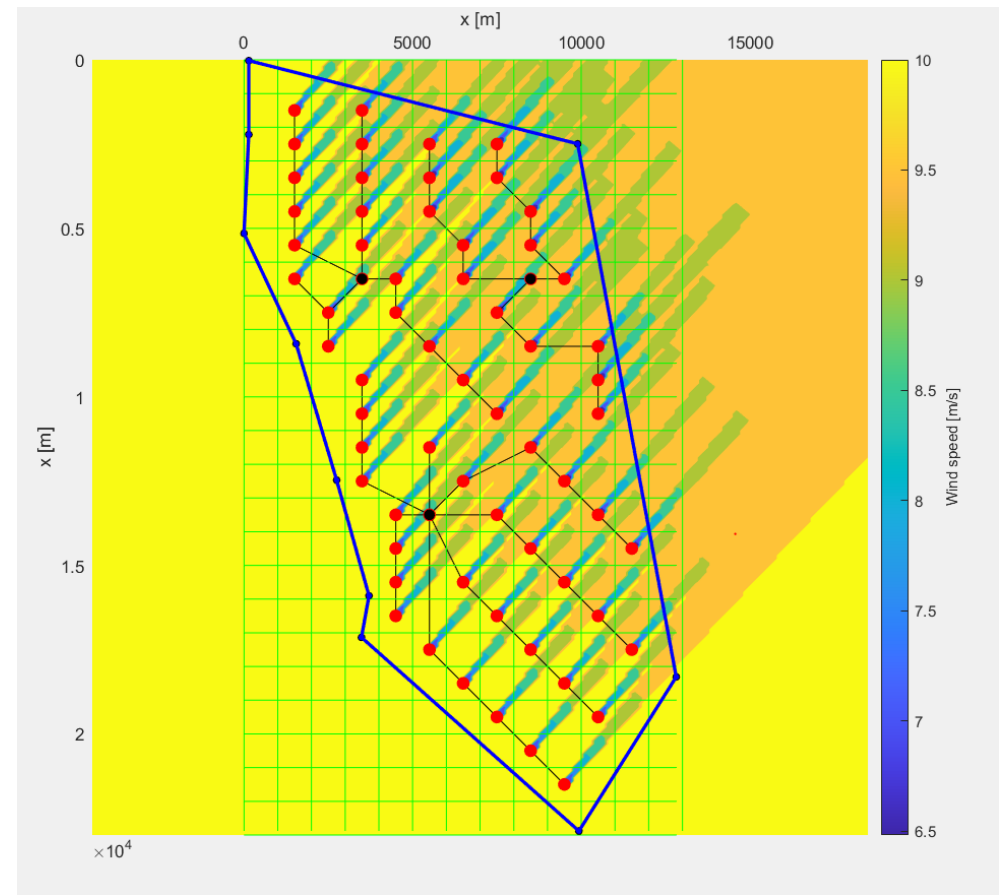


Fig. 2 – Wake effect and cabling

# EolSupra20



**22 GW**

of offshore wind capacity installed in Europe

**3,6 GW**

additional capacity installed in Europe in 2019



**621 MW**

Average size of a wind farm in 2019

The average size has almost **doubled** in the last decade



**59 Km**

Average distance to shore in 2019

The distance continues to increase and can go beyond

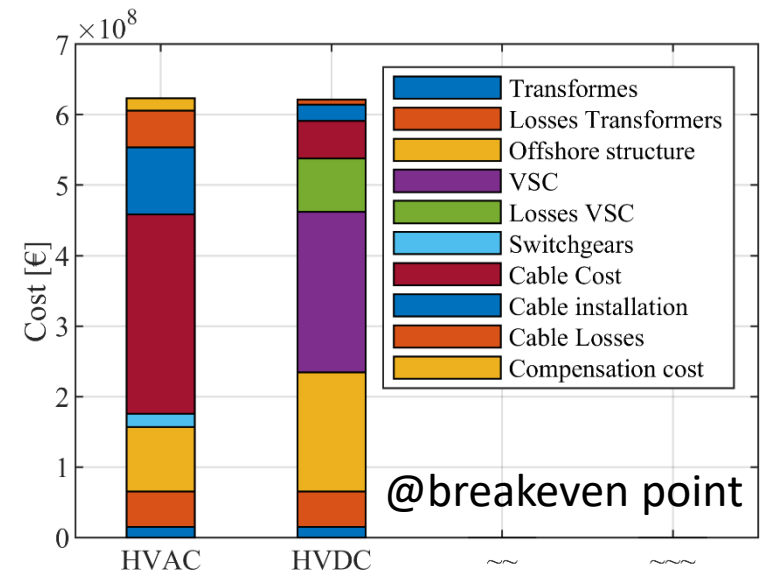
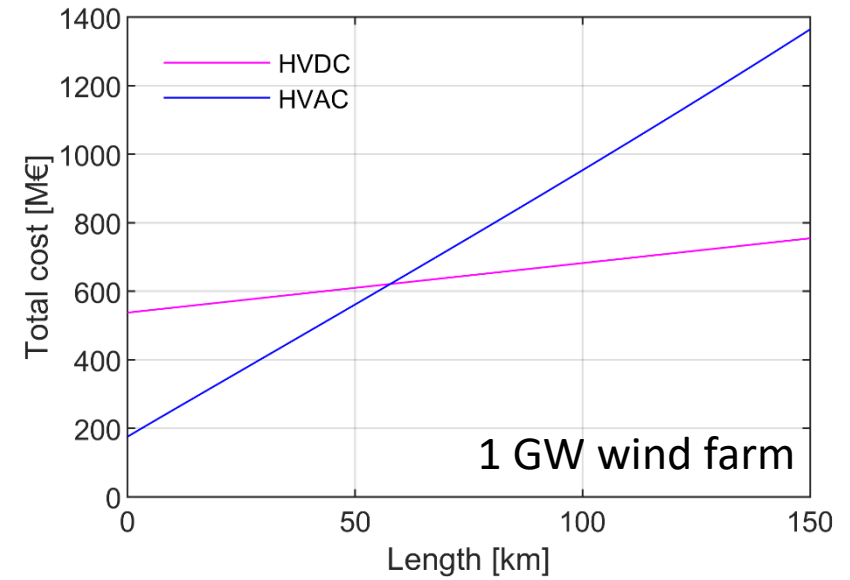
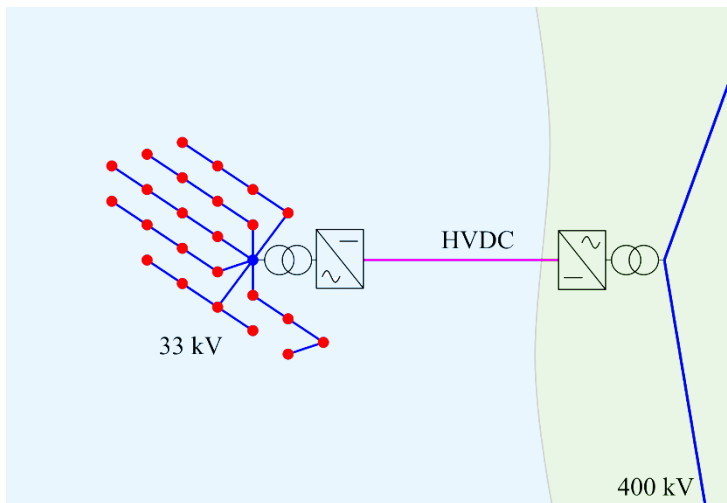
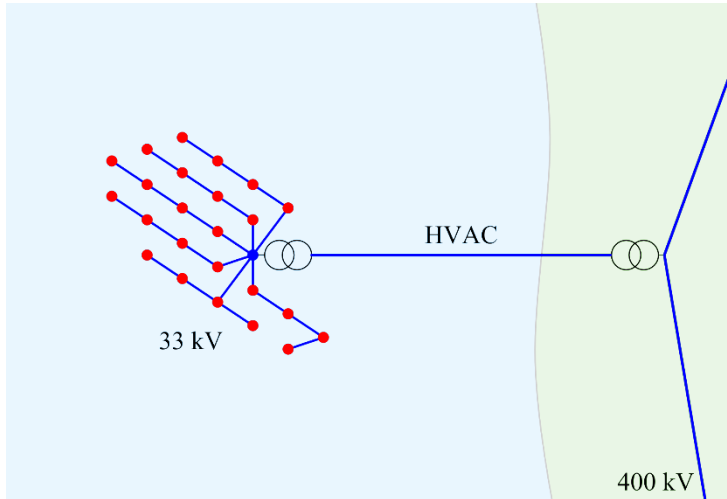
**120 km**



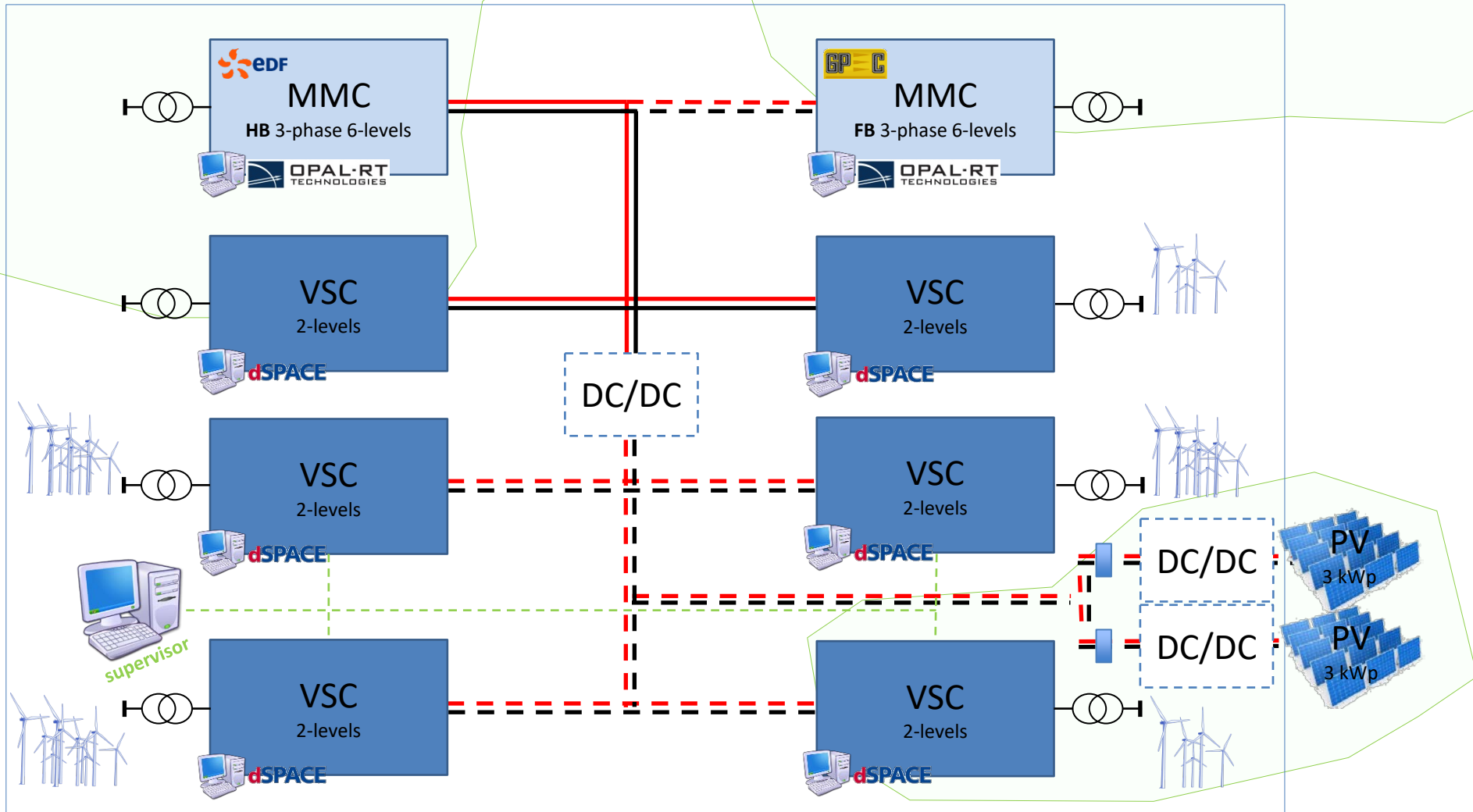
Due to the increased relevance of the offshore collection system and of the transmission system, what are the **optimal cable layout and optimal transmission system** to collect and transmit the power from the wind farm to the shore ?

# EolSupra20

## HVAC vs. HVDC



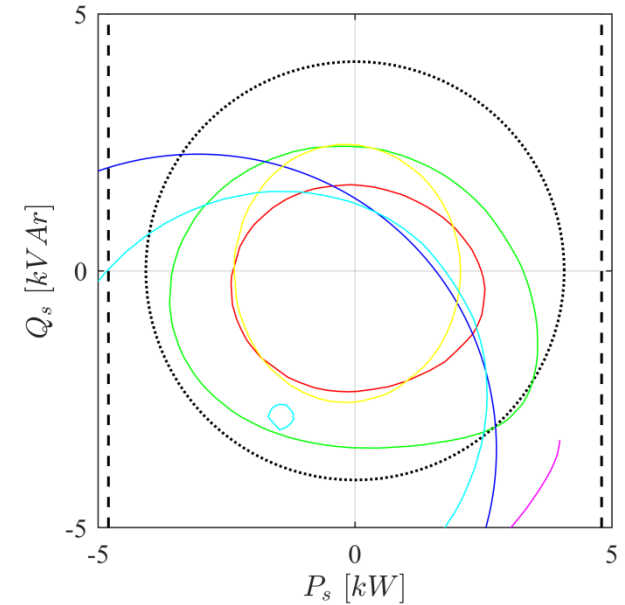
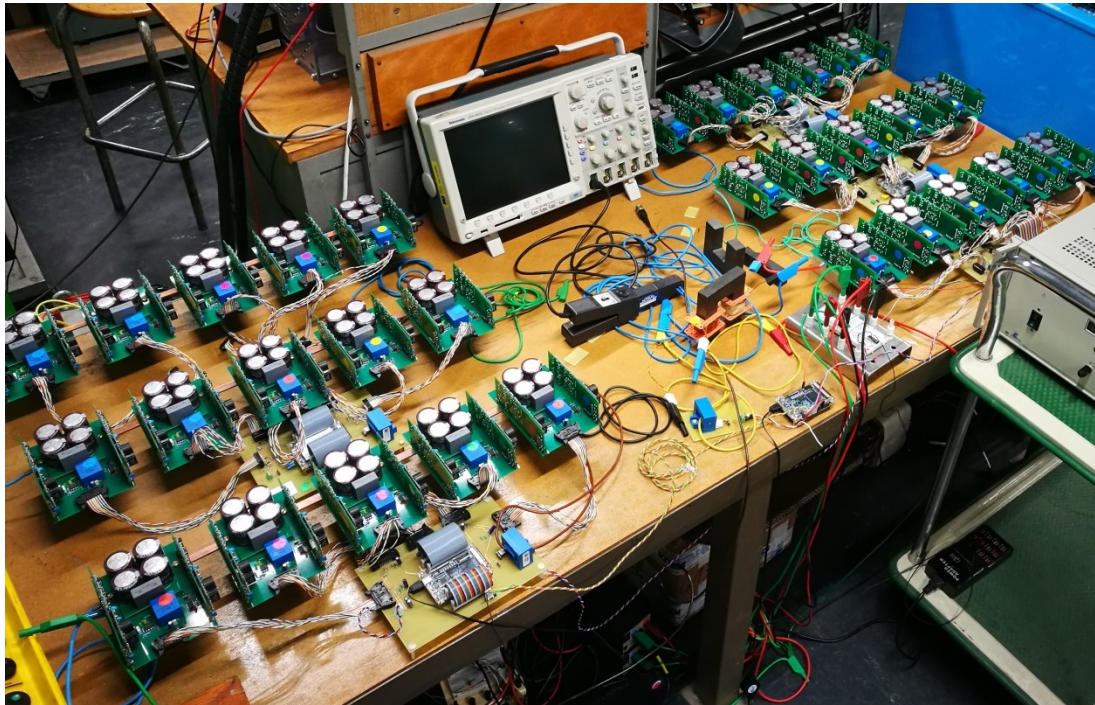
# GeePs MTDC Plateform (20210408)





# Full-bridge modular multilevel converter

- Conception and construction of a 3-phase 6-level full-bridge MMC
- Contribution to the sizing of the MMC



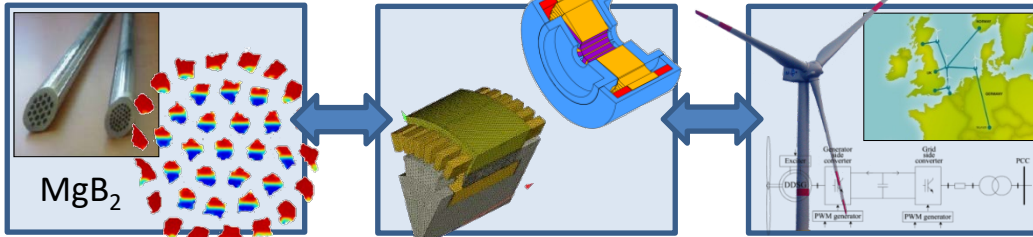
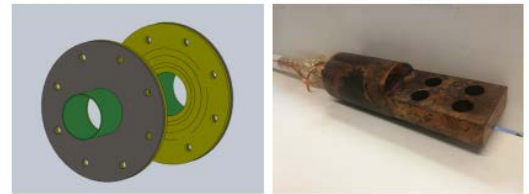
MMC PQ diagram with external and internal limits:

- ..... AC grid current
- DC grid current
- modulation index
- IGBT current
- module capacitor voltage ripple
- module capacitor current ripple
- arm current
- module capacitor average voltage

[1] B. Džonlaga, "Contribution to the sizing of the modular multilevel converter," PhD thesis, University Paris-Saclay, GeePs, Gif-sur-Yvette, France, 2019.



# Superconducting components for the grid



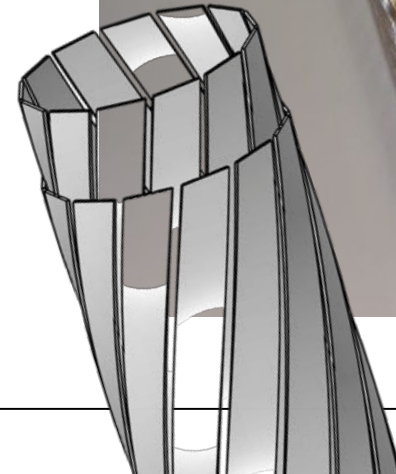
EolSupra20



SC cable



Superconducting power filter



# The Troubled Quest for the Superconducting Wind Turbine

By Samuel K. Moore



Photo: Jeumont Electric  
**Precision Manufacturing:** Workers build the stator of Ecoswing's onshore generator.

EolSupra20's superconducting design did manage to beat its version of a turbine built using conventional technology with respect to LCOE. It chimed in at €119 per megawatt-hour (\$140/MWh) compared with €129/MWh (\$152/MWh) for the conventional turbine. The difference, according to Quéval and the EolSupra20 team, was the substantially lower generator mass enabled by the superconductors. At 178 metric tons, the fully superconducting generator was barely more than one-third of the conventional generator's bulk.

EolSupra20's LCOE is quite noticeably higher than that of InnWind's reference 20-MW turbine, which is €93 (\$108)/MWh. Quéval points out that LCOE is, to some extent, a local affair. InnWind's aim was the deeper waters of

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**Merci !**