



Comparison of LCoE of Superconducting direct drive generators for a 10 MW offshore wind turbine

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Outline

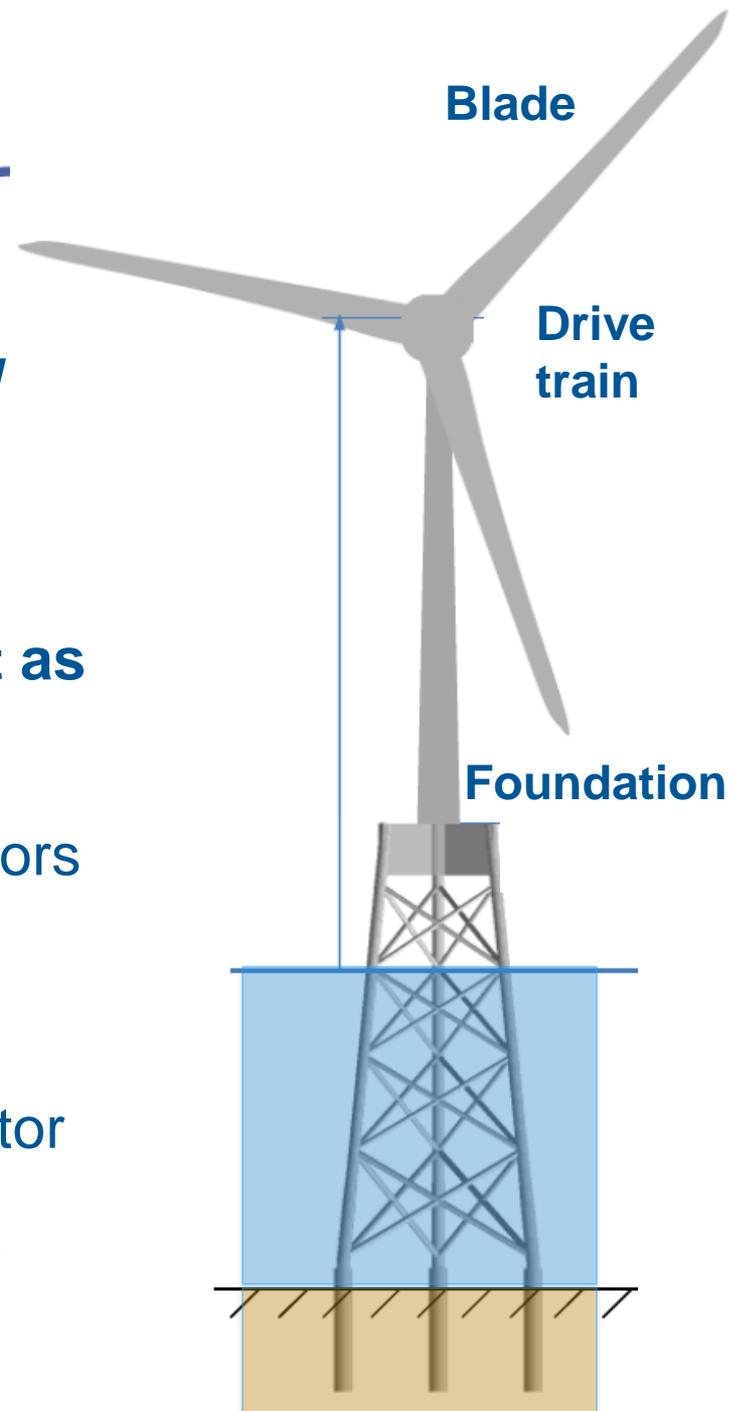
INNWIND.EU

$P_{\text{turbine}} = 10\text{-}20 \text{ MW}$

$D_{\text{rotor}} = 178\text{-}252 \text{ m}$

$H_{\text{water}} = 50 \text{ m}$

- **Non-contact drive train as compact as permanent magnet direct drive**
- Superconducting Direct Drive generators
 - MgB_2 medium and $\text{RBa}_2\text{Cu}_3\text{O}_7$ high temperature superconductors.
- Magnetic Pseudo Direct Drive generator
 - Magnetic gear + generator
- Levelized Cost of Energy comparison



Contribution to INNWIND.EU WP3



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TU Delft

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The University
Of
Sheffield.



Magnomatics®

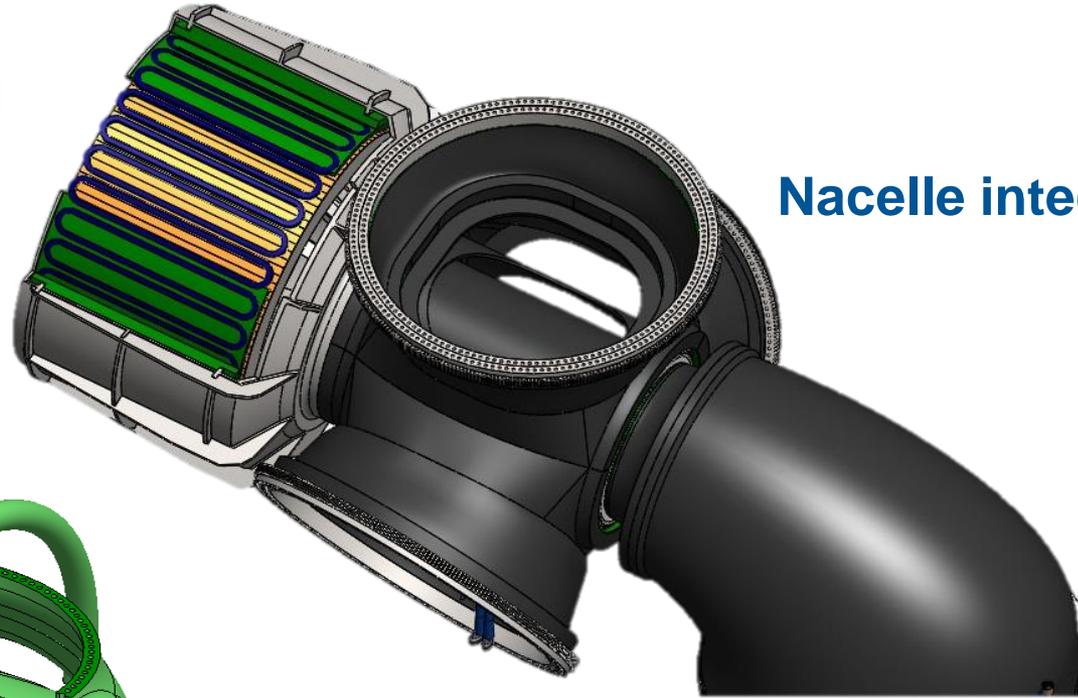
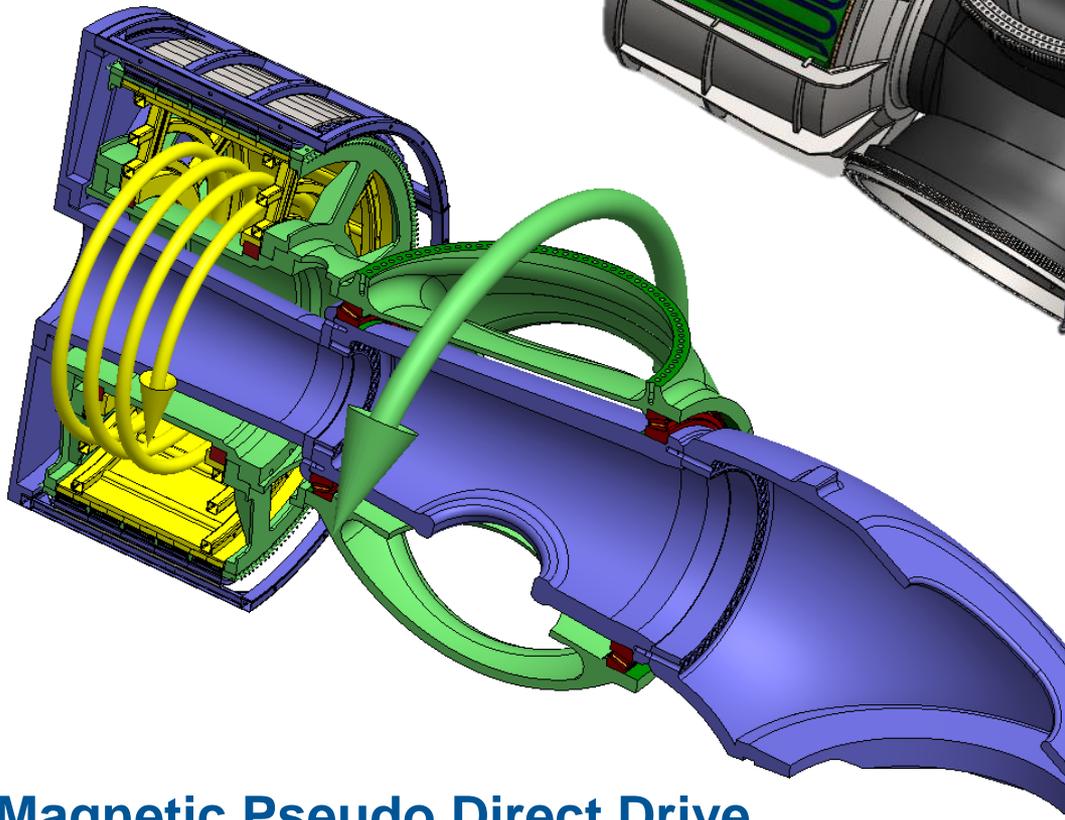


Leibniz
Universität
Hannover

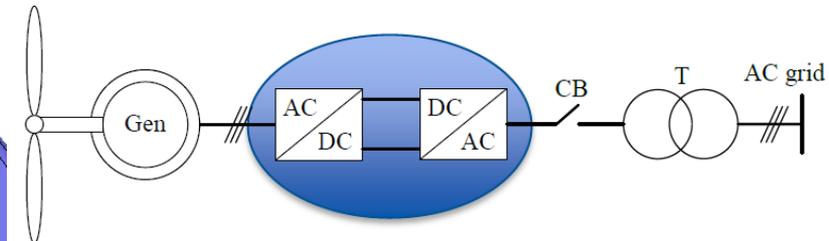
Electro-mechanical conversion

Superconducting
Direct Drive

Nacelle integration



Power electronics



Magnetic Pseudo Direct Drive

Levelized Cost of Energy (LCoE) of energy plant

Cost of Energy

$$CoE = \frac{C}{E} = \frac{\sum_{i=0}^{LT} C_i}{\sum_{i=0}^{LT} E_i}$$

Life time LT
Cost year i
Energy year i

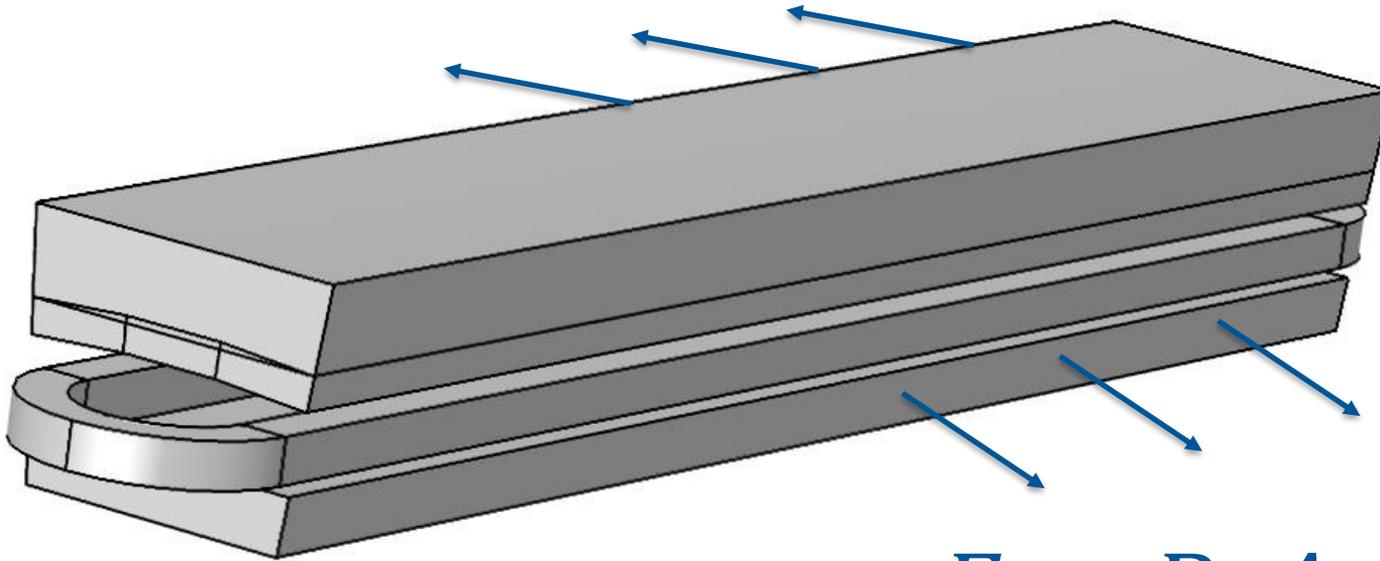
Levelized Cost of Energy

$$LCoE = \frac{C}{E} \Bigg|_{t=0} = \frac{\sum_{i=0}^{LT} C_i \frac{1}{(1+w)^i}}{\sum_{i=0}^{LT} E_i \frac{1}{(1+w)^i}} = \frac{C_D + C_R}{a \cdot E_{AEP} \cdot LT} + \frac{O_i}{E_{AEP}}$$

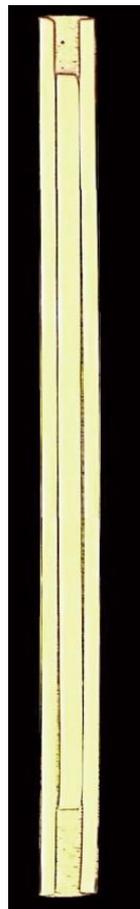
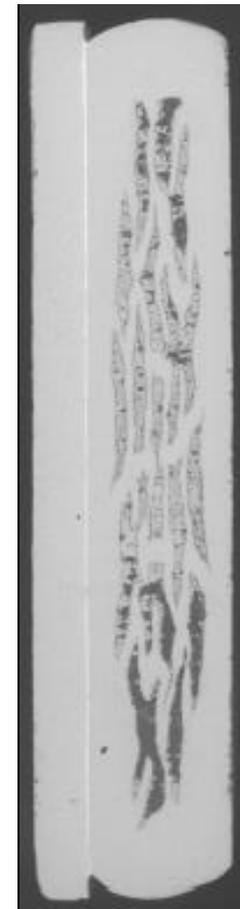
Generator
Turbine & foundation
O&M Cost
Interest rate
Finance factor
Annual energy production



Superconducting Direct Drive

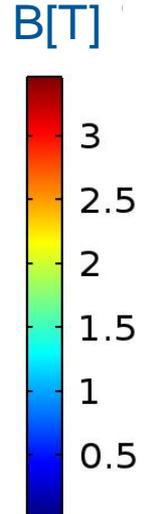
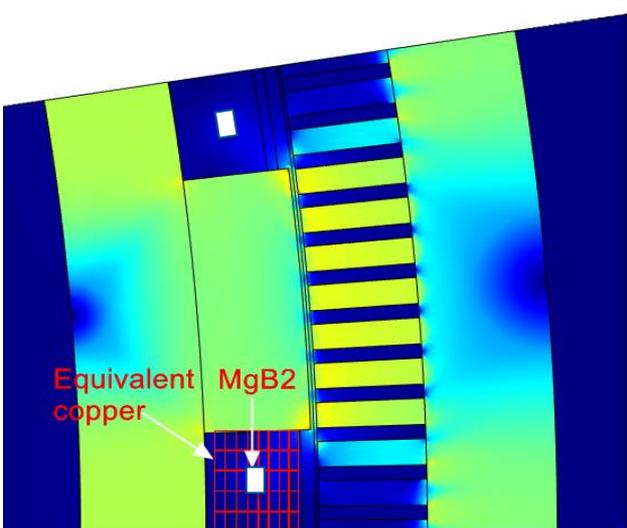


| | |
|----------------|---------------|
| MgB_2 | RBCO |
| 39 K | 93 K |



4 €/m 100 €/m

$$F_d \sim B_p A_S$$



F_d : Shear force density
 B_p : Peak magnetic Field
 A_S : Armature current load

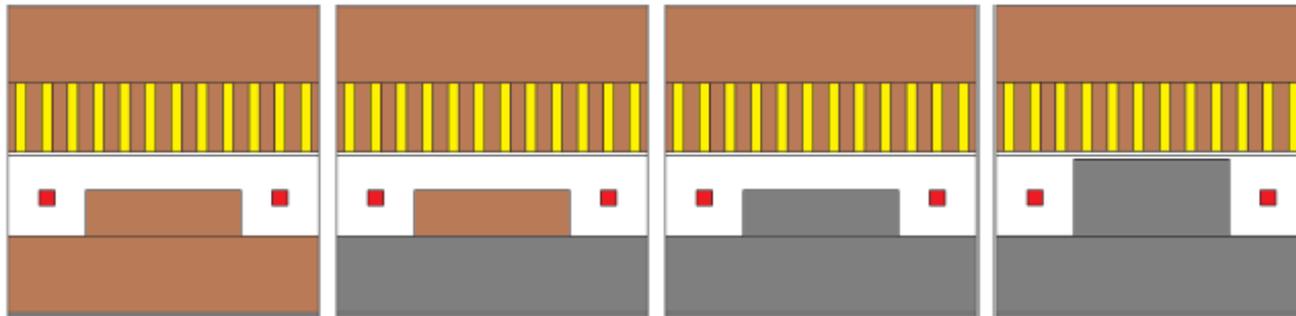
SC: $J \sim 100-330 \text{ A/mm}^2$
 Cu: $J \sim 2-3 \text{ A/mm}^2$

Topology : MgB_2 + Cu + Si steel + G10 ?

G10
15 €/kg

**Cop-
Per**
15 €/kg

MgB_2
4 €/m

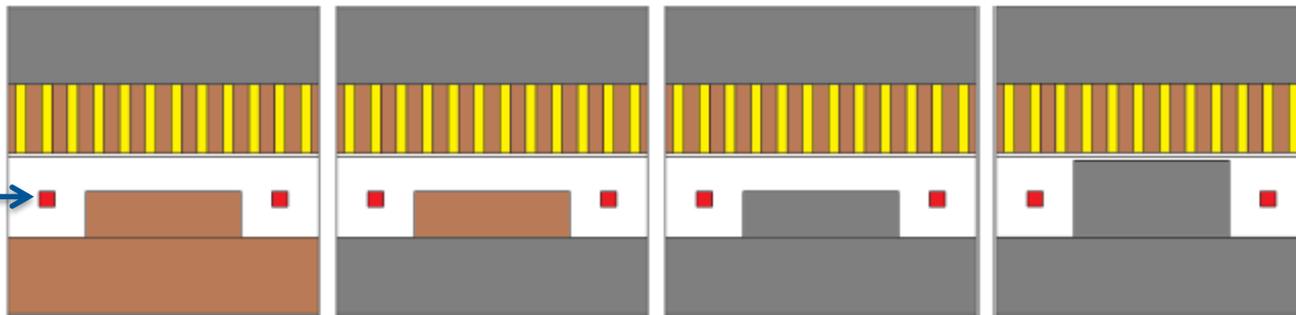


(a) T1

(b) T2

(c) T3

(d) T4

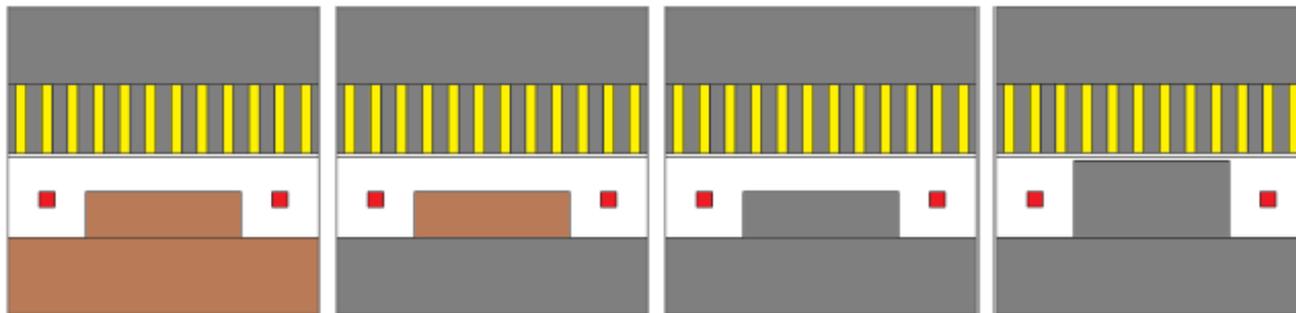


(e) T5

(f) T6

(g) T7

(h) T8



(i) T9

(j) T10

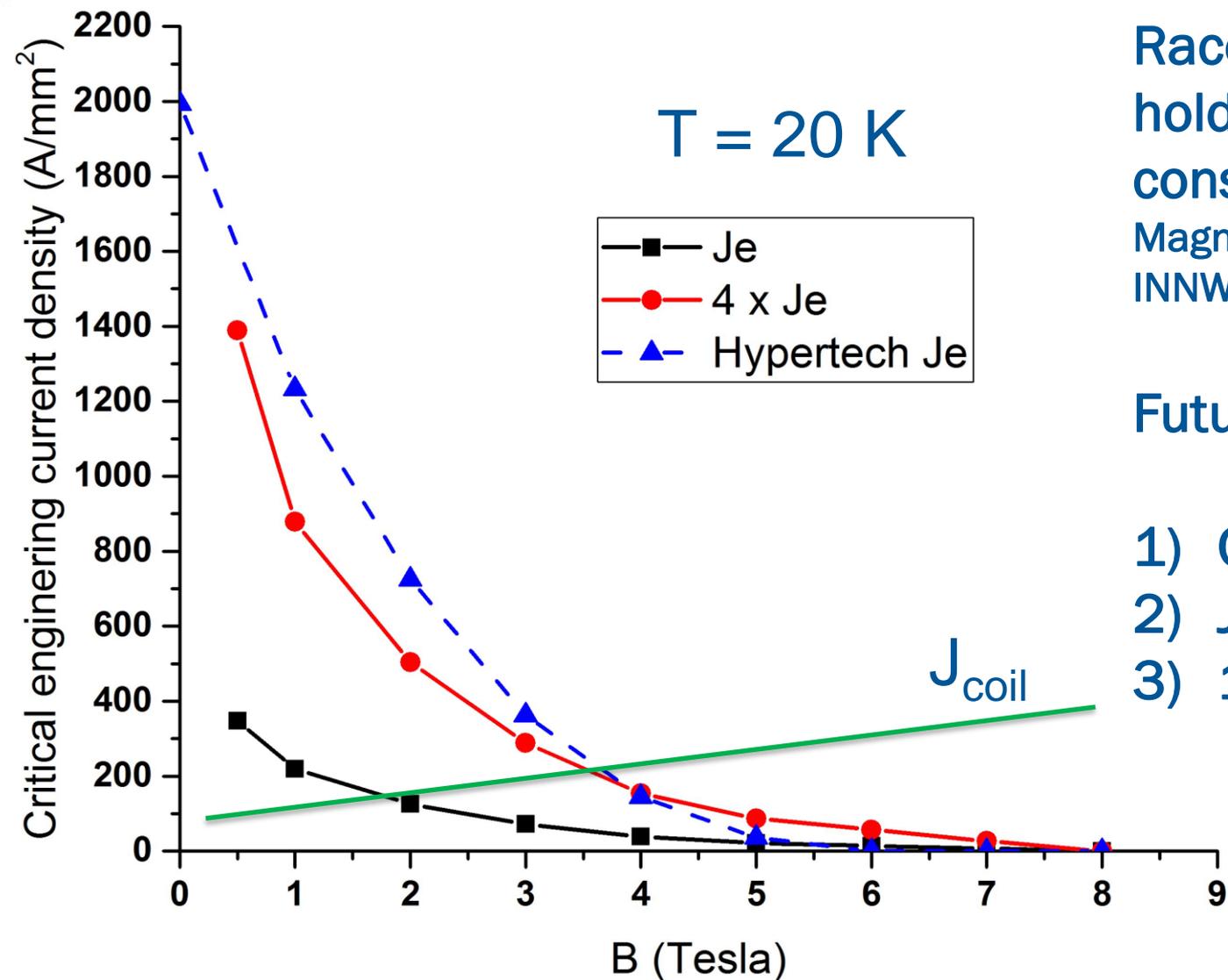
(k) T11

(l) T12

Iron
3 €/kg



MgB₂ tape Columbus Superconductors



Race track coil
holding 5 km
constructed.

Magnusson (1LPS-12)
INN WIND.EU D3.13

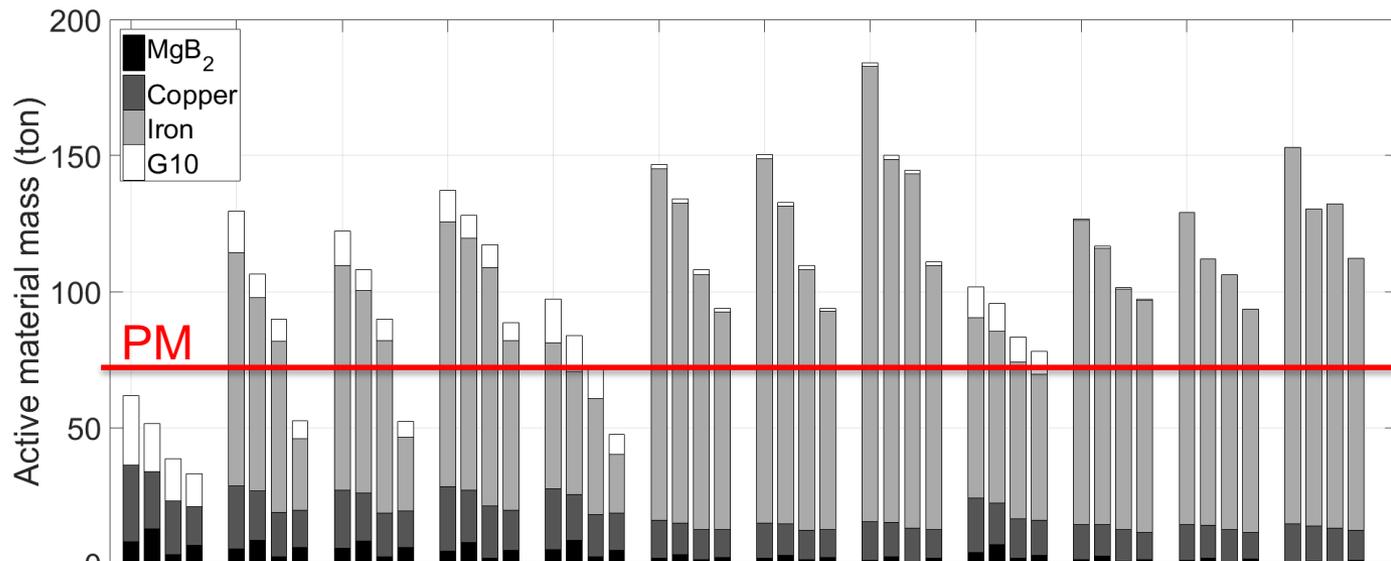
Future Scenarios

- 1) Cost $\rightarrow \frac{1}{4}$
- 2) $J_e \rightarrow 4 \times J_e$
- 3) 1 + 2

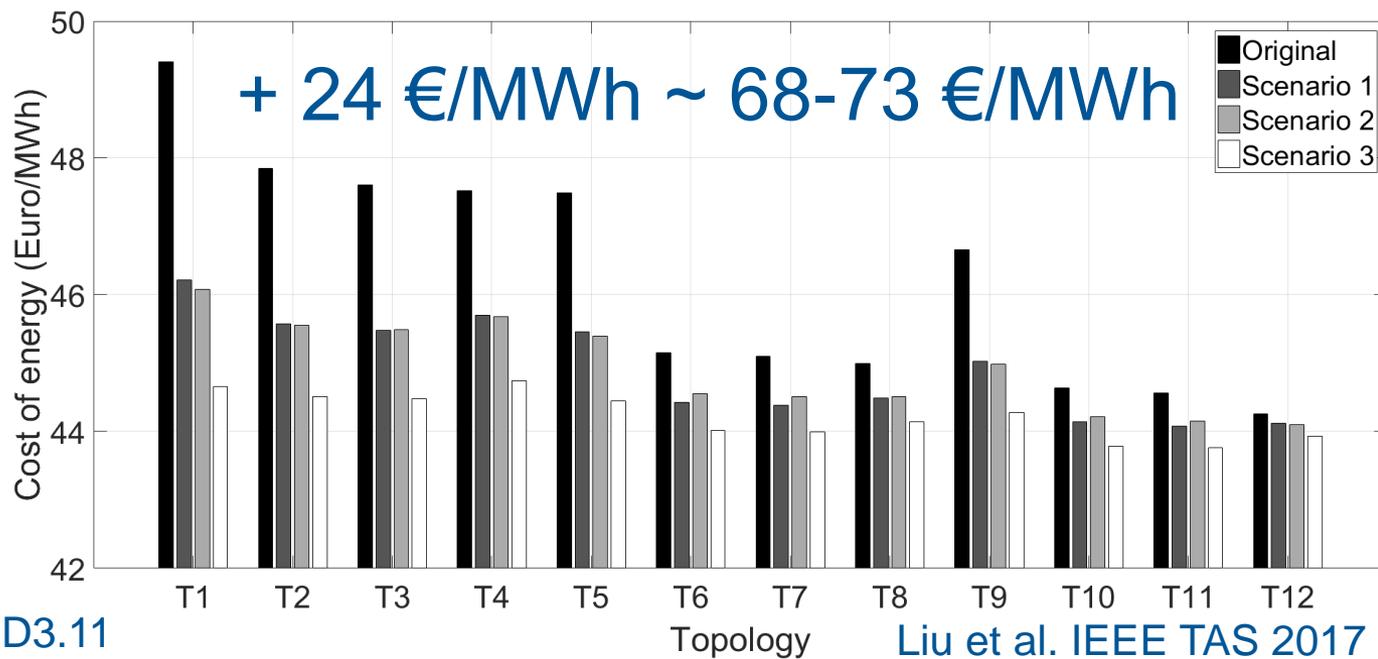
Optimized 10 MW

$$LCoE_{eq} = \frac{C_{act} + C_{other}}{a \cdot E_{AEP} \cdot T_{LT}}$$

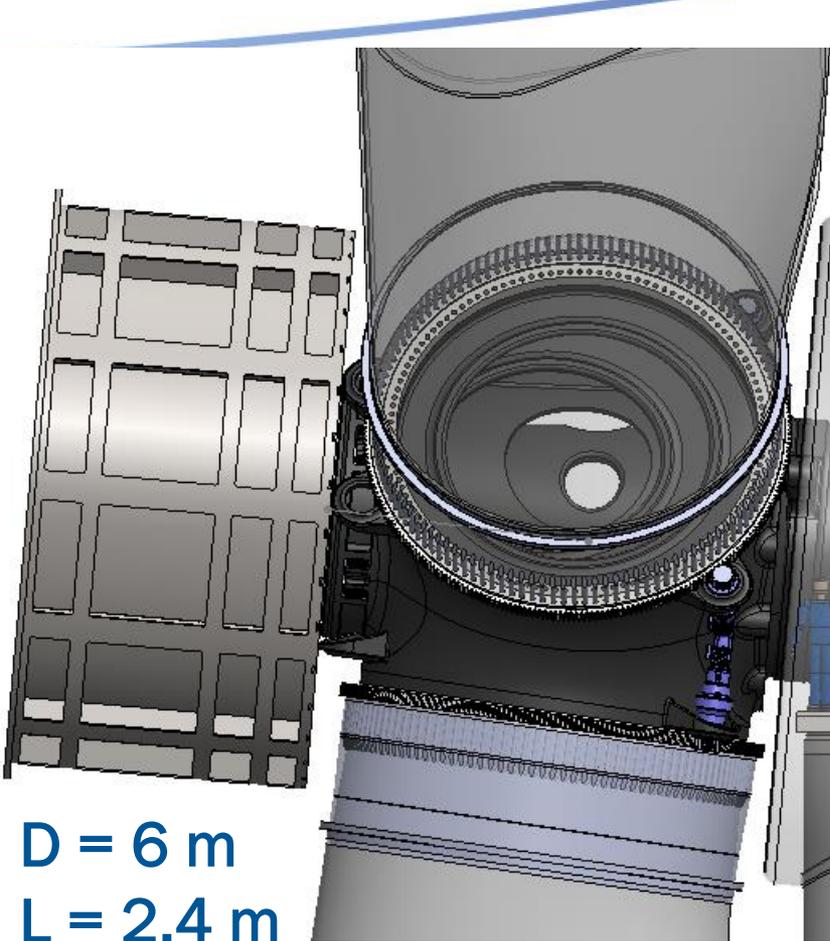
- With iron:
cheap but heavy
- No iron:
light but expensive



- Future?
- 1: SC cost ¼
 - 2: SC 4 x J_e
 - 3: Both 1 & 2



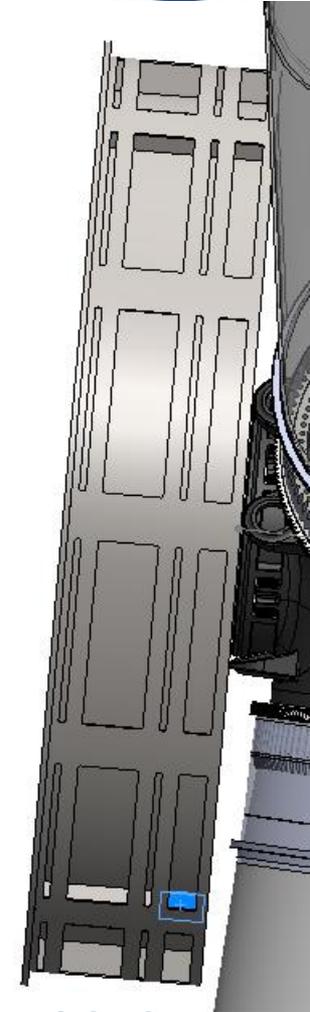
Nacelle integration of iron topology (T11)



D = 6 m
L = 2.4 m
305 ton



D = 8.4 m L = 1.3 m
m ~ 286 ton
< m_{PM} ~ 325 ton



D = 10.8 m
287 ton

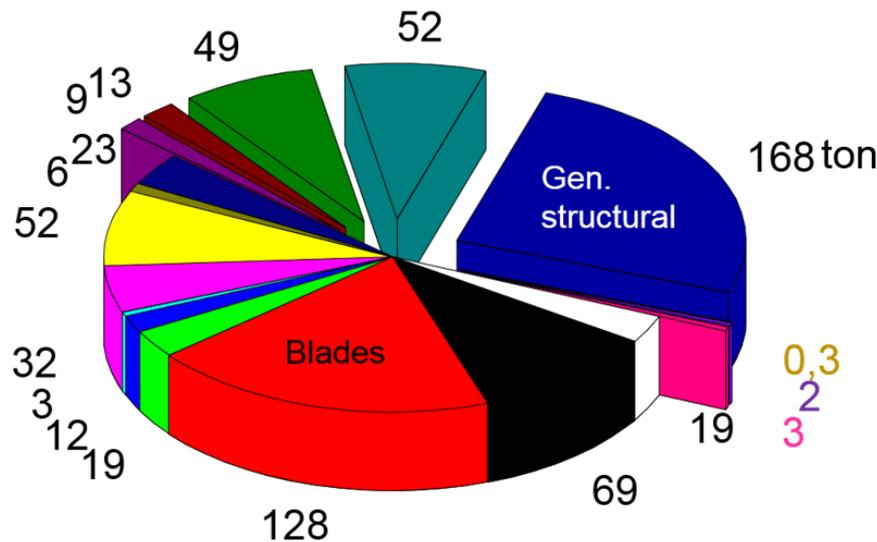
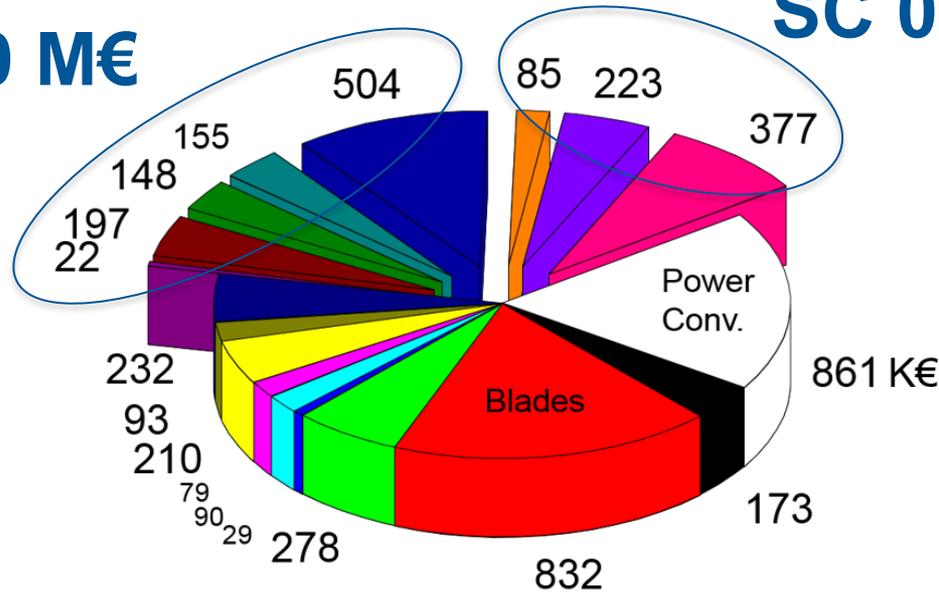


Cost and mass breakdown of 10 MW MgB₂ nacelle

Gen 1.0 M€

SC 0.7 M€

Total
4.6 M€



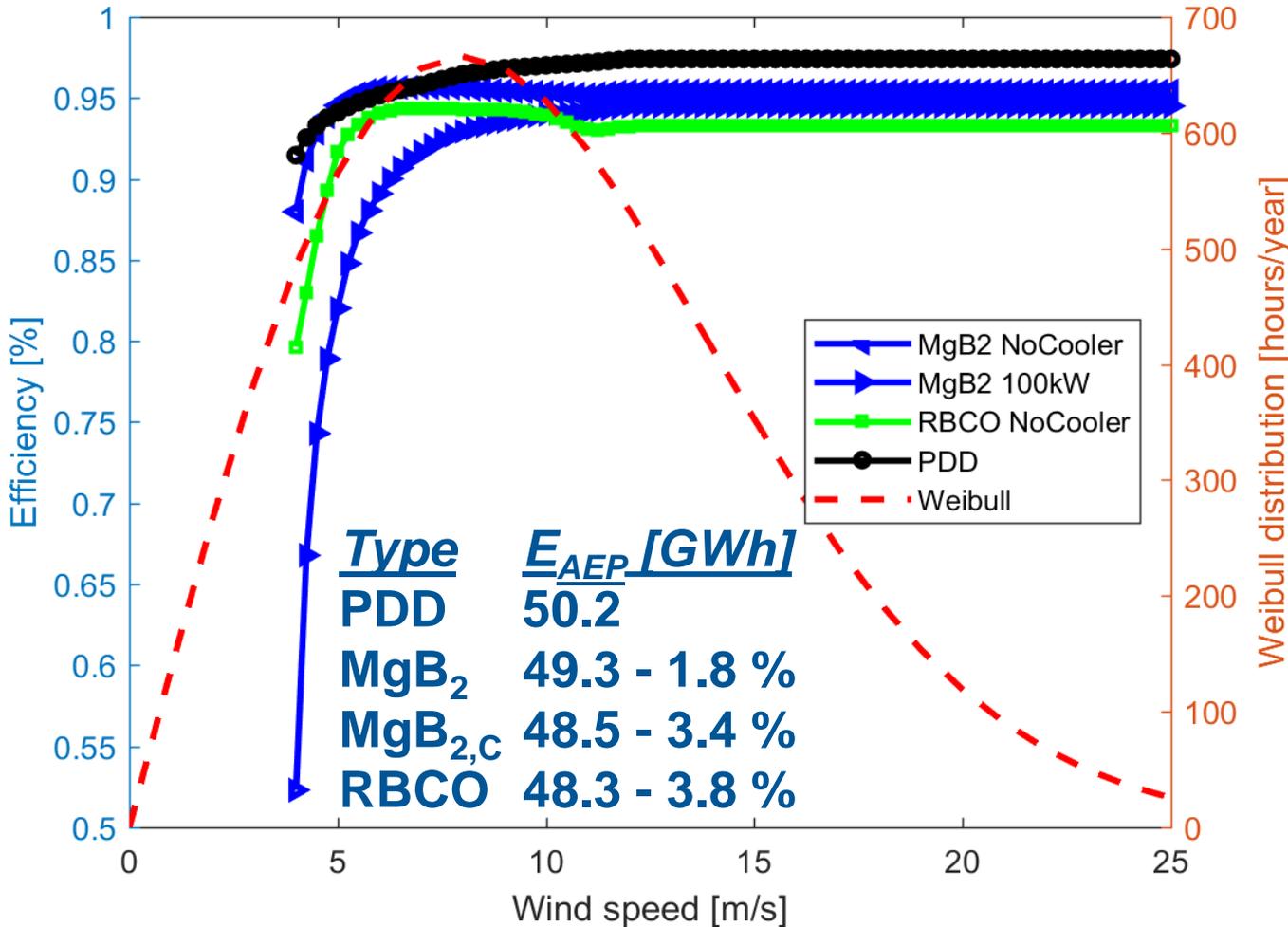
- Hub
- Blade
- Pitch bearing
- Other rotor
- Main bearing
- Kingpin
- Mainframe
- Yaw
- Other nacelle
- Generator KingPin
- Copper
- Iron armature
- Iron field
- Gen. structural
- MgB₂
- Coldh & Compres
- Cryostats
- Power converter



Levelized Cost of Energy (LCoE)

Modular cryostats of Suprapower project mapped onto INN WIND.EU generator: 15 cold heads ~ 100 kW

$$LCoE = \frac{C_D + C_R}{\alpha E_{AEP} LT} + \frac{O}{E_{AEP}}$$

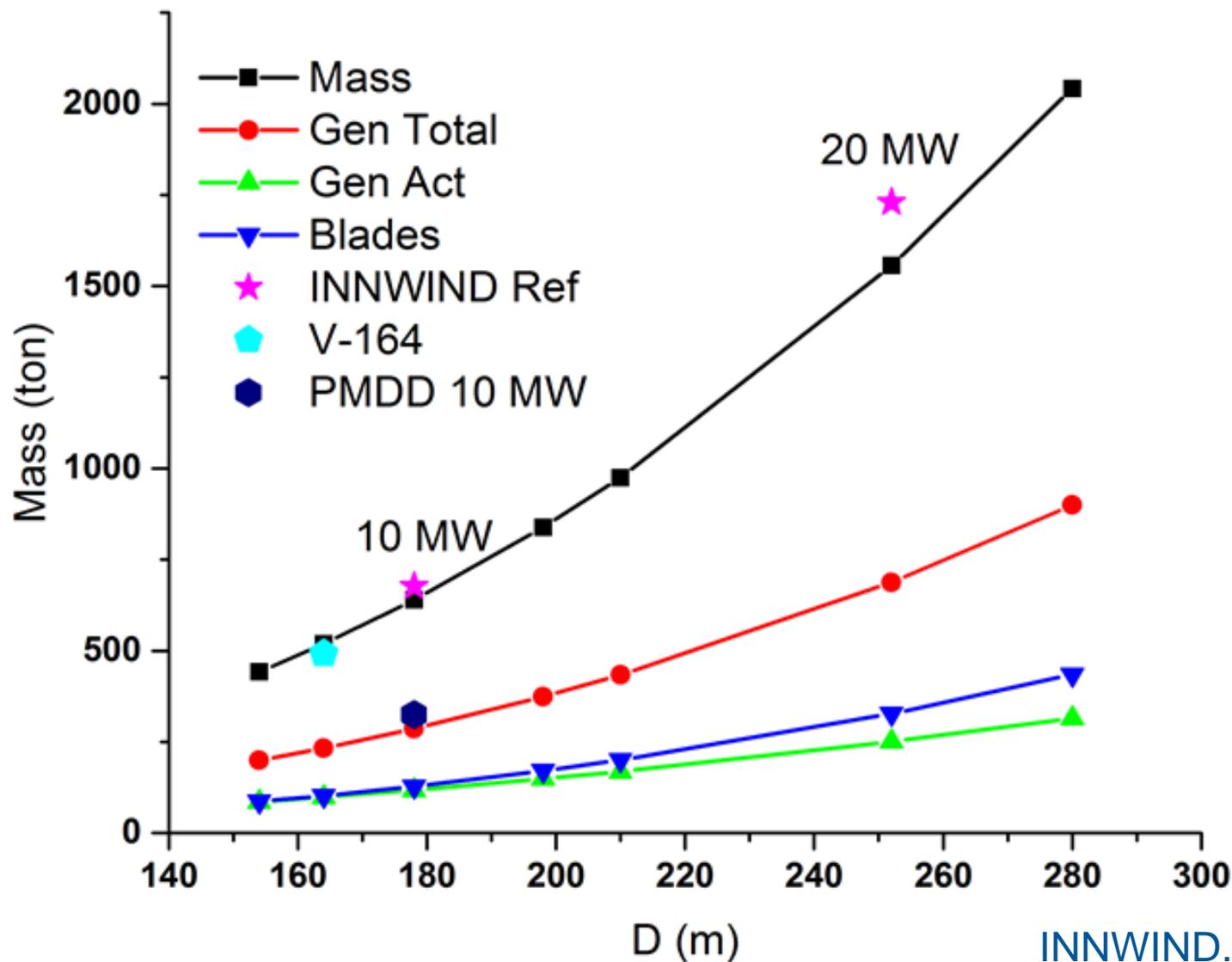


| Type | Cost [M€] |
|------------------|-----------|
| PDD | 1.7 |
| RBCO | 2.1 + 24% |
| MgB ₂ | 2.6 + 53% |

| Type | $\Delta LCoE$ [%] |
|------------------|-------------------|
| PDD | ~ 0 |
| RBCO | ~ + 5 |
| MgB ₂ | ~ + 5 |

$C_R \sim 17$ M€
 $LT = 25$ years
 $a = 0.55$

Rotor nacelle assembly (RNA) mass scaling



Conclusions

- **Superconducting Direct Drive**
 - Iron cored topology most economical now, but not light weight
 - Cheaper and better MgB_2 can result in other topologies.
 - Cryostat and cooling more expensive than MgB_2 !
 - 10 MW MgB_2 : $D = 8.4$ m $L = 1.3$ m m ~ 286 tons
 - MgB_2 : Race track coil demonstrated $\Delta LCoE \sim + 5 \%$
 - RBCO: Race track coil demonstrated. $\Delta LCoE \sim + 5 \%$
 - Removes dependency of Rare Earth Elements
- **Magnetic Pseudo Direct Drive**
 - Superior in term of efficiency and cost. $\Delta LCoE \sim - 0 \%$
 - Increased Rare Earth Elements dependency
- MgB_2 scaled to 20 MW: $D = 10.8$ m $L = 2.3$ m m ~ 650 tons.
- Next focus 13-15 MW (Dong Energy no subsidy bid for offshore wind in 2024).

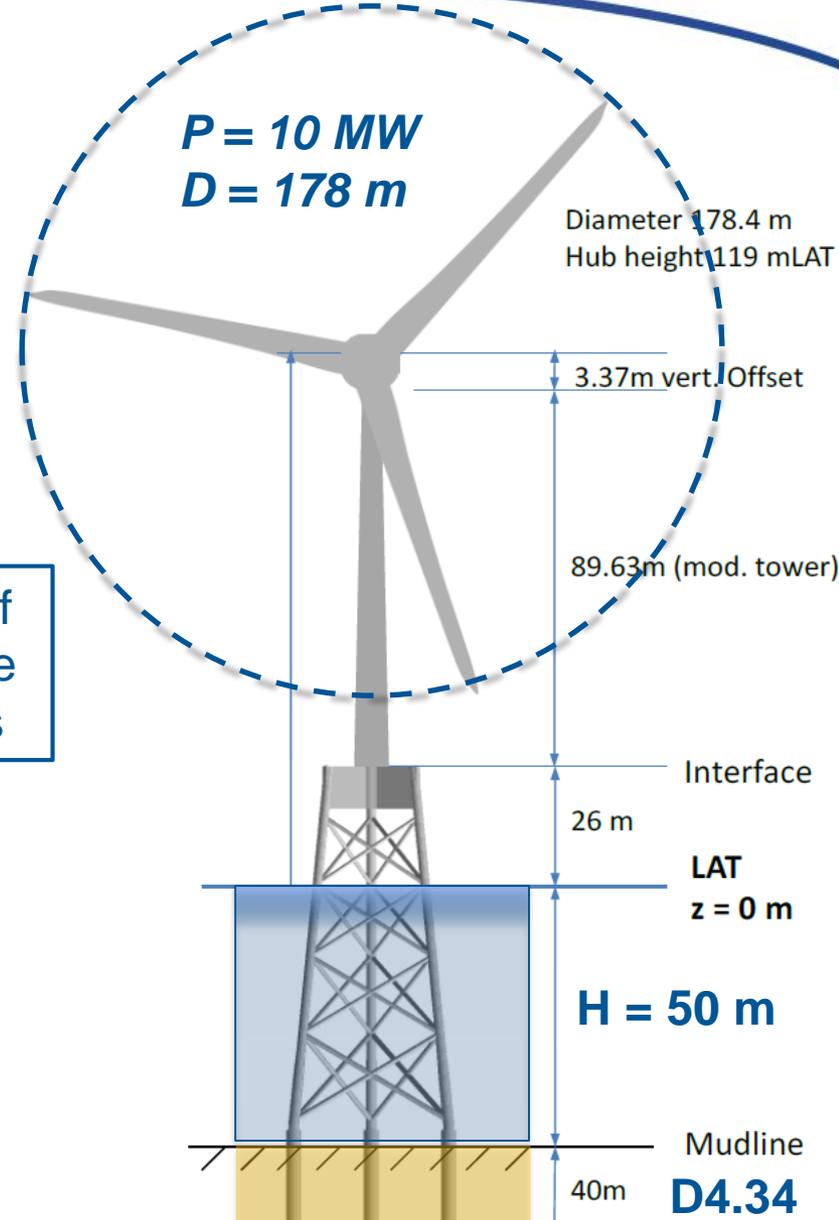


How to beat the square-cube law?

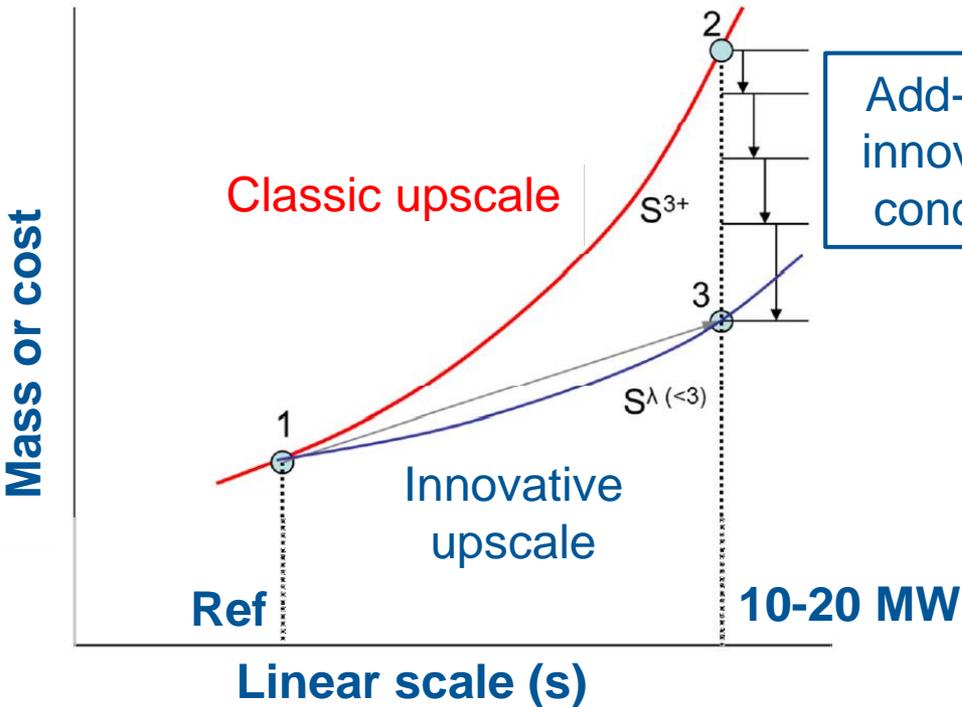
$$Power = \frac{\pi}{8} \rho v^3 D^2 C_p \sim D^2$$

$$M_{turbine} \sim D \times w \times t \sim D^3$$

$$M_{turb+jacket} = c_1 D^3 + c_2 D^2 H$$



Add-on of innovative concepts

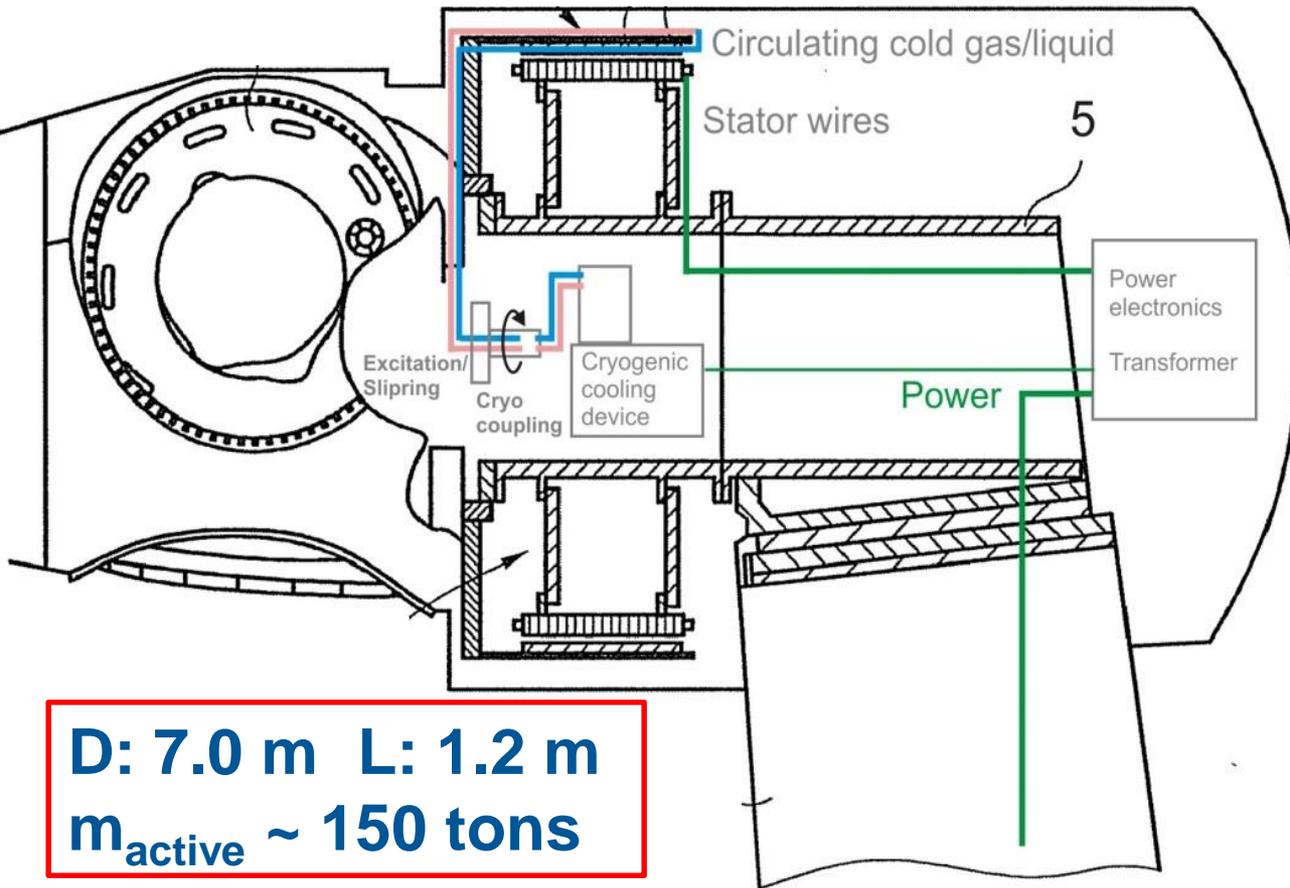


SC pole pair demo

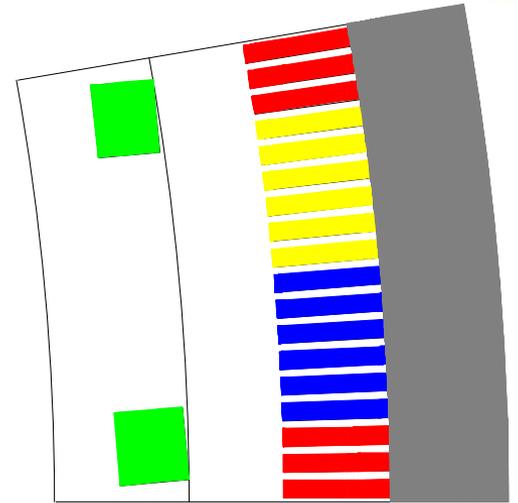
SIEMENS

”As high operation temperature as possible → HTC”

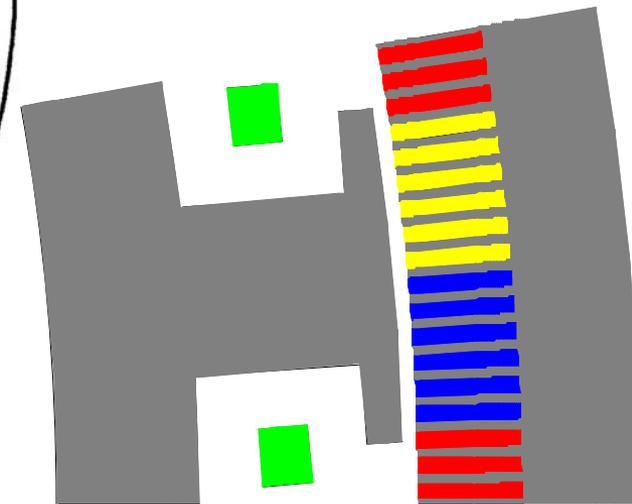
INNWIND.EU D3.12



D: 7.0 m L: 1.2 m
 $m_{\text{active}} \sim 150$ tons



Air-core stator, air-core rotor



Iron-core stator, iron-core rotor