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

Asger B. Abrahamsen, Senior Research Scientist @ DTU Wind Energy

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INNWIND.EU

\[ P_{\text{turbine}} = 10-20 \text{ MW} \]
\[ D_{\text{rotor}} = 178-252 \text{ m} \]
\[ H_{\text{water}} = 50 \text{ m} \]

- Non-contact drive train as compact as permanent magnet direct drive

- Superconducting Direct Drive generators
  - MgB\(_2\) medium and RBA\(_2\)Cu\(_3\)O\(_7\) high temperature superconductors.

- Magnetic Pseudo Direct Drive generator
  - Magnetic gear + generator

- Levelized Cost of Energy comparison
Contribution to INNWIND.EU WP3

D. Liu & Henk Polinder, Delft University of Technology (NL)
N. Magnuson, SINTEF (N)
A. Thomas & Z. Azar, Siemens Wind Power (DK / UK)
E. Stehouwer & B. Hendriks, DNV GL (NL)
A. Penzkofer & K. Atallah, University of Sheffield (UK)
R. S. Dragan & A. Meyers, Magnomatics (UK)
F. Deng & Z. Chen, Aalborg University (DK)
D. Karwatzki & A. Mertens, University of Hannover (D)
M. Parker & S. Finney, University of Strathclyde
Asger B. Abrahamsen (asab@dtu.dk), DTU Wind Energy (DK)

Project website: www.innwind.eu
Electro-mechanical conversion

Superconducting Direct Drive

Nacelle integration

Magnetic Pseudo Direct Drive

Power electronics
Levelized Cost of Energy (LCoE) of energy plant

Cost of Energy

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

Levelized Cost of Energy

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

- Life time LT
- Cost year i
- Energy year i
- Generator
- Turbine & foundation
- O&M Cost
- Interest rate
- Finance factor
- Annual energy production
Superconducting Direct Drive

\[ F_d \sim B_p A_S \]

- \( F_d \): Shear force density
- \( B_p \): Peak magnetic Field
- \( A_S \): Armature current load

**SC:** \( J \sim 100-330 \text{ A/mm}^2 \)

**Cu:** \( J \sim 2-3 \text{ A/mm}^2 \)

\begin{align*}
\text{MgB}_2 & : 39 \text{ K} \\
\text{RBCO} & : 93 \text{ K}
\end{align*}
Topology: \( \text{MgB}_2 + \text{Cu} + \text{Si steel} + \text{G10} \) ?

- **G10**: 15 €/kg
- **MgB\(_2\)**: 4 €/m
- **Copper-Per**: 15 €/kg
- **Iron**: 3 €/kg

Liu et al. | IEEE TAS | 2017
MgB$_2$ tape Columbus Superconductors

Race track coil holding 5 km constructed. Magnusson (1LPS-12) INNWIND.EU D3.13

Future Scenarios

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

Liu et al. IEEE TAS 2017
Optimized 10 MW

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

**Future?**
1: SC cost $\frac{1}{4}$
2: SC $4 \times J_e$
3: Both 1 & 2

+ 24 €/MWh $\sim$ 68-73 €/MWh

\[
LCOE_{eq} = \frac{C_{act} + C_{other}}{a \cdot E_{AEP} \cdot T_{LT}}
\]
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 MgB$_2$ nacelle

Gen 1.0 M€

SC 0.7 M€

Total 4.6 M€

INNWIND.EU D3.11
Levelized Cost of Energy (LCoE)

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

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

<table>
<thead>
<tr>
<th>Type</th>
<th>Cost [M€]</th>
<th>(\Delta LCoE) [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDD</td>
<td>1.7</td>
<td>~ 0</td>
</tr>
<tr>
<td>RBCO</td>
<td>2.1 + 24%</td>
<td>~ + 5</td>
</tr>
<tr>
<td>MgB(_2)</td>
<td>2.6 + 53%</td>
<td>~ + 5</td>
</tr>
</tbody>
</table>

\(C_R \sim 17\) M€
LT = 25 years
\(a = 0.55\)
INNWIND.EU D3.44
Rotor nacelle assembly (RNA) mass scaling

![Graph showing mass scaling for different wind turbines.](image-url)
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?

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

\[
M_{\text{turbine}} \sim D \times w \times t \sim D^3
\]

\[
M_{\text{turb+jacket}} = c_1 D^3 + c_2 D^2 H
\]
SC pole pair demo

"As high operation temperature as possible → HTC"

INNWIND.EU D3.12

D: 7.0 m  L: 1.2 m  \( m_{\text{active}} \approx 150 \) tons

Air-core stator, air-core rotor

Iron-core stator, iron-core rotor