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Towards the First Installation of a Direct Drive Superconducting Generator on a Commercial Wind Turbine

Jesper Hansen, Envision Project Manager
Coordinator of the EcoSwing Consortium

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Superconductors are smart materials to work with

- High current density
  - **100 x** that of copper*
- Low Ohmic dissipation
  - **100 mV** rotor voltage*
- Low thermal losses
  - **100 W** at cryogenic temperatures*
  - **10 kW** at room temperature*
- Low material cost
  - **1/10th** of copper **

* Round numbers

** Comparing at the same current.. Like semiconductors, superconductor wire cost massively depend on manufacturing volume.

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What could superconductors do for wind turbine drive trains?

- Current mindset:
  - Geared drive trains are lightweight, cost efficient, and proven.

    Vs.
  - Direct drive has no fault-prone gearbox: It is thus preferable, and therefore it is higher Capex

- Superconductor mindset:
  - Direct drives are lightweight, cost effective and reliable.

- **However, is this realistic?**

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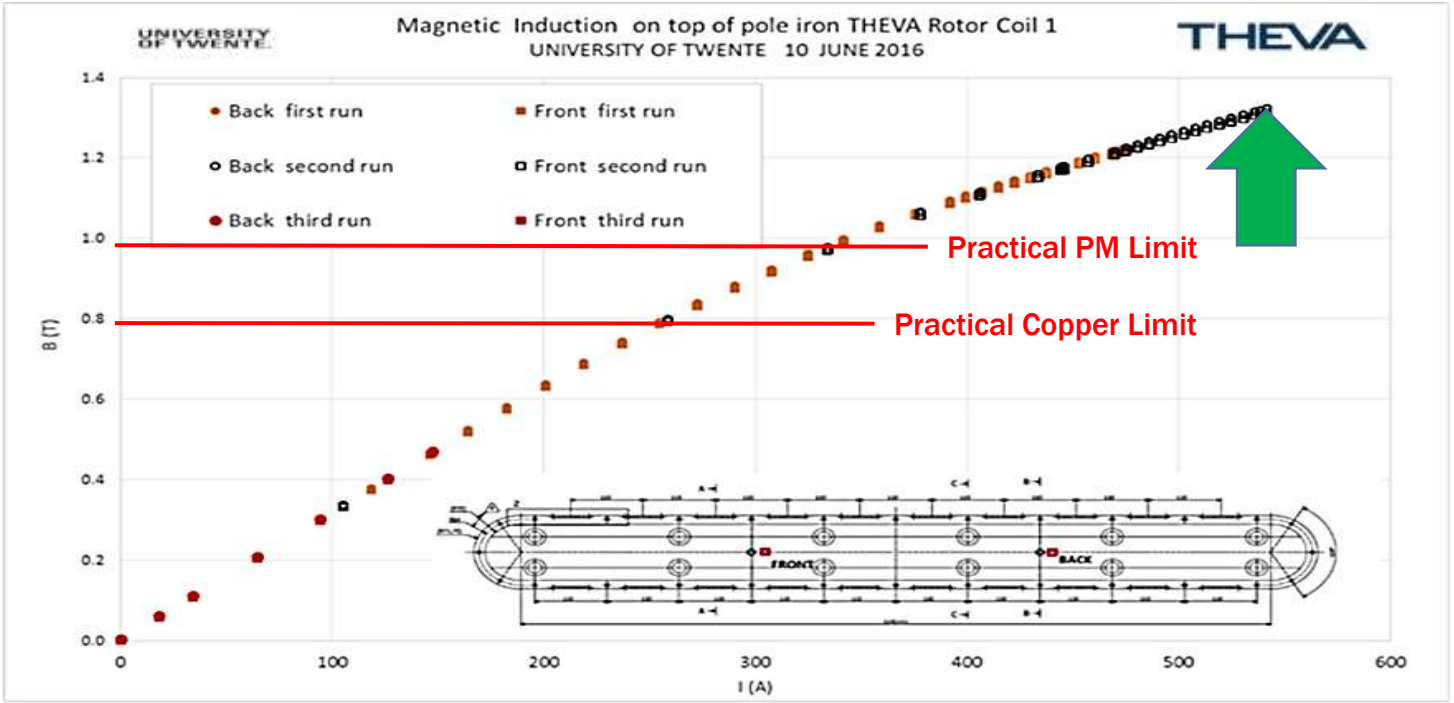
Very Powerful Operation of the Superconductor Coils

Magnetic flux verified to exceed permanent magnets and copper coils



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Expectations and motivation
Market driven motivations for using HTS

- As power sizes go up Permanent Magnet Generator (PMG) beat Doubly Fed Induction Generator with gearboxes (DFIG)
  - Large DFIG becomes too heavy and too costly to maintain
  - Direct Drive (DD) have less maintenance, higher part load efficiency, better scalability
  - **The future of big wind turbine drivetrains belongs to DD machines i.e. without gearboxes**
- Future wind turbines are on floating platforms i.e. top mass must go down
  - Future drivetrains must be significantly lighter relative to existing DD solutions
  - High power density, low costs and low weight are the benchmarks for the future
  - **PMG technology is at the moment the only candidate.**

Superconductor Generators shows bigger potential than PMG as the wind turbines grows in power

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Core ambitions

- Design, develop and manufacture a full scale multi-megawatt direct-drive superconducting wind generator
- Install this superconducting drive train on an existing modern wind turbine in Thyborøn, Denmark
  (3.6 MW, 15 rpm, 128 m rotor)
- Prove that a superconducting drive train is cost-competitive

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Platform for technology validation

- **Program:** EU Horizon 2020
- **Reference:** 656024
- **Start Date:** 2015-03-01
- **End Date:** 2019-03-01
- **Total Cost:** EUR 13,846,594
- **EU Contribution:** EUR 10,591,734.

- The idea is to replace a PM generator with a superconducting generator
- This includes power conversion and refrigeration equipment.

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Integrated consortium

- 9 Partners from 5 countries working for a common goal

ENVISION

ECC 5

JEUMONT Electric

DELTA ENERGY SYSTEMS

THEVA

SHI Cryogenics Group

Fraunhofer

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- Project web site: www.ecoswing.eu

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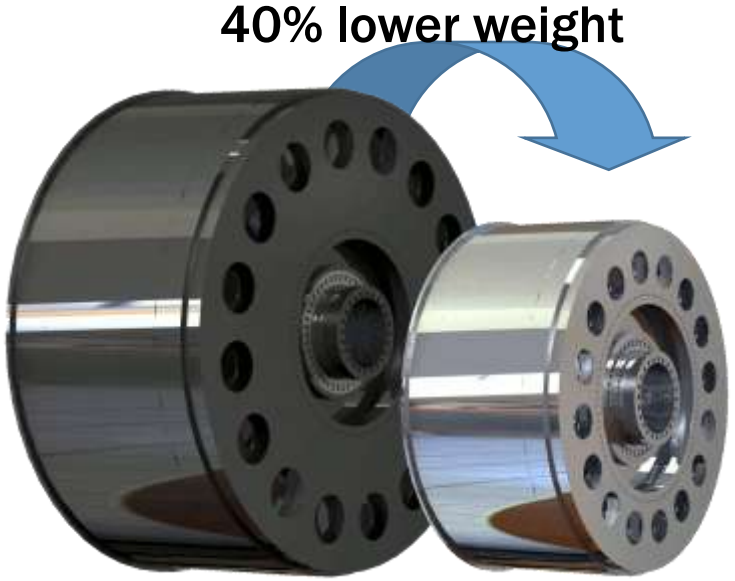
Main design goals



Existing PM in GC-1 Superconducting

- **All roads capability:** diameter limited to < 4 m
- **Low cost design:** Commercial components for superconductors as much as possible
- **Low weight design:** Optimized for low top head mass
- **Mainstream markets:** 3.6 MW for on-shore and off-shore.

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EcoSwing generator
Design specifications

	Design Specification
Generator terminal power	3.6 MW
oD generator frame	4,000 mm
Rated speed	15.0 rpm
Stator type	With iron core sheets
Stator primary cooling	Radial air cooling
Stator voltage	710 V
Axial core length	1,142 mm
Stator coils	Form wound copper coils, mica insulation system, VPI, class F
Bearings	2 main
Free mechanical air gap	13 mm
HTS wire dimensions, bare	12 x 0.2 mm^2
Current density in HTS pack	~ 100 A/mm^2
Efficiency (rated)	~ 92%
Current loading	132 kA/m
Cogging torque	< 0.5%
Load torque ripple	< 1.5%
THD stator voltage	~ 1 %

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Superconducting coils

- 500 m of high performance superconductor
- Potted using commercial resin, glass fiber reinforced
- Steel package for bolt mounting
- Operating temperature ~30 K (-240 °C)
- Conduction cooled with cold heads.

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Cooling of Coils

- Conduction cooling by commercial cryogenic equipment
- No liquid cooling
- Only a few grams of cooling gas for the entire superconducting rotor.

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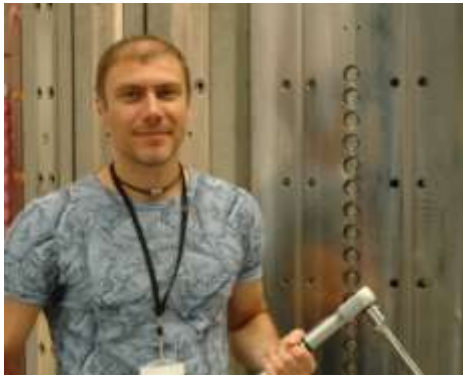
SHI Cryogenics Group

Assembly at Jeumont
Stator, superconducting rotor, cast shaft



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Assembly at Jeumont

Stator, superconducting rotor, full converter

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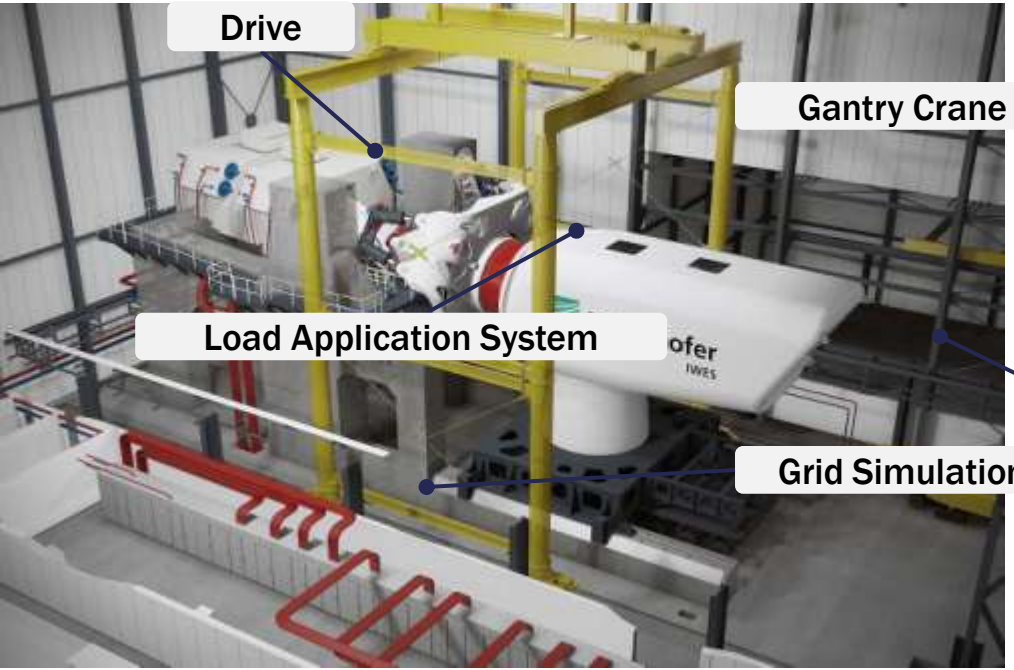
JEUMONT Electric

Ground based test at Dynamic Nacelle Laboratory



- Fraunhofer IWES execute tests in its DyNaLab facility
  - Nacelle testing lab
  - Max torque 13 MNm
  - Max power 15 MW.

Bremerhaven, Germany

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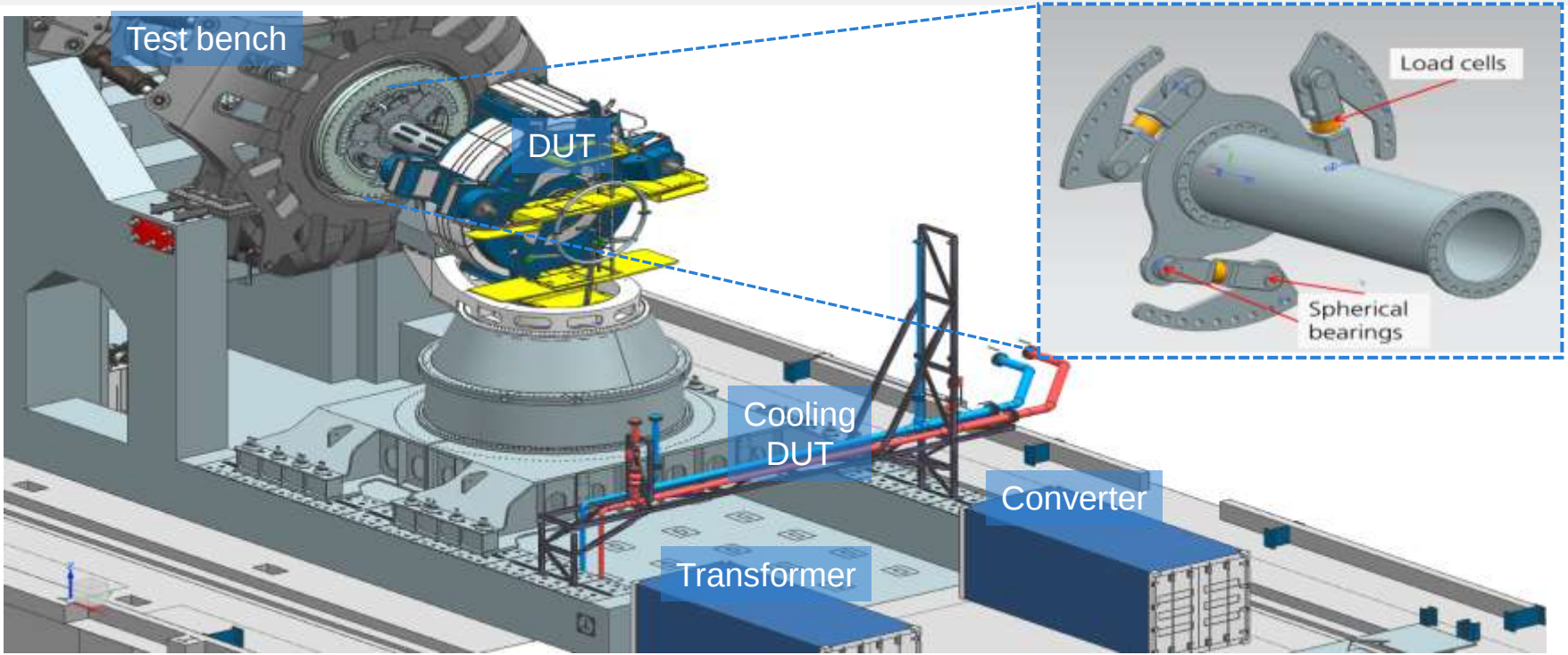
Ecoswing test setup



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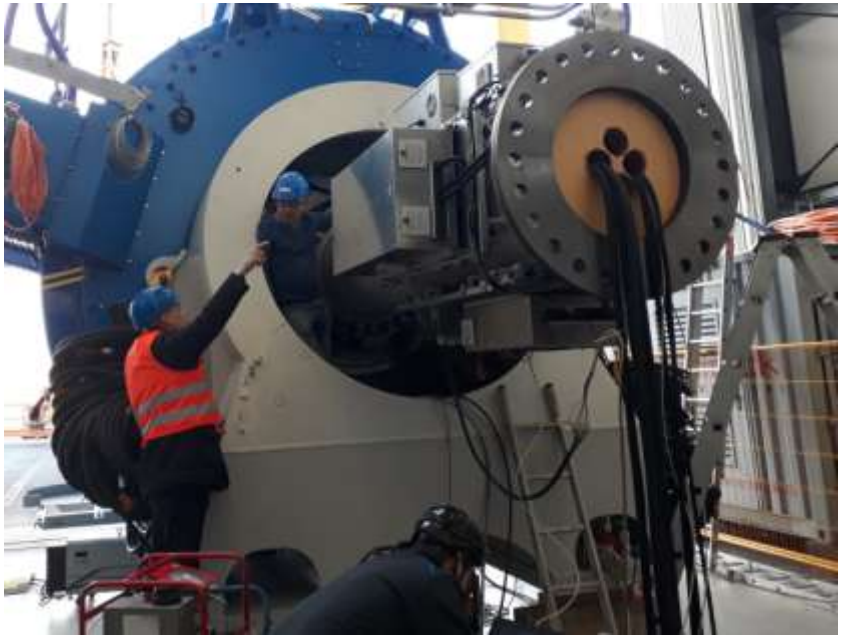
Assembly at IWES
Hall, EcoSwing generator



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Assembly at IWES
Lifting, Installation at DyNaLab

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GC-1 wind turbine site
Nissum Bredning, Thyborøn, Denmark

- The GC-1 site is located nearshore to Nissum Bredding, which connects to the North Sea.
- GC-1 site is indicated as well as the route of the ship from Bremerhaven with the EcoSwing generator.
- Close to the GC-1 there are docking facilities.
- Deep water and suitable for docking of a ship.

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Some perceived and real risks of using superconductors

ecoswing

Risk	Priority	Reason
Superconducting machines will not work	Low	Many prototypes and many commercial applications prove that superconductors work
Cryogenics are too complex	Low	Cryogenics is an established industry (MRI scanners, LNG tankers…)
Superconducting wire not available at low enough cost	High	Like semiconductors the price is extremely sensitive on volume. Chicken and egg problem. Need to form supply chain alliances
Superconductivity is an unknown to the engineering people in a specific subject	Medium	In the wind industry there is no established design base existing.

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Technology entry barriers as seen by a potential end-user

- Superconductor cost is much too high
  - Establish stable alliancies with manufacturers of superconductors
- Cryogenics need to be hardened for harsh wind climates
  - Demonstrate to the manufacturers that wind can be an important market for cryogenics
- Technology viewed as complex
  - We need to be open to technology changes—complexity per se is neither good, nor bad (compare IC to radio bulb)
  - However, reliability is absolutely important

It is thus difficult to predict a market model (and consequently to jump with both feet into superconductivity)

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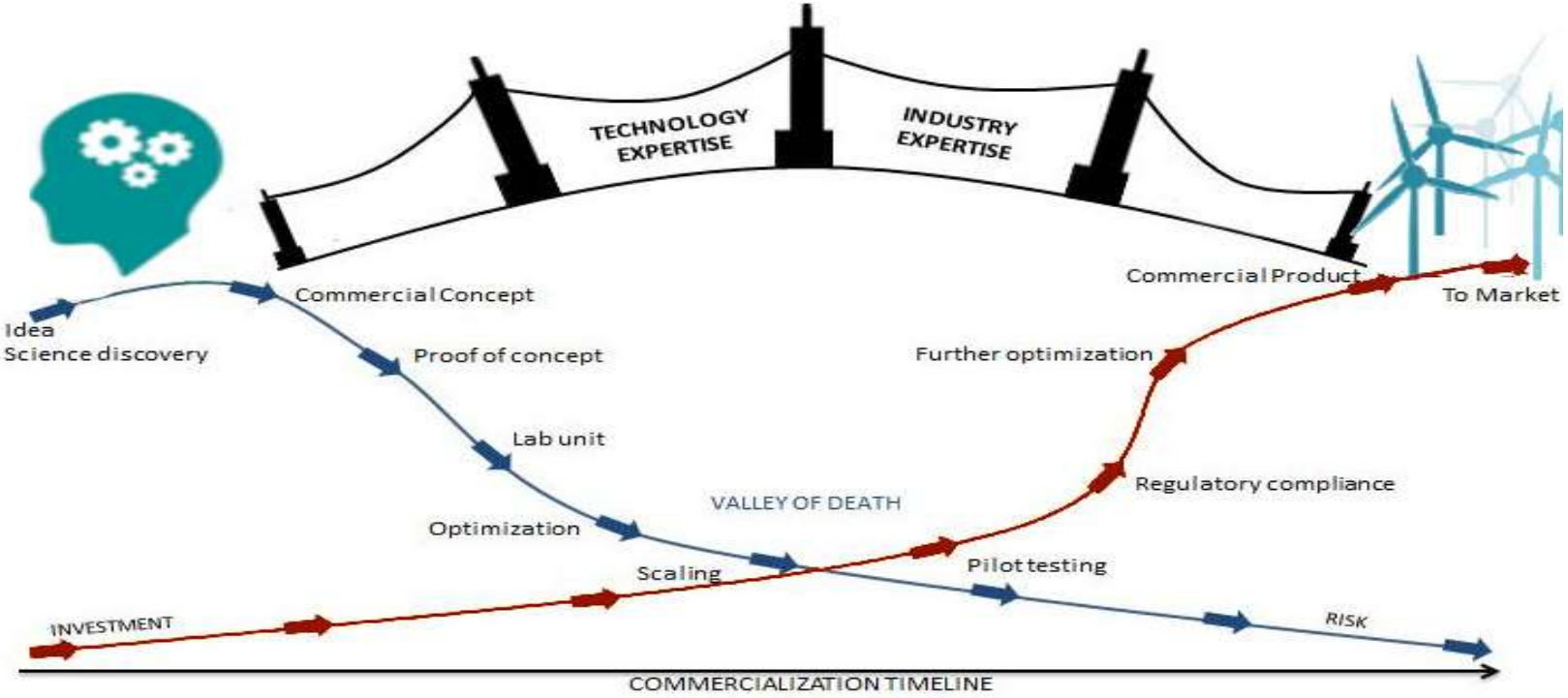
Building bridges to successful commercialization



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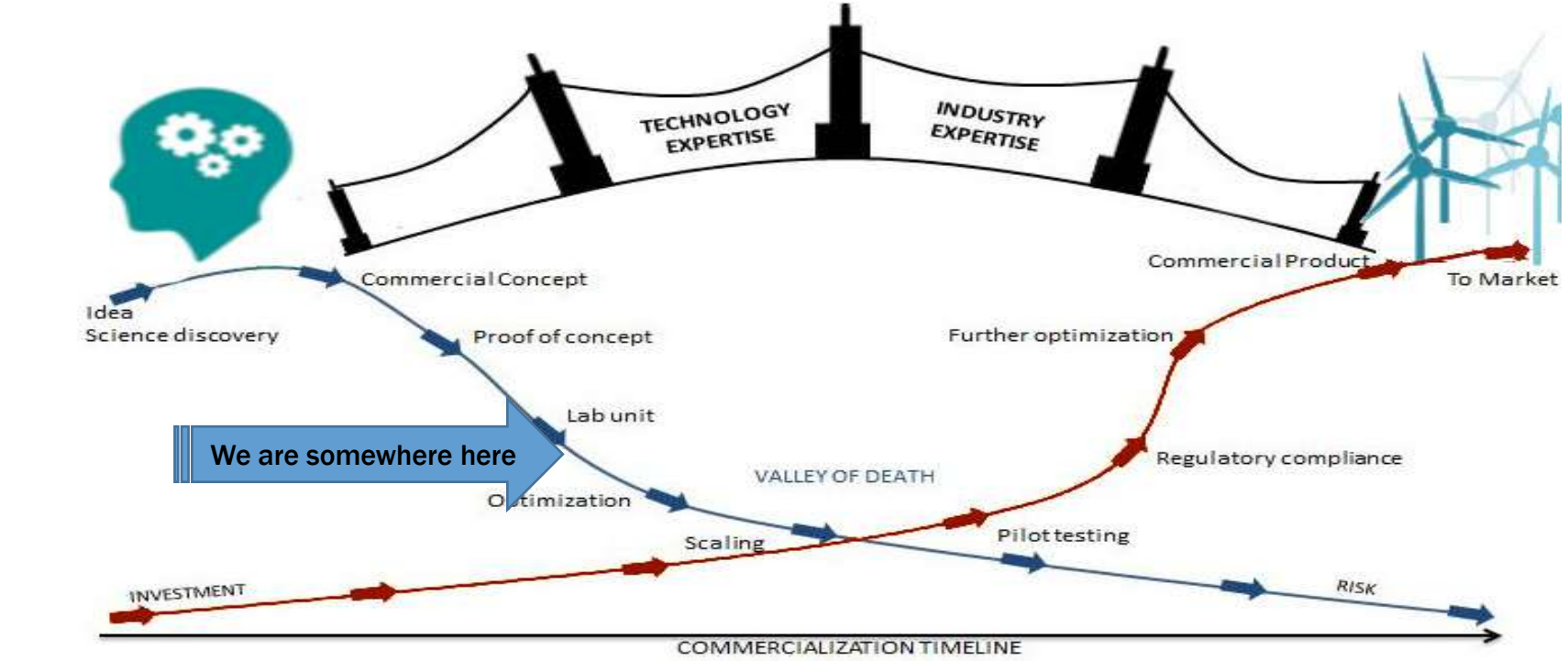
The quest is not over…
…but we are faithfully moving on



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Conclusion

- Superconductive generators could become technically and financially interesting
  - There is significant development effort Europe-wide (and world-wide, too)
  - For commercial application in the wind market, superconductivity needs to solve a supply-chain problem
- Please watch out for the results at IWES and for the turbine installation
- Follow us on www.ecoswing.eu

The best way to predict the future - is to invent it
(Alan Curtis Kay)

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