Dynamic Cable Rating of AC export cables for Offshore Wind Farms applications

Baltic InteGrid
Integrated Baltic Offshore Wind Electricity Grid Development

Juan-Andrés Pérez-Rúa
DTU Wind Energy
Copenhagen - Denmark
23rd May, 2018

DTU

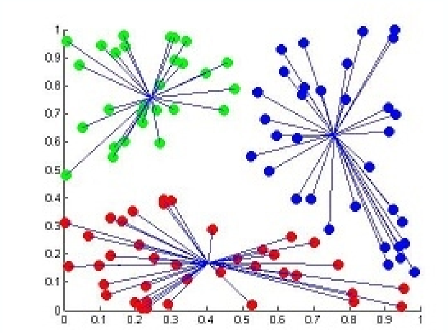
EU STRATEGY FOR THE BALTIC SEA REGION FLAGSHIP

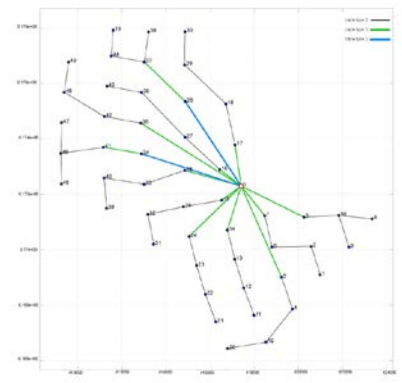
Interreg Baltic Sea Region

EUROPEAN UNION
EUROPEAN REGIONAL DEVELOPMENT FUND

Agenda

1 THE OFFSHORE WIND FARM ELECTRICAL SYSTEM DESIGN AND OPTIMIZATION PROBLEM





Source: Fischetti, Martina, and David Pisinger. "Optimizing wind farm cable routing considering power losses." *European Journal of Operational Research* (2017).

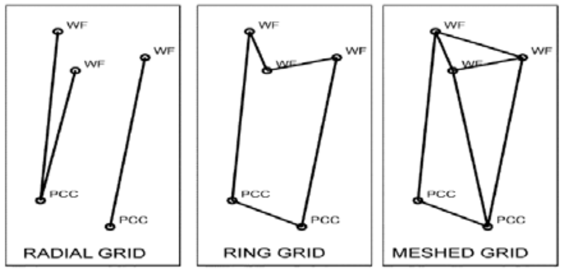
Given a large-scale offshore wind farm with coordinates location of WTs, geographical and meteorological information of the site under study

1) Determine the number and location of OSSs and allocate each WT to a OSS

2) For each sub-group optimize the CS (Collection System)

3) For each sub-group optimize the TS (Transmission System)

4) Determination of the optimal connection between OSSs



Ergun, Hakan, Dirk Van Hertem, and Ronnie Belmans. "Transmission system topology optimization for large-scale offshore wind integration." IEEE Transactions on Sustainable Energy 3.4 (2012): 908-917.

Given a large-scale offshore wind farm with coordinates location of WTs, geographical and meteorological information of the site under study

↓

This is given in the BIG project → **1) Determine the number and location of OSSs and allocate each WT to a OSS**

↓

2) For each sub-group optimize the CS (Collection System)

↓

3) For each sub-group optimize the TS (Transmission System)

↓

This is important for meshed networks and should take into account market prices → **4) Determination of the optimal connection between OSSs**

Given a large-scale offshore wind farm with coordinates location of WTs, geographical and meteorological information of the site under study

1) Determine the number and location of OSSs and allocate each WT to a OSS

2) For each sub-group optimize the CS (Collection System)

3) For each sub-group optimize the TS (Transmission System)

4) Determination of the optimal connection between OSSs

We focus on this

1 THE OFFSHORE WIND FARM ELECTRICAL SYSTEM DESIGN AND OPTIMIZATION PROBLEM

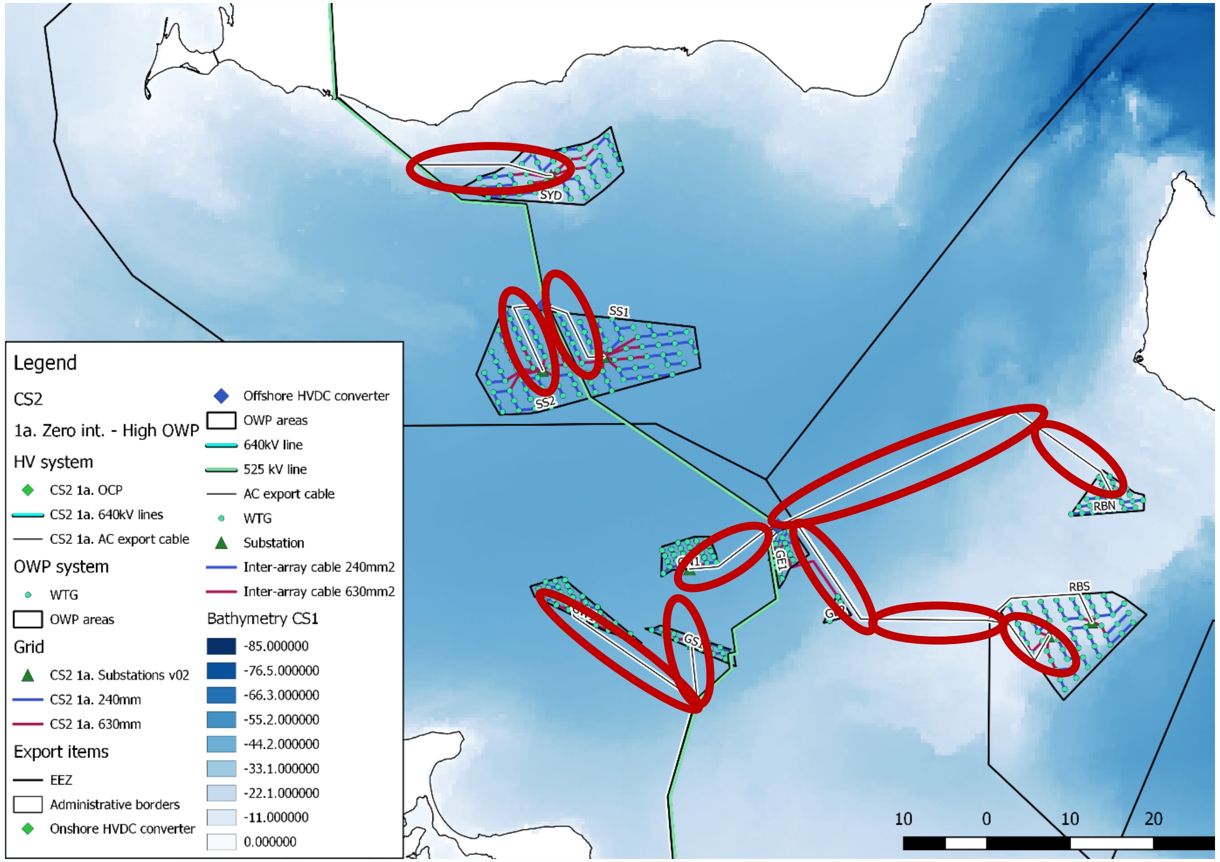
2 OPTIMIZING THE AC EXPORT CABLE OF OWF: THE PROBLEM DEFINITION

3 OPTIMIZING THE AC EXPORT CABLE OF OWF: THE PROPOSED METHODOLOGY

4 APPLICATION TO CASE STUDIES IN THE BALTIC INTEGRID PROJECT

5 SUMMARY

Optimization target: AC Transmission Cables

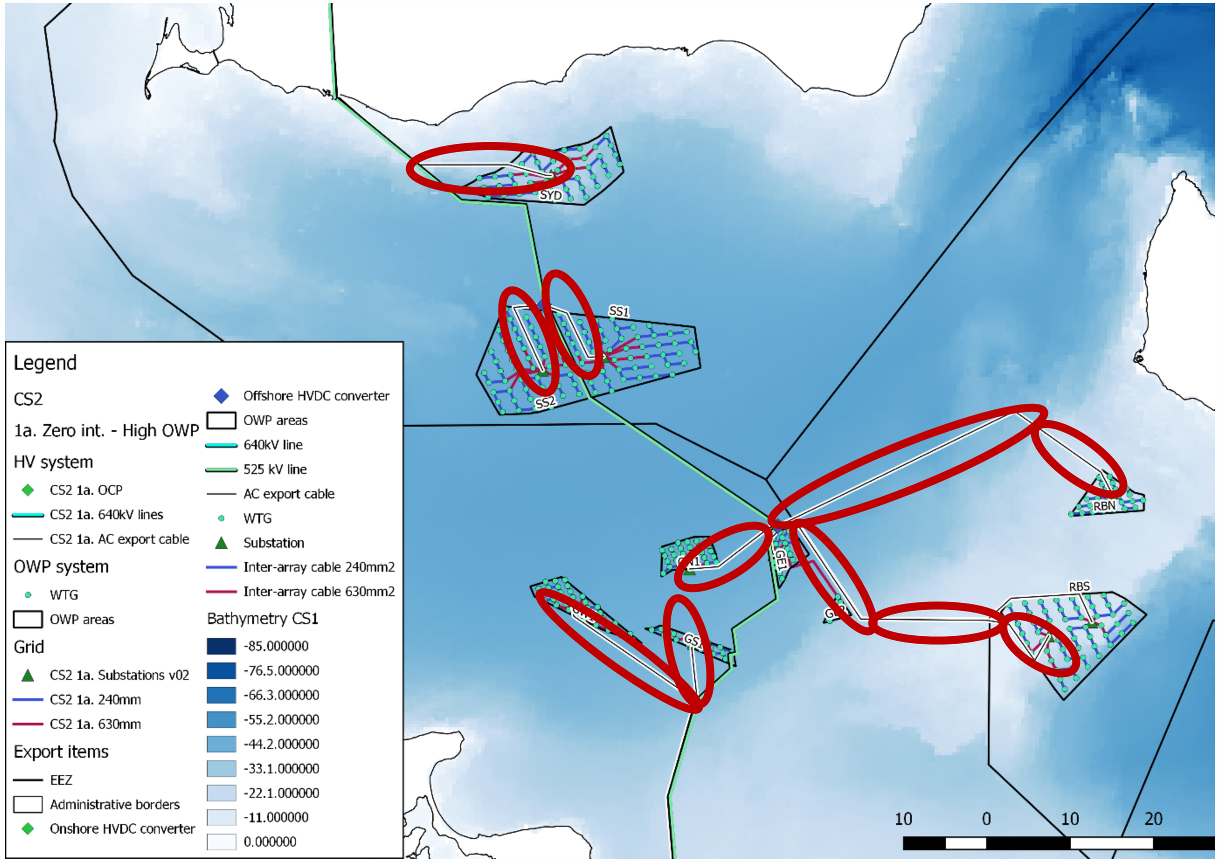


Case study 2 (Germany – Sweden – Denmark)
Partial Integration and High OWP

AC Transmission Cable

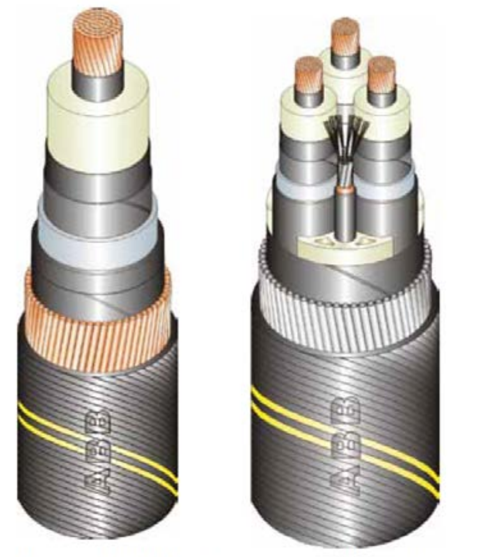
- OWF direct connection to shore or ACDC converter
- Power flow given by the OWF production
- Simulation of OWF power generation drives to simulation of cable power flow

Optimization target: AC Transmission Cables



Case study 2 (Germany – Sweden – Denmark)
Partial Integration and High OWP

AC Transmission Cable



A transmission cable is defined by:

- **Conductor cross-section**
- **Insulator material and geometrical features**
- Mechanical and electrical protective layers
- Jacket material

2 Optimizing the AC export cable of OWF: the problem definition

Single-core cable with lead sheath and wire armour

Three-core cable with optic fibers, lead sheath and wire armour

How to size a transmission cable?

According to IEC-60287 model

- Static equation dependent on: physical installation conditions, soil thermal resistivity, cable materials thermal information and ambient temperature.
- Positively correlated variables: $I_C \rightarrow T_C$.
- Maximimize I_C by considering $T_C = 90$ °C.

Single-core cable with lead sheath and wire armour

Three-core cable with optic fibers, lead sheath and wire armour

How to size a transmission cable?

Challenge with IEC-60287 model

- Acceptable and practical for traditional power systems.
- It is not optimal for Offshore Wind Farms (capacity factors ≈ 0.4 – 0.5)

Solution

- **Dynamic Sizing of cables** considering the restricting factor of **conductor temperature** (to maximize the lifetime of the insulator).

Single-core cable with lead sheath and wire armour

Three-core cable with optic fibers, lead sheath and wire armour

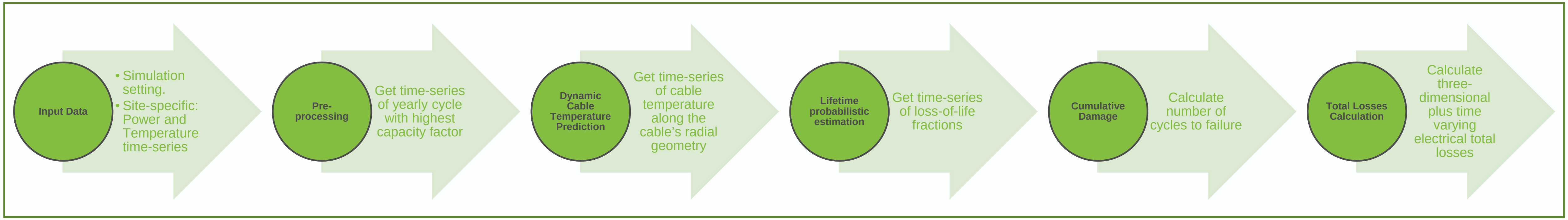
How to size a transmission cable?

What the new criterion should include?

- The **dynamics of the system** and time-varying variables.
- The **capacitive currents**.
- A **probabilistic lifetime estimation of cables**.

Agenda

The proposed methodology

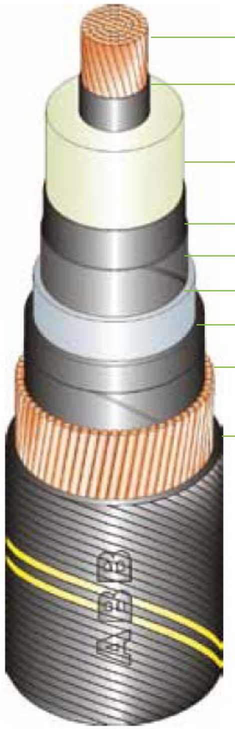


Lifetime Estimation and Performance Evaluation Framework (LEPEF)

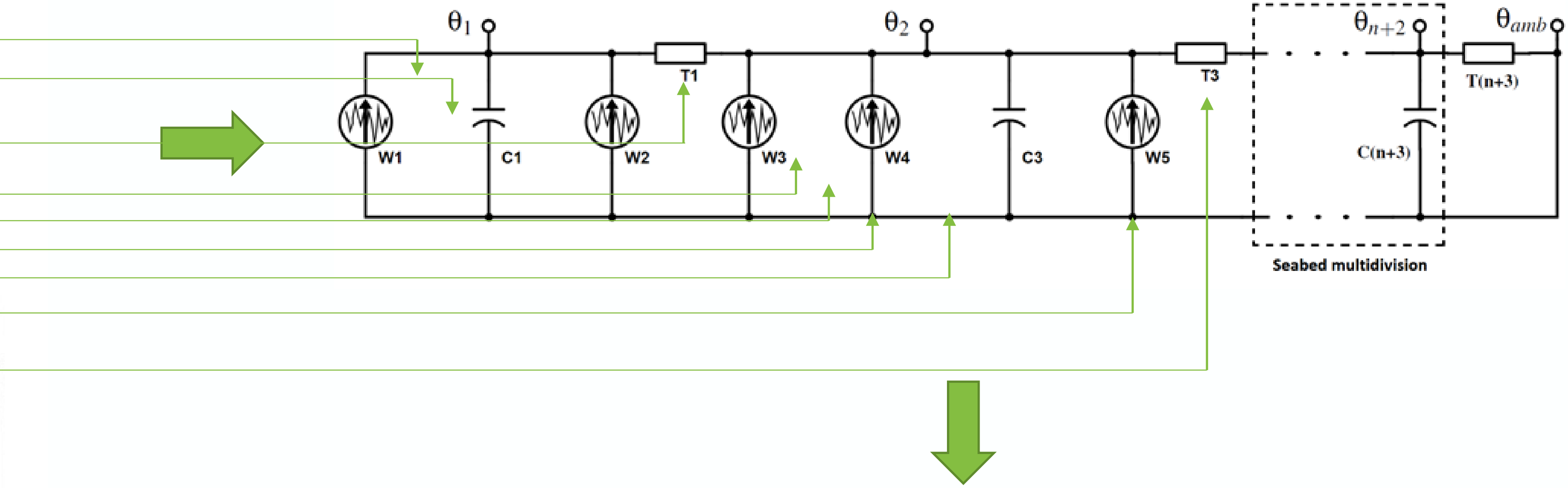
Dynamic Cable Temperature Prediction

- Thermo-Electrical Equivalent Model

Thermo-Electrical Equivalent (TEE) circuit model for a single-core HV submarine cable



Single-core cable with lead sheath and wire armour



$$
\begin{bmatrix} \dot{\theta}_{n+2} \\ \dot{\theta}_{n+1} \\ \vdots \\ \dot{\theta}_3 \\ \dot{\theta}_2 \\ \dot{\theta}_1 \end{bmatrix} = \begin{bmatrix}
-\left(\frac{1}{T(n+2)C(n+3)} + \frac{1}{T(n+3)C(n+3)}\right) & \frac{1}{T(n+2)C(n+3)} & 0 & \cdots & 0 & 0 & 0 & 0 \\
\frac{1}{T(n+1)C(n+1)} & -\left(\frac{1}{T(n)C(n+1)} + \frac{1}{T(n+1)C(n+1)}\right) & \frac{1}{T(n)C(n+1)} & \cdots & 0 & 0 & 0 & 0 \\
\vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
0 & 0 & 0 & \cdots & \frac{1}{T4C4} & -\left(\frac{1}{T3C4} + \frac{1}{T4C4}\right) & \frac{1}{T3C4} & 0 \\
0 & 0 & 0 & \cdots & 0 & \frac{1}{C3T3} & \frac{-1}{C3}\left(\frac{1}{T1} + \frac{1}{T3}\right) & \frac{1}{T1C3} \\
0 & 0 & 0 & \cdots & 0 & 0 & \frac{1}{T1C1} & \frac{-1}{T1C1}
\end{bmatrix} \times \begin{bmatrix} \theta_{n+2} \\ \theta_{n+1} \\ \vdots \\ \theta_3 \\ \theta_2 \\ \theta_1 \end{bmatrix} + \begin{bmatrix} \frac{\theta_{amb}}{T(n+3)C(n+3)} \\ 0 \\ \vdots \\ 0 \\ \frac{1}{C3}(W2 + W4(P_{series_y}) + W5(P_{series_y})) \\ \frac{1}{C1}(W3 + W1(P_{series_y}))) \end{bmatrix}
$$

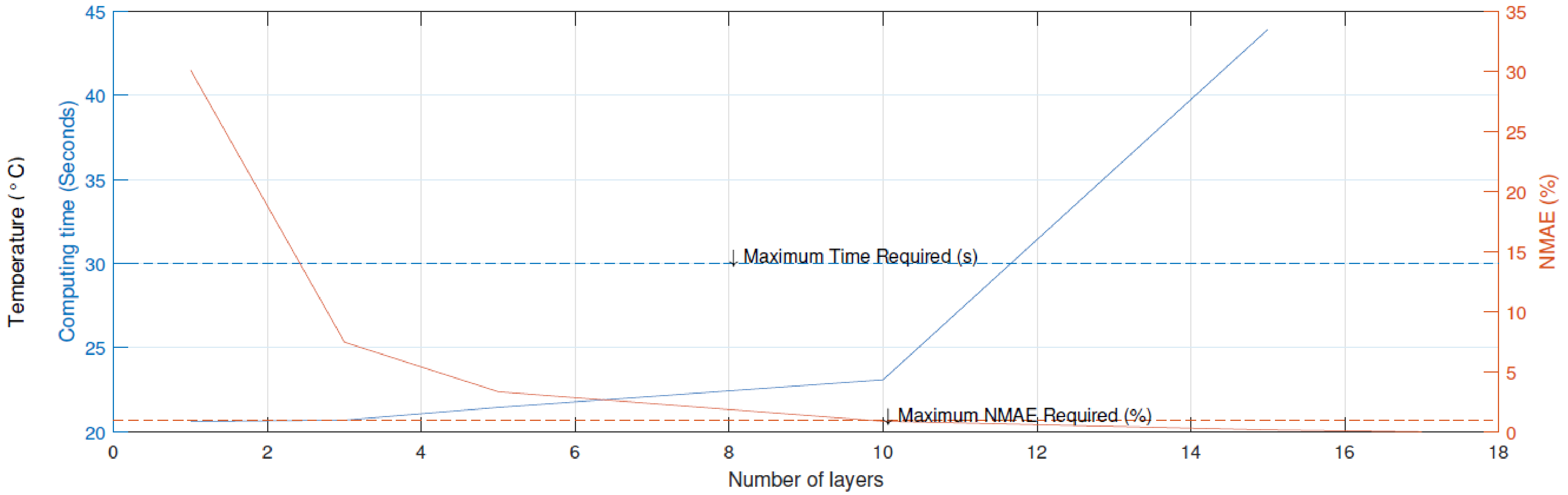
system of ordinary differential equations (ODE)

Dynamic Cable Temperature Prediction

➢ Thermo-Electrical Equivalent Model:

Calibrating the model for a Cable XLPE-245 kV-630 mm^2

Multidivision of the seabed around the cable



NMAE vs computational time of the cable temperature calculation for synthetic input data

Lifetime Probabilistic Estimation

- Arrhenius-IPM

$$L_D(E,T,P_D) = \left[\frac{-\ln(1-P_D)}{D}\right]^{\frac{1}{\beta_t}} \cdot \alpha_0 \cdot e^{\left(-B\left(\frac{1}{T_0}-\frac{1}{T}\right)\right)} \left(\frac{E}{E_0}\right)^{-\left(n_0 - b\left(\frac{1}{T_0}-\frac{1}{T}\right)\right)}$$

$$D = \frac{l_D}{l_T} \cdot \left(\frac{r_D}{r_T}\right)^2$$ → Probabilistic enlargement failure law

P_D → Failure probability [p.u]

T → Conductor temperature [K] = T_C (t) : (Power(t), distance)

E → Electric field [kV/mm]

L_D → Lifetime prediction [hours]

Cumulative damage

- Miner's law

$$K = \frac{1}{\sum_{k=1}^{h} LF_k}$$

LF_k → Loss-of-life fractions in a cycle step [p.u]

K → Number of cycles to failure

Total losses calculation

- More holistic approach

$$TL = \sum_{l=1}^{l_{D_T}} \sum_{k=1}^{h} R_c(l,k) \cdot I(l,k)^2$$

$I(l,k)$ → Current [A]. (Function of the distance and time)

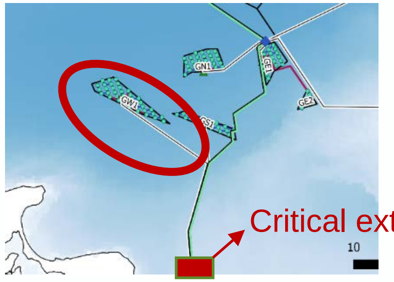
$R_c(l,k)$ → Conductor resistance [Ohm]. (Function of the distance and time)

TL → Total losses [MWh]

Agenda

Dynamic Temperature Cable Prediction

Optimization target:
AC Transmission Cables



Case study 2 (Germany – Sweden – Denmark)
Partial Integration and High OWP

Arcadis Ost 1 (GW1) OWF

Total Installed Capacity = 456 MW

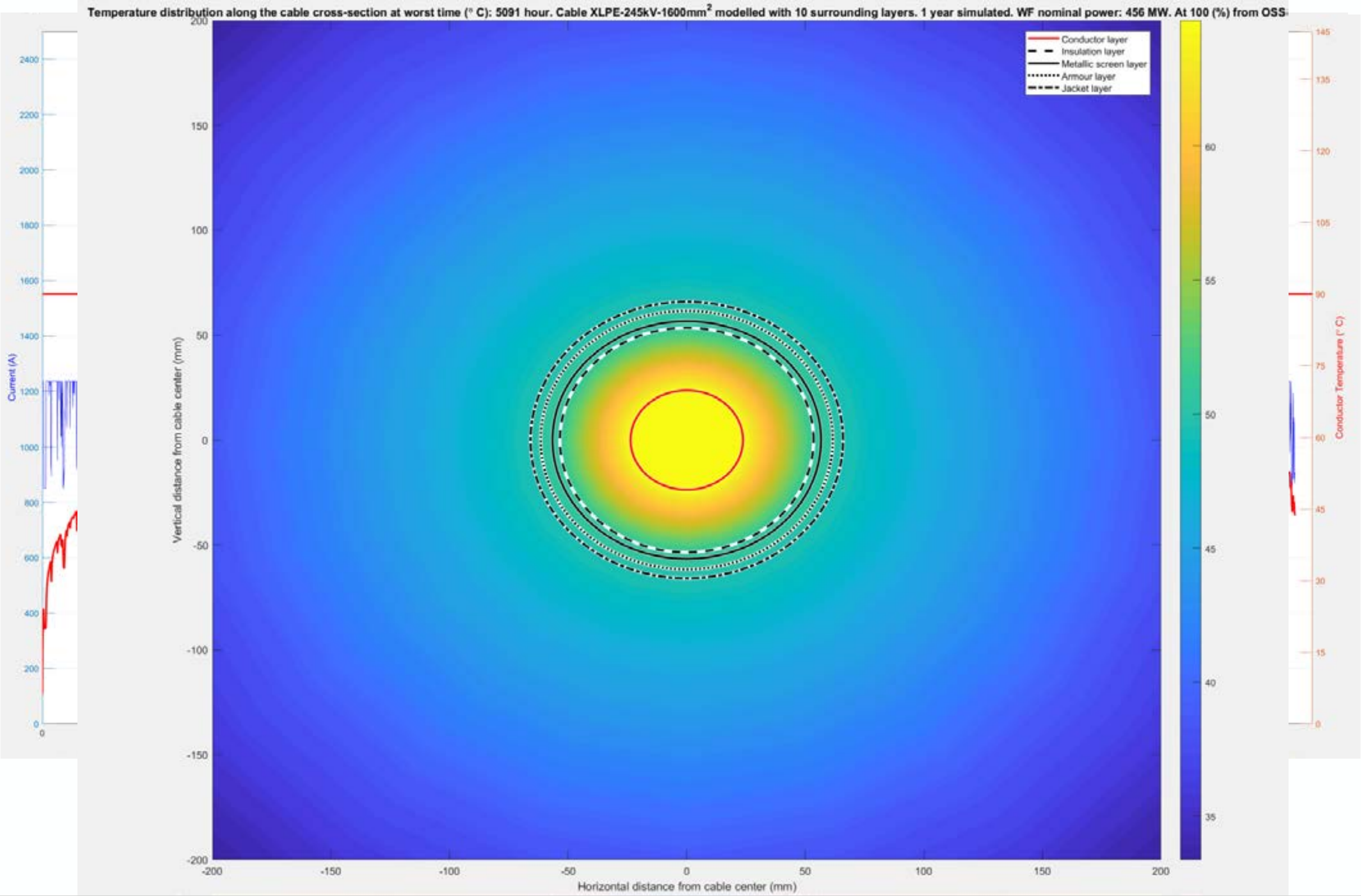
Export cable size = **XLPE 1600 mm²**

Length = 89.71 km

2-meters above sea Temperature Time Series (year 2007)

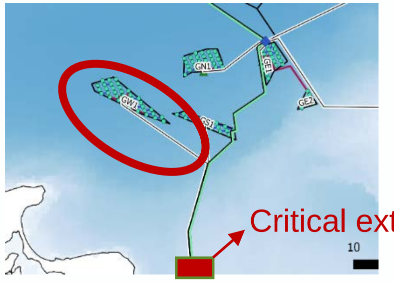
Conductor Temperature Dynamic Response

Observe the yearly variations of the boundary temperature. Spanning [-3 °C ,– 22 °C]



Dynamic Temperature Cable Prediction

Optimization target:
AC Transmission Cables



Case study 2 (Germany – Sweden – Denmark)
Partial Integration and High OWP

Arcadis Ost 1 (GW1) OWF

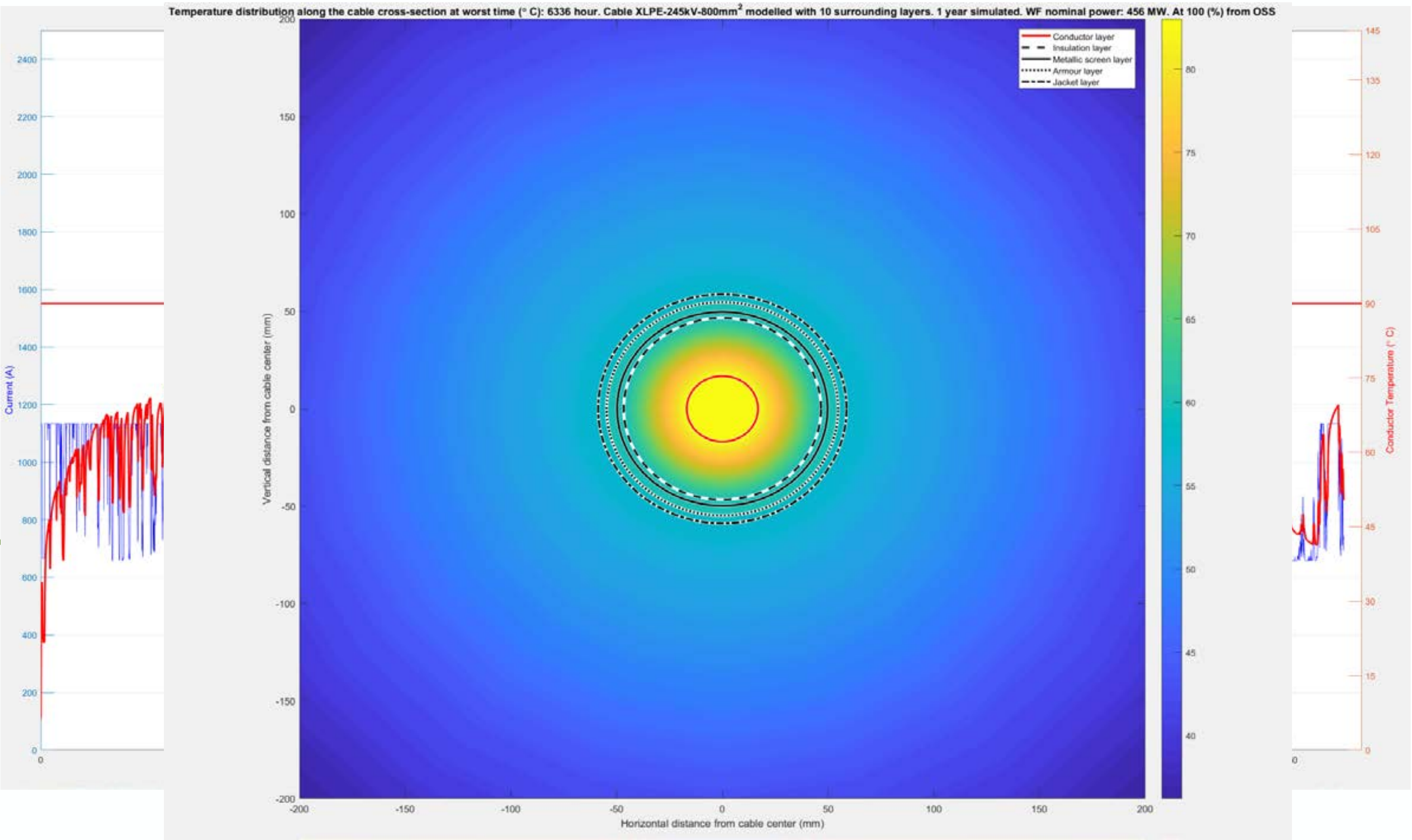
Total Installed Capacity = 456 MW

Export cable size = **XLPE 800 mm²**

Length = 89.71 km

Conductor Temperature Dynamic Response

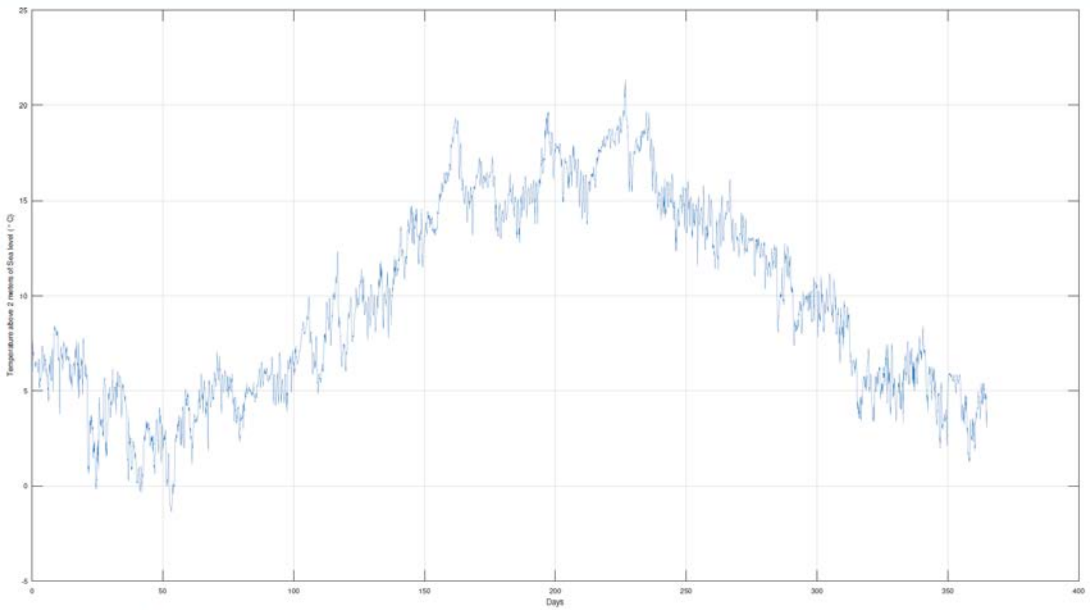
2-meters-above-Sea Temperature Time Series (year 2007)



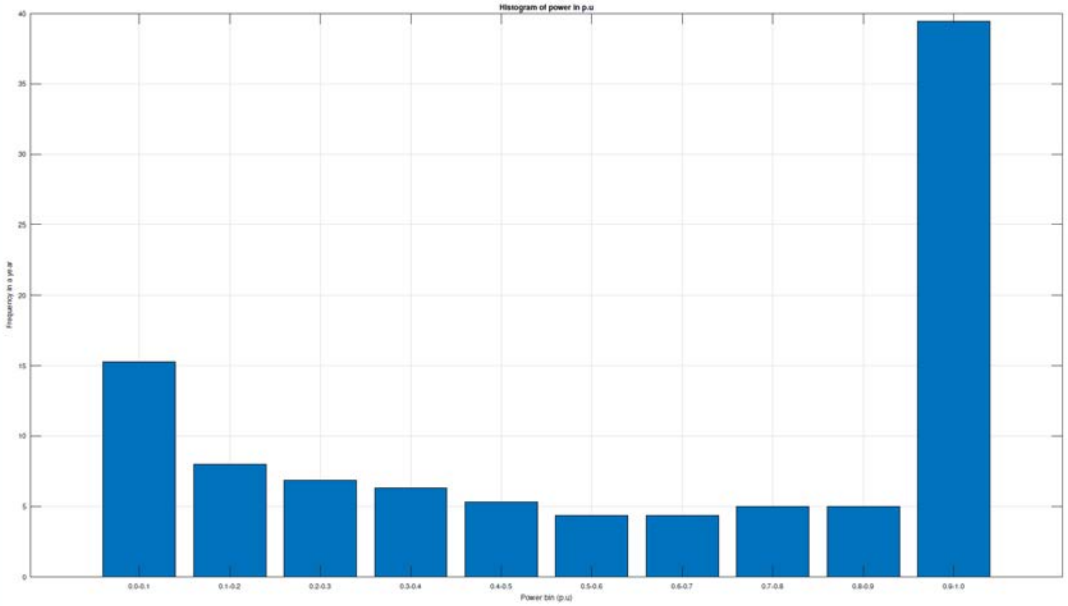
Three OWFs applications with **Dynamic Temperature Cable Prediction**

OWF	Power (MW)	Distance (km)	Cable & Max Temp. (IEC Methodology)	Cable & Max Temp. (Proposed Methodology)	Percentage cost saving (%)
GW1	456	89.71	1600 mm^2 @ 65 °C	**800** mm^2 @ 83 °C	35
RBN	216	18.54	630 mm^2 @ 35 °C	**500** mm^2 @ 38 °C	10
SS2	600	41.79	1600 mm^2 @ 72 °C	**1200** mm^2 @ 83 °C	17

Dynamic Temperature Cable Prediction + Lifetime Probabilistic Estimation + Cumulative Damage



2 meters-above-sea temperature time-series

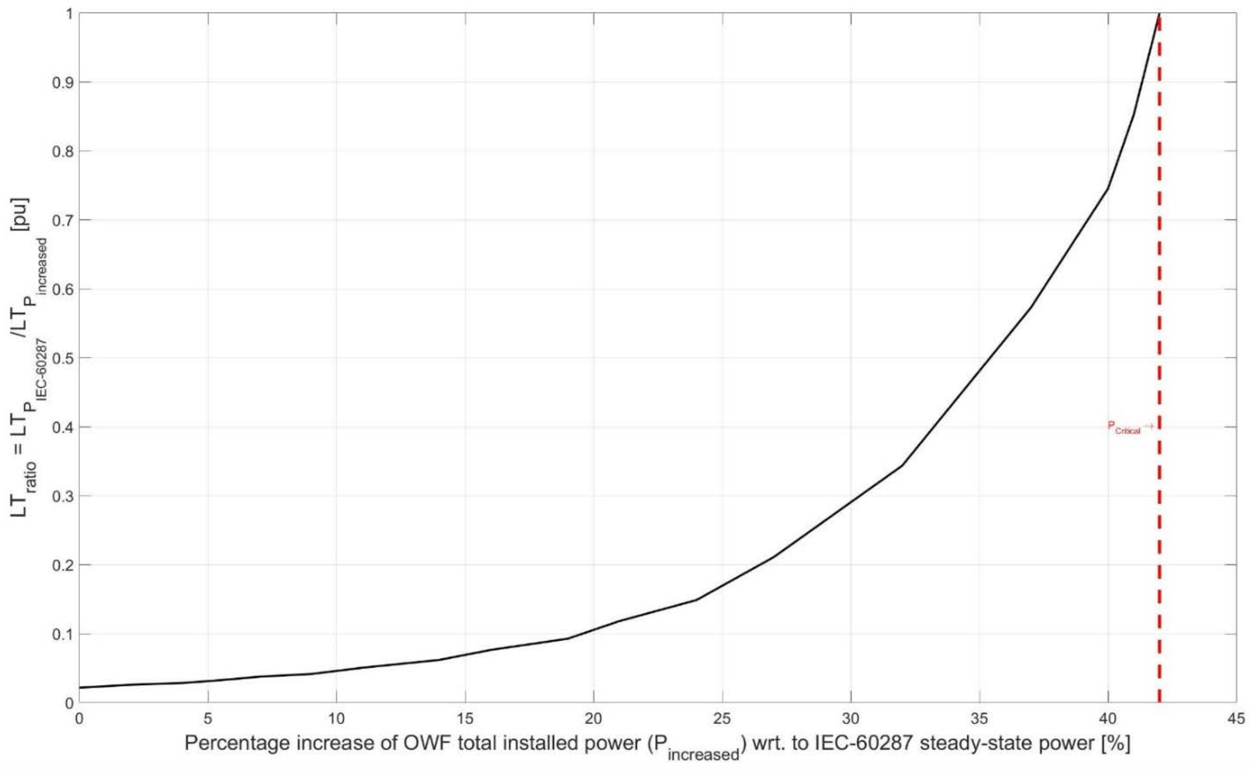


Power generation histogram

RBN OWF temperature and power generation time-series

Dynamic Temperature Cable Prediction + Lifetime Probabilistic Estimation + Cumulative Damage

- Results for a cable 630 mm² XLPE-245 kV and total length 50 km.
- Based on cable with lifetime of 30 years, failure probability of 5%, 1 km total length, operating at continuous rated conditions ($T_n = 90°$ and $E_n = 12.20\ kV/mm$)



An increase of 42% of transmissible power can be achieved!

Agenda

5 SUMMARY

- The current criterion used for sizing AC cables for OWF applications is outdated.

- By means of the proposed methodology, the maximization of cables power transmission capability for OWF applications has been achieved, respecting the maximum degradation allowed to the cable insulation.

- Remarkable potential economic savings/incomes can be achieved by means of optimum sizing of AC submarine cables.

- Future works will be focused on

- Extending the methodology for different technologies of AC cables.
- Extending this methodology for sizing DC cables.
- Application of different probabilistic lifetime estimation models and sensitivity analysis of them.
- Extending the methodology for applications in real time with sensing of time-dependent variables, such as the thermal resistivity of the soil, the specific heat of the soil, the power generated and others.

© 50Hertz

Questions & Discussions

Thank you

© EnBW