OFFwind – Offshore Wind Turbine Farms

October 2022 – October 2025

Interreg Aurora
Co-funded by the European Union

MERINOVA TECHNOLOGY CENTRE
Tampereen yliopisto Tampereen ammattikorkeakoulu
YRKESHÖGSKOLAN NOVIA
LULEÅ TEKNISKA UNIVERSITET
SINTEF
LAPIN LIITTO

OFFwind basic facts

- **PRIORITY**
  Smart and sustainable growth
- **SPECIFIC OBJECTIVE**
  Smart specialization, research and innovation
- **TOTAL PROJECT BUDGET**
  1 374 000 Euro

The OFFwind project contributes primarily to the following UN Sustainable Development Goals:

7 AFFORDABLE AND CLEAN ENERGY

13 CLIMATE ACTION

Goals and aims of the project

The overall objective of the OFFwind project: *To boost the uptake of offshore wind energy in the Aurora area by overcoming the arctic challenges.*

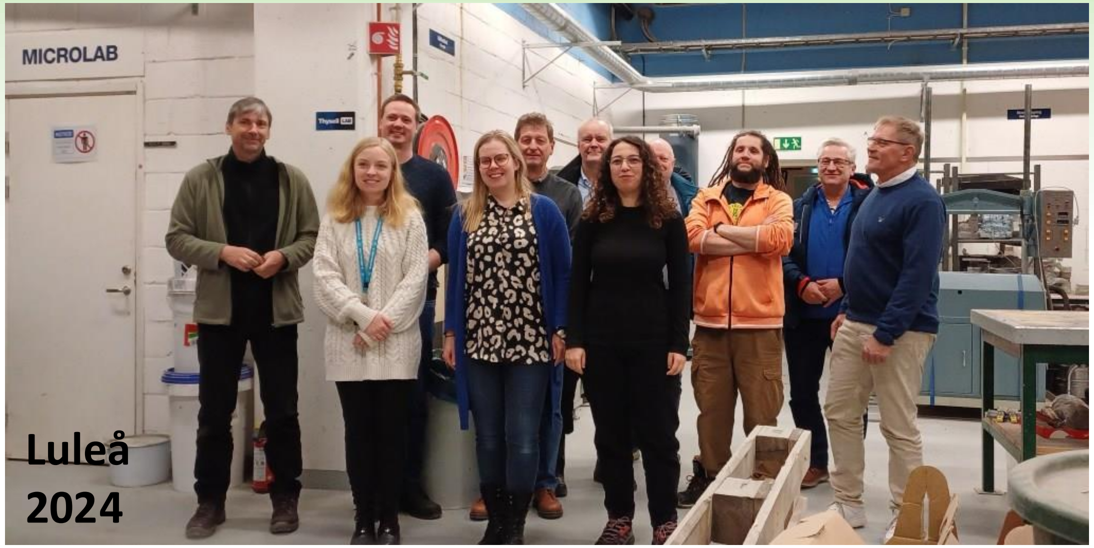
OFFwind aims at providing solutions, through case studies, to the limiting arctic challenges caused by harsh weather conditions (ice, wind, waves, snow) by developing methods and models to reduce the effect of these; deicing methods, ice mechanical models for ice to structural interaction and dimensioning criteria, assessing wind and waves forces and loads, seabed conditions and access to farms and use of zero-carbon emitting building materials.

A consortium that provides complimentary skills to the project

- Concrete technology (LTU, SINTEF Narvik, NOVIA)
- Ice conditions (SINTEF/LTU)
- Ice mechanical & ice - structural interaction (SINTEF Narvik, LTU)
- Dimensioning criterias, access/ice conditions, icing and /deicing (TAU, LTU, NOVIA)
- Surface modifications and coatings (TAU)
- Wave forces (SINTEF)

Interreg Aurora
Co-funded by the European Union

Many online meetings and yearly meet-ups



MERINOVA TECHNOLOGY CENTRE · Tampereen yliopisto Tampereen ammattikorkeakoulu · YRKESHÖGSKOLAN NOVIA · LULEÅ TEKNISKA UNIVERSITET · SINTEF · LAPIN LIITTO

Interreg Co-funded by the European Union
Aurora

Excursions


Wind Farm site, Korsnäs 2023


Hailuoto Bridge construction site, Oulu region 2024


Wind Farm site, Korsnäs 2024

Today's seminar

We want to present and give the participant some insight to our cross-border team and joint research. Much more to read and discover on our web page:

https://offwindproject.com/publication/

Coming up next:

Why Offshore Wind in the Arctic?

Johan Wasberg (Merinova, FI)

Partner Spotlight: SINTEF Narvik

Bjørnar Sand (SINTEF Narvik, NO)

Material Development

Magdalena Rajczakowska (LTU, SE) and Heli Koivuluoto (TAU, FI)

Highlights from the Project and Next Steps

Bjørnar Sand (SINTEF Narvik, NO) and Petra Ylitalo (Novia, FI)

Interactive Q&A

Interreg Aurora Co-funded by the European Union

Why Offshore Wind in the Arctic ?

Johan Wasberg

Senior Expert

Oy Merinova Ab

Great potential

Norway: Offshore goal 30.000 MW, **140 TWh** by 2040, partly in the Arctic

Sweden: 10 projects in the Sea and Gulf of Bothnia, 33.100 MW, **122 TWh**

Finland: 24 offshore projects in progress, 43.800 MW, around **160 TWh**

In total **422 TWh**

Present use of electricity 2023: **377 TWH**

- Norway 127 TWh
- Sweden 170 TWh
- Finland 80 TWh

Interreg Aurora Program Area

Interreg Aurora
Co-funded by the European Union

Location maps

Norwegian Continental Shelf (2023 Identifisering av utredningsområder for havvind)

Planned offshore wind parks in Sweden – including the 13 offshore wind parks rejected by the Swedish government on November 4, 2024. (Source: Regeringskansliet)

Some of the offshore wind areas being considered in the Sea and Gulf of Bothnia.
The Korsnäs case study area is indicated with a red arrow.

Sweden: The 10 projects in the Sea and Gulf of Bothnia

Name and area	Location	Depth meters	Capacity Max MW	Number of turbines	Production, TWh/a
Polargrund 300 km²	Kalix	45	1 800	120	10
Bothnia Offshore Sigma, 640 km²	Gävleborg	30-80	3 700	143	13,6
Eystrasalt 949 km²	Hudriksvall	35–40	3 900	256	15
Bothnia Offshore Lambda, 323 km²	Hudriksvall	40-80	1 600	93	6
Gretas Klackar 1 162 km²	Iggesund		1 800	103	7,5
Sylen 524 km²	Söderhamn		8 675	350	29
Gävle Öst 400 km²	Söderhamn		5 500	324	18
Fyrskeppet 488 km²	Örnskär, Uppland	47	2 800	187	11
Olof Skötkonung 162 km²	Gävle	18–75	1 625	70	7,5
Najaderna 350 km²	Gävle	30–75	1 700	67	5
Total 10 parks 4 298 km²		18–80 m	33 100 MW	1 713	122,6 TWh/a

Offshore wind power transmission system

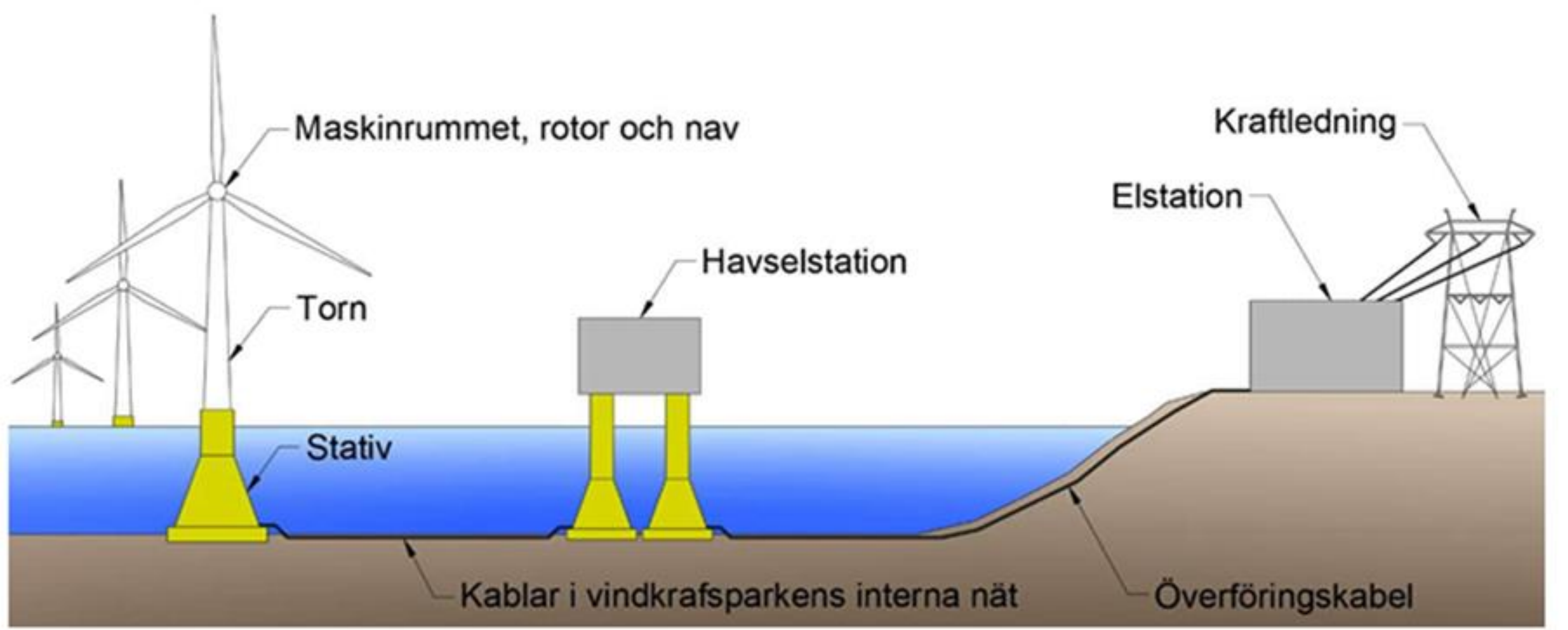
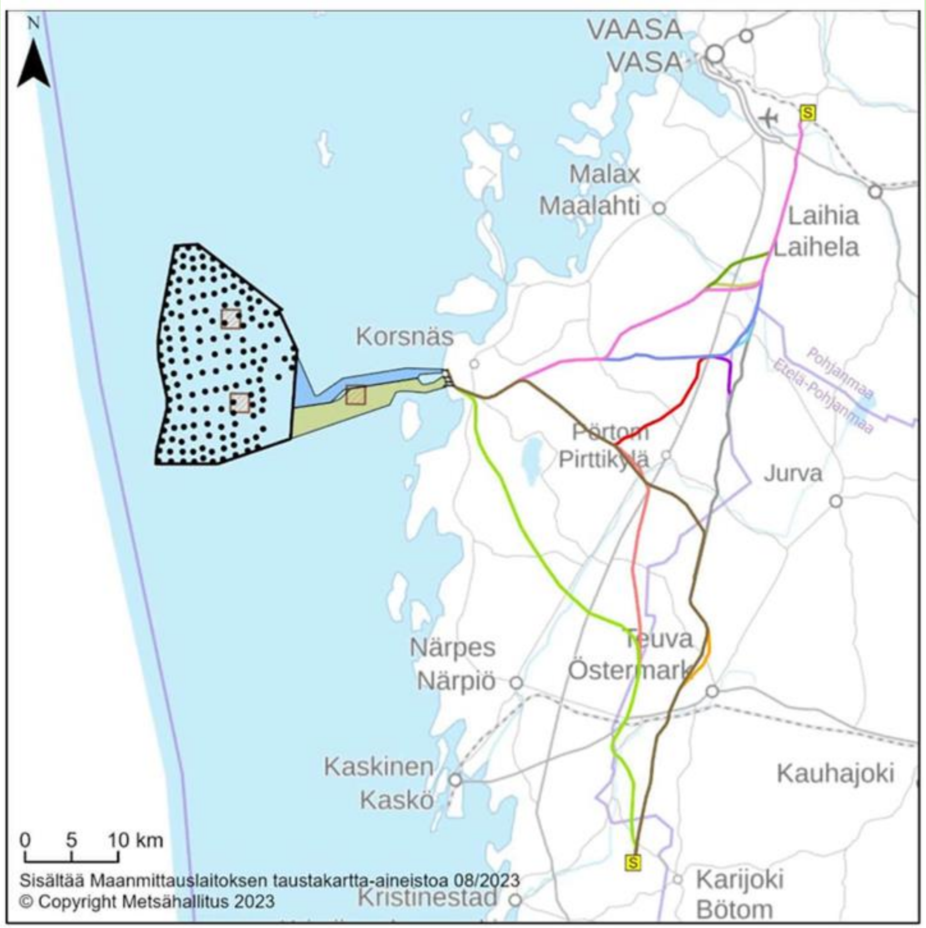


Illustration of a possible power transmission system from the sea to the mainland
Source.: Forststyrelsen and Vattenfall

The Korsnäs case

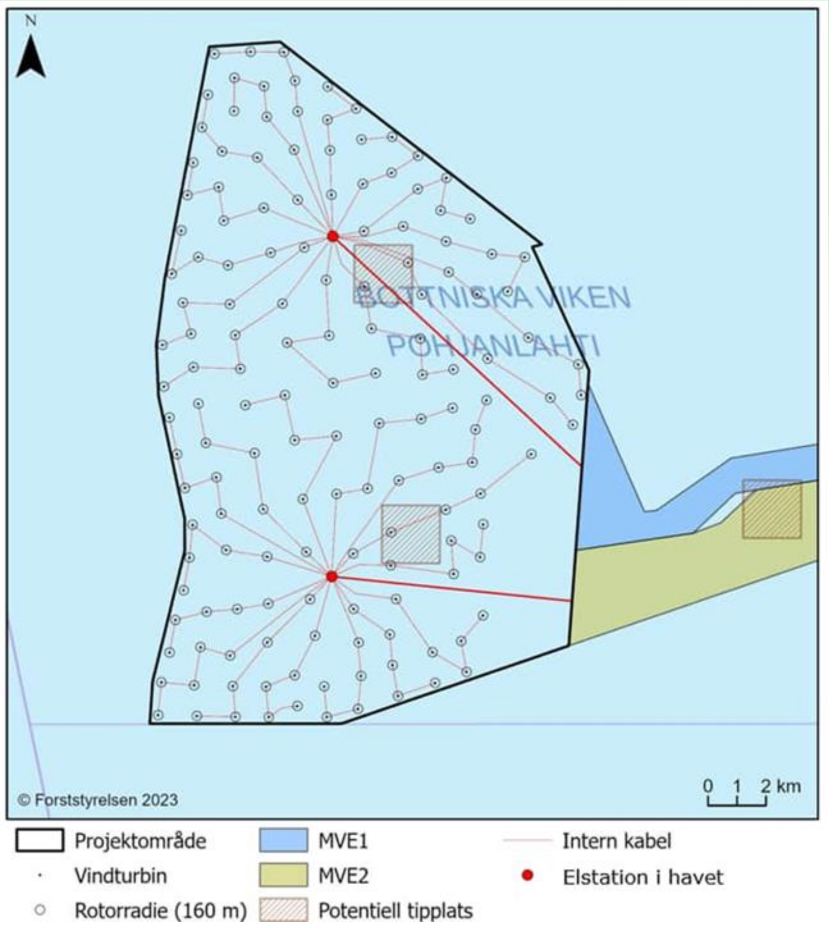


*Map of the Korsnäs offshore area, **two alternative routes for the sea cables** to the mainland, and **the power line routes to the alternative connection points** to the national grid. Source: Forststyrelsen and Vattenfall, Korsnäs EIA program 2024.*

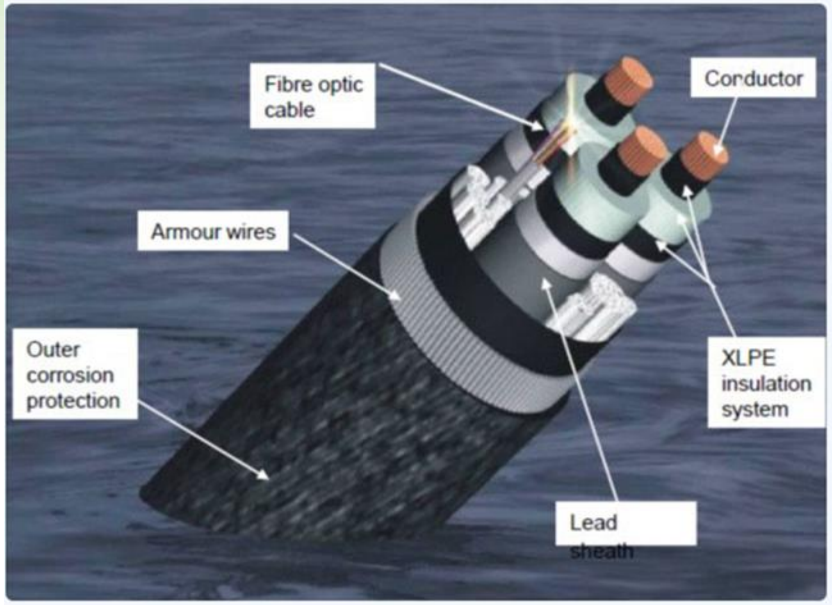
Korsnäs, power transmission

- Between the turbines and 1-2 power stations in the park with 3 phase AC submarine power cables
- 2 alternative power cable routes to the mainland are evaluated
- 1 power station will be built where the submarine cable reaches the mainland
- New power lines will be built to the Fingrid power station in Toby Korsholm, ≈ **55 km**, and/or south to the planned power station in Åback, Kristinestad ≈ **80-85 km**

Interreg Aurora
Co-funded by the European Union
OFFwind
MERINOVA TECHNOLOGY CENTRE
Tampereen yliopisto Tampereen ammattikorkeakoulu
YRKESHÖGSKOLAN NOVIA
LULEÅ TEKNISKA UNIVERSITET
SINTEF
LAPIN LIITTO



Example of turbine location and submarine cables to the sea-based power station in the Korsnäs park. Source: Forststyrelsen and Vattenfall



Transmission between the turbines and the 1-2 power stations in the park will be done with 3 phase AC submarine power cables. Source: European Subsea Cables Association

Korsnäs offshore park, some key features

Total area:	274 km2
Distance from mainland:	15-30 km
Water depth:	Mainly 10-40 meters but varies 8-70 meters
Wind speed:	Around 9,3 m/s at 100 m, around 10 m/s and 200 meter hight
Number of turbines:	Max 150
Turbine capacity:	Max 25 MW
Turbine hight:	Max 350 m
Total capacity:	Max 2,3 GW
Annual production:	Max 7 TWh
Turbine distance:	1-2 km

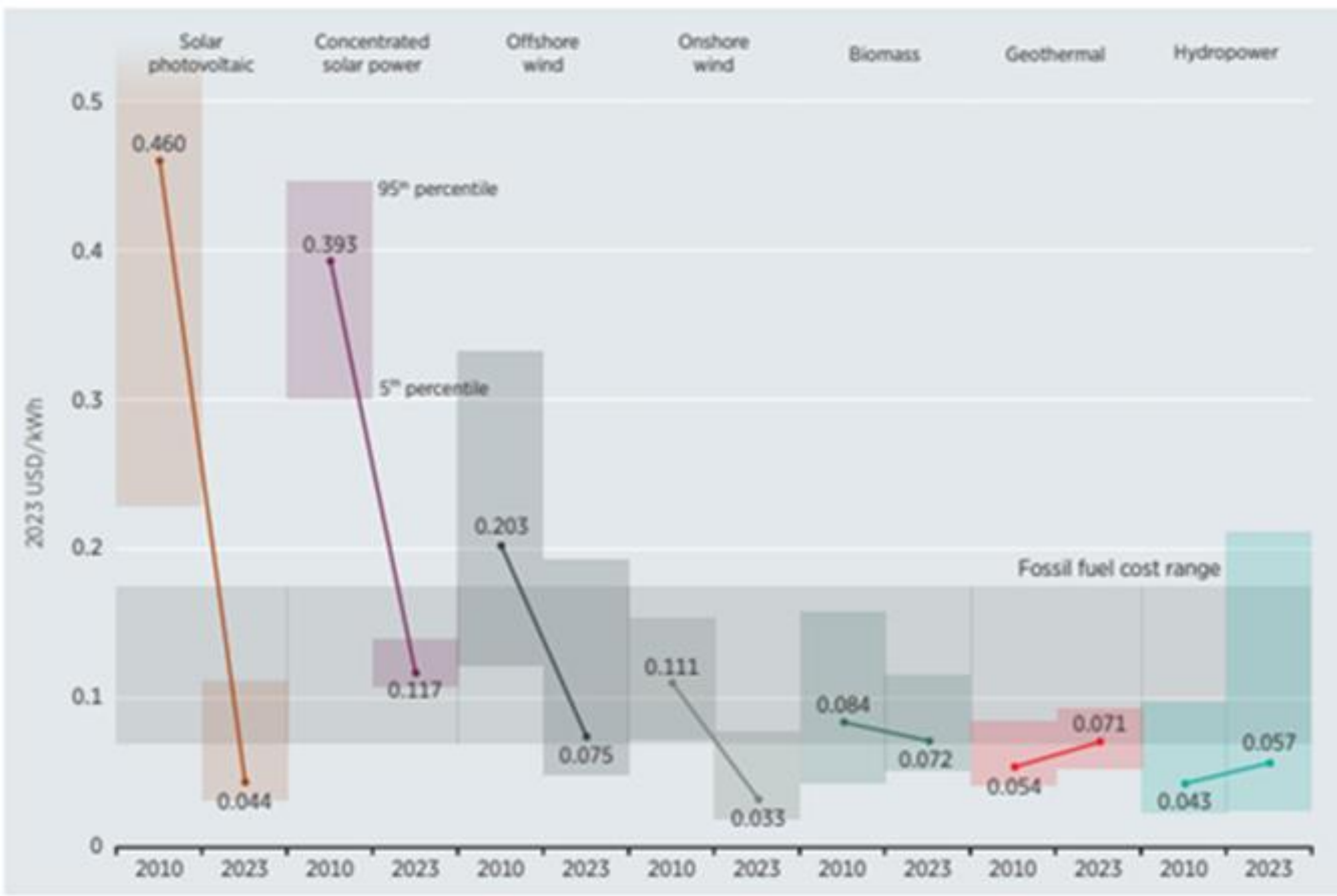
Interreg Aurora
Co-funded by the European Union
OFFwind
MERINOVA TECHNOLOGY CENTRE
Tampereen yliopisto Tampereen ammattikorkeakoulu
YRKESHÖGSKOLAN NOVIA
LULEÅ TEKNISKA UNIVERSITET
SINTEF
LAPIN LIITTO

Some Arctic offshore challenges

- Icing on turbine rotors
- Pack ice and brift ice – ice damage to submarine cables
- Remote locations – accessability , O&M, long distances to grid connection points
- Limited transmission capacity North –South
- Salty environment
- Evolving industry and technology development
- Cost of the generated electricity

Collaboration between research, industry, and public actors is crucial to overcome the challenges.

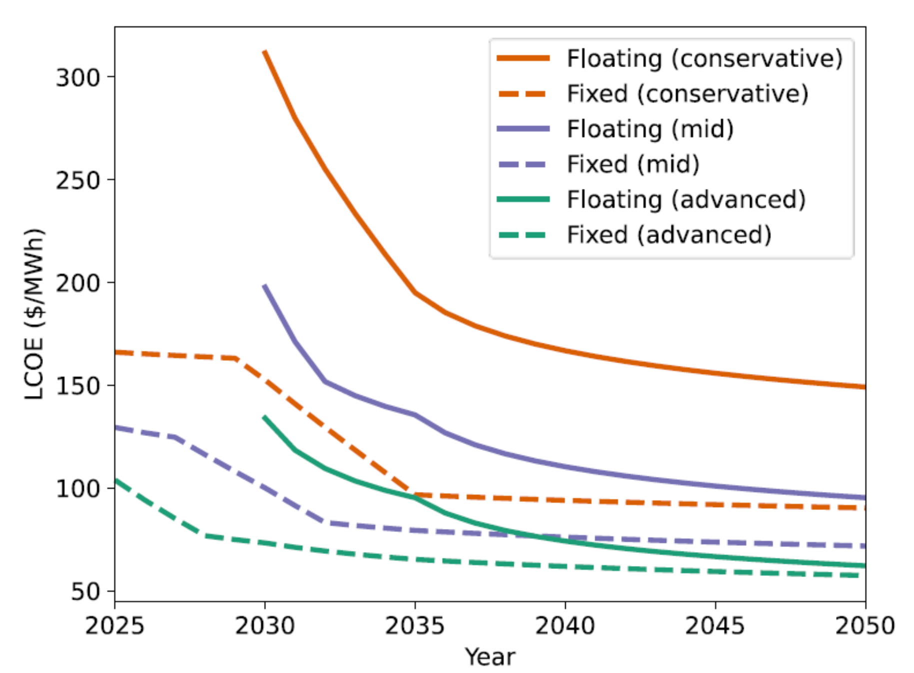
Present energy costs



Global LCOE from newly commissioned, utility-scale renewable power technologies, 2010 and 2023. Source: IRENA "Renewable power Generation Costs in 2023"

Estimated future offshore energy costs

Source if not otherwise stated: Fuchs, Rebecca, Gabriel R. Zuckerman, Patrick Duffy, Matt Shields, Walt Musial, Philipp Beiter, Aubryn Cooperman, and Sophie Bredenkamp. 2024. *The Cost of Offshore Wind Energy in the United States From 2025 to 2050*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5000-88988. https://www.nrel.gov/docs/fy24osti/88988.pdf.



LCOE ($/MWh) at the point of interconnection for reference fixed-bottom and floating offshore wind energy projects.

Year	Fixed bottom offshore park	Floating offshore park
2030	100	198
2035	79	136
2050	72	95
2050 advanced scenario	57	62

Estimated LCOE ($/MWh) at the point of interconnection for reference fixed-bottom and floating offshore wind energy projects according to the mid scenario. (Note 1 Euro = 1,16 USD in October 2025)

Offshore wind turbines

Preliminary environmental and technical feasibility study of offshore wind turbines in ice-infested waters

Bjørnar Sand

SINTEF Narvik

Preliminary environmental and technical feasibility study of offshore wind turbines in ice-infested waters

Interreg Aurora
Co-funded by the European Union

Offshore Wind Park

- Located in cold-region marine environments with seasonal and dynamic sea ice conditions (Baltic Sea, Bay of Bothnia)
- Full implementation of an Early-Phase Development of an offshore wind park is outside the scope of this project

Primary objective:

- Understand environmental loads - Ice and Metocean Pre-Assessment
- Evaluate technical feasibility of gravity-based foundations (GBFs) for wind turbines in ice-infested areas

Project Focus Areas

Develop general framework for:

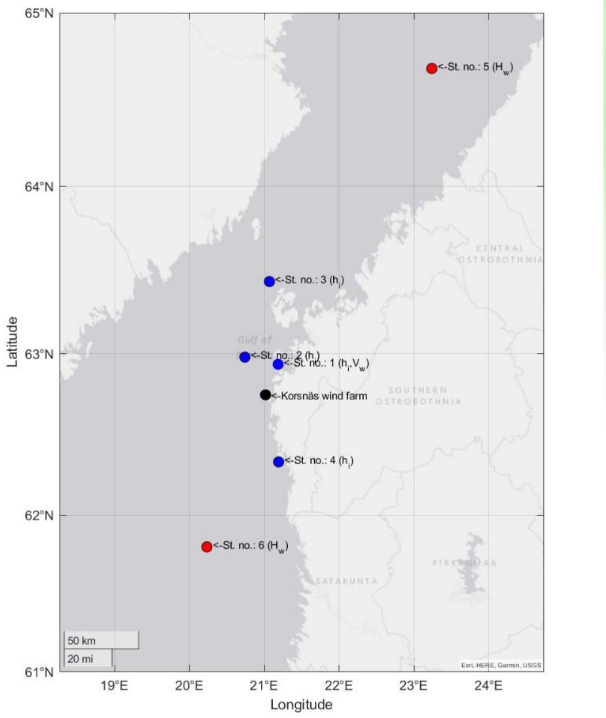
- Ice and Metocean Pre-Assessment
  - Study of ice conditions, wind, waves, and currents relevant to offshore wind site
- Feasibility assessment of gravity-based foundations (GBFs)
  - Conceptual design of the gravity-based reinforced concrete foundation for offshore windmills in ice infested waters.

Case study: Korsnäs wind farm area outside Vaasa off the Finnish west coast

- Capacity of 1.3 GW and a potential annual production of 5 TWh.
- First phase of the project: 70 to 100 turbines with a nominal power of 12 to 22 megawatts would be built in the area 222 km^2 .
- Distance from Shore is about 14 km.
- Average wind speed on the site may exceed 9 m/s.
- The water depth at the project site is mainly 10 to 30 m and is well suited for wind turbines with bottom-fixed foundations.

Data are downloaded from the Finnish Meteorological Institute:

- 4 weather stations and 2 wave buoys
- Temperature data for estimating ice thickness
- Marine weather observations
- wind speed, wind gusts speed and directions
- Wave height, wave periods and wave directions



Location of the weather stations. https://en.ilmatieteenlaitos.fi/download-observations.

Station no.	1	2	3	4	5	6
Observation station	Korsnäs Bredskäret	Maalahti Strömmingsbådan	Mustasaari Valassaaret	Kaskinen Sälgrund	Perämeri Wave buoy	Selkämeri wave buoy
Station ID	101479	101481	101464	101256	137228	134246
Latitude	62.93488	62.97839	63.43508	62.33382	64.68410	61.80010
Longitude	21.18485	20.74008	21.06856	21.19081	23.23800	20.23267
Estimated parameters	h_i, V_w	h_i	h_i	h_i	H_w, T_w	H_w, T_w

Ice Thickness Estimation Using Generalized Extreme Value analysis

Interreg Aurora
Co-funded by the European Union

Objective:

- Estimate extreme ice thickness for structural design in offshore wind farms.

Method:

- Applied the Generalized Extreme Value (GEV) distribution to annual maximum ice thickness data.

Source:

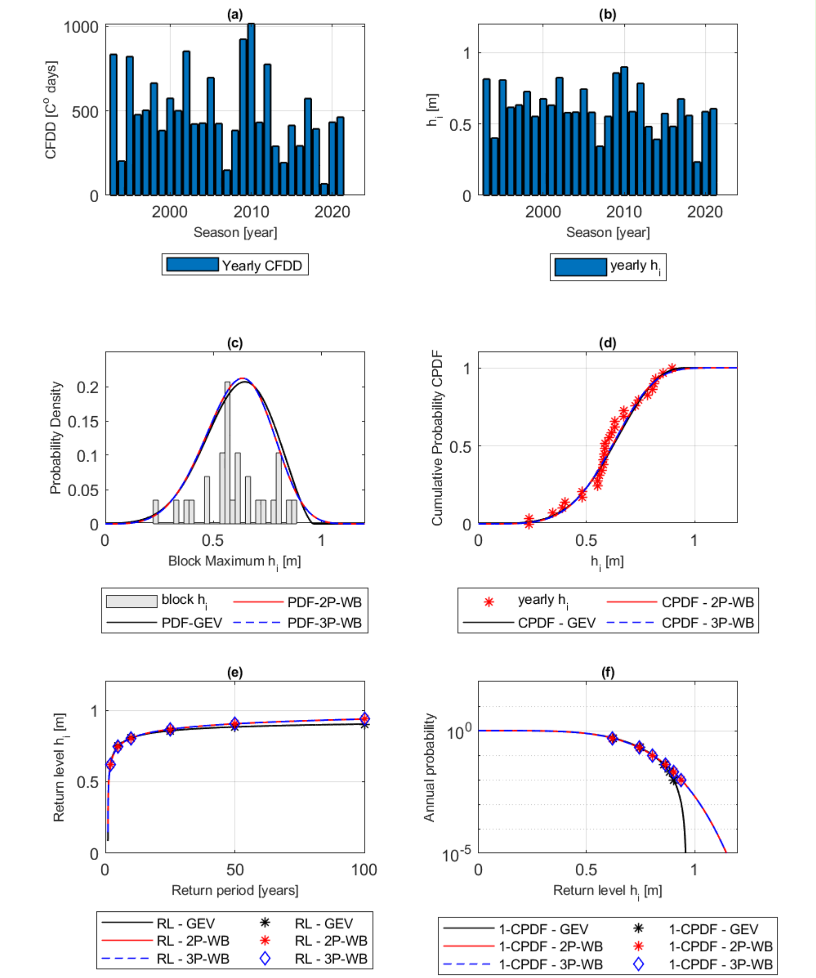
- Finnish Meteorological Institute (FMI) weather station at Korsnäs Bredskäret.

Result:

- Derived from fitted GEV model to historical data.
- The return levels of ice thickness were interpolated across the four weather stations to obtain representative return level values for the Korsnäs wind farm area.
- 50-year return level of ice thickness: 0.77 meters

Interpolated values of return level of thickness for Korsnäs wind farm area.

Korsnäs wind farm area		Return level h_i [m]		
Return period [Year]	Annual probability	GEV	2P-WB	3P-WB
2	0.5	0.49	0.49	0.49
5	0.2	0.61	0.61	0.61
10	0.1	0.67	0.67	0.67
25	0.04	0.73	0.73	0.73
50	0.02	0.76	0.77	0.77
100	0.01	0.80	0.80	0.80



OFFwind
MERINOVA TECHNOLOGY CENTRE
Tampereen yliopisto Tampereen ammattikorkeakoulu
YRKESHÖGSKOLAN NOVIA
LULEÅ TEKNISKA UNIVERSITET
SINTEF
LAPIN LIITTO

Characteristic ice, wind, and wave conditions for Korsnäs wind farm

Interreg
Co-funded by the European Union
Aurora

- Generalized Extreme Value (GEV) analysis of historical data.
- 50-year return values for the following environmental variables:

Characteristic ice, wind, and wave conditions for Korsnäs wind farm:

Level ice thickness	Wind speed	wind gust speed	Maximum ice velocity	Wave height	Maximum height sea level	Minimum height sea level
h_i^{50} [m]	V_w^{50} [m/s]	V_G^{50} [m/s]	V_i [m/s]	H_w^{50} [m]	H_{SL}^{max} [m]	H_{SL}^{min} [m]
0.77	21.9	27.4	0.55	7.6	1.44	-1.03

Optimization Framework for Gravity-Based Foundations in Ice-Infested Waters

Interreg Co-funded by the European Union
Aurora

Purpose

- Preliminary feasibility assessment of gravity-based concrete foundations for offshore wind turbines in ice conditions.

Framework Highlights

- MATLAB-based optimization platform
- Focus on geometric optimization- Aims to minimize concrete volume

Design Constraints

- Stability: Sliding, overturning, bearing capacity according DNV-RP-C212
- Structural stress limits: Combination of eigen loads and environmental loads
- Ballast weight: Required for additional stability
- Stability evaluation approach based on DNV-RP-C212
  - Ultimate limit state (ULS)
  - Using partial factors on loads and soil properties

Load Considerations

- Eigen Loads: Rotor-Nacelle Assembly (RNA) , Steel tower, gravity based
- Environmental Loads: Ice pressure (level ice & ridges) , Wind loads on tower, Nacelle thrust forces

Case study: Korsnäs wind farm area outside Vaasa off the Finnish west coast

Interreg Aurora
Co-funded by the European Union

The conceptual design is based on the IEA 22 MW Reference wind turbine (RWT)

Korsnäs wind farm area:

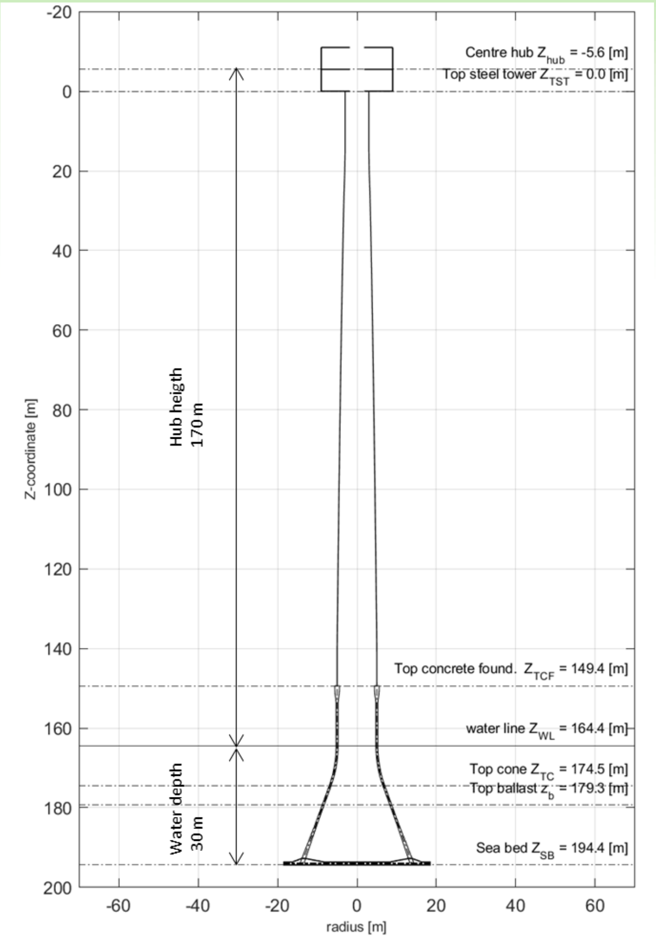
- Water depth: 30 m
- Seabed properties: dense sandy moraine
- Design standard: DNV-ST-0437 (DLC 9.1)
- Focus: 50-year sea ice conditions during power production

Key Load Values

- Thrust force acting at the hub (max): 2.66 MN
- Wind pressure: Distributed along tower height
- Ice forces calculated according to ISO 19906:
  - Level ice: 10.08 MN
  - Ice ridge : 19.55 MN

Key parameters for proposed design of 22 MW OWT with gravity-based reinforced concrete foundation.

Parameter	Value
Power rating [MW]	22
Rotor diameter [m]	283
Number of blades	3
Cut-in wind speed [m/s]	3
Rated wind speed [m/s]	11
Cut-out wind speed [m/s]	25
Hub height [m]	170
RNA mass [t]	1208
Tower top diameter [m]	6
Tower base diameter [m]	10
Steel Tower mass [t]	1574
Water depth [m]	30.0
Volume of ballast [m^3]	16242
Mass of ballast [t]	32483
Volume concrete [m^3]	2531
Mass of concrete [t]	6327



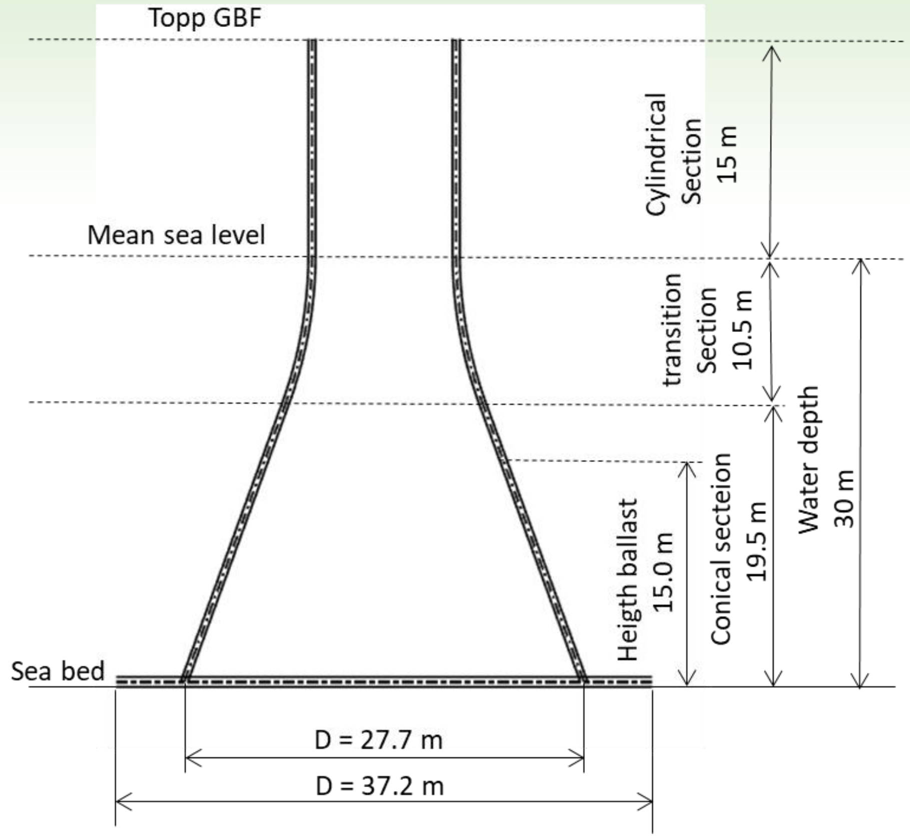
Conceptual design of gravity-based concrete foundation

The gravity-based foundation is a reinforced concrete structure with a total height of 45 m:

- Cylindrical upper section: 15 m high, 10 m diameter – supports the wind turbine tower and RNA.
- Transition section: 10.5 m high, 30 m radius – transfers forces to the broader base.
- Conical lower section: 19.5 m high, 27.2 m bottom diameter – distributes forces efficiently into the seabed.
- Base plate: 37.2 m diameter – resists sliding and overturning by increasing footprint.
- Ballast: Sand filled up to 15 m height – enhances stability in ice-infested waters.

This design offers a stable and efficient foundation for offshore wind turbines in dense moraine and sea ice environments.

Conceptual design for Korsnäs wind farm area



Interreg Aurora
Co-funded by the European Union
OFFwind
MERINOVA TECHNOLOGY CENTRE
Tampereen yliopisto Tampereen ammattikorkeakoulu
YRKESHÖGSKOLAN NOVIA
LULEÅ TEKNISKA UNIVERSITET
SINTEF
LAPIN LIITTO

Nonlinear finite element analysis of ice-structure interaction

The commercial finite element software LS-DYNA (Release 14) has been used for modelling the gravity-based offshore windmill.

Structural dynamics:

- Steel tower and gravity based concrete foundation is modelled with shell elements.
- The rotor-nacelle assembly (RNA) is modelled with volume elements
- The weight of the rotor blades are accounted for by using added mass on the volume if the nacelle.

Hydrodynamics

- The Arbitrary Lagrange–Euler Element (ALE) method is employed to account for fluid-structure interaction.
- ALE formulation is used for water and air.
- A contact-type algorithm is employed to handle the coupling between the water and the structure.

Aerodynamics – simplified approach:

- Aerodynamic forces is simulated by applying a single trust force at the centre of the hub.

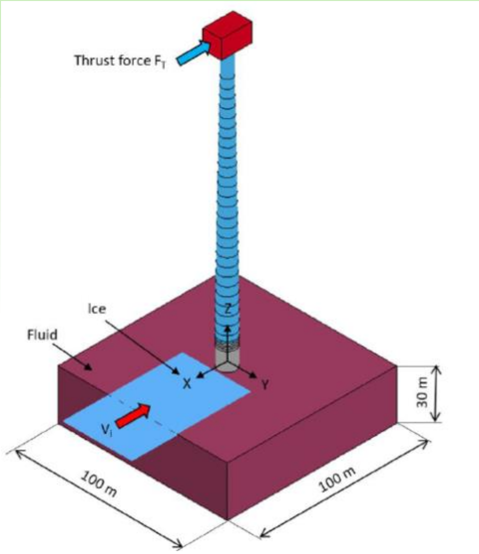
Ice-structure dynamics:

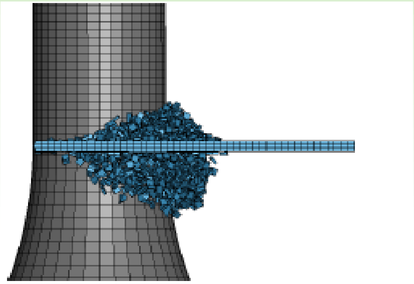
- Modelled by contact and friction between structure and level ice capable of simulating ice induced vibration and ice rubble build up

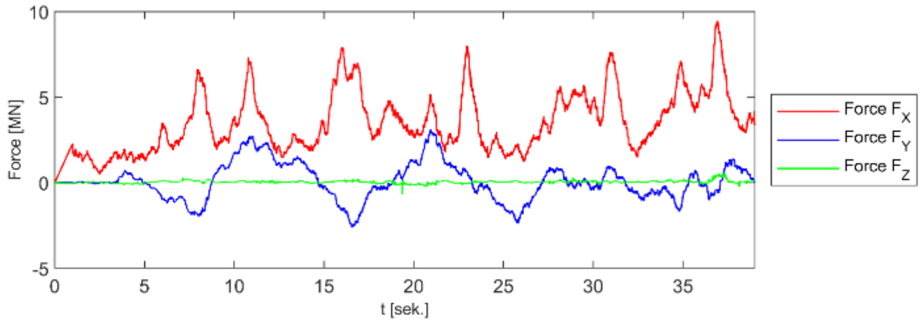
Structure- foundation dynamics – simplified approach:

- Using a spring-model to account for the stiffness of the soil

Level ice and the OWT interaction model with fluid-structure interaction coupling.







Interreg Co-funded by the European Union
Aurora
OFFwind
MERINOVA TECHNOLOGY CENTRE
Tampereen yliopisto Tampereen ammattikorkeakoulu
YRKESHÖGSKOLAN NOVIA
LULEÅ TEKNISKA UNIVERSITET
SINTEF
LAPIN LIITTO

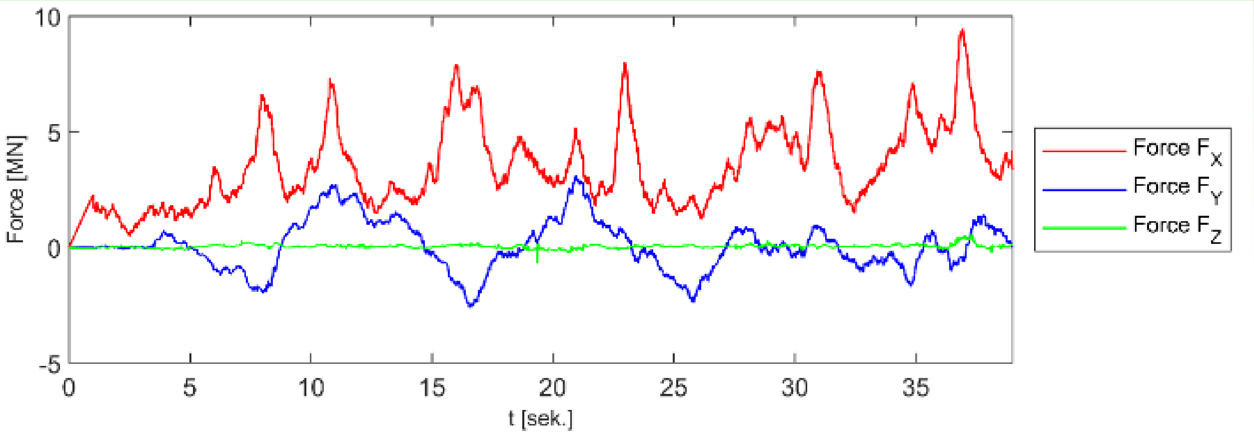
Numerical results for ice speed Vi = 0.25 m/s

Mechanical properties of the ice sheet were characterized by uniaxial compressive strength:

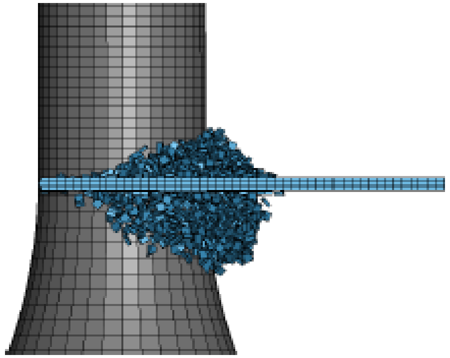
- 3.7 MPa in the horizontal direction.
- 6.7 MPa in the vertical direction.

- Maximum global ice force F_X = 9.47 MN occurs at 36.9 s, with an average of 3.54 MN.
- The plot illustrate the progressive force build-up and subsequent fluctuations during ice-structure interaction.
- The numerical force curves show characteristic cyclic patterns.
- Capturing the effects of crushing, cleavage, rubble accumulation, and dynamic failure mechanisms.

Time series of global ice forces for ice thickness 0.77 m and ice speed 0.25 m/s.



Snapshot of ice failure and rubble formation at time t = 40 seconds



Thank you for your attention.

OFFwind

Interreg Aurora

Co-funded by the European Union

Material development: concrete technology

Magdalena Rajczakowska, Andrzej Cwirzen

Luleå University of Technology, Sweden

Bjørnar Sand

SINTEF Narvik, Norway

Tom Lipkin

Yrkehögskolan Novia, Finland

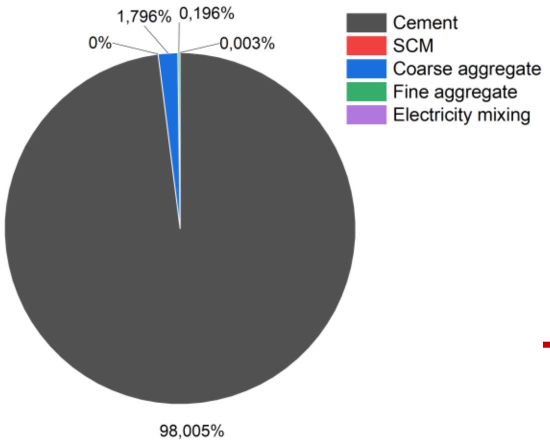
MERINOVA TECHNOLOGY CENTRE
Tampereen yliopisto Tampereen ammattikorkeakoulu
YRKESHÖGSKOLAN NOVIA
LULEÅ TEKNISKA UNIVERSITET
SINTEF
LAPIN LIITTO

Environmental impact of offshore wind

79% and 70% to the **climate change impact** onshore and offshore respectively from impacts are due to extraction and production of materials (Bonou et al., 2016)

Foundation % contribution to Climate change:
18% onshore, 29% offshore (Bonou et al., 2016)

Concrete is the **most used material** in offshore wind foundations — and a major source of **embodied CO_2**



concrete *[ton/MW]*

Source	Location	ton/MW
(Priyanka and Garrett, 2015)	Onshore	457
(Schreiber et al., 2019)	Onshore	400
(Savino et al., 2017)	Onshore	417
(Kalt et al., 2022)	Onshore	502
(Adibi et al., 2017)	Onshore	577
(Adibi et al., 2017)	Onshore	380
(Martínez et al., 2009)	Onshore	350
(Ardente et al., 2008)	Onshore	560
(Oebels and Pacca, 2013)	Onshore	511
(Vestas, 2022)	Onshore	357
(Ghenai, 2012)	Onshore	403
AVERAGE	Onshore	447
(Elshkaki and Graedel, 2014)	Offshore	619
(Arvesen et al., 2013)/(Venås, 2015)	Offshore	619
(Kalt et al., 2022)	Offshore	791

From (Savvidou and Johnsson, 2023), CC license

https://doi.org/10.1016/j.spc.2023.07.012

Concrete in offshore wind

Concrete in harsh exposure conditions

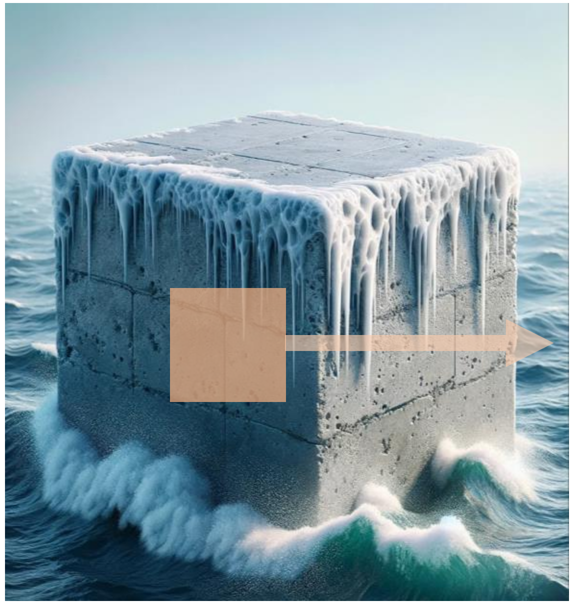
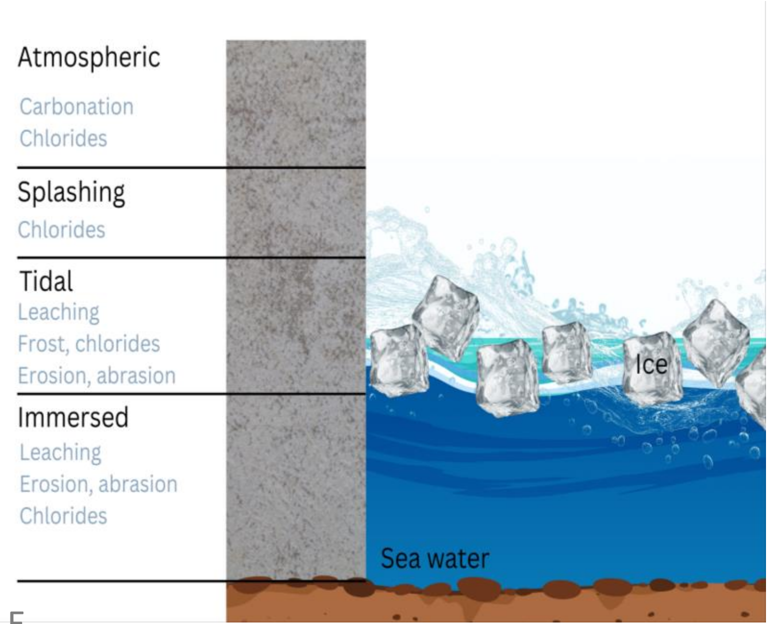


Image from DALL-E



Created based on (Li et al, 2022), https://doi.org/10.1617/s11527-022-02027-2

Arctic marine environments expose concrete to freeze-thaw, ice abrasion, and chlorides - often acting together

Durability is the key driver of service life and ultimately of carbon, cost, and safety in offshore structures

OFFwind objective

Goal

Build a high-level, decision-support framework linking:

Materials → Durability → Service life → CO_2 impact

Identify gaps in current practice for offshore concrete

What we explored

Can we reduce embodied CO_2 with low-clinker alternatives?

Will those mixes still perform under Gulf of Bothnia conditions?

Where are the key challenges and future research paths?

Image from DALL-E

Activities that we carried out

Determination of the R&D gaps based on current state of the art (LTU)

Modified LCA framework design (LTU)

LCA calculation for different concrete scenarios (LTU)

Durability screening of selected low carbon concrete mixes (accelerated lab tests, 1-year exposure using captured natural seawater in lab conditions, Novia + LTU)

Contributions to scientific paper, conference presentation (NCR 2025),
4 reports

LTU + SINTEF

Multi-Criteria Sustainability Assessment for Concrete in Nordic Offshore Wind Applications

Magdalea Rajczakowska
Ph.D., Postdoc
Luleå University of Technology
971 87 Luleå, Sweden
e-mail: magdalena.rajczakowska@ltu.se

Bjørnar Sand
Ph.D., Senior Research Scientist
SINTEF Narvik, Rombaksveien 47, 8517 Narvik
e-mail: bjornar.sand@sintef.no

Andrzej Cwirzen
M.Sc., Ph.D., Professor and Head of Subject
Luleå University of Technology
971 87 Luleå, Sweden
e-mail: andrzej.cwirzen@ltu.se

ABSTRACT
This study integrates durability metrics with cradle-to-gate carbon assessments for low-carbon concrete mixes used in offshore wind foundations at the Korsnäs site. Four types of concrete were evaluated using a composite sustainability index that combines GWP with durability parameters (freeze–thaw resistance, chloride penetration, and compressive strength). Preliminary results indicate that incorporating durability reduces mix differences, with the Hybrid element yielding the lowest index and potentially saving ~1,329 tonnes of CO_2 per foundation.

Key words: Offshore wind energy, Low-carbon concrete, Life cycle assessment (LCA)

LTU

R&D Challenges: Concrete Technology for Offshore Wind Foundations in Ice-Infested Waters

1. Introduction

Offshore wind development in the Aurora region, spanning Sweden, Norway, and Finland, must address harsh marine and ice-prone environments, especially in the Gulf of Bothnia and subarctic coastal zones. Freeze-thaw cycles, ice loads and abrasion, chloride penetration, and bio-colonization intensify structural demands for concrete foundations. Simultaneously, the sector faces growing pressure to adopt low-carbon materials, meet biodiversity goals, and address social acceptance challenges.

Concrete has evolved over the years, from a grey material to an intelligent composite with many functions. Emerging technologies offer new design possibilities. Yet many of these remain undertested due to the coupled degradation mechanisms typical of this region. Furthermore, concerns around invasive species, underwater noise, and environmental compliance demand a broader understanding of how offshore concrete can evolve beyond passive durability to become an active ecological interface.

The following outlines key R&D objectives, reviews the state of the art, and presents specific research challenges relevant to the Aurora region.

2. R&D Objectives

1) Low-carbon concrete systems for offshore Arctic use

Why: Cut embodied CO_2 without compromising safety in cold, saline, ice-loaded sites and marine context.

Objective: Develop/qualify regional SCM and aggregate sources for concrete mixes complying with XS3/XF4 exposure classes and possible low-temperature casting.

2) Durable surfaces under marine-ice degradation

Why: Combined degradation mechanisms characteristic of the Aurora region, including abrasion, freeze-thaw, and chlorides, contribute to decreased service life and increased maintenance costs for offshore.

Objective: Verify performance limits for combined mechanisms that would inform design guidelines

3) Advanced (more efficient) fabrication methods for offshore components

Why: Hybrid casting and additive manufacturing (3DCP) can enable efficient, function-integrated parts, but need verification in arctic environments

Objective: Establish applicability for hybrid/3D-printed elements in offshore

4) Smart materials and monitoring for reliability

Why: Access to offshore structures during their service life is limited; early detection and passive resilience reduce risk and operations, and maintenance

LTU

LULEÅ UNIVERSITY OF TECHNOLOGY

OFFSHORE CONCRETE LCA – METHOD & SCENARIOS

Magdalena Rajczakowska, Andrzej Cwirzen, Tom Lipkin
Luleå University of Technology

LTU + Novia

LULEÅ UNIVERSITY OF TECHNOLOGY

DURABILITY SCREENING OF LOW-CARBON MORTARS UNDER SIMULATED MARINE EXPOSURE

Magdalena Rajczakowska, Andrzej Cwirzen, Tom Lipkin, Julein Walser
Luleå University of Technology, Novia

Novia

Use of Slag in Concrete Production for Offshore Wind Power Foundations

1. General Information

What we refer to as the green transition requires innovation and action in every possible way. A part of this transition is the shift from fossil fuels to renewable energy sources such as wind power. In Finland, wind power is almost entirely land-based. Offshore wind power has significant potential, but many challenges are associated with it.

Another aspect of the green transition is that even the production supporting it should be carried out with low carbon emissions. Both concrete and steel are used as construction materials for wind power. Notably, each of these materials accounts for approximately 8% of global carbon dioxide emissions. Therefore, it is reasonable to pursue all available means to reduce emissions from these materials.

This study aims to provide information on how more environmentally friendly concrete can be used in the foundations of offshore wind power structures.

2. Objective of the Study

Currently, the most realistic and feasible way to reduce emissions from concrete use is to replace traditional Portland cement (OPC) with alternative binders. There are many potential alternative binders that could be used in the concrete industry in the future. However, due to strict regulations, many of these alternatives are not yet permitted.

Finnish concrete standards do allow the use of by-products from the steel industry, such as slag. Although slag has been used for a long time, it has been used sparingly in traditional building construction.

The objectives of this study were:

- To compare concrete mixes with varying amounts of slag to mixes containing only cement. Two different cement products were used.
- To verify that the strength development of the concrete aligns with the values specified by the cement manufacturer.
- To assess the impact of accelerating admixtures.
- To assess the impact of air-entraining admixtures.
- To compare the strength of samples stored in water (+21°C) with those stored outdoors for one year.

Co-funded by the European Union
Interreg Aurora

Interreg Aurora
Co-funded by the European Union

Result highlights – LCA framework

Pseudo-service life:

An estimated service life based on a durability parameter. It serves as a “proxy” for actual performance and can be used to normalize the carbon footprint against durability.

Scenario	w_{comp}	w_{FT}	w_{Cl}	Justification
A	0.3	0.4	0.3	Balanced emphasis on all factors, with freeze–thaw given slightly more importance.
B	0.4	0.3	0.3	Compressive strength is prioritized due to stricter structural demands.
C	0.2	0.5	0.3	Freeze–thaw is heavily weighted for severe cold climates or frequent icing.
D	0.3	0.2	0.5	Chloride ingress is prioritized (e.g., very corrosive marine environment).
E	0.33	0.33	0.34	Almost equal weight to all factors; minimal bias toward any single parameter.

$$\text{Integrated Sustainability Index (ISI)} = \frac{E}{f \times D}$$

where:

- E is the total carbon emissions per unit volume (e.g., kg CO_2eq/m^3),
- f is the compressive strength (e.g., MPa at 28 or 112 days),
- D is a durability parameter (such as a pseudo-service life or an FT scaling value correlated with service life).

https://link.springer.com/article/10.1617/s11527-020-01535-3?fromPaywallRec=false

https://link.springer.com/article/10.1617/s11527-020-01535-3?fromPaywallRec=false

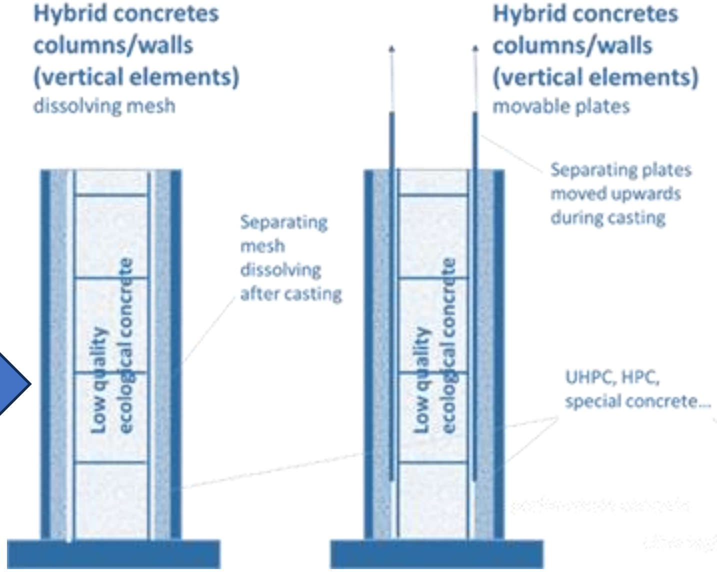
Result highlights – LCA framework

Gulf of Bothnia, characterized by ice loads and (moderate) saline exposure.

Reference Wind Turbine (22 MW) with gravity-based foundation (approx. 2531 m^3 concrete).

Four mixes considered: REF (NC), SCM, UHPC, SCM, and Hybrid (SCM + UHPC layer).

NC (100% PC)
SCM (35wt.% replacement)
UHPC (800kg/m^3 of PC)
UHPC + 50%wt.% SCM



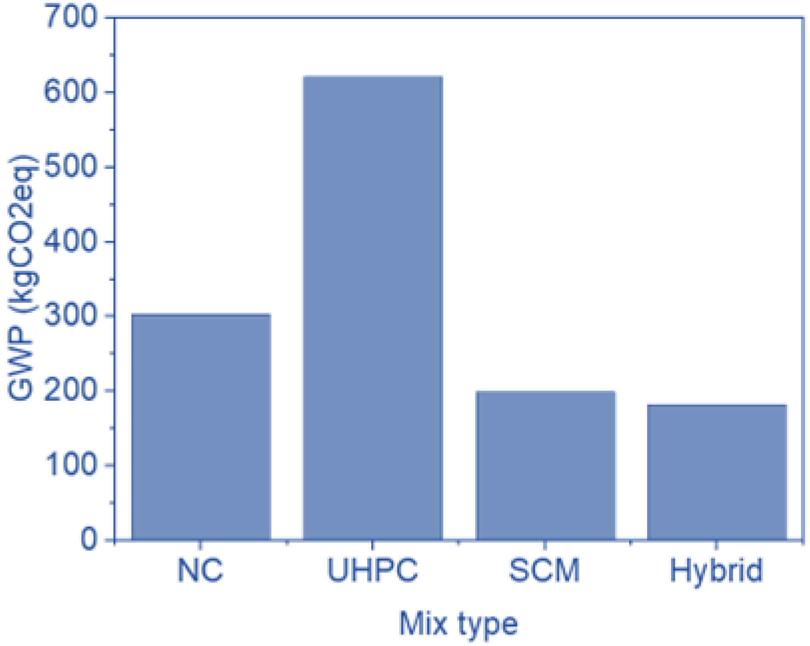
Hybrid project, financed by SBUF, Andrzej Cwirzen materials

OFFwind MERINOVA TECHNOLOGY CENTRE Tampereen yliopisto Tampereen ammattikorkeakoulu YRKESHÖGSKOLAN NOVIA LULEÅ TEKNISKA UNIVERSITET SINTEF LAPIN LIITTO

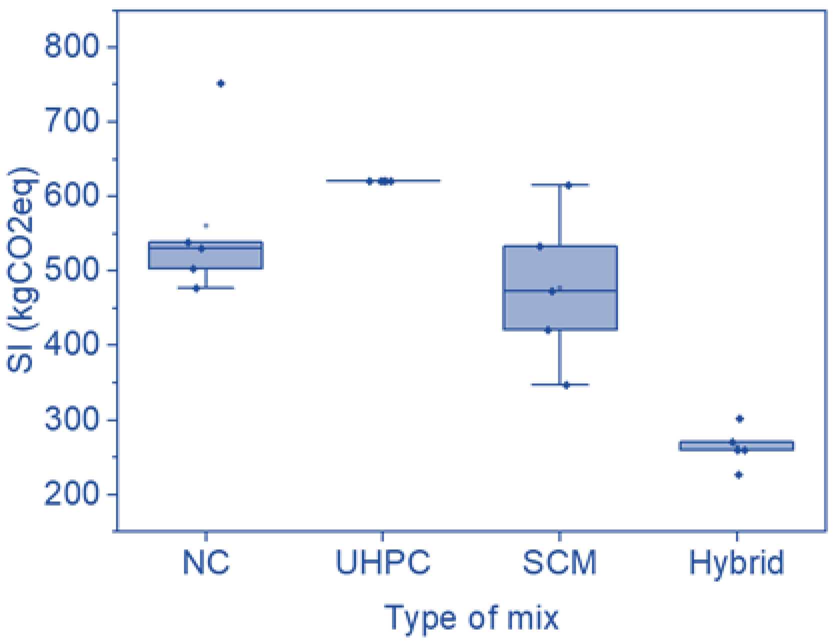
Interreg Aurora

Co-funded by the European Union

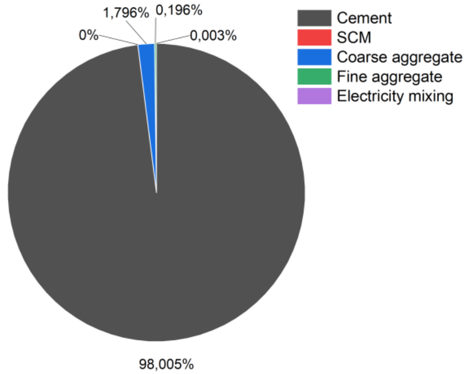
Result highlights – LCA framework



On carbon alone, SCM appeared most favorable.



Incorporating durability reduced differences among REF, SCM, and UHPC.



OFFwind

MERINOVA TECHNOLOGY CENTRE

Tampereen yliopisto
Tampereen ammattikorkeakoulu

YRKESHÖGSKOLAN NOVIA

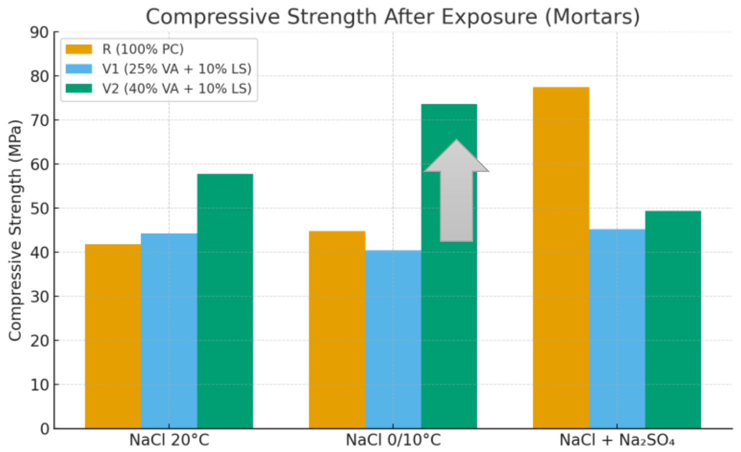
LULEÅ TEKNISKA UNIVERSITET

SINTEF

Interreg Aurora
Co-funded by the European Union

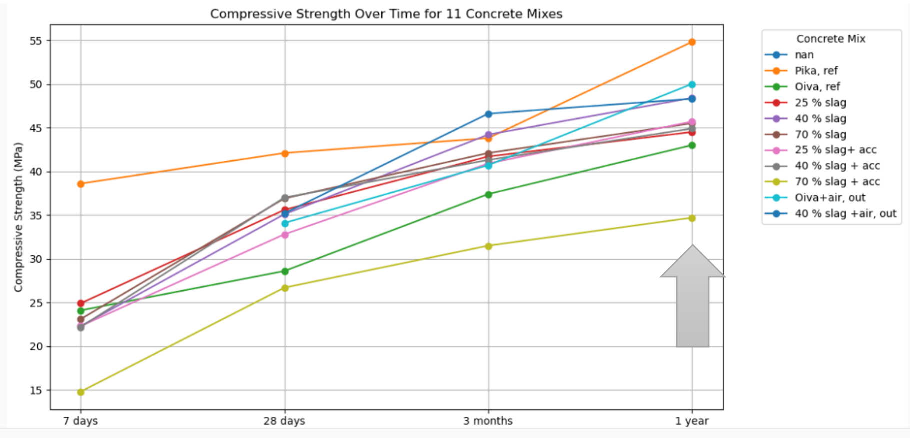
Result highlights – durability tests

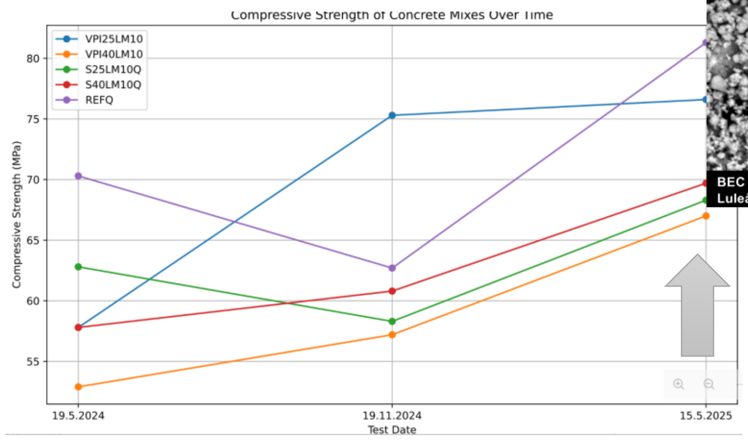
Accelerated laboratory tests

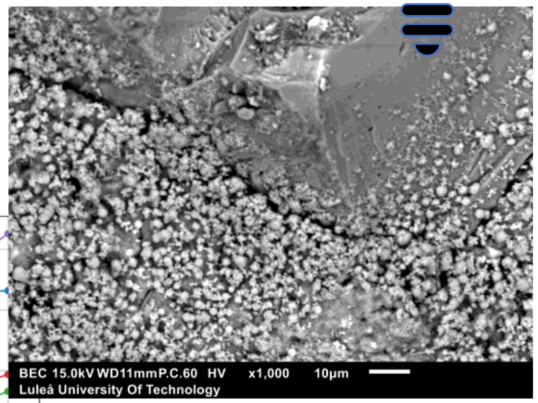


V2 (VA-rich) good in NaCl, especially cold
Reference (100% PC) better in sulfate
Gulf of Bothnia water: mild effect, short-term
These are early signals - directional only
More evidence needed

Marine water laboratory tests

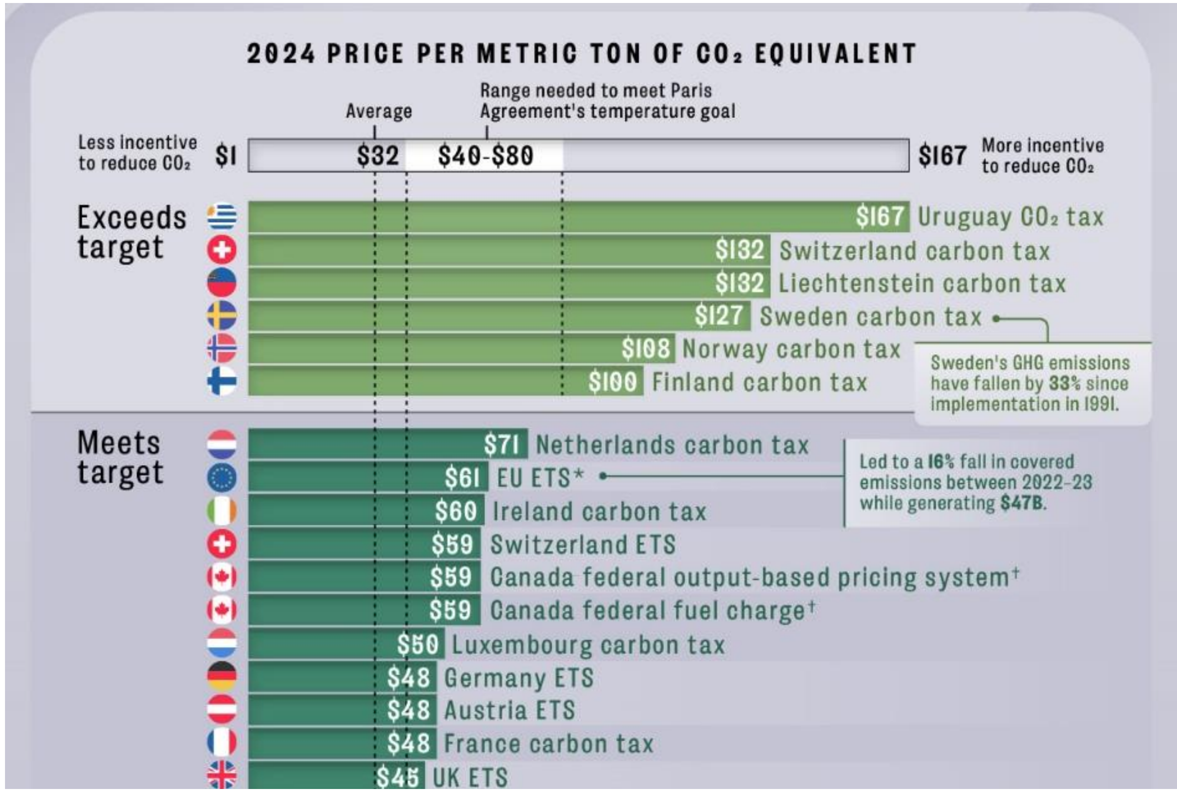






later strength development + denser pore structure ?

System-level implications



https://decarbonization.visualcapitalist.com/visualized-the-price-of-carbon-around-the-world-in-2024/
Data according to World Bank

Applying the optimized durability strategy could yield approx. 1,329.11 t CO_2 saved per foundation (GBF ≈ 2,531 m^3 concrete for the 22 MW RWT).

72 foundations scale to 0.09570 Mt CO_2 avoided, with an estimated cost saving $10.34 M based roughly on current carbon tax estimations

Carbon prices in the future? – the impact can be higher

Challenges and action paths - material

Materials and durability

Map regional SCMs/aggregates: performance, CO_2e, logistics

Formulate mixes for freeze–thaw, chloride, and ice resistance

Explore hydrophobic or ice-resistant coatings

Monitoring and repair

Integrate smart additives for in-situ sensing
Test self-healing agents below 5 °C

Validate underwater repair materials

Link sensors to digital twins for predictive maintenance

Construction technology

Develop hybrid systems (e.g. UHPC shells on low-carbon cores)

Design printable marine-grade mixes

Develop digital fabrication workflows for offshore components

Challenges and action paths – environment and updake

Environmental protection

Design bioreceptive textures for native colonisation, ice resistance

Integrate noise-dampening geometries into marine concrete

Lifecycle Assessment (LCA)

LCA must reflect durability and exposure

Build database for materials (CO_2, durability)

Develop AI-supported LCA scenario tools

Collaboration/uptake

Coordinate with other Interreg projects (e.g., Ar2CorD)

Joint pilots

Durability collaboration network

Interreg Aurora Co-funded by the European Union
OFFwind
MERINOVA TECHNOLOGY CENTRE
Tampereen yliopisto Tampereen ammattikorkeakoulu
YRKESHÖGSKOLAN NOVIA
LULEÅ TEKNISKA UNIVERSITET
SINTEF
LAPIN LIITTO

Conclusions and outlook

Low-carbon concrete for offshore is promising, but only if durability evidence is included.

Volcanic ash mixes show promise in chloride environments

LCA must include service life and real exposure conditions to guide decisions

Pilot tests needed to validate materials in cold marine zones

Shared tools and data can reduce uncertainty and duplication

Collaboration across regions will accelerate uptake

Building materials group at LTU

OFFwind

Interreg Aurora

Co-funded by the European Union

Highlights of the OFFwind Project – Webinar 29.10.2025

Material Development - Coatings

Betül Aktas, Heli Koivuluoto

Tampere University

Materials Science and Environmental Engineering

Coating Technologies Research Group, Icing Research

Photos: Jonne Renvall/TAU

MERINOVA TECHNOLOGY CENTRE · Tampereen yliopisto Tampereen ammattikorkeakoulu · YRKESHÖGSKOLAN NOVIA · LULEÅ TEKNISKA UNIVERSITET · SINTEF · LAPIN LIITTO

How OFFwind is exploring new coating and protection technologies for concrete structures to improve resilience and reduce lifecycle costs?

Interreg Aurora
Co-funded by the European Union

Concrete in sea water suffers from…

Challenges in cold sea water

- Saltwater corrosion
- Freeze-thaw cracking
- Ice impact / friction

Why address these issues?

- Importance of improving concrete longevity
- Reducing maintenance costs in maritime structures

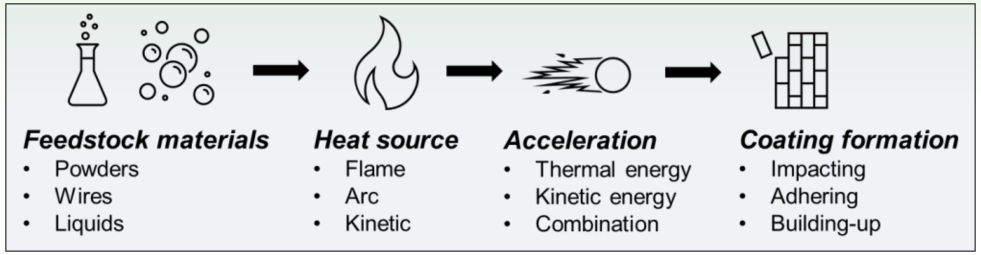
Corrosion | Icing
Ice impact / friction | Chloride penetration
Sulphate attack

S. W. Tang, Y. Yao, C. Andrade, and Z. J. Li, "Recent durability studies on concrete structure," *Cem Concr Res*, vol. 78, pp. 143–154, Dec. 2015, doi: 10.1016/J.CEMCONRES.2015.05.021.

How OFFwind is exploring new coating and protection technologies for concrete structures to improve resilience and reduce lifecycle costs?

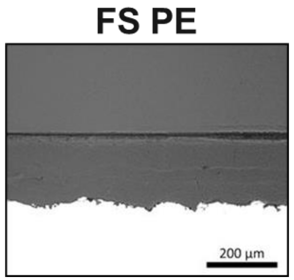
Interreg Aurora | Co-funded by the European Union

Thermal spraying as coating production technology



- Wide range of coating and substrate materials
- High coating production rate and efficiency
- Good coating properties

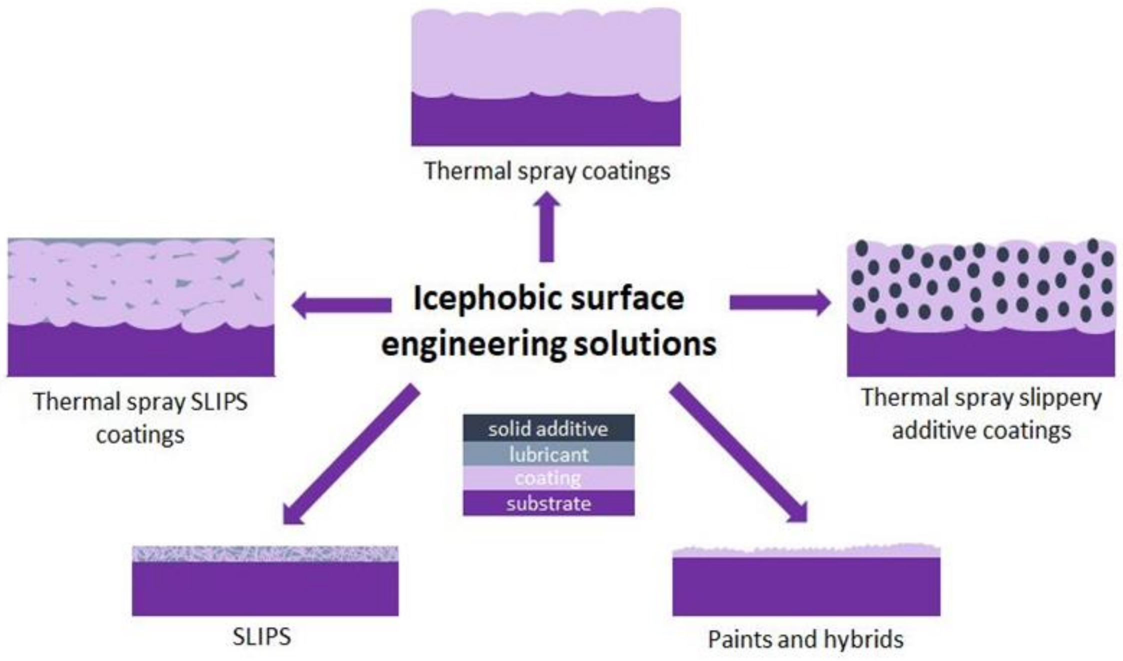
- Potential of thermally sprayed coatings
  - Industrial manufacturing process
  - Large surfaces
  - Onsite coating production
  - Automated and manual processes



Coating techniques: [*https://www.tuni.fi/en/research/coating-techniques*](https://www.tuni.fi/en/research/coating-techniques)

How OFFwind is exploring new coating and protection technologies for concrete structures to improve resilience and reduce lifecycle costs?

Thermal spraying as coating production technology



H. Koivuluoto et al., Thermally sprayed coatings: Novel surface engineering strategy towards icephobic solutions, Materials, 13(6) 2020, 1434

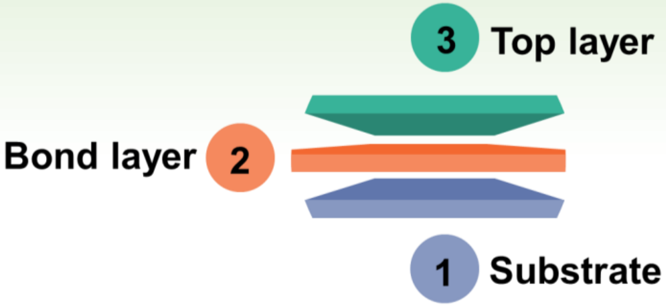
Interreg Aurora
Co-funded by the European Union
OFFwind
MERINOVA TECHNOLOGY CENTRE
Tampereen yliopisto Tampereen ammattikorkeakoulu
YRKESHÖGSKOLAN NOVIA
LULEÅ TEKNISKA UNIVERSITET
SINTEF
LAPIN LIITTO

How OFFwind is exploring new coating and protection technologies for concrete structures to improve resilience and reduce lifecycle costs?

Interreg Co-funded by the European Union

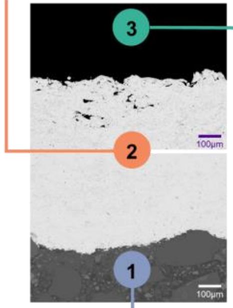
Aurora

Multilayered coating system for protection



2 Electric arc spraying of Zn

- Promoting adhesion
- Corrosion protection
- Industrial method for large components



Concrete 1

3 Flame spraying of PE

- Icephobicity and hydrophobicity [2]
- Corrosion protection
- Industrial and versatile method for large component


Proceedings – Int. Workshop on Atmospheric Icing of Structures IWAIS 2024 - Narvik, June 18 – 21

Thermally Sprayed Coatings on Concrete for Icephobic Protection in Sea Water Environments

Betül Aktas[1], Magdalena Rajczakowska[2], Niklas Kandelin[1], Andrzej Cwirzen[2], Heli Koivuluoto[1]

OFFwind

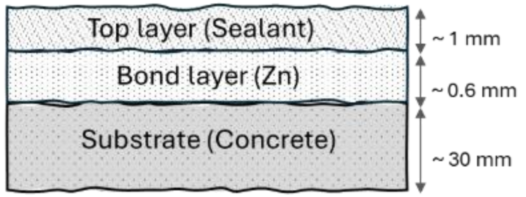
MERINOVA TECHNOLOGY CENTRE · Tampereen yliopisto Tampereen ammattikorkeakoulu · YRKESHÖGSKOLAN NOVIA · LULEÅ TEKNISKA UNIVERSITET · SINTEF · LAPIN LIITTO

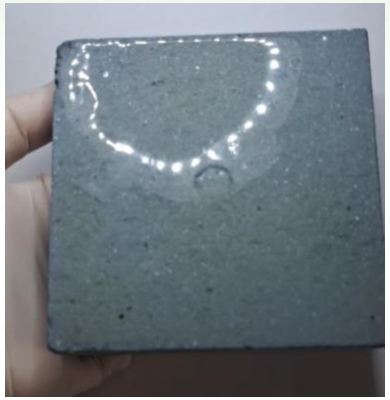
How OFFwind is exploring new coating and protection technologies for concrete structures to improve resilience and reduce lifecycle costs?

Interreg Aurora
Co-funded by the European Union

Multilayered coating system for protection

Sealing of thermally sprayed coatings





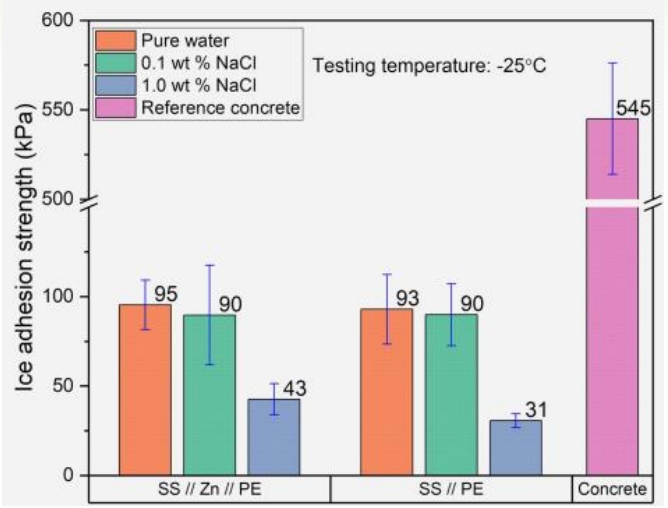
Thermal Spray 2025: Proceedings from the International Thermal Spray Conference
May 6–8, 2025; Vancouver, Canada
https://doi.org/10.31399/asm.cp.itsc2025p0369

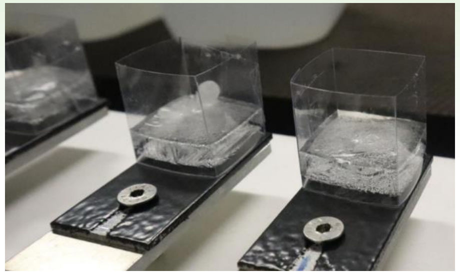
Thermally Sprayed Coatings for Concrete Protection in Cold Marine Environments

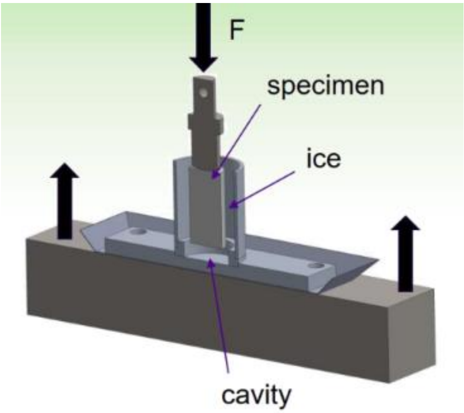
Betül Aktas, Heli Koivuluoto
Tampere University, Faculty of Engineering and Natural Sciences, Materials Science and Environmental Engineering, Tampere, Finland
betul.aktas@tuni.fi, heli.koivuluoto@tuni.fi

Magdalena Rajczakowska, Andrzej Cwirzen
Luleå University of Technology, Department of Civil, Environmental and Natural Resources Engineering, Luleå, Sweden

Icing testing







OFFwind

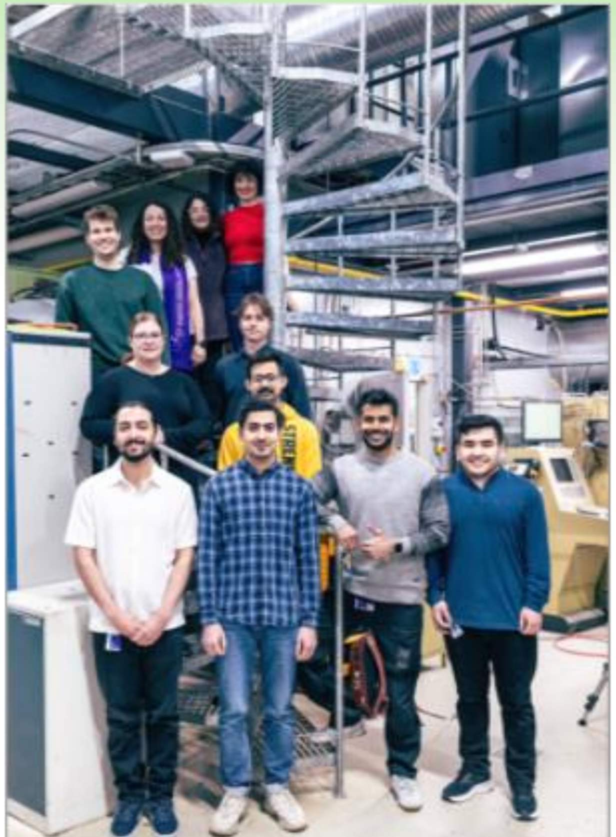
MERINOVA TECHNOLOGY CENTRE
Tampereen yliopisto Tampereen ammattikorkeakoulu
YRKESHÖGSKOLAN NOVIA
LULEÅ TEKNISKA UNIVERSITET
SINTEF
LAPIN LIITTO

Thank you for your attention!

Tampere University, Coating Technologies Research Group
Contacts:

Associate Professor Heli Koivuluoto
Heli.koivuluoto@tuni.fi

Doctoral Researcher Betul Aktas
Betul.aktas@tuni.fi



Tampere University
Coating Technologies and Icing Research Group

Photo: Jonne Renvall/TAU

OFFwind

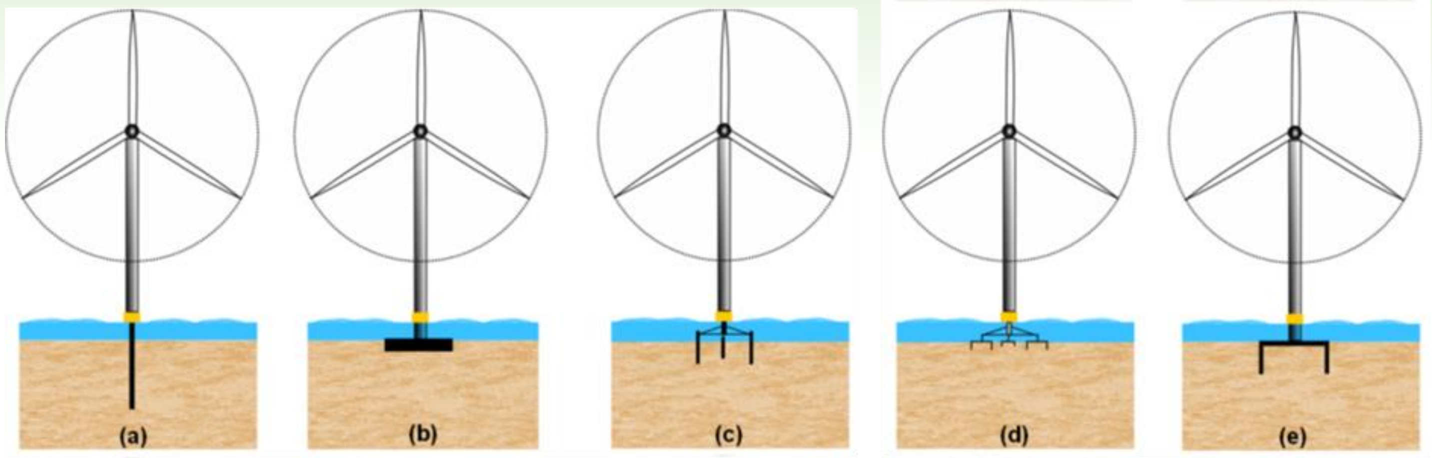
Bjørnar Sand

SINTEF Narvik

Interreg Aurora
Co-funded by the European Union

Types of foundation for offshore wind turbines

Bottom-fixed foundations



a) Monopile.

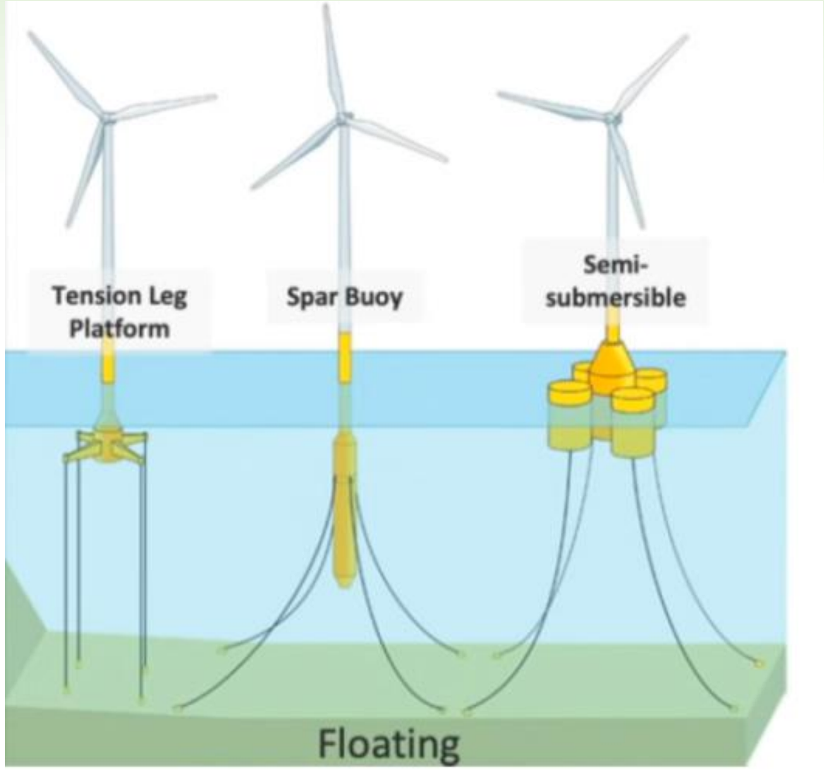
b) Gravity based

c) Multipod foundation

d) Jacket or lattice foundation

e) Suction caisson.

Floating foundations



Interreg Aurora
Co-funded by the European Union

Model OWT's that identifies the applied loads, and the system response

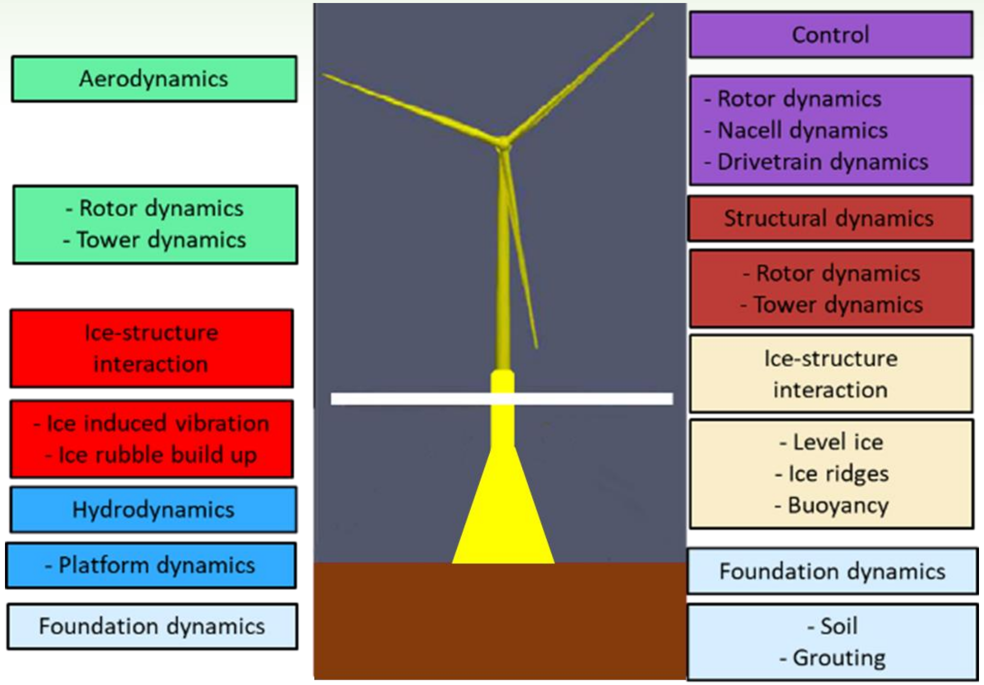
The external loads are caused by the

- wind, waves and currents.
- Ice loads become an important factor. In ice infested waters
- Ice-induced vibration may lead to fatigue failure of OWT structures.

For numerical modelling, the OWT can be divided into the following categories:

- Structural dynamics
- Hydrodynamics (fluid-structure interaction)
- Aerodynamics
- Ice-structure dynamics (ice-structure interaction)
- Structure- foundation dynamics (soil – structure interaction)

Gravity-based offshore wind turbine



Floating Wind – case study Nordavind D

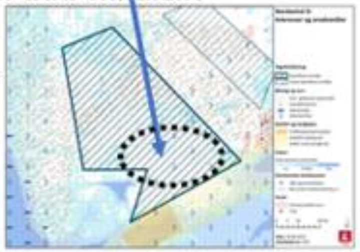
Latest Reference/Auction;

- The *Crown Estate Scotland* auctioned 8.600 km2 of sea space which could host almost 25 GW of offshore wind. 03 September 2024, (Flotation Energy/Vårgrønn), project Green Volt
- 80km off the coast of Northeast Scotland, 2.5 Billion GBP, up to 560 MW power (6.25 Billion GBP for a 1400 MW floating wind farm, i.e. 91 mrd NOK))
- latest Scottish auction (floating Wind Farm) *2,72 NOK/KW*

The Nordavind D Offshore Wind Farm

- 15 MW wind turbines
- 100 wind turbines (floating)
- 700 Km2 Turbine Area
- HVDC converter station (floating)
- 100 AC-array cables (to Offshore Converter station)
- 1 DC HV cable to Land station
- 1 Land Station
- Connection to National Power GRID

- 1500 MW in electrical power production
- Yearly Power Production 6,5 TWh (appr. 390 000 houses)



- SPAR type Turbine Foundation (concrete material)
- SPAR type Foundation for Converter Station (Substructure in concrete material)
- Converter Station (HWDC equipment "AC to DC" & Utility Systems, topside structure in steel), Topside weight 9 000 – 12 000 Tons
- Onshore/Land Station (DC to AC converting equipment)
- DC Transmission Cable
- 100 AC Array Cables

Interreg Aurora
Co-funded by the European Union
OFFwind
MERINOVA TECHNOLOGY CENTRE
Tampereen yliopisto Tampereen ammattikorkeakoulu
YRKESHÖGSKOLAN NOVIA
LULEÅ TEKNISKA UNIVERSITET
SINTEF
LAPIN LIITTO

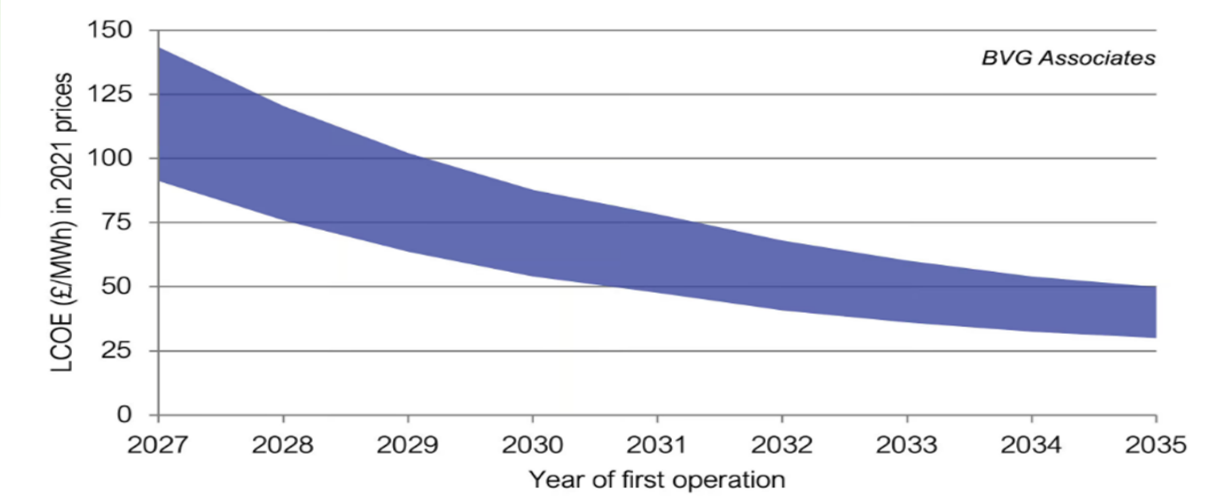
Technology Improvement Offshore Wind (NORDAVIND D)

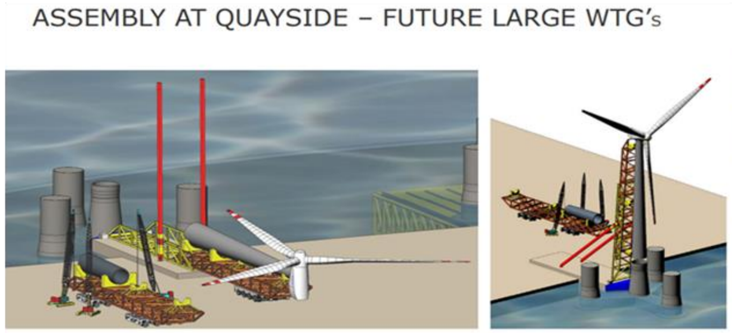
Factor for Technology Improvement, 2030-2035 = **0,58**
LCOE (2035) = 198 øre/Kwh * 0,58 ➔ **115 øre/Kwh**

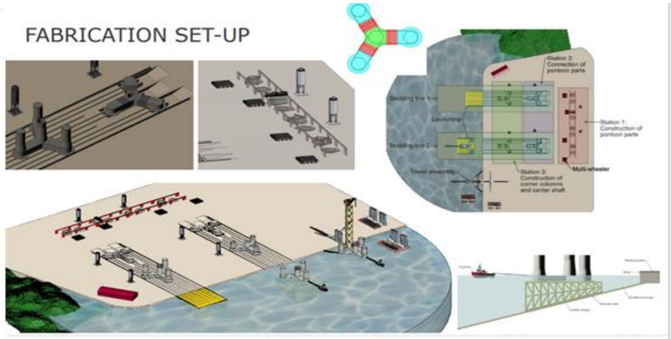
Technology Improvements;

- Low Carbon Concrete (concrete structures/design life, good stability, scalability, fatigue, cathodic protection etc.)
- Improved Surface Protection Systems
- Serial Production of Substructures
- Larger Turbines (serial production)
- More effective Mooring Systems
- More effective Installation
- Improved Array Cables
- Improved HVDC Cable
- Increased Operation/Service Life (50+ ?)
-
-

➔To reduce CAPEX/OPEX and LCOE







Next steps

- Working on a clustering project with a project in the Interreg Northern Periphery and Artic-programme. Project focus: “Low Carbon Concrete Solution in Cold Climate.”

- Working on ideas for Horizon-calls, national and nordic projects around drones, surveillance and defence in cold climate etc.

If you want to be involved in research around “business operation in cold climate,” please contact us for further discussion!

Interreg Aurora
Co-funded by the European Union

Thank you for your attention.