OFFwind Highlights No. 15 – NOV 2025

GREENER (AND SMARTER) CONCRETE FOR OFFSHORE WIND

Concrete in Nordic offshore wind foundations is being re-engineered using life cycle assessment to cut CO_2 emissions while preserving durability in ice, waves and saltwater. A hybrid solution combining low-carbon concrete with targeted UHPC zones emerges as a particularly promising option for long-lasting, climate-smart foundations.

Offshore wind power is widely described as a clean energy source, yet the materials used to construct turbines and foundations are associated with substantial environmental burdens. Large quantities of concrete and steel are required, and the production of these materials generates significant carbon dioxide emissions. Because the built environment accounts for a considerable share of global carbon emissions and resource use, the climate footprint of offshore wind infrastructure cannot be overlooked. Efforts within the OFFwind project have therefore been directed toward understanding how concrete used in offshore wind foundations can be made more sustainable while maintaining the mechanical performance and durability required in harsh marine conditions.

First Step: “Simple” Life Cycle Assessment of Concrete

As a first step, a “simple” life cycle assessment of concrete mixes was carried out. In this step, the focus was placed on cradle-to-gate emissions, from raw material extraction and cement production to the delivery of one cubic metre of concrete at the construction site. Global warming potential, expressed as kilograms of CO_2-equivalent per cubic metre, was used as the main indicator. By using one cubic metre as a functional unit, different mix designs could be compared on equal terms.

Within this framework, the dominant role of cement in the climate impact of concrete was highlighted (Figure 1). It was shown that most of the cradle-to-gate emissions originate from clinker in Portland cement and the energy required to produce it. To explore possible reductions, mixes with varying degrees of cement replacement by supplementary cementitious materials (SCMs) were examined. Ground-granulated blast furnace slag and other SCMs were introduced in increasing proportions, and the resulting emission reductions per cubic metre were calculated. In parallel, scenarios including recycled aggregates were investigated. In these scenarios, part of the natural aggregates was replaced by recycled aggregates from demolished concrete (Figure 2). The effects on the CO_2 footprint per cubic metre were found to be moderate compared with cement substitution, but a clear contribution to resource efficiency and circularity was identified.

Transport distances and modes were also varied to show how local sourcing versus long-distance shipping can influence the total cradle-to-gate emissions.

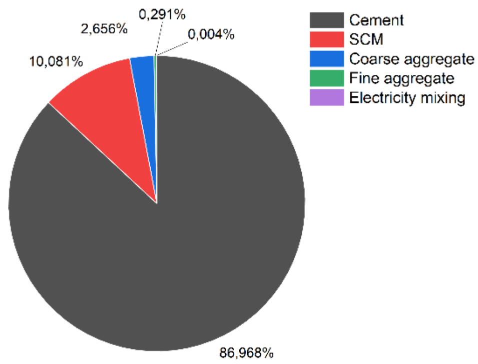

Figure 1. Distribution of carbon footprint per different concrete ingredients

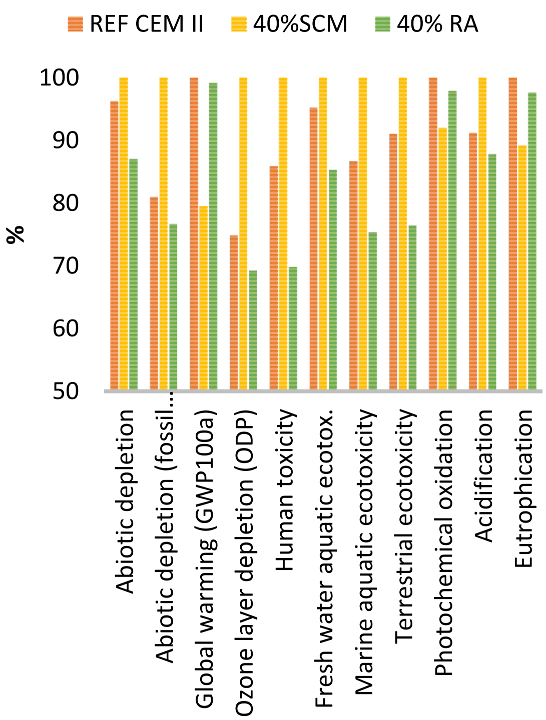

Figure 2. Comparison of environmental impact indicators for concrete with CEM II vs increased SCM amount and recycled aggregate

Strategies for Lower-Impact Concrete

On the basis of the simple LCA, several material strategies emerged as promising. Mixes containing ground-granulated blast furnace slag and similar SCMs were found to offer clear carbon advantages when they replaced a substantial share of Portland cement. When such binders were used, the total cradle-to-gate emissions per cubic metre could be noticeably lowered without necessarily compromising mechanical strength at standard ages.

More advanced approaches were also explored, including hybrid systems in which a low-carbon core concrete is combined with a protective layer of ultra-high-performance concrete (UHPC). UHPC is characterised by very high strength and exceptional durability, but also by a high initial carbon footprint due to its cement-rich composition and intensive processing. Instead of being excluded purely on this basis, UHPC was viewed as a targeted material that can be used in limited volumes where extreme durability is required. In such configurations, the bulk of the foundation can be made from a lower-carbon mix, while the UHPC layer protects critical zones against aggressive marine exposure.

These strategies together suggested that sustainability in offshore concrete should be understood as a combination of lower embodied emissions, efficient use of resources and extended service life, rather than as a single-parameter optimisation problem.

From Simple LCA to Multi-Criteria Sustainability Assessment

Because offshore wind foundations in Nordic waters are exposed to low temperatures, repeated freeze–thaw cycles, ice loads and seawater chlorides, durability plays a crucial role alongside initial emissions.

A mix that appears favourable in a simple LCA can perform poorly under such conditions, leading to early damage, frequent repairs and a shorter service life. To account for this, a multi-criteria sustainability assessment was developed in which environmental impact and durability are evaluated together.

This assessment was tailored to exposure conditions corresponding to classes XF4 and XS3 in EN 206, representing severe freeze–thaw action and strong chloride attack from seawater. A literature survey was carried out to identify concrete mixes that had been proposed or tested for such environments. For each candidate mix, data on compressive strength, freeze–thaw resistance and resistance to chloride penetration were collected and normalised to create a comparable set of durability indicators.

At the same time, cradle-to-gate LCAs were performed for these mixes using established software and databases, with global warming potential per cubic metre as the main output. When these carbon results were viewed on their own, mixes with SCM replacement showed reductions of roughly thirty to forty percent compared with a reference cement-rich concrete, while UHPC displayed approximately double the emissions because of its very high cement content.

Construction of a Durability-Integrated Sustainability Index

To integrate durability into the assessment, a composite durability index was constructed in which compressive strength, freeze–thaw resistance and chloride penetration resistance were combined with adjustable weights.

Different weighting scenarios were defined to represent possible local priorities. In very cold regions with frequent ice and de-icing actions, freeze-thaw resistance was given a higher weight, whereas in particularly corrosive marine waters, chloride resistance was emphasised. Balanced scenarios and cases where compressive strength was dominant because of structural demands were also considered.

The composite durability index was then combined with the carbon footprint to form a sustainability index defined as carbon emissions per unit of durability.

Lower values of this index indicate better overall sustainability performance. In simple terms, the index can be understood as describing how much climate impact is caused for each “unit” of durability delivered by a given concrete mix. A mix with relatively high emissions but very high durability can thus obtain a similar or even better index than a mix with lower emissions but poor long-term performance.

Comparison of Concrete Concepts

The durability-integrated sustainability index was applied to four representative concrete concepts. A normal concrete with one hundred percent Portland cement served as a reference. A low-carbon concrete with thirty-five percent cement replacement by natural pozzolan and limestone represented a typical low-carbon strategy. An ultra-high-performance concrete with very high cement content and strength was used as a durability-focused extreme. Finally, a hybrid concept was evaluated, in which a core of SCM-based low-carbon concrete was protected by an outer layer of UHPC corresponding to about ten percent of the total volume.

When only cradle-to-gate emissions were considered, the low-carbon and hybrid mixes showed clearly lower footprints than the reference concrete, while the UHPC mix appeared much less favourable.

Once the durability-integrated sustainability index was applied, the picture changed. The differences between UHPC, the low-carbon mix and the reference mix became less pronounced because the superior durability of UHPC was allowed to compensate partly for its high emissions.

Across all weighting scenarios, the hybrid concept consistently achieved the lowest sustainability index. This indicated that the strategic use of UHPC only where it is most needed, combined with a low-carbon core, can provide an attractive combination of low emissions and high durability.

Case Study of the Korsnäs Offshore Wind Farm

To illustrate the implications at project scale, the method was applied to a case study of gravity-based foundations for the planned Korsnäs Offshore Wind Farm in the Gulf of Bothnia. A reference turbine of twenty-two megawatts with a gravity-based foundation requiring approximately 2,531 cubic metres of concrete was considered. By replacing a purely conventional concrete solution with the hybrid concept, potential savings of about 1,329 tonnes of CO_2 per foundation were indicated.

For a wind farm with seventy-two such foundations, this would correspond to a total reduction of nearly 0.096 million tonnes of CO_2. When typical carbon prices and related economic factors were included, these emission reductions were translated into potential cost savings estimated at more than ten million US dollars for the wind farm. Through this case study, it was shown that choices made at the level of mix design and material selection for a single cubic metre of concrete can scale up to very substantial environmental and economic effects at the level of an entire offshore wind project.

Conclusions and Outlook

The combined results from the initial simple LCA and the subsequent multi-criteria sustainability assessment demonstrate that a narrow focus on low-carbon concrete is not sufficient for offshore foundations in Nordic conditions. A mix with a low cradle-to-gate footprint can be unfavourable over the full life cycle if it is vulnerable to freeze–thaw damage or chloride-induced corrosion and therefore requires frequent repairs and early replacement. Conversely, a solution with somewhat higher initial emissions can be more sustainable if it provides a much longer service life with limited maintenance. The hybrid concept, in which a low-carbon core is protected by a UHPC shell in critical zones, was consistently found to perform well because materials were used according to their strengths.

Further work should be aimed at refining the durability-integrated framework, improving service-life modelling, and enlarging the database of candidate mixes and material combinations. Additional case studies for different foundation types and locations are being developed so that the method can be adapted to a variety of offshore projects. In this way, it is intended that future offshore wind foundations in the Nordic region will not only withstand demanding environmental conditions but also minimise their long-term carbon footprint through intelligent material selection guided by integrated sustainability metrics.

AUTHOR:

Magdalena Rajczakowska

Postdoctoral researcher

Luleå University of Technology, Sweden

magdalena.rajczakowska@ltu.se

Interreg Aurora

Co-funded by the European Union

LAPIN LIITTO

MERINOVA TECHNOLOGY CENTRE

LULEÅ UNIVERSITY OF TECHNOLOGY

NOVIA UNIVERSITY OF APPLIED SCIENCES

Tampere University

SINTEF