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

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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)

1. INTRODUCTION

Despite legislative struggles, the rapid expansion of offshore wind energy in the Nordic region has been recognized as a critical step toward fulfilling European Union revised Renewable Energy Directive EU/2023/2413 of increasing the renewable energy share to at least 42.5% by 2030 Although this expansion contributes to carbon reduction goals, it also introduces concrete technology challenges in the North Sea, Baltic Sea, and the Gulf of Bothnia. These locations are characterized by harsh cold-weather conditions, frequent freeze–thaw cycles, ice loading, and exposure to saline water, all of which necessitate particular attention to material durability [1].

Traditional approaches to concrete sustainability have primarily focused on reducing embodied carbon through the use of low-carbon cementitious materials, such as fly ash and ground granulated blast-furnace slag (GGBS) [2]. However, it has been observed that some life cycle assessments (LCAs) do not adequately account for service-life reductions due to freeze–thaw deterioration or chloride-induced corrosion, which may lead to frequent repairs or early replacement. Such omissions can lead to under- or overestimations of the actual environmental impacts [3].

In response to these concerns, a preliminary durability-integrated LCA approach is proposed to support material selection for offshore wind foundations in northern climates. A composite sustainability perspective is adopted to assess the performance of various concrete mixes in the planned offshore wind farm's Korsnäs gravity-based foundation conceptual design.

2. PROPOSED APPROACH

2.1 Literature study

An extensive review of published studies was conducted to identify concrete mixes incorporating supplementary cementitious materials (SCMs) that meet the XF4 and XS3 exposure requirements specified in the EN 206 standard. The outcome of this literature study was a database of potential mixes, catalogued with durability attributes such as freeze–thaw performance, chloride penetration resistance, and compressive strength measurements.

2.2 Cradle-to-gate LCA framework

For the selected mixes in the database, a cradle-to-gate life cycle assessment (LCA) was performed using SimaPro software and the Ecoinvent database. A boundary was defined from raw material extraction to the exit of the concrete batching plant, including the production, transportation, aggregate processing, and mixing operations. All assumptions were made in accordance with ISO 14044 guidelines. The Global Warming Potential (GWP), measured in kilograms of CO_2-equivalent per cubic meter, was used as the primary indicator. CML-IA baseline V3.10 / World 2000 method was used for the calculation.

2.3 Sustainability Index

The durability properties identified in the literature were normalized to a 0–1 scale. These normalized values were then combined into a composite durability index (D) with specific weights attributed to the durability parameters. A weight sensitivity analysis was conducted to account for the possibility that certain durability attributes might hold greater importance in five scenarios (Table 1). For each variation, the composite durability index (D) was recalculated.

Table 1 – Scenarios for durability factor weights.

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.

A sustainability index (SI) was introduced to integrate both cradle-to-gate emissions and the composite durability index. This metric is given by:

$$SI = \frac{GWP}{D} \quad (1)$$

A lower SI indicates a better overall balance, characterized by fewer embodied emissions per unit of durability. While this approach does not fully simulate long-term service life or complex repair scenarios, it provides a first-level comparative view that incorporates both carbon impact and key durability aspects.

2.4 Case study application

For a preliminary calculation, three mixes were selected from the database with corresponding durability parameters, including normal concrete (NC), Ultra-High-Performance Concrete (UHPC), and a concrete mix with 35% cement replacement with natural pozzolan and limestone (SCM). In addition, the Hybrid mix combined a lower-quality 50% SCM-based core with a protective UHPC layer (10% volume), following the promising results from [5].

The mixes were applied for the case study of the Korsnäs Offshore Wind Farm, located in the Gulf of Bothnia, which has been proposed as a viable site for large-scale offshore wind energy deployment in Finland. A 22 MW Reference Wind Turbine (RWT) is planned with a gravity-based foundation (GBF) to manage the challenges posed by the region's dense moraine seabed and heavy sea ice loads. The concrete used for these foundations, with a total volume of approximately 2531 m^3, contributes significantly to the total project emissions, resulting in interest in lowering the carbon footprint. However, aggressive freeze–thaw cycles, ice-induced impact forces, and saline exposure can compromise the long-term performance of specific low-carbon mixes. Therefore, to identify how proposed mixes perform, both in terms of cradle-to-gate greenhouse gas emissions and durability, when deployed in the analysis following the proposed framework.

3. RESULTS

Initial LCA calculations indicated that the SCM and Hybrid mixes achieved cradle-to-gate carbon reductions ranging from approximately 30% to 40% relative to a 100% PC reference (NC). On the other hand, as expected, UHPC demonstrated a double GWP compared to REF due to its high PC content of approximately 800 kg/m^3. Nevertheless, the combined assessment showed that these relations have changed. When durability parameters were incorporated, the performance differences among UHPC, the reference mix (NC), and the SCM mix narrowed considerably. In contrast, the Hybrid mix consistently maintained a strong overall sustainability score across all scenarios, despite having lower absolute strength. The weight sensitivity analysis further demonstrated that, although ranking positions were generally stable, small changes in weighting factors for freeze–thaw or chloride ingress could alter the order of SI performance. It indicates the importance of accurately identifying local priorities in a given exposure class. The durability factor can be interpreted as an equivalent measure of service life, including repair and maintenance costs, in the analysis. In other words, a higher durability score implies a longer practical service life with fewer repairs, which can result in a reduced foundation size and improved overall sustainability.

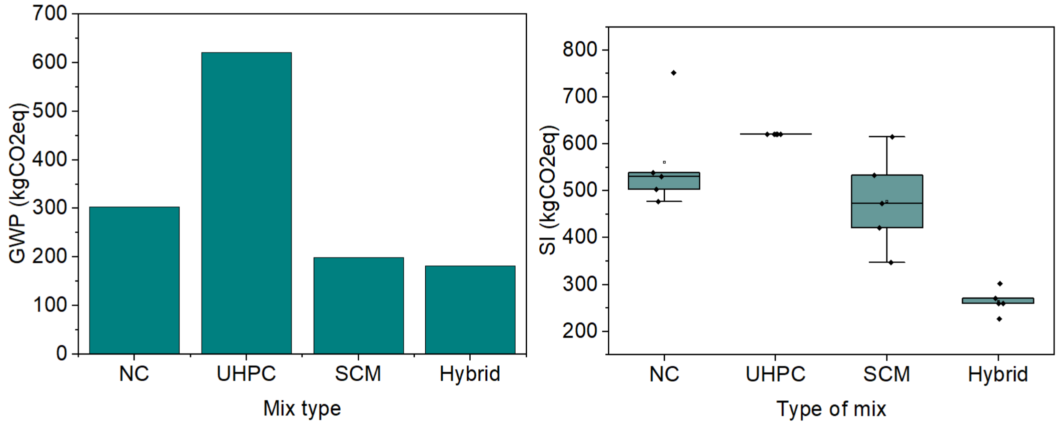

Figure 2 – Results of sustainability assessment. Left: Global warming potential. Right: Sustainability Index. Lower SI values indicate less carbon impact per unit of durability (or a better trade-off between carbon footprint and performance).

Implementing the optimized durability strategy can yield significant savings. In our analysis, approximately 1329.11 tonnes of CO_2 per foundation can be saved. Extrapolated to a farm with 72 foundations, this amounts to roughly 0.09570 million tons of CO_2 in total savings, translating into an estimated cost savings of about $ 10.34 million.

4. CONCLUSIONS

The analysis shows that integrating durability parameters with carbon assessments provides a refined tool for evaluating low-carbon concrete mixes for offshore wind foundations, in a more realistic way:

- Incorporating durability metrics reduces differences among UHPC, REF, and SCM mixes, leading to a more balanced sustainability assessment.
- UHPC's high strength may allow for reduced foundation sizes, while the Hybrid approach maintains robust performance despite lower absolute strength.
- Optimized designs can save approximately up to 1329 tonnes CO_2 per foundation.
- The composite sustainability index facilitates lifecycle cost reduction and risk management, offering benchmarks for contractors, designers, and policy-makers.

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