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Multicriteria LCA framework

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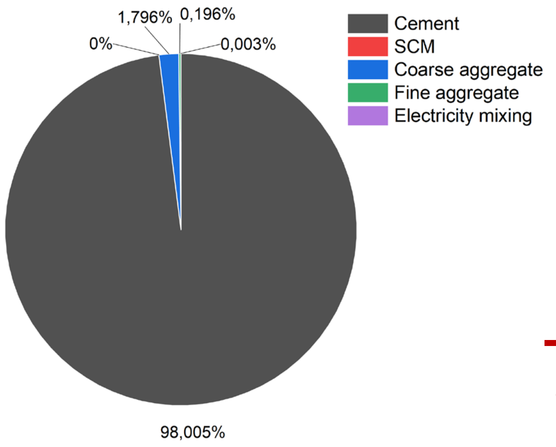
Environmental impact of offshore wind

Aurora

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

OFFwind

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Concrete in offshore wind

Concrete in harsh exposure conditions

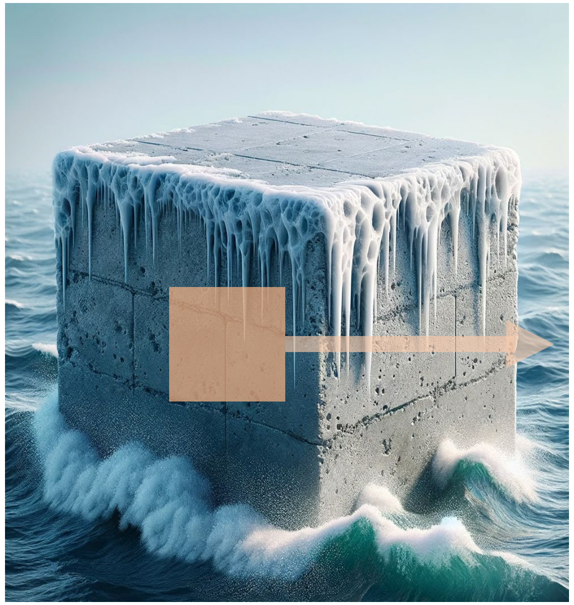
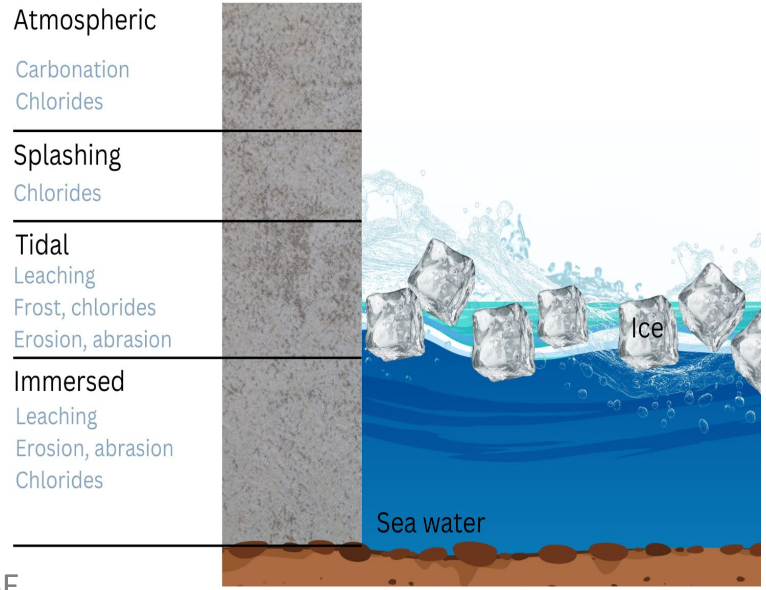


Image from DALL-E



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

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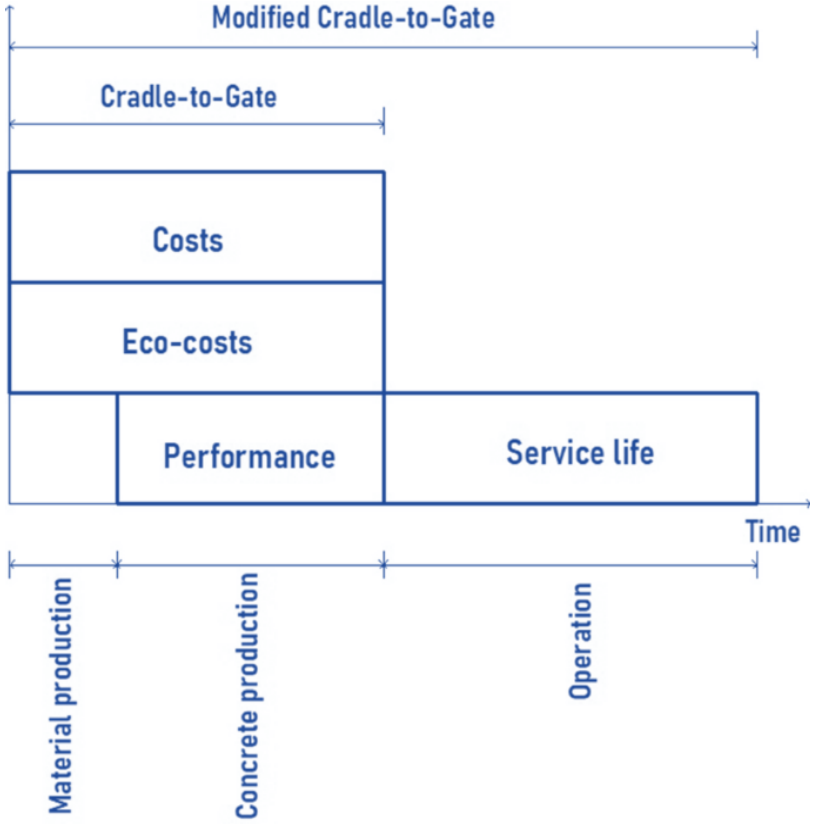
Durability-based LCA concept



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.

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

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

Proposed framework in this project

Literature study: mixes meeting EN 206 XF4 and XS3 exposure classes.

LCA performed in SimaPro with Ecoinvent, CML-IA method, cradle-to-gate scope.

Durability parameters normalized and combined into composite index

Three factors: compressive strength, freeze–thaw, chloride ingress.

Weighting scenarios A–E to reflect differing environmental and structural priorities.

Composite durability index D is recalculated under each scenario.

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.

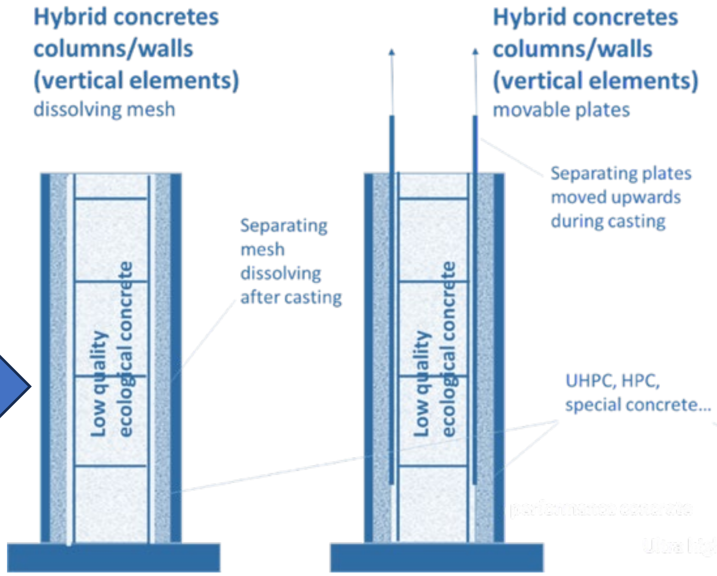
Case study - Korsnäs Wind Farm

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).

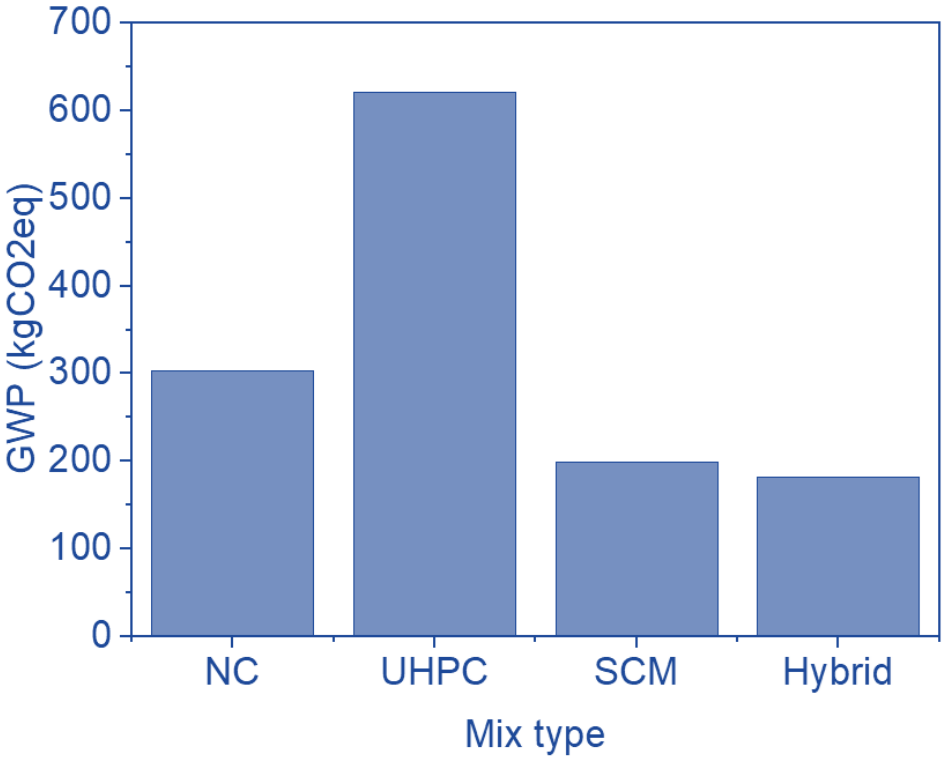
Four mixes considered: REF (NC), SCM, UHPC, SCM, and Hybrid (SCM + UHPC layer).

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



Hybrid project, financed by SBUF, Andrzej Cwirzen materials

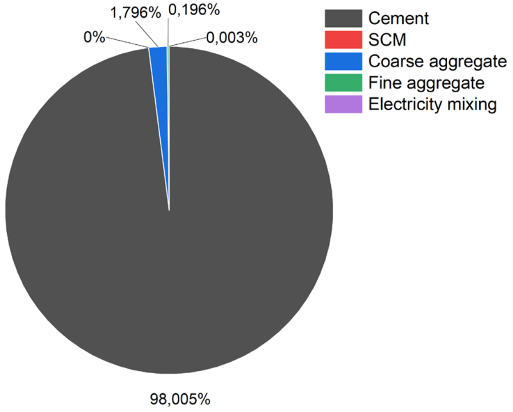
Environmental assessment



SCM and Hybrid mixes showed 30–40% lower GWP

GWP of UHPC was roughly double GWP of NC due to high cement content.

On carbon alone, SCM appeared most favorable.



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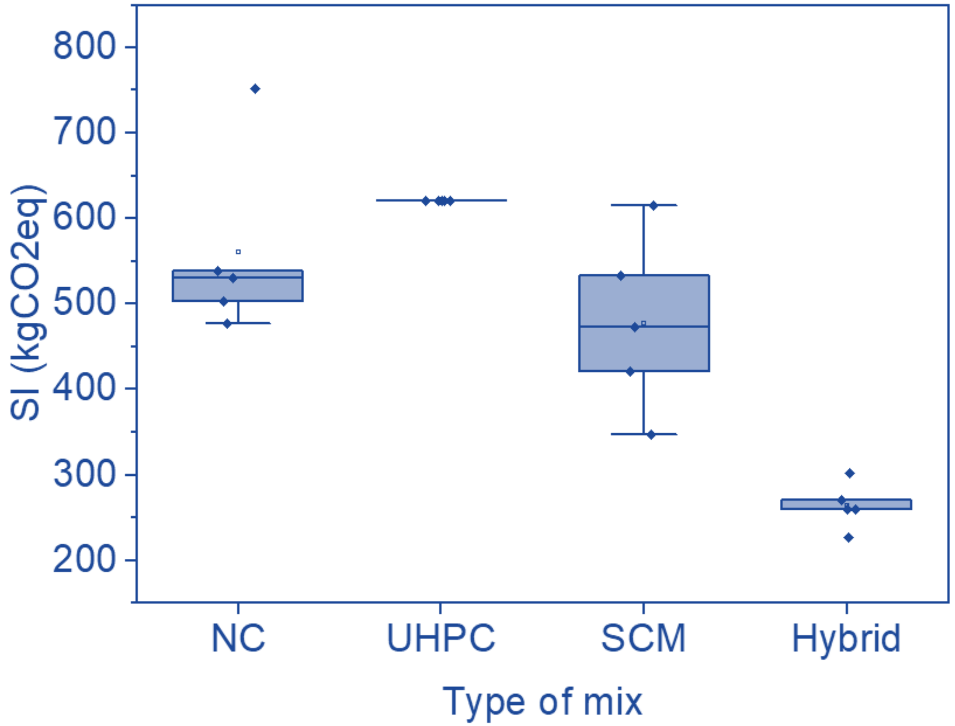
Integrated sustainability index



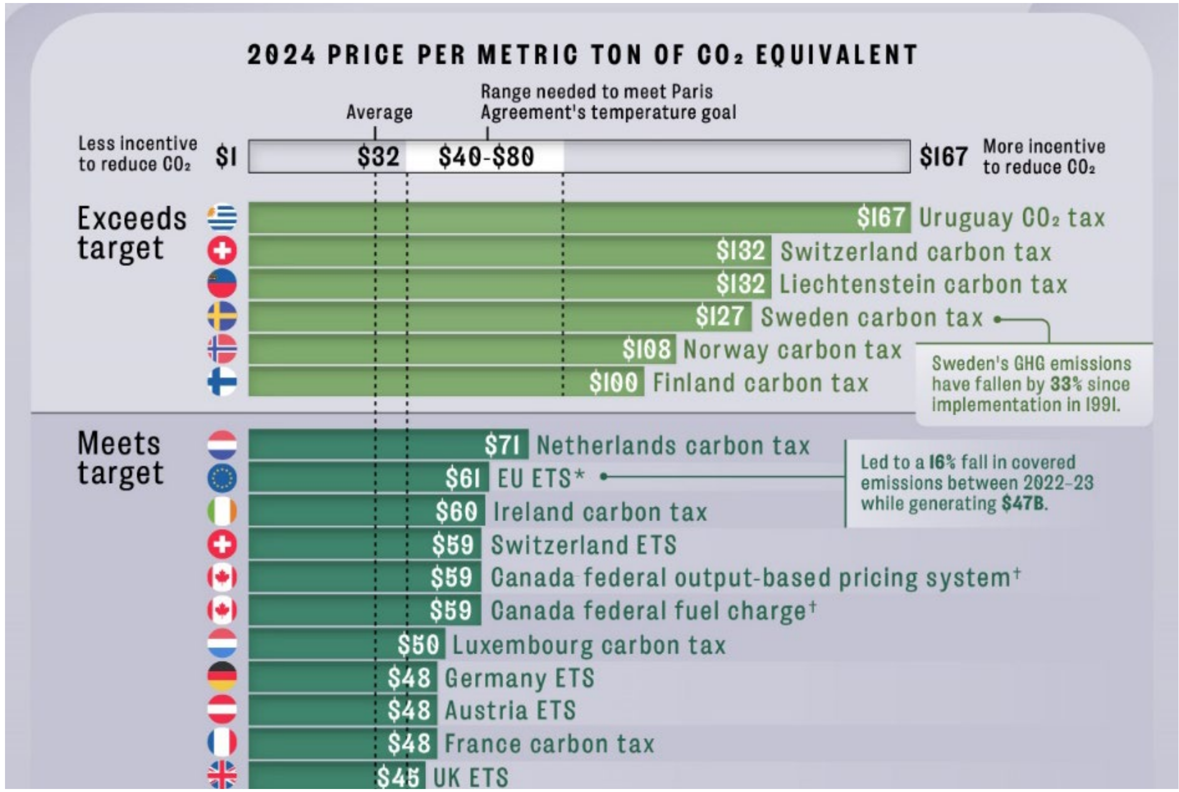
Incorporating durability reduced differences among REF, SCM, and UHPC.

Hybrid consistently achieved favorable SI across all weighting scenarios.

Ranking stability is demonstrated, but variability is visible, with an emphasis on chloride or freeze–thaw.

SI should be interpreted as a first-level screen; final decisions should reflect site-specific priorities (XF4 vs XS3) and structural demands

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

Conclusions

Durability-integrated LCA gives a more balanced view. SI highlights where the carbon emissions can be "earned back" via performance.

Durability-guided layer strategies can be more sustainable offshore than bulk UHPC or bulk SCM alone. UHPC may be justified in targeted layers/zones rather than as a full-volume material;

Some "simplifications" to be addressed:

- durability inputs are lab/literature-based; field validation remains a priority.
- current LCA is cradle-to-gate; downstream modules (repairs, end-of-life, logistics) may further amplify durability effects
- scenario choices affect SI; more detailed sensitivity analysis needed