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Life cycle assessment of ocean alkalinity enhancement using hydrated carbonate minerals

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The ocean currently absorbs roughly one quarter of anthropogenic carbon dioxide emissions but this uptake has driven ~30% increased ocean acidification, with ecological risks [1]. Ocean alkalinity enhancement (OAE) is being explored as a scalable carbon dioxide removal (CDR) approach that may also mitigate acidification. Hydrated carbonate minerals such as ikaite ($CaCO_3 \cdot 6H_2O$) are promising because they dissolve readily in seawater, increasing alkalinity and enabling durable CO_2 storage primarily as bicarbonate. However, the life-cycle environmental performance of ikaite-based OAE remains poorly constrained.

Here we present a cradle-to-grave life cycle assessment (LCA) of ikaite-based OAE, combining a baseline assessment for 2024 with a prospective LCA (pLCA) to 2100 across four regions: Norway, Canada, Russia, and USA-Alaska. The functional unit is the gross removal of 1 tCO_2 from the atmosphere. Foreground inventory data are based on industrial-scale process assumptions for ikaite production, transport, spreading, and dissolution, while background systems are modelled using ecoinvent and scenario-consistent projections via Premise/REMIND [2]. Region-specific OAE efficiencies are applied to capture spatial variability in CO_2 uptake [3].

Baseline results indicate that ikaite-based OAE is net-negative in all regions, but strongly dependent on electricity carbon intensity. Net greenhouse-gas results range from -638 kg CO_2-eq tCO_2^{-1} in Norway to -28.3 kg CO_2-eq tCO_2^{-1} in Russia. Hotspot analysis identifies electricity-intensive ikaite production (notably water circulation and pressure-swing operations) as the dominant contributor, while limestone quarrying and transport are secondary. Under a Paris-aligned decarbonisation pathway, climate performance improves substantially and converges across regions by 2100 (-672 to -677 kg CO_2-eq tCO_2^{-1}), alongside lower endpoint damage scores (-2.40 to -5.08 Pt). In contrast, a no-policy/fossil-intensive scenario yields higher impacts and reduced climate benefits.

Overall, ikaite-based OAE can provide strong net CO_2 removal, but sustainability is governed by access to low-carbon electricity, process efficiency, and deployment in cold-water regions.

References

[1]IPCC (2023), Climate Change 2023: Synthesis Report.

[2]Sacchi et al. (2022), Renew. Sustain. Energy Rev. 160, 112311.

[3]Zhou et al. (2024), Nat. Clim. Chang. 15, 59–65.

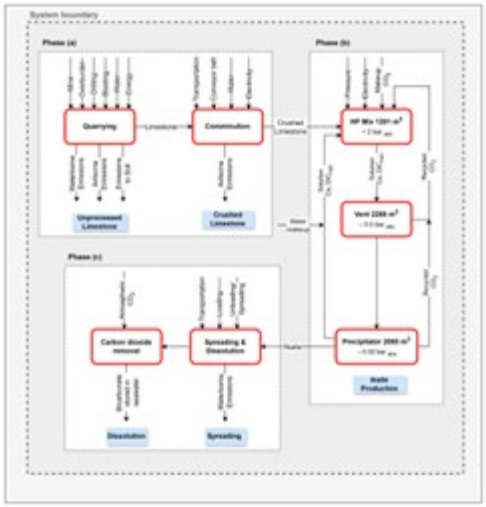

Fig. 1: System boundaries of ikaite-based OAE.

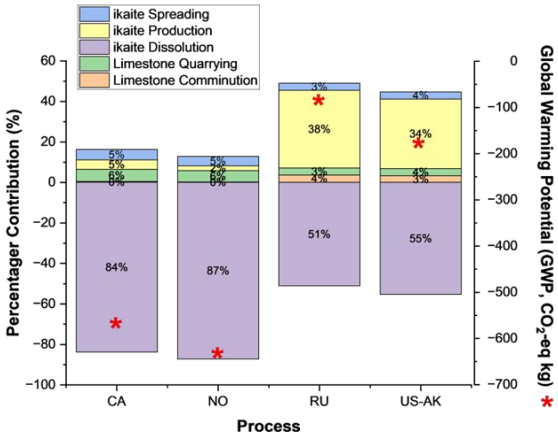

Fig. 2: Contribution breakdown of ikaite production and deployment subprocesses; red dots indicate Global Warming Potential (GWP100) across all locations for the year 2024.