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LETTER

Ocean liming can help achieve the Paris climate target

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Abstract

To stabilize global mean temperature and stay below critical thresholds, deep emission reductions have to be complemented with carbon dioxide removal. A broad portfolio of options is necessary to enable sufficient potential and mitigate sustainability concerns. So far, integrated assessment models have almost exclusively considered options on land. In this study, we show that ocean liming can make a substantial contribution to achieving ambitious climate mitigation targets. Due to the expected time needed for scale-up, the deployment potential in the first half of the century is limited, such that ocean liming can hardly reduce peak temperature. However, in the second half of the century, substantial deployment may be economically competitive. In addition, the availability of ocean liming reduces the dependence on other carbon removal options, and specifically on bioenergy. This could reduce the pressure on land and improve the sustainability of ambitious climate mitigation scenarios. However, impacts on the ocean ecosystems are still poorly understood and need to be clarified before deployment. In light of the remaining uncertainties and global and regional limitations, we suggest to limit the maximum global deployment of ocean liming in integrated assessment models to 5 $GtCO_2$/yr carbon uptake.

1. Introduction

Carbon dioxide removal (CDR) plays an increasingly important role in ambitious climate change mitigation pathways. With the carbon budget dwindling with every year that global CO_2 emissions continue to rise and climate impacts becoming more and more visible, the world may rely on CDR not only to balance residual emissions and achieve climate stabilization, but also to achieve net-negative CO_2 emissions that can draw down global mean temperature after exceeding the 1.5 °C limit. The scale of total global CDR requirements is still uncertain and depends on the speed and depth of emission reductions. Scenarios compatible with 1.5 °C with low overshoot show a median of 8.9 $GtCO_2$/yr CDR in 2050 and a 25–75 percentile range of 7.6–11 $GtCO_2$/yr (Smith *et al* 2024). Not only the scale of total global CDR is uncertain, but even more so the composition of the portfolio of options that should be used, and their regional and temporal distribution.

Currently, 2 $GtCO_2$/yr are removed as part of land use, land-use change and forestry activities ('conventional CDR'), while only 0.0013 $GtCO_2$/yr come from novel CDR (Smith *et al* 2024). Conventional CDR methods alone might not have enough potential, and the carbon stored in the land sink is not permanently bound and may be released again due to changed management or climate damages (Babiker and Berndes 2022, Zickfeld *et al* 2023). Land-intensive CDR methods raise concerns about land competition, food and water security, and biodiversity loss (Smith *et al* 2015, Edelenbosch *et al* 2024). Novel CDR will be needed to fill the gap, but many methods are not only expensive or energy-intensive, but also come with sustainability concerns (Smith *et al* 2024).

Novel CDR methods considered in the literature are direct air carbon capture and storage (DACCS) (Keith *et al* 2006), bioenergy with carbon capture and storage (BECCS) (Obersteiner 2001), biochar production (Smith 2016, Lehmann *et al* 2021), enhanced weathering of rocks (Hartmann *et al* 2013, Stler *et al* 2018), and a variety of ocean-based methods (Gattuso *et al* 2021). Transformation pathways analyzed in the AR6 primarily represent afforestation/reforestation (AR) and/or BECCS and some include DACCS and enhanced rock weathering (Strefler *et al* 2021, Riahi *et al* 2022), while ocean-based options have been largely missing in integrated assessment models (IAMs) so far, except for Fuhrman *et al* (2023) who found only a small contribution from direct ocean capture.

Expanding the CDR option portfolio to ocean methods could address some of the concerns associated with land-intensive CDR options. Ocean alkalinity enhancement increases the ocean pH by spreading alkaline material in the surface layer of the ocean, which enhances ocean CO_2 uptake resulting in durable carbon removal. Using quicklime (ocean liming, OL) is one of the most promising options to enhance alkalinity from a technological point of view (Renforth 2019, Foteinis *et al* 2022, Kowalczyk *et al* 2024), mainly because quicklime readily dissolves in water and its production process is already scaled to gigatons (Caserini *et al* 2021). In this study, we rely on the process and parameterization provided by Kowalczyk *et al* (2024). Quicklime (CaO) is produced from limestone via calcination, which is an energy-intensive process that requires high-temperature heat (Kheshgi 1995, Renforth and Henderson 2017, Kowalczyk *et al* 2024). We assume the energy-related and process-based CO_2 released in this process to be captured and stored geologically to increase the carbon-removal efficiency of this method. As quicklime is very reactive, we assume that it is mixed with water to produce hydrated lime ($Ca(OH)_2$), which is then spread in the ocean via ships (see Methods and SI for more detailed description of the process). Though calcination of limestone is a mature technology that is widely used in cement production, several knowledge gaps and challenges remain that must be resolved. Most importantly, the potential impact of OL on marine ecosystems is still unknown (Santinelli *et al* 2024). Precipitation (crossing critical saturation thresholds of carbonate minerals, which reduces the atmospheric CO_2 uptake) must be avoided as it undermines the method's efficiency (Fuhr *et al* 2022, Moras *et al* 2022, Hartmann *et al* 2023), and high-efficiency areas of the ocean need to be identified. Monitoring, reporting, and verification is yet another challenge, as it is technically very difficult to track the carbon that enters the ocean as part of the ocean carbon cycle (Morganti *et al* 2025). From a technological perspective, although the calcination process is well-known, low carbon alternatives such as electric calciners are not yet commercially available, and the precise distribution mechanism of hydrated lime via ships needs to be developed. Energy and carbon storage availabilities are uncertain, and finally, policies and legal regulations must be put in place before OL could be scaled up successfully.

If these challenges and concerns can be resolved, OL could make a significant contribution to reaching pledged climate targets. In this study, we aim to determine the cost-effective contribution of OL to achieving the Paris climate target under varying assumptions that reflect key uncertainties, focusing on energy system conditions. The competition with other mitigation technologies for geological carbon storage (GCS) and energy is crucial for a comprehensive assessment of the potential contribution of OL to the Paris climate target, and is comprehensively and consistently assessed in REMIND. We will analyze trade-offs, but also key benefits of large-scale OL deployment. To our knowledge, this is the first study that includes OL in climate change mitigation pathways and investigates its potential impact on reaching climate goals.

2. Methods

In this study, we investigate the potential contribution of OL to the Paris climate target from a systemic, techno-economic perspective using the global energy-economy-climate model REMIND (Baumstark *et al* 2021, Luderer *et al* 2024) version 3.5.0. REMIND provides consistent, comprehensive, and cost-effective pathways for climate change mitigation under different assumptions that capture the interactions between all sectors and world regions.

REMIND includes not only BECCS and re- and afforestation as CDR options, but also DACCS. Carbon removal can also occur when synthetic fuels derived from atmospheric or biogenic carbon are combined with CCS, or are used to produce materials such as long-lived plastics. AR follows an exogenous pathway derived from the model MAgPIE (Dietrich *et al* 2019, 2023). The bioenergy used for BECCS relies on a supply curve that is also derived from MAgPIE. DACCS uses solid sorbents, which requires low-temperature heat as well as electricity (Broehm *et al* 2015, Beuttler *et al* 2019). BECCS, DACCS, OL, as well as the industry and fossil energy compete for GCS.

The parameterization of OL relies on Kowalczyk *et al* (2024) (see also supplementary note 1). The main steps of OL are mining and transport of limestone, calcination to produce quicklime, hydration to hydrated lime, and distribution of hydrated lime via ships. We account for costs, energy requirements, the fate of captured CO_2, and CO_2 emissions. The calcination process requires high-temperature heat, and may use either traditional calciners which rely on gas or hydrogen, or novel electric calciners which may also use electricity. Energy costs are calculated endogenously in the model (see figure S11). We assume that the CO_2 from the process emissions from calcination, as well as from natural gas use if that is the energy source for the high-temperature heat, are captured with a capture rate of 90%, the remaining 10% are emitted to the atmosphere. We subtract this released CO_2 from the ocean uptake and report only the net CDR effect as ocean CDR. The model endogenously decides whether the captured CO_2 is stored underground or used for synthetic fuels with potential re-release. From an energy system perspective, cost-efficient OL deployment is thus mainly limited by energy and GCS availability. Due to the necessary technological development and inclusion in climate policy, we assume OL to start not before 2035.

In addition to the type of calciner, other important uncertainties concern the ocean uptake efficiency, i.e. how much CO_2 is taken up by the ocean per unit of alkalinity added, and the costs and energy requirements for distributing the alkaline material. The uptake efficiency varies depending on temperature and partial pressure of CO_2 in the atmosphere, as well as regional characteristics of the ocean, e.g. geochemical aspects. First studies estimate spatially explicit efficiencies for different parts of the ocean, highlighting issues such as incomplete air-sea CO_2 exchange and changes in circulation patterns and other ocean conditions between seasons and years, which may remove surface water from contact with the atmosphere and thus cause delays and affect efficiencies. (Ho *et al* 2023, Zhou *et al* 2024). As we do not explicitly model the ocean and alkalinity discharge location in our study, we assume a homogeneous efficiency across the entire ocean that is constant over time, but use a mid-range estimate of 0.9 $tCO_2/tCa(OH)_2$ (range estimated to be 0.7–1.1 $tCO_2/$ $tCa(OH)_2$) (Kowalczyk *et al* 2024). The distribution costs and energy requirements depend on the amount of alkalinity that can be discharged over time. Recent findings indicate that a fast discharge may lead to secondary precipitation, which may significantly decrease the efficiency of OL (Moras *et al* 2022, Hartmann *et al* 2023, Kowalczyk *et al* 2024). We therefore assume a concentration limit of 20 $gCa(OH)_2/m^3$. Distribution costs then depend on the volume of seawater that can be covered per ship (see SI for details). A sensitivity analysis covering both a lower efficiency estimate and a lower discharge rate is provided in the SI.

We compare scenarios with OL with a scenario without OL (*noOL*). So far, ambitious climate mitigation scenarios have often shown a high reliance on biomass (Bauer *et al* 2018, Riahi *et al* 2022) as well as on GCS. Limiting biomass has been one of the most important drivers of higher mitigation costs as it is an important commodity for the energy transition and for BECCS, which has so far been one of the most important CDR options. We therefore vary the bioenergy availability (no explicit limit vs limits of 60, 80, and 100 EJ bioenergy globally) and GCS availability (limitation due to a precautionary limit on the injection rate equivalent to ~20 $GtCO_2$/yr vs a maximum of 4 $GtCO_2$/yr). The resulting scenarios are listed in table 1.

Table 1. Scenarios with and without OL are limited either in terms of bioenergy availability, or geological carbon storage.

	Default	Limited bioenergy	Limited GCS
With OL	OL	OL bioenergy 60/80/100 EJ	OL GCS limited
Without OL	noOL	noOL bioenergy 60/80/100 EJ	noOL GCS limited

All scenarios remain below a cumulative carbon budget of 650 $GtCO_2$ from 2020 to 2100, which is consistent with a limited overshoot over 1.5 °C global mean temperature increase (Arias *et al* 2021, Forster *et al* 2024). Using MAGICC 7.5.3 (Meinshausen *et al* 2011, Kikstra *et al* 2022), all scenarios have a 50% probability to peak below 1.65 °C (see supplementary figure S5). Different regions follow different carbon price pathways differentiated by GDP per capita, such that richer countries start with a higher carbon price than poorer countries. Carbon prices converge to a globally uniform value by 2050 and remain constant thereafter (see supplementary note 1). Even with a constant carbon price, learning and system inertia lead to further decline of gross emissions as well as scale-up of CDR. This leads to continued but varying reductions of net-CO_2 emissions. All scenarios reduce global mean temperature after the peak, but the temperature they reach in 2100 differs (see supplementary figure S5). Assumptions regarding socio-economic drivers such as population, gross domestic product, dietary choices, and energy demand follow medium estimates as defined in the shared socio-economic pathway SSP2 (Riahi *et al* 2017).

3. Results

3.1. OL has limited impacts on the climate until mid-century, but may enable large temperature reductions in the second half of the century.

We find that OL is a competitive CDR option in 1.5 °C scenarios with low overshoot. With default settings, annual CDR via OL reaches 8.5 $GtCO_2$/yr by 2050 (figure 1(a)). At this level, OL could potentially contribute significantly to national and regional net-zero emission targets. Limiting the availability of

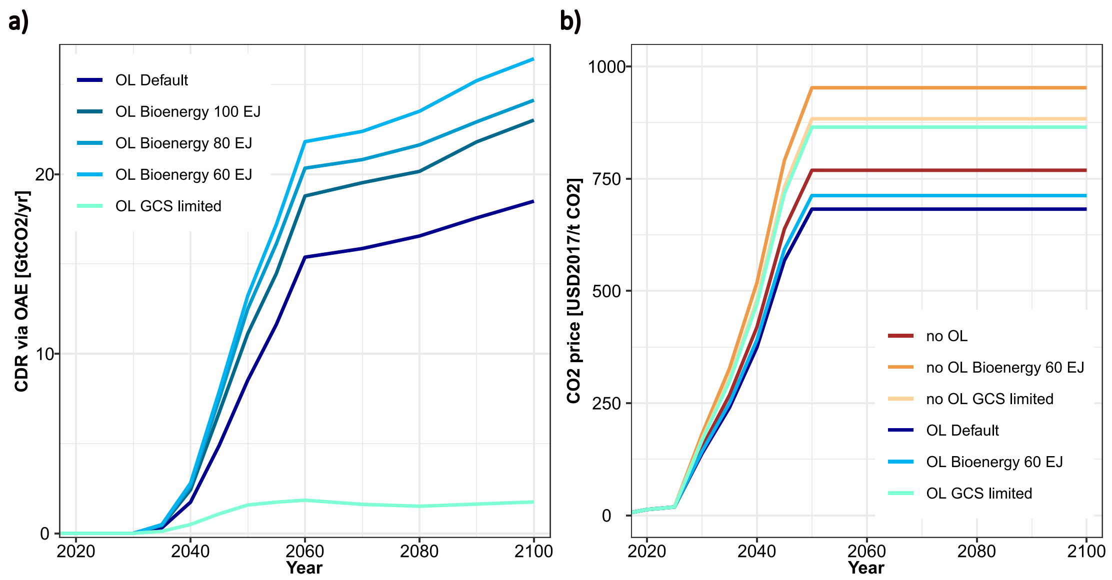

Figure 1. (a) Global net carbon removal via ocean liming and b) average global carbon price in the 21st century for scenarios with OL (blue colors) and without OL (brown colors) under default assumptions (dark blue/brown), and with limitations of bioenergy (medium blue/brown) and geological carbon storage availability (light blue/brown).

bioenergy both increases residual emissions and limits the availability of BECCS and therefore increases the demand for other CDR options (figure S6), which leads to a higher OL deployment in 2050 of 11.1–13.2 $GtCO_2$/yr. As OL depends on the availability of carbon storage, a limitation of GCS reduces OL deployment in 2050 to 1.6 $GtCO_2$/yr (see also GCS in figure S7). However, as there is technological development necessary such that we expect OL to start not before 2035, and then scale-up takes time, cumulative CDR via OL until 2050 amounts to only 13–96 $GtCO_2$, which has little impact on global mean temperature in 2050. Due to the small impact of OL on global mean temperature by mid-century, there is also only limited impact of OL availability on the carbon price necessary to limit peak temperature to a low overshoot above the 1.5 °C limit (figure 1(b)). In the 2nd half of the century the scenarios show a large techno-economic potential for OL of 1.8–26.4 $GtCO_2$/yr in 2100 (figure 1(a)), enabling significant net-negative emissions of up to −25 $GtCO_2$/yr (figure S8) and therefore global mean temperature reductions of more than 0.6 °C by 2100 if GCS is not limited as opposed to 0.28 °C without OL (figure S5). Further, it is important to note that the large techno-economic potential strongly depends on the assumptions on ocean uptake efficiency and distributional cost. More pessimistic assumption about either decreases the cost-effective deployment in scenarios to less than 1.1–2.4 Gt CO_2/yr in 2050 and 6–9.1 Gt CO_2/yr in 2100, and pessimistic assumptions about both lead to OL being deployed almost not at all (see supplementary note 2).

3.2. Energy system effects

OL is an energy-intensive technology that requires large amounts of high-temperature heat for the calcination process. Traditional calciners use gases to provide this heat, but if electric calciners were developed and used, electricity could be used instead of gases. Electricity is almost completely decarbonized in the second half of the century, whereas the traditional calciner would require either green hydrogen or CCS for decarbonization. In addition, OL requires liquid fuels for distributing the hydrated lime in the ocean via ships. The energy requirements of OL for heat are comparable to direct air capture processes (Kowalczyk *et al* 2024). However, due to the higher capital costs at least in the near term, DACCS is used only if OL is limited or not available (figure S6). The final energy required for the large-scale OL emissions of 18.5 $GtCO_2$/yr in 2100 in the OL default scenario (figure 2(a)) is a significant share of about 12% of total global final energy (figure 2(b)). As fossil gases get expensive due to the high carbon price, and low-carbon gases are expensive due to their scarcity, the model invests mainly in electric calciners (figure S10). Therefore, the main additional energy requirement is electricity, with liquid fuels for distribution contributing a much smaller additional energy requirement (figures 2(b) and (c)).

The liquid fuels required for the distribution of alkalinity are supplied mainly by more synthetic liquids (figure S9). The higher demand for energy in combination with a lower carbon price leads to a slightly slower phase-out of fossils, with more residual fossils left in the system in 2100, and more

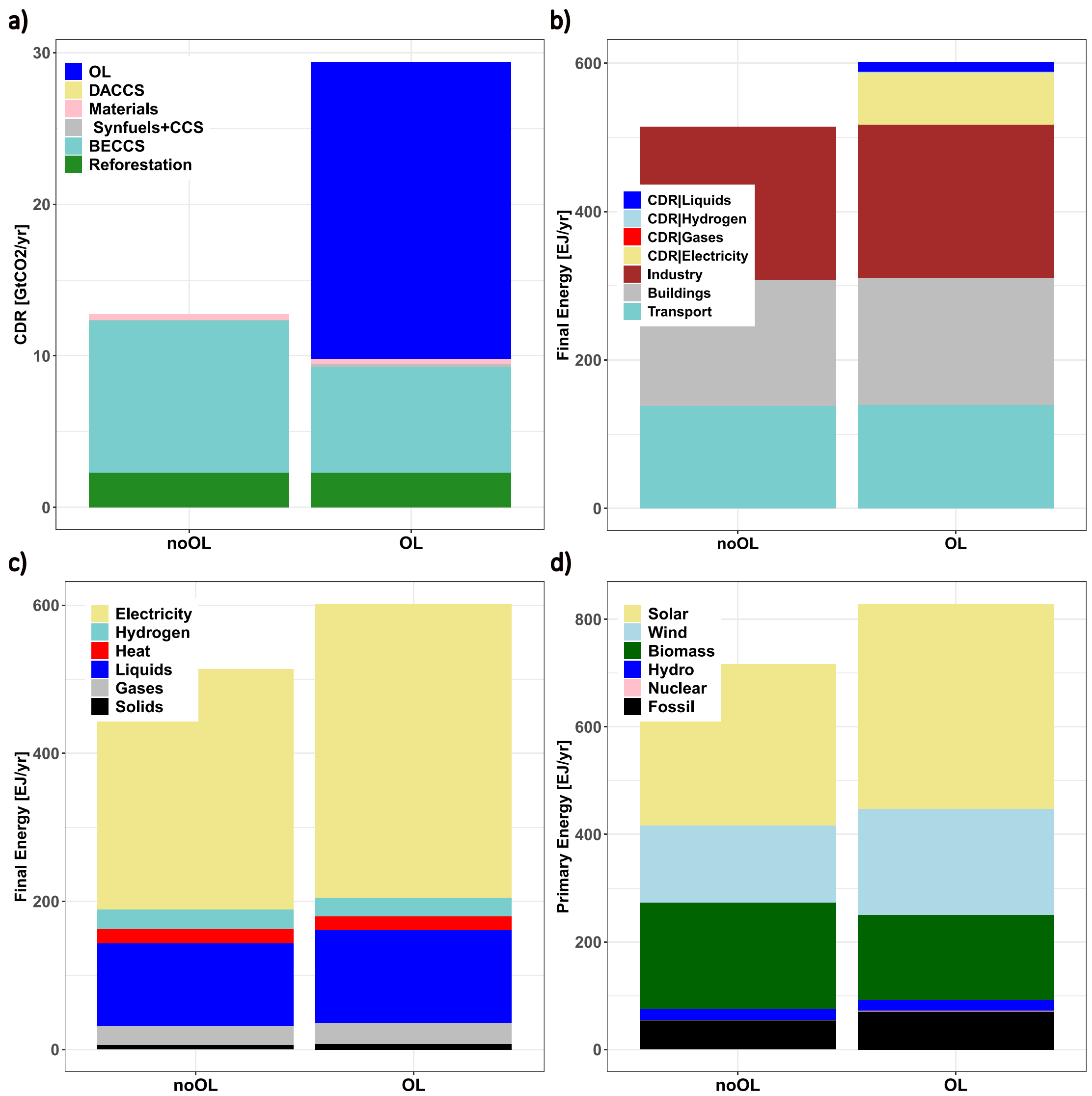

Figure 2. Global CDR and final energy demand in 2100 for the default scenarios without and with ocean liming. (a) CDR portfolio, (b) total final energy by sector, (c) total final energy by carrier, (d) total primary energy by carrier.

renewable electricity needed (figure 2(d)). Note that the energy demand for the other sectors remains almost unchanged (figure 2(b)). This is due to the scenario design, where the climate target is a limitation of the peak carbon budget, equivalent to a limitation of peak temperature. After net-zero CO_2 emissions and therefore the peak carbon budget is reached, the carbon price remains constant. As shown above, OL has only marginal impact on the peak budget. It is mainly deployed in the second half of the century, and largely additional to other mitigation measures, and therefore adds to the reduction of global mean temperature after the peak.

3.3. Global and regional limitations

So far, we have only considered techno-economic interdependencies of OL deployment with the energy system. However, OL deployment is also limited by physical constraints. The sea surface area is about 361 million square kilometers. Following Kowalczyk *et al* (2024) and assuming a spreading of alkalinity within the upper two meters of the surface, with a concentration limit of 20 $gCa(OH)_2/m^3$, yields a maximum amount of 14.44 $GtCa(OH)_2$ that could be spread in the entire ocean. With the medium uptake efficiency of 0.9 $tCO_2/tCa(OH)_2$, this would imply a limit of 13 $GtCO_2$ ocean uptake. If alkalinity application was restricted to the exclusive economic zones (EEZ) and 2 m depth, and equilibration with the atmosphere would be fast enough such that the alkalinity application could be repeated every year, this would limit ocean uptake to 5 $GtCO_2$/yr. As of now it is unclear whether OL would be preferable in the EEZ or at high sea. Uptake efficiencies differ by local conditions, and there is still uncertainty regarding where high-efficiency areas are. Also, coastal zones have various other uses like fishery or marine protection areas that may hinder application of alkalinity. However, it might be easier to create a legal framework for OL in EEZs, and the lower water depths and tides lead to a better mixing of waters and prevent sinking of alkaline waters to deep oceans. These numbers are not an absolute upper limit, as the alkalinity could be spread deeper than 2 m, and the same area could be covered more than once a year, depending on the time it takes for the respective ocean layer to equilibrate again with the atmosphere. The depth of the mixed layer depends on the exact definition and varies geographically and over seasons, but is usually assumed to be around 10 m (De Boyer Montégut *et al* 2004, Treguier *et al* 2023). Due to this uncertainty, we adopt a precautionary approach of 2 m, but provide a sensitivity of up to 10 m in supplementary note 3.

Focusing on the provision of ships as one aspect of logistics, Caserini *et al* (2021) calculated a global ocean uptake potential of 4.4 $GtCO_2$/yr CO_2 from OL by using free capacities in existing cargo and container ships leading to 3.3 $GtCO_2$/yr, plus 1.1 $GtCO_2$/yr from a new fleet of 1000 ships. Again, more ships could potentially be built, especially towards the end of the century. However, in light of these two estimates, we suggest a precautionary global limit of 5 $GtCO_2$/yr ocean uptake for OL in standard IAM scenarios, corresponding to distribution of alkalinity in the entire EEZs at 2 m depth and a concentration limit to avoid secondary precipitation. This limit is applied on a regional level, corresponding to the respective areas of the EEZ. OL is still a very new concept, with significant technical, legal, and ecological uncertainties, and such a limitation would also avoid the implicit impression that OL could be a silver bullet type solution at least for net-negative emissions in the 2nd half of the century. A limitation would also limit externalities such as impacts from quicklime mining at gigaton scale, or from building new ships and ports that may be necessary at larger scale, but are currently not considered in the model. Considering the performative power of IAM scenarios, and the difficulties to bear all assumptions in mind that may not always be obvious, also calls for a limitation of single uncertain technologies.

In REMIND, OL deployment is concentrated in a few regions, namely reforming economies, Middle-East and North Africa, Latin America, USA, and Canada, New Zealand and Australia (CAZ) (figure 3, see supplementary note 1 for regional resolution of REMIND). This concentration is a result of the techno-economic perspective, as these regions have large GCS and renewable energy potentials, but mostly limited bioenergy supply and therefore limited competition for GCS from BECCS.

This regional concentration exacerbates the share of total final energy that is used for OL (figure 2(b)) in regions with high deployment. A limit of 5 $GtCO_2$/yr ocean uptake based on the areas of the EEZs reduces the regional concentration. Note that not all regions exhaust their limit, such that global deployment

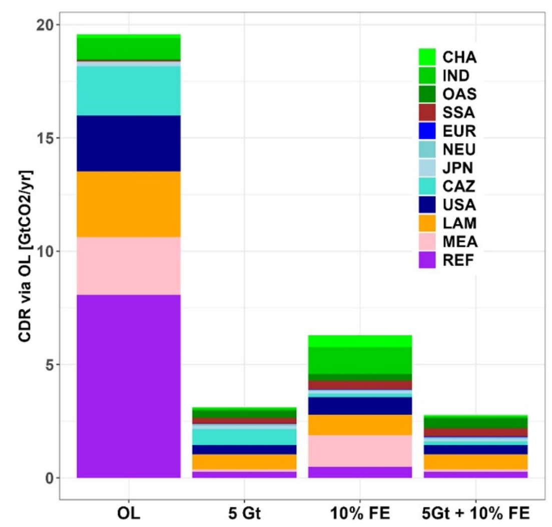

Figure 3. Regional distribution of OL in the default scenario (*OL*), with a global limit of 5 GtCO2/yr (*5 Gt*), with a regional limit of 10% of final energy used for OL (*10% FE*), and a combination of the global and regional limit (*5Gt + 10% FE*). See SI for region definitions in REMIND.

reaches only about 3 $GtCO_2$/yr. This is largely due to the exhaustion of the annual regional GCS potential, so these regions could only deploy more OL at the expense of other technologies using GCS like BECCS. Without OL limitation, the model results imply that the CAZ region uses half of its total final energy in 2100 for OL, and still about 28% with the 5 $GtCO_2$/yr limit. Even though some regions have large energy supply potentials compared to their population-dependent final energy demand, it is conceivable that a high share of final energy dedicated to CDR would be associated with scale-up difficulties and externalities not captured in techno-economic IAMs. We therefore suggest limiting regional CDR deployment such that it may not require more than 10% of total final energy. The combination of the limitations based on the areas of the EEZs and on final energy share lead to a global ocean uptake of 2.8 $GtCO_2$/yr in 2100 with a more balanced regional distribution.

3.4. OL reduces reliance on bioenergy, but not on GCS

In the literature, limitations of bioenergy and GCS availability have been identified as the main drivers of economic costs in transformation pathways with high mitigation ambition (Kriegler *et al* 2014). In our scenarios, the availability of OL allows for a strong limitation of bioenergy from 160 EJ down to 60 EJ with a carbon price increase of less than 5% (figure 4). When OL is limited, the carbon price increases by 14%, and when OL is not available, the carbon price increases by 24% when bioenergy is limited to 60 EJ. The picture changes when GCS is limited. In that case, carbon prices are much higher in general, and

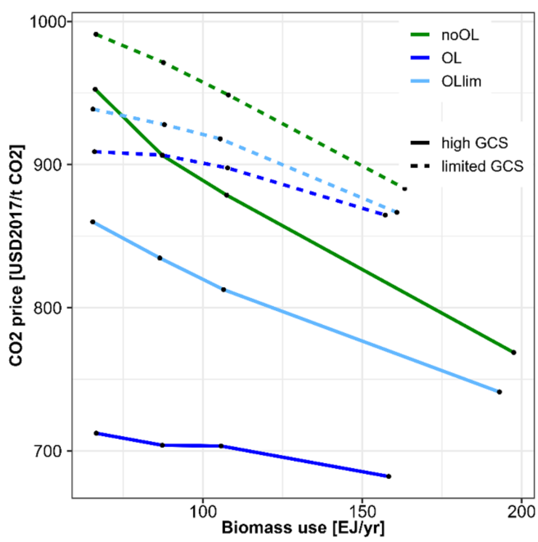

Figure 4. Sensitivity of the required carbon price in 2050 on the availability of biomass. Scenarios without ocean liming (dark green) show a much higher sensitivity than scenarios with full (dark blue) or limited (light blue) ocean liming. If GCS is limited (dashed lines), carbon prices are generally higher, but the sensitivity to biomass availability remains weak in scenarios with OL, and is significantly weaker than in scenarios without OL.

as the limitation of GCS also limits OL, the differences between scenarios with and without OL are less pronounced.

Since the amount of bioenergy that can be supplied sustainably is uncertain, the development of OL could hedge against the risk of lower bioenergy availability. However, OL cannot address risks related to high geologic storage requirements and deployment.

4. Discussion

In this study, we have shown that at least from a techno-economic perspective, OL could make a substantial contribution to achieving the Paris climate target, especially in the 2nd half of the century. OL is shown to be one of the few CDR options that can potentially deliver large amounts of net-negative emissions without requiring excessive amounts of land.

However, OL still comes not only with technical and legal uncertainties, but also unknown effects on the ocean ecosystem. More research on the ecological effects is therefore urgently needed. Besides the ecological effects, also the physical effects like the ocean uptake efficiency, which may vary locally as well as in dependence of the CO_2 concentration in the atmosphere, need to be explored.

One limitation of this study is, that we focused on techno-economic and energy system effects, and did not model the ocean explicitly. We therefore used a medium uptake efficiency, which is probably a rather conservative estimate given that areas with high efficiency would be preferred. If the efficiency turned out to be much lower in all areas that are targeted for deployment, then the potential would be reduced significantly. We also did not model explicitly where the alkalinity is distributed. The regional potential of OL depends on energy and GCS availability, and the relative costs of OL compared to other mitigation options, as well as access to ports and shipping capacity. Since we do not model ports and shipping capacity explicitly, we restricted deployment for all regions based on the size of their EEZ and distribution at a precautionary depth of 2 m therein. This is a very conservative estimate for the depth of the mixed layer, most likely greater depths could be used which would increase the potential. Yet, it is unlikely that the entire EEZ area could be used for deployment. Given the many uncertainties, the 2 m limit leading to a maximum of $GtCO_2$/yr globally is a transparent and cautionary global bound. However, it is uncertain whether EEZs would be preferred due to easier access, or rather avoided due to the larger share of marine protected areas (Pike *et al* 2024). In addition, a legal and governance framework regulating spreading is necessary to achieve significant deployment that avoids negative side-effects. One major techno-economic uncertainty is the number of and additional cost from additional ships and potentially also harbors that may be needed, as well as additional mines for limestone. Harbor capacity could be an additional regional limitation, that would require more dedicated research beyond the scope of this study.

OL could reduce the need for other CDR options such as BECCS and DACCS as well as the reliance on bioenergy in general, and therefore also relieve the pressure on land and energy systems. Due to the high pressure on land in many ambitious mitigation scenarios, this lower demand for bioenergy would improve sustainability in that aspect. This positive pathway sustainability effect has to be weighed against the uncertainties on ocean ecosystems, again underlining the need for more research in that area. Given the potential benefits of OL and the uncertainties and negative effects of other technologies, further research and development of OL can be a strategy to mitigate risks from either failure of other options, or higher demand for CDR than expected, e.g. due to a higher climate sensitivity.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.5281/zenodo.15607248.

Code availability

The REMIND code is available under the GNU Affero General Public License, version 3 (AGPLv3) via GitHub. The model version used in this study is 3.5.0, which can be downloaded at https://github.com/remindmodel/remind/releases/tag/v3.5.0.

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Author contributions

JS designed, produced and analyzed the scenarios, produced the figures, and was the lead author. KK provided the parameterization of OL and the implementation in the model. TD and VH contributed to the development and implementation of global and regional bounds. LB is responsible for development and maintenance of the model. All authors contributed to the development of the model, the presented ideas, the figure design, and to the text.

Conflict of interest

The authors declare no competing interests.

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