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Ocean-based Negative Emission Technologies

OCEAN NETs

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Author(s)	James Campbell, Spyros Foteinis, Mohammad Madankan, and Phil Renforth
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Abstract: A common challenge in many ocean-based negative emissions technologies (NETs) is the difficulty of developing new global industries and supply chains, which could be necessary for their much needed rapid and large-scale deployment. Therefore, to facilitate roll-out, existing industries and infrastructure should preferably be utilised. For ocean alkalinity enhancement (OAE) by CaO, i.e., ocean liming (OL), the lime can be produced by calcination of limestone using the spare capacity in the cement industry. For OAE by NaOH, i.e., electrochemical brine splitting (EBS), the NaOH can be produced by electrolysis of waste brines from the desalination sector. In this case study, we investigate the realistic OAE potential of Spain, because of its large availability of limestone, its increasing spare cement kiln capacity, and its large and growing desalination industry. This case study shows Spain has a high potential for alkalinity addition to the oceans. Specifically, the total CDR capacity of Spain via OAE is 24.4 Mt yr.$^{-1}$ with contributions of 22.6 Mt of CO_2 removed by OL and 1.8 Mt of CO_2 removed by EBS, assuming these processes are driven solely by renewable energy. Further, this case study provides a realistic estimate of the CO_2 removal potential and life cycle emissions for alkalinity enhancement for a given region, in contrast to more general global or continental studies before it. By doing so, Spain's annual carbon dioxide removal (CDR) capacity by OAE is also identified. Future work will look to include coastal enhanced weathering of olivine to the portfolio of Spain's OAE approaches.

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List of abbreviations, acronyms, and definitions

CCS	Carbon capture and storage
CDR	Carbon dioxide removal
EBS	Electrochemical brine splitting
LCA	Life cycle assessment
LCIA	Life cycle impact assessment
NETs	Negative emissions technologies
OAE	Ocean alkalinity enhancement
OL	Ocean liming

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1. Introduction

1.1 Context

This document comprises the deliverable 6.4 of the OceanNETs project. OceanNETs is a European Union (EU) project funded by the Commission's Horizon 2020 program under the topic of negative emissions and land-use based mitigation assessment (LC-CLA-02-2019), coordinated by GEOMAR Helmholtz Center for Ocean Research Kiel, in Germany. OceanNETs respond to the societal need to rapidly provide a scientifically rigorous and comprehensive assessment of negative emission technologies (NETs) also known as carbon dioxide removal (CDR) technologies or approaches. The project focuses on analysing and quantifying the environmental, social, and political feasibility and impacts of ocean-based NETs. Its overall objective is to identify and fill the fundamental knowledge gaps on specific ocean-based NETs and provide more in-depth investigations of NETs that have already been suggested to have high CDR potential and sustainability and/or also provide potential co-benefits. It will identify to what extent, and how, ocean-based NETs can play a role in keeping climate change within the limits set by the Paris Agreement.

1.2 Purpose and scope of the deliverable

The purpose and scope of this deliverable (6.4) is to provide realistic scenarios for two different ocean-based NETs. Specifically, removing CO_2 from the atmosphere by increasing ocean alkalinity (ocean alkalinity enhancement, 'OAE') could form an essential part of the European strategy for net-zero carbon emission targets. However, previous modelling experimentation has been largely driven by attempts to elicit a specific response in the Earth/ocean-system models. There has been little work constrained by what might be 'realistic' for current and future supply chains. For this reason, in this deliverable, a life cycle assessment (LCA) for two OAE technologies, namely ocean liming (OL) when using spare capacity of existing cement plants and the electrochemical brine splitting (EBS) of waste brines produced by the desalination industry was conducted to identify the life cycle carbon emissions, i.e., carbon footprint, of these two NETs. Previous work focused on the global potential of these technologies, and here an additional layer of realism is provided by restricting the spatial extent of the analysis. To this end, Spain (including its main islands) was used as the case study, owing to its very large spare capacity of the cement industry and to its strong and growing desalination industry. Site-specific case studies, like this one, can refine deployment scenarios with realistic geographic and industrial constraints such as transportation distances, electricity CO_2 intensity, and resource abundance. The intention is that the data generated by this regional LCA case study will be adapted for use by ocean/carbon cycle modellers within the OceanNETs consortium and beyond. The work builds upon previous deliverables from WP 6 that conceptually describes the case studies via LCA. This could be used within deliberative work with stakeholders, or to help constrain or contextualise economic or governance work.

1.3 Relation to other deliverables

This deliverable (6.4) relates to all deliverables in WP 6 (6.1, 6.2, 6.3, 6.5, 6.6), but also WP 2 and WP 4.

2. Background

The concept of OAE, also known as ocean alkalinisation, was first proposed by Khesghi (1995) in the mid-90s and since then it has been identified that OAE has the potential for large-scale CDR (Renforth and Henderson, 2017; National Academies of Sciences, Engineering, and Medicine. 2022). Here, two emerging methods of OAE are examined in terms of life cycle carbon emissions and potential for CDR in the Spanish setting, namely OL (Ilyina et al., 2013) and EBS (Thiel et al, 2017).

2.1 Ocean liming

In OL, lime (CaO), or more likely slaked lime ($Ca(OH)_2$), is added to the ocean, increasing its alkalinity and drawing down CO_2 into the form of dissolved bicarbonate. The lime is produced by the mining, grinding, and calcining of limestone ($CaCO_3$), a low cost and widely available material, and then it is spread in the ocean for alkalinity enhancement. In order to be used for CDR, the process should be net negative, i.e., the life cycle carbon emissions should be (significantly) lower than the amount of CO_2 that is drawn down from the atmosphere (Figure 1). For this reason, the CO_2 produced in the calcination step should preferably be captured and stored (e.g., geologically) using traditional carbon capture and storage (CCS) technology and/or valorised (carbon capture and utilisation (CCU)) using permanent solutions such as creating carbon-based aggregates for the construction industry.

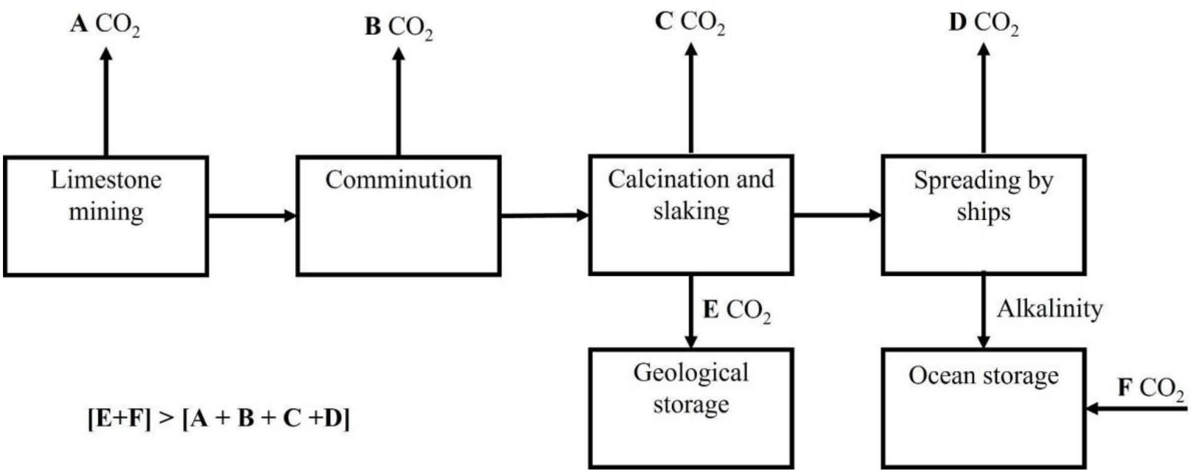

Figure 1: Simplified process flow diagram for ocean liming.

2.2 Electrochemical brine splitting

Brines such as seawater, can be electrochemically treated to produce $NaOH_{(aq)}$ which in turn can be dispersed in the ocean for alkalinity enhancement and CDR. Waste brines from the desalination industry are more concentrated than seawater (typically they contain twice the amount of salt), while the produced alkalinity (NaOH) could possibly be dispersed to the ocean via existing brine disposal pathways (Figure 2). There are two main electrochemical methods for generating alkalinity from brines: electrolysis and electrodialysis. Electrolysis produces high-concentration $NaOH_{(aq)}$ (approx. 32 wt.%), along with by-products $H_{2(g)}$ and $Cl_{2(g)}$ which must be sold to existing markets or safely combined to form $HCl_{(aq)}$ and stored through reaction with alkaline materials (Willauer et al., 2014). Electrodialysis produces lower concentration $NaOH_{(aq)}$ (approx. 1-2 wt.%) along with $HCl_{(aq)}$ and negligible amounts of $H_{2(g)}$ and $O_{2(g)}$ that are vented (Eisaman et al., 2012). Electrolysis tends to be more energy-intensive than electrodialysis (higher voltage and current requirements) since it involves the decomposition of water. Electrodialysis, on the other hand, is relatively more energy-efficient as it primarily focuses on ion transport across membranes, requiring lower applied voltages and current densities (Kumar, Du, and Lienhard, 2021). However, electrodialysis is less mature than electrolysis, with approximately 99.5% of NaOH production worldwide being produced through electrolysis and specifically by the chloralkali process (Du et al., 2018). In electrolysis $H_{2(g)}$ can be burned for energy, or utilised, but the $Cl_{2(g)}$ can be difficult to dispose of and is a potential environmental hazard. In electrodialysis, a use or neutralisation pathway must be found for the dilute $HCl_{(aq)}$, for example, by neutralisation upon contact with abundant sources of mineral alkalinity.

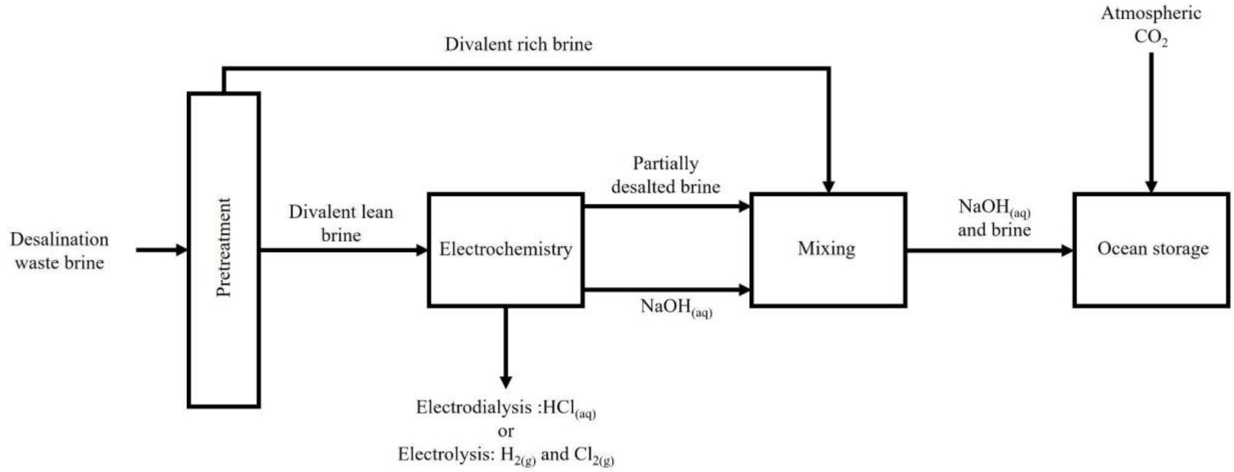

Figure 2: Simplified process flow diagram for electrochemical treatment of waste brine from a desalination plant (adapted from Satterfield et al., 2023).

2.3 Integrating OAE with existing industries and schemes

A common challenge in many OAE approaches, such as OL, is the difficulty in creating new global industries and supply chains "from scratch". A more rapid deployment of OAE technologies at scale could be facilitated by tapping into, or reforming, existing industries. For example, in OL, the calcination step could occur within the pre-existing spare kiln capacity of the cement industry (Renforth et al., 2013). This means new kilns and grinding circuits do not need to be constructed, but rather CCS/CCU technology should be incorporated into an existing industry.

Table 1 Qualitative comparison of two prominent OAE methods: ocean liming and electrochemical brine splitting.

	Ocean liming	Electrochemical brine splitting
Alkalinity phase and chemical form	Solid CaO or $Ca(OH)_2$	Aqueous NaOH
Relevant industry	Cement and concrete (spare kiln capacity)	Desalination (waste brines)
Feedstock	Limestone rock, whose main mineral is calcite ($CaCO_3$)	Waste brines (typically 50 - 70 g L^{-1} of dissolved salts), or seawater
Thermodynamic minimum energy input	178 kJ per mole of CaO from $CaCO_3$	212 kJ per mol NaOH from NaCl
Main by-products	CO_2 (captured by CCS)	H_2 or Cl_2 (electrolysis), or dilute HCl (electrodialysis)
Main energy input	Calcination heat >800°C	Electricity for brine splitting
Cost	\$ 45-180 tCO_2^{-1} (Beccari Barreto, 2022)	\$ 604 tCO_2^{-1} [Electrodialysis] (de Lannoy et al., 2018; Eisaman et al., 2018)
Potential co-benefits	Facilitates decarbonisation of the cement industry	Critical metals production (Loganathan et al., 2017)

Similarly, for EBS, the desalination industry could be a source and vector for the production and delivery of alkalinity in the form of NaOH. Desalination waste brines provide a more promising feedstock for electrochemical splitting than seawater, due to higher concentrations of the necessary alkali cations. Desalination plants are usually close to shore and they already dispose of waste brines by pipes to the ocean. Thus, integrating alkalinity production for OAE with the desalination sector presents an opportunity for cost-effective scaling of this CDR approach. Furthermore, other OAE techniques such as coastal enhanced weathering could be integrated into existing coastal zone management practices, such as dredging operations, land reclamation, and beach nourishment. However, these are outside the remit of this deliverable, which focuses on realistic scenarios for the deployment of OL and EBS.

2.4 Benefits and drawbacks of examined ocean alkalinity approaches

Table 1 shows a qualitative summary, and comparison, of the key technical features of OL and EBS. To produce one mol of NaOH from NaCl, 212 kJ are consumed (House et al., 2007), whereas to produce one mol of CaO from $CaCO_3$, 178 kJ are consumed (Elliott et al., 2001). Based on thermodynamics alone, OL ought to have lower cost and environmental impact than EBS. However, real world technical and logistical considerations mean that this may not be the case. For example, limestone mines may be located far from the ocean, requiring substantial transportation, whereas the brine wastes are already being produced at coastal locations. Furthermore, brine splitting is electrical, whereas lime production requires heat for calcination, and likely requires burning of additional natural gas or fossil fuels reducing its long term sustainability. Therefore, each approach has its advantages and disadvantages, while through LCA the environmental performance of both can be optimised, thereby, enabling the exploitation of their full capacity which can be impactful in the fight against climate change. LCA can advise on the environmental aspects of both approaches, focusing on their carbon emissions, while through sensitivity analysis different pathways to optimise their environmental performance can be examined, namely the introduction of solely renewable electricity to drive both processes.

2.5 Spain's ocean alkalisation potential

Spain aims to achieve a 90% reduction in greenhouse gas (GHG) emissions by 2050 compared to 1990 levels, resulting in a decrease from 334.3 $MtCO_2eq$ in 2018 to 28.9 $MtCO_2eq$ in 2050 (Sun et al., 2021). The geochemical CDR potential for Spain has already been evaluated elsewhere and shown to be significant based on maximum carbonation or enhanced weathering potential of the available alkaline resources (Bullock et al., 2023). However, the realistic ocean alkalisation potential has not been investigated, especially not within a life cycle context. As mentioned above, in this deliverable we investigate realistic deployment scenarios for ocean alkalinisation in the Spanish setting, based on production of alkalinity using existing infrastructure located in Spain, i.e., cement imports are not included in the analysis. Due to its arid climate in its southern regions and high agricultural irrigation demand, Spain has a constant need for desalinated water (in Spain, desalination water is used for irrigation at scale). As a result, a strong and expanding desalination industry is already in place in Spain, with a total output of 5 million m^3 of desalinated water per day (Zarza and Novo, 2022), and this might be expected to grow by a factor of 3.2 by 2050 (Gao et al., 2017). This expansion will lead to an approximate tripling of the already significant quantity of waste brines produced which presents opportunities for their use for OAE through EBS. Furthermore, limestone is highly abundant in Spain, boasting some of the largest limestone and marble quarries in the world (Figure 3A). Moreover, current annual cement production is 15 Mt, down significantly from its 2007 high of 46 Mt (see Figure 3B), meaning that existing cement kilns already have a high spare capacity, especially when compared to other EU countries (Sanjuán et al., 2020). These features, together with easy accessibility to the large water bodies (Atlantic Ocean and the Mediterranean Sea), mean that Spain has a great potential for OAE.

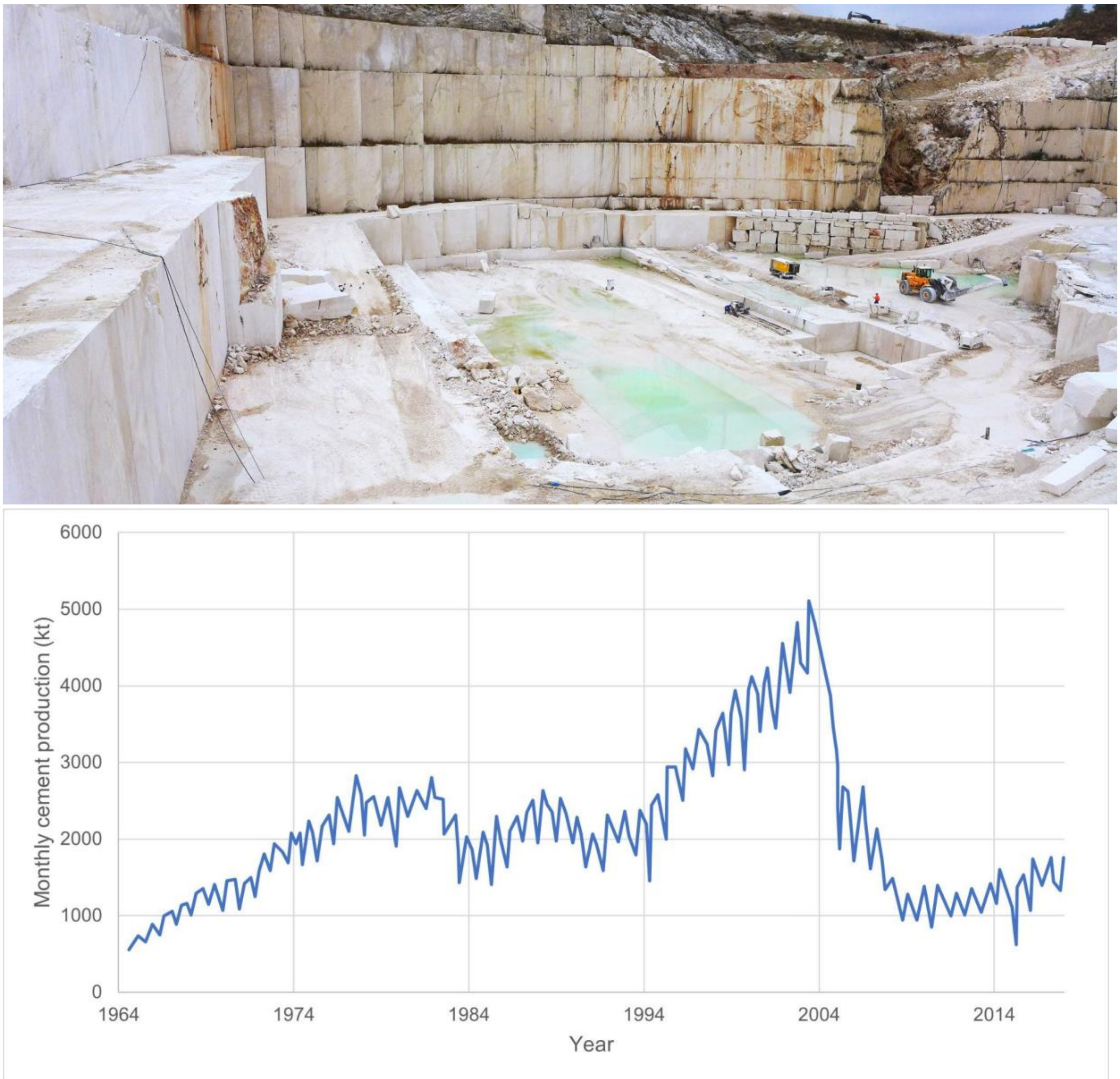

Figure 3: A. Photographic image of limestone quarry in Spain. B. Spanish cement production value in kilotonnes per month (extracted from https://tradingeconomics.com/spain/cement-production)

3. Method

3.1 Plant, quarry, and port data collection and distance calculation

Cement plant data were obtained from the Spatial Finance Initiative and specifically from its Global Database of Cement Production Assets, which includes details for cement production plants globally (3117 cement plants), including the ones in Spain, and provides information about their location, plant type, total capacity and other data (McCarten et al., 2021). Desalination plants, commercial ports and limestone quarries were located using online searches with aid from chatGPT to improve the search and translate into google locations. All of these data were then input to QGIS software (version 3.22) to map the location of the cement and desalination plants, as well as of the commercial ports and limestone quarries (Figure 4). The road transport distance of individual cement plants to each of the limestone quarries and ports in Spain were extracted by applying URL requests for routes (road transport was chosen as transportation mode) from Bing Maps (www.bingmapsportal.com). An Application Programming Interface (API) was used for an automated data extraction process and the minimum transport distance between each cement plant to the nearest limestone quarry and port was obtained. These transportation distances were then used to inform the LCA results of OL and account for carbon emissions attributed to overland transportation. In EBS overland transportation is not considered since desalination plants are near the shore while existing submerged pipes for brine disposal could potentially be used for alkalinity dispersion to seawater. Finally, it was identified that the cement plants that exists in Spain's islands do not hold large potential for OL, and therefore these were excluded from the analysis, but this is not the case for desalination plants and especially for those in the islands which produce large quantities of brines and therefore can be promising for OAE.

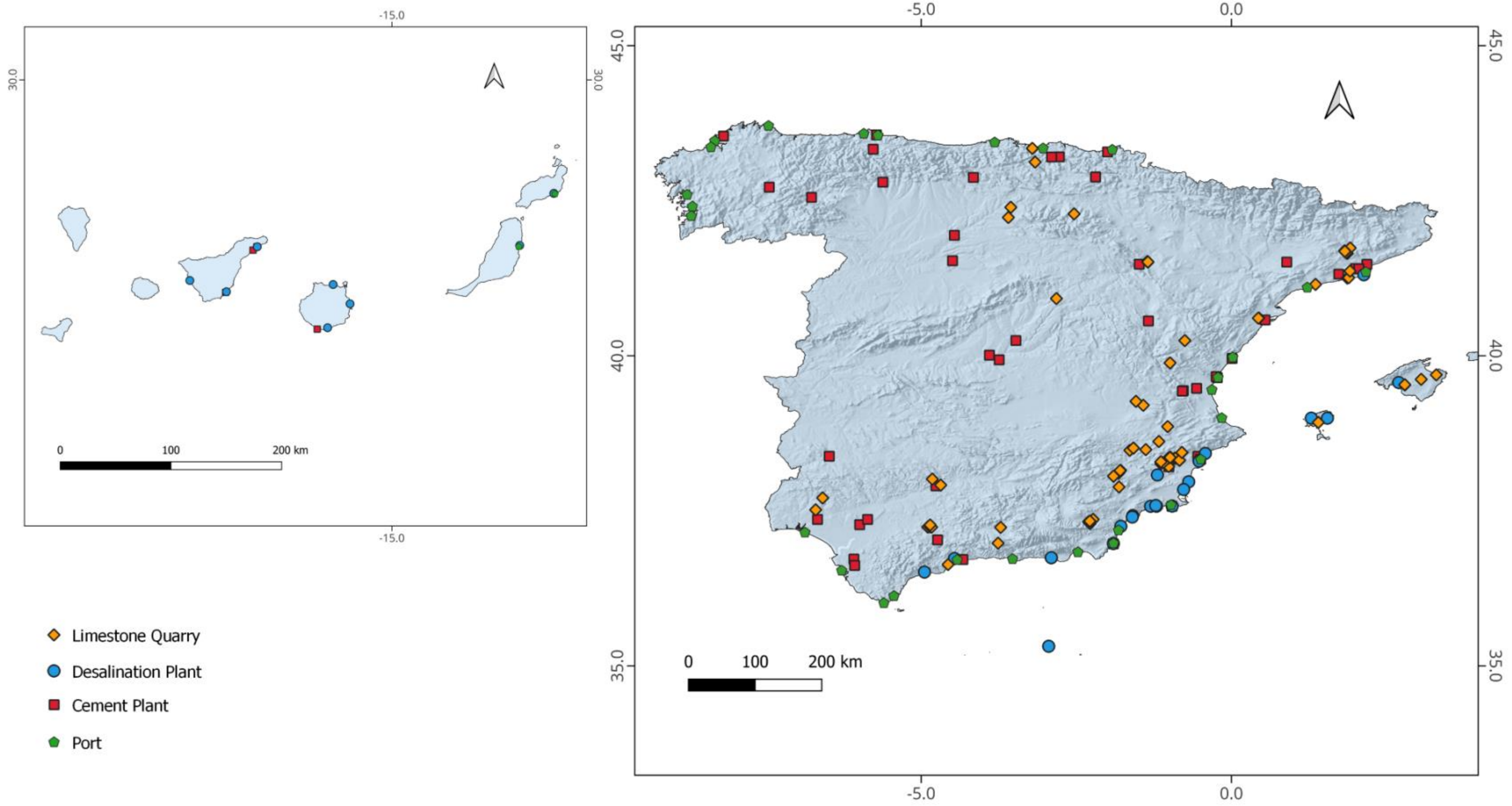

Figure 4: Locations of active limestone quarries (orange diamonds), active cement plants (red squares), commercial shipping ports (green stars), as well as desalination plants (blue circles).

3.2 LCA modelling

The environmental sustainability of OL and EBS was examined by means of LCA and here the main results for each approach are presented and discussed. Specifically, focus is placed on their carbon footprint, since in order for them to act as CDR their life cycle carbon emission should be (significantly) lower than the amount of atmospheric CO_2 that they remove. As is the case with most CDR approaches, it was identified that energy use in OL and EBS is the main contributor to their life cycle carbon emissions. For this reason, apart from energy from fossil fuels, i.e., natural gas burning, and grid electricity, an improved scenario was examined, whereby the electricity demand for OL including the calcination heat (via electric-powered plasma-torch kilns) is provided by abundant onshore wind. Similarly, for EBS the improved scenario examined replacing grid electricity with renewable electricity, where onshore wind was considered for mainland Spain and offshore wind for the Canary islands.

3.2.1 Ocean liming

For OL, a full LCA has already been conducted and verified by undergoing peer review (Foteinis et al., 2022). Specifically, in OL, limestone is mined from limestone quarries, then transported to the cement plant to be ground, calcined, and hydrated, before being spread on the ocean by boat (Figure 1). To provide realism for this case study, the LCA model was adapted to reflect the conditions in the Spanish setting. This was achieved by including in the analysis Spain's current electricity mix, instead of the Europe's mean electricity mix which was considered in deliverable 6.2, and the actual overland transportation distances for each cement plant (from the nearest quarry to the cement plant and then to the nearest port, see Section 3.1). Furthermore, in the LCA for OL, the main environmental hotspot was the energy input (heat and electricity) that currently derives mainly from fossil fuel burning. Therefore, as mentioned above, an improved scenario was also considered, whereby heat and electricity is provided by wind energy. Finally, the exact spare capacity of each individual cement plant was not considered separately, but the spare capacity of the cement industry of Spain was considered by using historical data. Then, this spare capacity was considered for each individual cement plant. To instil realism further and make the estimate for the spare capacity more conservative, the spare capacity of existing lime calcining systems in Spain was not considered, since it is assumed that this is captured by the cement industry spare capacity. Finally, it should be noted that the earliest deployment of OL system is assumed to be 2030 and at that point we assume that existing cement plants will be retrofitted to include CCS, which is a prerequisite for OL to be net negative (Foteinis et al., 2022).

3.2.2 Electrochemical brine splitting

For EBS the electrolysis of brines was chosen as the method for production of alkalinity, due to its higher technology readiness level (TRL) than electrodialysis. Specifically, electrolysis, specifically the chlor-alkali process, is used at scale for NaOH production (e.g., 99.5% of the NaOH that is used in reverse osmosis desalination plants is produced through electrolysis (Du et al., 2018). Online searches were used to locate Spain's largest desalination plants (>1000 m^3 per day) and the plant websites were used to obtain the production rate of desalinated water. Transportation is assumed to occur via pipeline to a distance of 1 km from the shoreline next to the desalination facility, i.e., through existing waste brine pipeline disposal. This would require high dilution and therefore ship transport and spreading should be used as an alternative in future LCA work.

Different systems have been proposed for NaOH production from desalination brines, which remains a niche application. One of the most detailed studies is the one of Du et al. (2018), where the process design and energy efficiency of an EBS system for NaOH production from desalination brines is presented. The LCA model for the EBS for OAE was based on the Du et al. (2018) system, which is also the source of the life cycle inventory (LCI) data. Briefly, the system comprises nanofiltration (NF), to remove sulphate, Ca^{2+}, and Mg^{2+} ions, electrodialysis (ED) and mechanical vapour compression (or evaporation) to concentrate the permeate up to NaCl saturation (27%), while chemical softening by adding small amounts of the produced NaOH and ion exchange (IX) is used to further purify the saturated brine before electrolysis (Figure 5). Initial LCA modelling for this system highlighted that electricity is, by and large, the main environmental hotspot. Therefore, here the analysis is restricted to the life cycle carbon emissions of electricity consumption.

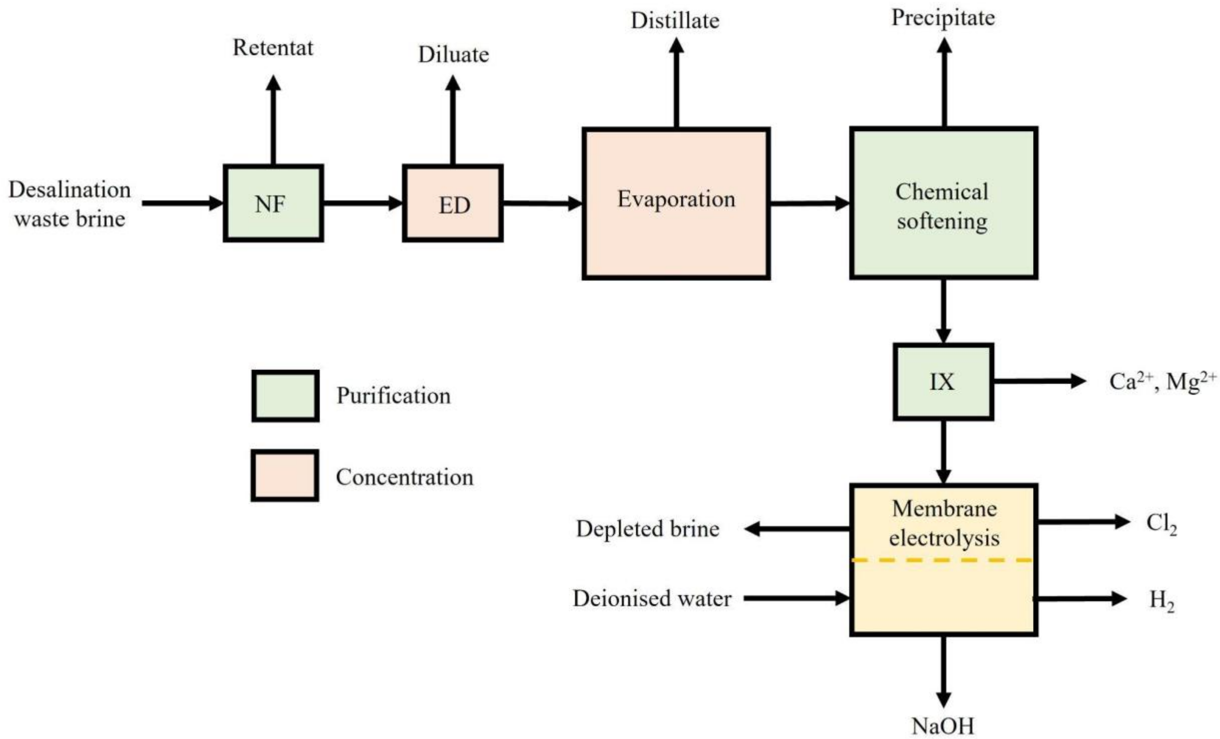

Figure 5: Simplified diagram of electrolysis of waste brine adapted from Du et al. (IX=ion exchange. ED=electrodialysis. NF=nanofiltration)

4. Results and discussion

4.1 Carbon footprint of existing cements plants when used for ocean liming

For OL first, the life cycle carbon emissions of existing cement plants when used to produce lime were identified. It was assumed that these are equipped with CCS, which uses grid electricity, while natural gas burning provides the calcination heat. Then, the life cycle carbon emissions for lime hydration, loading, and spreading to the sea were also considered and the total carbon footprint of the process was identified to amount to 401 kgCOeq per tonne of CO_2 removed from the atmosphere. This value is fairly similar to Europe's mean life cycle carbon emissions for OL (435 kgCO_2eq tCO_2^{-1}), since natural gas is used in both cases in calcination but the carbon emissions from Spain's electricity mix are lower compared to Europe's mean electricity. To make the results more realistic and further constrain them on the actual case study, i.e., Spain, the actual overland transportation distances (from the limestone mine to the cement plant and then to the port) were also considered (Section 3.1). Then, the relevant life cycle carbon emissions from overland transportation were also estimated and these were added to each cement plant to obtain OL's total carbon footprint for each specific cement plant. Results are shown in Figure 6, where the effect of overland transportation is also presented. Specifically, in the base scenario (electricity mix for Spain's grid and natural gas burning for calcination), transportation plays a lesser role in the total carbon footprint of the process, since even at the most inland cement plants overland transportation contributes up to around 42% of the total carbon footprint. This contribution is not negligible, particularly when considering that the carbon footprint of lime production is already high. The effect of overall transportation is more clear below, where the improved scenario is examined, which is responsible for significantly fewer carbon emissions.

4.2 Carbon footprint of of existing cements plants for ocean liming when using renewable energy

The electricity consumption (mainly for CCS) from Spain's grid and particularly the energy (natural gas) input for limestone calcination were the main environmental hotspots of OL (Foteinis et al., 2022). For this reason, here an improved scenario where renewable energy is used to drive the process is examined. Specifically, onshore wind was assumed to provide the electricity input whereas calcination was also assumed to be electricity driven (plasma torches). In this scenario, OL's carbon footprint (excluding overland transportation) reduces significantly, since this is around an order of magnitude lower than the base scenario, i.e., 46 instead of 401 kgCO_2eq tCO_2^{-1}. In this scenario, the impact of transportation becomes more apparent, since in many cases transportation is the main contributor to OL's total environmental footprint. Specifically, for the cement plants that are situated near the coastline transportation's contribution on OL is typically up to 20%. However, this is not the case for the cement plants that are situated further inland, with those that are near Madrid exhibiting much larger carbon footprints, since transportation contributes up to 86%. The results for the total carbon footprint of each examined cement plant, along with the contribution of overland transportation, are shown in Figure 7. Therefore, as results in Figure 7 highlight, to optimise the CDR potential of OL

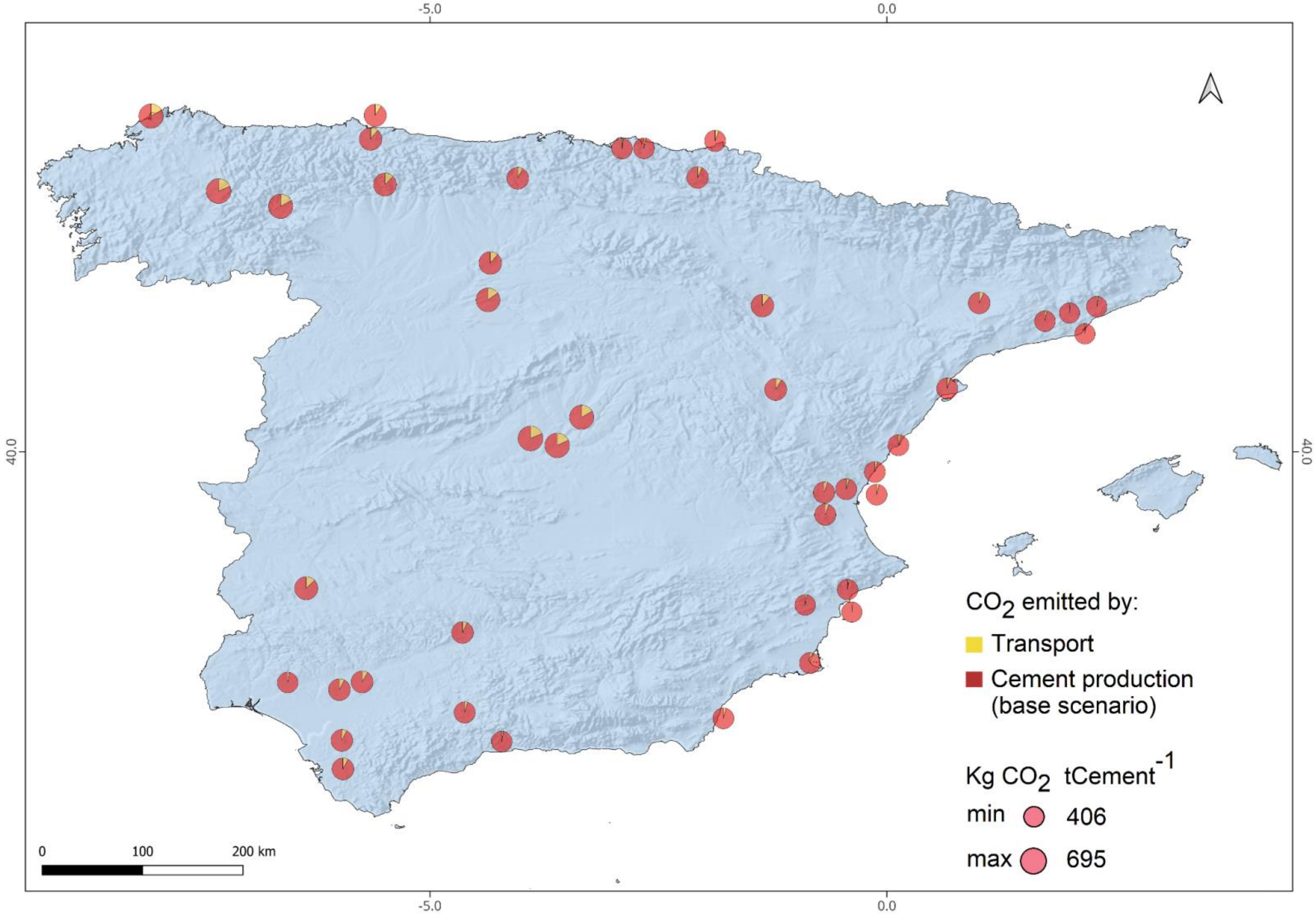

Figure 6: The total life cycle carbon emissions and the contribution of overland transportation on ocean liming's total carbon footprint.

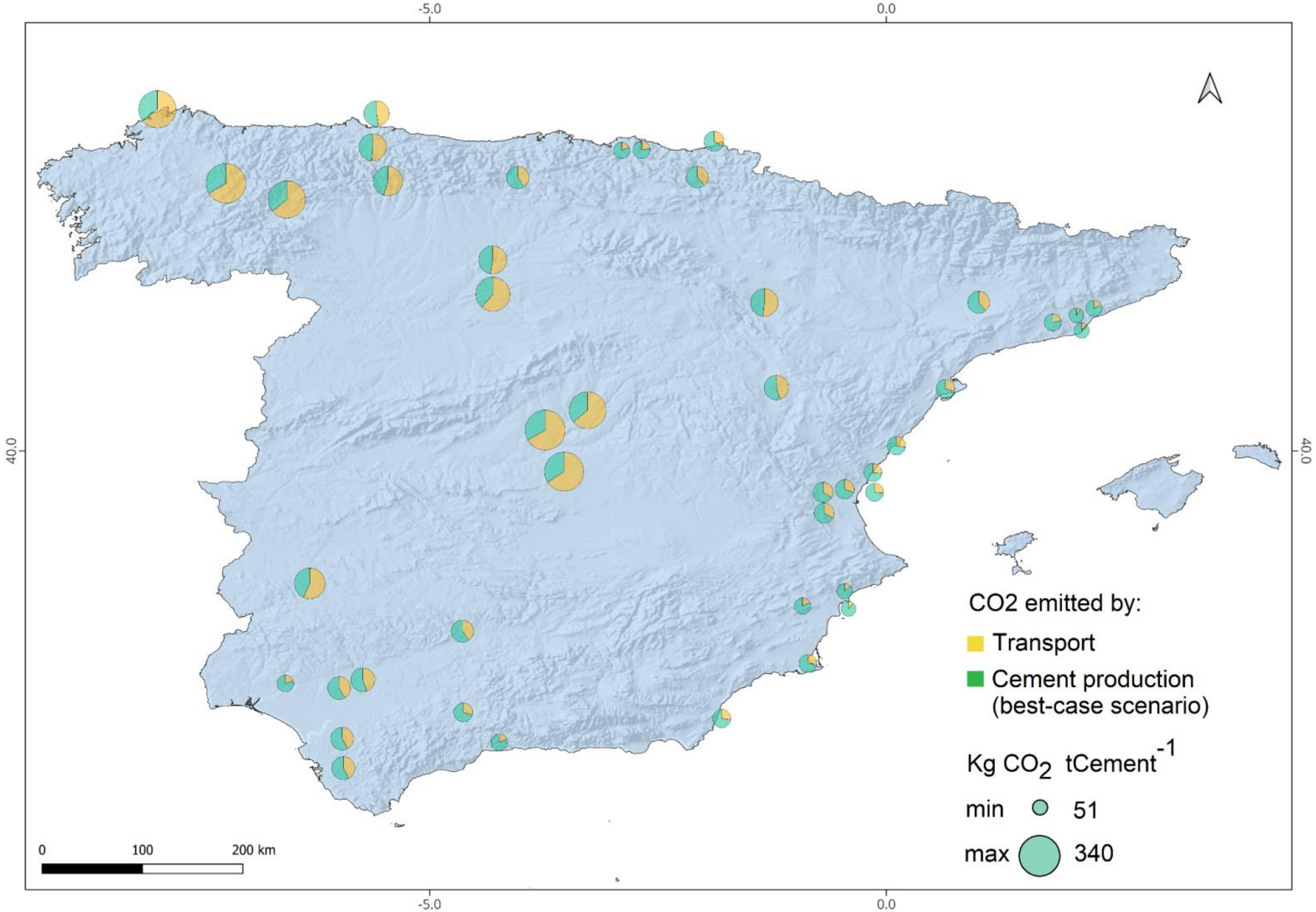

Figure 7: The total life cycle carbon emissions and the contribution of overland transportation on ocean liming's total carbon footprint when using renewable electricity.

limestone mines and cement plants next to the coastline should be the preferred option, provided that ports are already in place. However, even though the most inland cement plants have higher carbon footprints these are the cement plants that are near Madrid, Spain's capital, and as such have very high capacities.

4.1.3 Spain's annual capacity for ocean liming

After the total life cycle emissions of the process were estimated, then the spare capacity of each cement plant was considered to identify Spain's potential for CDR through OL. Here, the spare capacity of the Spanish total cement industry was first estimated and then allocated to the cement capacity of each individual plant. For this reason the historic consumption trends of the Spanish cement sector were considered. Specifically, due to urbanisation, the sector began to expand during the 1950s, growing to 27.6 Mt in 1991 (before the Summer Olympic Games in Barcelona), and then more than doubled from 1997 to 2007 (from 26.8 to 56.0 Mt), but when recession hit Spain cement consumption dwindled since from 2007 to 2013 was reduced by 81% (https://www.globalcement.com/magazine/articles/1015-the-cement-industries-of-the-iberian-peninsula). In 2022 cement consumption in Spain was at 14.9 Mt and cement exports at 5.6 Mt (https://www.globalcement.com/news/item/15317-spanish-cement-consumption-falls-slightly-in-2022), which when put together are roughly 37% of the 2007 cement capacity. This implies that currently an enormous spare capacity exists, which is as high as 63% of the total (assuming 2007 as the reference year) or 35.5 Mt yr^{-1}. It might be possible that some cement plants have ceased their operation since 2007 and for this reason here the total capacity of the cement plants that are captured in the analysis is restricted to 39.4 Mt. It should be noted that it is possible to bring back to life decommissioned cement plants, but this is beyond the scope of this report, while by choosing a much lower total capacity than the maximum cement capacity of 2007 an additional layer of realism is instilled in the analysis.

The 63% spare capacity was then ascribed to the cement production capacity of each examined plant (total capacity 39.4 Mt) to identify their potential for OL. Then the life cycle carbon emissions were subtracted to identify CDR potential of each cement plant (see Figure 8). It should be noted that here the life cycle carbon emissions for the improved scenario (wind energy) and the ones for overland transportation were considered. In total, 22.6 Mt of CO_2 could be annually drawn down from the atmosphere if the spare capacity of the examined cement plants was to be used for OL. As can be seen in Figure 8, the cement plants that are near or on Spain's Mediterranean coastline have large CDR potential when used for OL, as well those in Madrid. The large CDR potential of the cement plants that are near the coastline is attributed both to their capacity and to the low carbon emissions from overland transportation, while the large capacities of the inland cement plants is attributed to their high total cement production capacity and by extension to their very high spare capacity for OL compared to the other cement plants. However, the carbon penalty from overland transportation for these plants is high and therefore other means of transport such as train transport or even electric trucks should be considered in potential future OL operations in Spain. Such suggestions were made in WP6.2 and elsewhere (Foteinis et al., 2022) and it is highly likely that as the cement industry

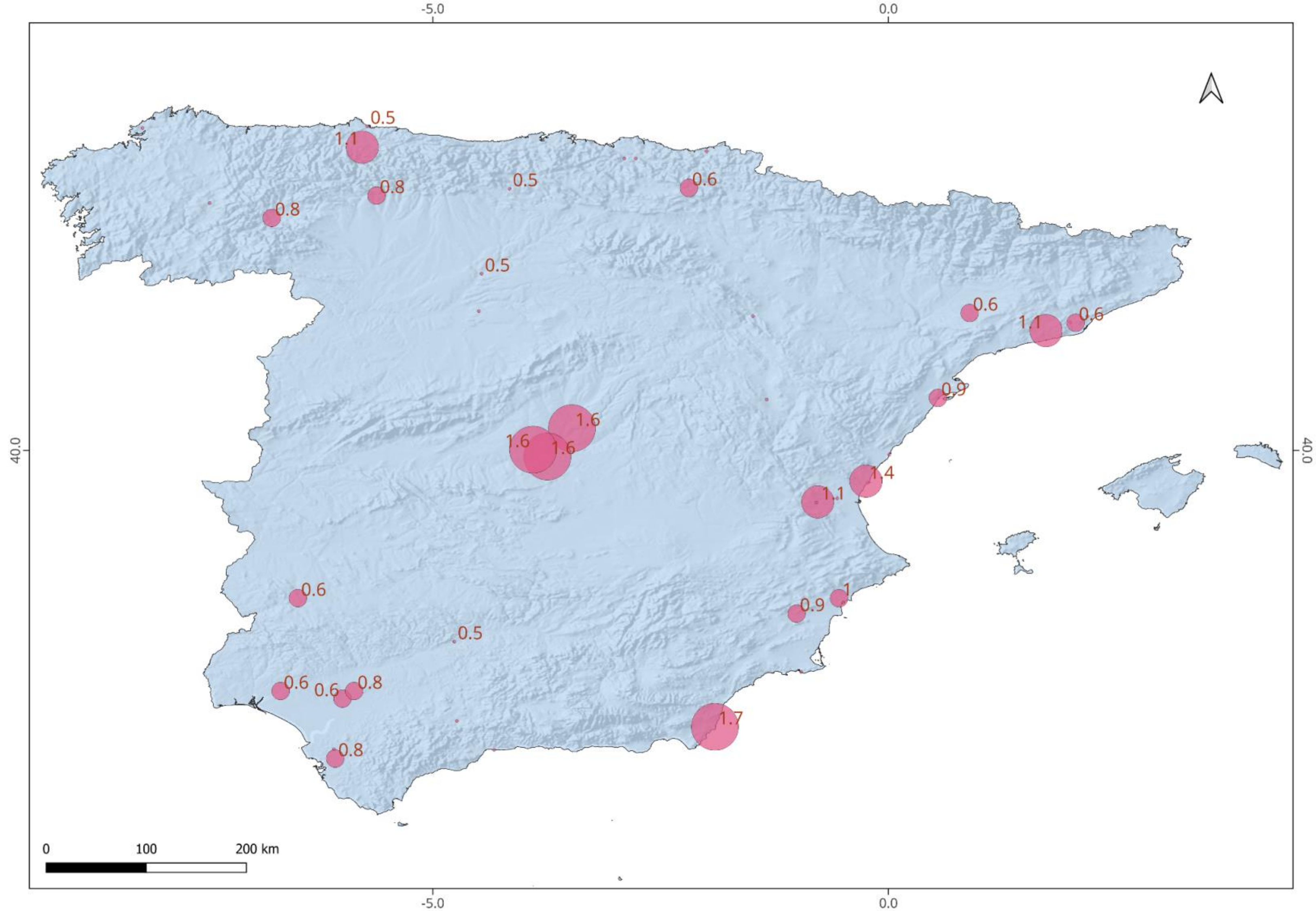

Figure 8: The annual CDR capacity of each cement plant when their spare capacity is used for OL in Mt CO_2 $yr.^{-1}$.

decarbonizes, so does the transportation industry, making the transportation distance a less important parameter in terms of carbon emissions.

4.4 Carbon footprint of electrochemical brine splitting

For EBS through electrolysis, LCA suggested that electricity consumption is, by and large, the main environmental hotspot of the process and as such it dominates its carbon footprint. Therefore, focus is placed here on electricity consumption. As in the case with OL, two scenarios are examined: i) the base scenario where electricity originates from Spain's current energy mix and ii) the improved scenario, whereby electricity is provided by wind energy. For the latter scenario onshore wind was assumed to be used in the desalination plants that are located in mainland Spain and offshore wind for the ones located in the islands.

Note that, when electricity from Spain's grid is used to drive the process, then EBS through electrolysis is not net negative and therefore cannot be used for CDR. However, this is not the case for the improved scenario where renewable electricity is used to drive the process.

Specifically, when electricity from Spain's grid is used, then EBS appears not to be net negative, since the total life cycle carbon emissions for the production of 1 kg of dry NaOH amount to 0.996 kg CO_2 eq. From stoichiometry, 2 moles of NaOH are required to remove 1 mole of CO_2 or in other words, at best, 1 kg of NaOH can remove up to 0.55 kg of CO_2.

Therefore, the carbon footprint of EBS should be greatly reduced for this technology to become net negative and be considered for CDR. Other approaches such as electrodialysis which, in theory, is 60% less energy intensive than electrolysis could be used to reduce EBS's carbon footprint but the technology is not yet mature. Another possibility is to solely use renewable energy to drive the electrolysis process and this is the improved scenario examined herein. Due to the fact that Spain's electricity mix has an overall high carbon footprint, owing to fossil fuel burning, renewable electricity, in this case onshore and offshore wind, can greatly (by an order of magnitude) reduce EBS's life cycle carbon emissions. Specifically, when using onshore wind in the Spanish setting the production of 1 kg of NaOH would only release 0.0796 kgCO_2eq while when using offshore wind this value is at 0.176 kgCO_2eq. In this sense, the life cycle emissions of EBS are less than 15% of its CDR stoichiometric capacity and therefore this technology could hold great promise for OAE in Spain where a strong and expanding desalination industry exists.

Spain's total annual capacity for OAE when EBS is driven by renewable electricity is shown Figure 9. As can be seen, there is great potential for CDR when using low carbon emissions electricity since in total 1.8 Mt of CO_2 can be annually removed if the existing brine output was to be used for EBS and then for OAE. Moreover, the already large quantities of waste desalination brines that are produced are expected to significantly increase in the near future. Specifically, the current CDR potential of EBS is estimated at 1.8 Mt whereas in 2050 this is expected to grow to 4 Mt since globally it is expected that the industry will more than double by 2050.

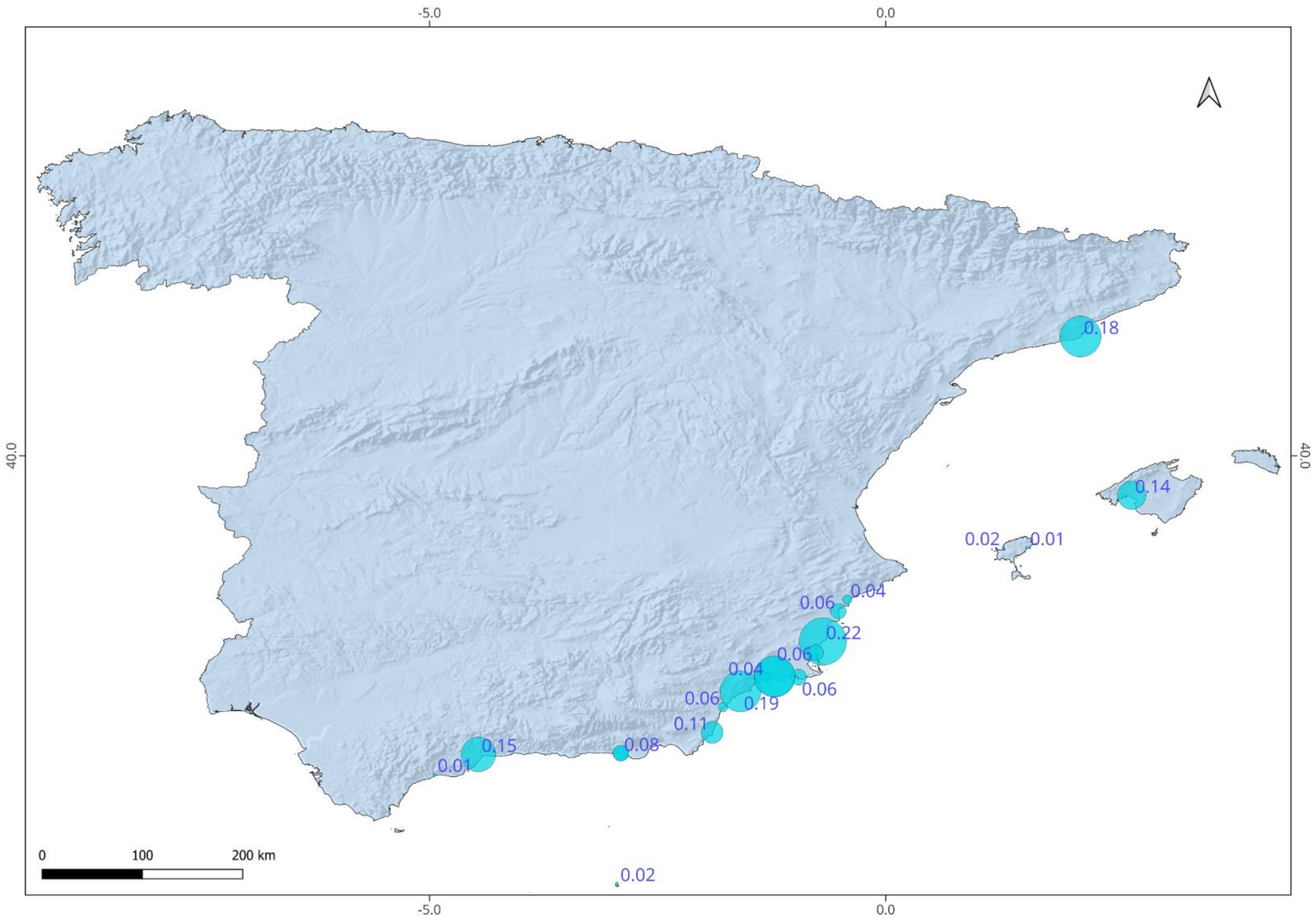

Figure 9: The annual CDR capacity of each desalination plant when using wind energy to drive EBS in $MtCO_2$ $yr.^{-1}$.

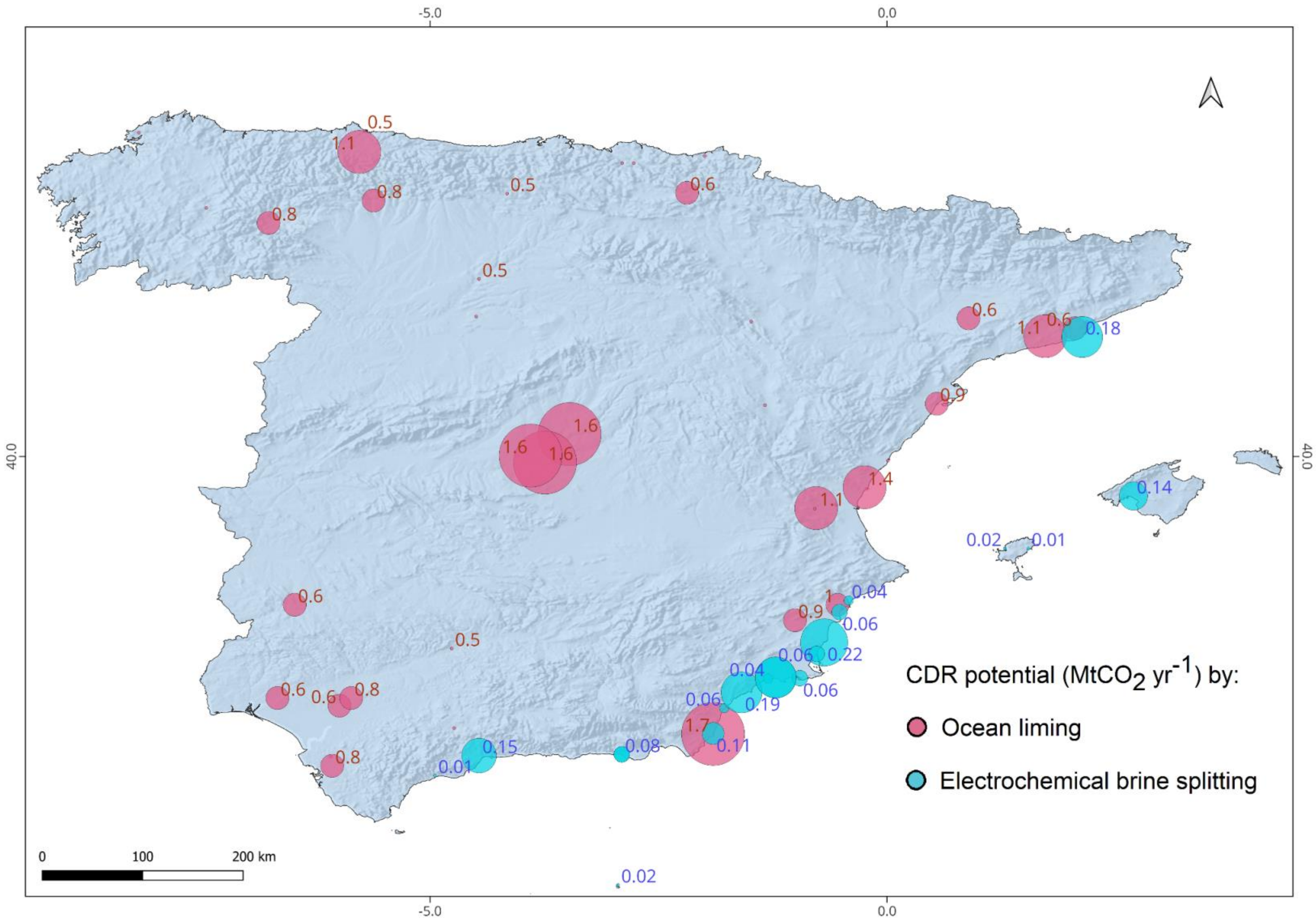

Figure 10: Spain's annual CDR capacity when using both OL and EBS in $MtCO_2$ yr.$^{-1}$.

4.7 Spain's total annual capacity for carbon dioxide removal

In Figure 10 Spain's annual CDR capacity when using both OL and EBR driven by renewable electricity is shown. The total CDR capacity is 24.4 Mt $yr.^{-1}$, which is the sum of the annual CDR potential of OL and EBS when using renewable energy to drive them. From this score EBS contributes around 13% while the remaining 87% is attributed to OL. The desalination industry in Spain is not as mature as the cement industry, while NaOH has lower potential for CDR when used for OAE and these are the reasons for the much larger contribution of OL in the total CDR capacity of Spain. However, the desalination industry is rapidly expanding in Spain while alternative, but not mature yet, technologies, such as electrodialysis can possibly further reduce EBS carbon footprint and therefore further improve its CDR potential. As such both approaches have a very good capacity for CDR and focus should be placed on further examining opportunities to progress their TRLs and introduce them at scale in Spain and globally.

5. Conclusion

This deliverable explored realistic scenarios for two ocean-based NETs, namely ocean liming (OL) and electrochemical brine splitting (EBS) for increasing ocean alkalinity and achieving carbon dioxide removal (CDR) in the Spanish setting. The document highlighted the importance of conducting a life cycle assessment (LCA) to evaluate the environmental performance of these NETs, with a particular emphasis on their carbon footprint. The use of LCA allowed for the identification of key factors influencing the carbon emissions of OL and EBS, such as energy use and transportation distances. By integrating OL and EBS with existing industries and infrastructure, such as the cement and desalination industries, rapid large-scale deployment of CDR can be initiated and sustained. The total CDR potential of Spain via OL and EBS was estimated to be 24.4 $MtCO_2$ $yr.^{-1}$, assuming these processes are driven by renewable energy. Overall, this deliverable has contributed to the understanding of the potential and challenges of OAE in a regional setting and could provide valuable inputs for further research, modelling, and decision-making within the OceanNETs project and beyond.

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