

Ocean-based Negative Emission Technologies



Deliverable Title	Realistic deployment scenarios/pathways that can be used to constrain Earth System models
Lead	Heriot-Watt University (HWU) and University of Oxford (UOXF)
Related Work Package	6
Related Task	6.2
Author(s)	Spyros Foteinis and Phil Renforth
Prieto Dissemination Level	Public
Due Submission Date	30/06/2021
Actual Submission	29/11/2021
Project Number	869357
Start Date of Project	01. July 2020
Duration	60 months

Abstract: Realistic alkalization scenarios, under the global context, are proposed and examined, which can be extent to include spatial considerations and specific technical and regulatory constraints. Results provide a set of stylistic projections of total mineral (carbonate and silicate) addition, with its temporal timeframe spanning from as early as 2025 up to 2100). Among others, these estimates can be used to constrain model simulations that will be carried out in Work Package 4.



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement number 869357.

Table of contents

6.2.1 Introduction	3
6.2.2 The potential of carbonate and silicate minerals for atmospheric CO ₂ uptake through OAE	6
6.2.3 Mining and comminution infrastructure in Europe and further afield	7
6.2.4 Investment in new and environmentally friendly infrastructure	9
6.2.5 Use of waste and by-product materials for OAE	12
6.2.6 Potential deployment scenarios	13
6.2.6.1 Use of minerals from the construction aggregates industry	13
6.2.6.2 Potential deployment scenario at global scale	18
6.2.6.2.1 Silicate minerals for coastal enhanced weathering	18
6.2.6.3 Silicate minerals application coastal enhance weathering	21
6.2.6.3.1 Optimistic scenario with low allocation of silicate minerals from the construction aggregates industry	21
6.2.6.3.2 Optimistic scenario with mean allocation of silicate minerals from the construction aggregates industry	22
6.2.6.3.3 Optimistic scenario with high allocation of silicate minerals from the construction aggregates industry	24
6.2.6.2.2 Silicate minerals application mean scenario	26
6.2.6.2.3 Silicate minerals application pessimistic scenario	29
6.2.6.3 Silicate minerals application using electrochemistry	32
6.2.6.3.1 Optimistic scenario	33
6.2.6.3.2 Mean scenario	35
6.2.6.3.1 Pessimistic scenario	36
6.2.6.4 Carbonate minerals application.....	38
6.2.6.4.1 Carbonate minerals application optimistic scenario.....	38
6.2.6.4.2 Carbonate minerals application mean scenario.....	42
6.2.6.4.3 Carbonate minerals application pessimistic scenario.....	44
6.2.7 Conclusions	47
6.2.8 Bibliography	50

6.2.1 Introduction

On a global scale, climate is grossly modulated by the availability of minerals that are found in the earth's surface (Bufe et al., 2021). Specifically, the main process that the earth employs for regulating the concentration of atmospheric carbon dioxide (CO₂) is through the natural weathering of calcium (Ca) and magnesium (Mg) bearing silicate rocks (Schuiling, 2012), whereby their dissolved products in seawater (oceans), will uptake CO₂ from the atmosphere and transformed it into (bi)carbonate ions. There, carbon will remain stored, mainly as bicarbonate ions, for up to hundreds of thousands of years (Renforth, 2019) and eventually precipitate as limestones and dolomites (Schuiling and Tickell, 2010). As a result, the oceans comprise large carbon sinks, annually sequestering 0.5 Gt CO₂ (Renforth and Henderson, 2017) or ~26% of the anthropogenic CO₂ emissions (Figuerola et al., 2021). Currently, the oceans hold ~38,000 Gt carbon (C) as (bi)carbonate, which is forty times higher than the corresponding C concentration in the atmosphere (Renforth and Gore, 2017).

Even though this natural process can, in theory, address climate change, the rates of the reactions that govern the uptake of atmospheric CO₂ are relatively slow (Taylor et al., 2016) and cannot cope with the increasing anthropogenic CO₂ emissions (Schuiling and Tickell, 2010). Therefore, research has now focused on improving the rate of these reactions, mainly through the mining, processing, and spreading of silicate and/or carbonate rocks either: i) in land (mainly in humid tropics where weathering reactions are faster (Schuiling, 2012)), a process known as enhanced weathering (EW) (Bach et al., 2019), or ii) the oceans, a process known as ocean alkalinity enhancement (OAE) (Bach et al., 2019; CEA Consulting, 2019) or artificial ocean alkalization (AOA) (Gore et al., 2019). In both cases additional benefits, in terms of nutrients addition and mitigating acidification in soils and/or the ocean can be achieved (Schuiling and Tickell, 2010).

Specifically, the increased CO₂ absorption by the oceans has led to drastic changes in carbonate chemistry balance, -never seen before in geological timescales (~300 million years) (Hönisch et al., 2012)-, greatly affecting the mean natural pH levels with ocean acidity having increased by ~26% since the Industrial Revolution, i.e., the mean pH value dropped from 8.2 to 8.1 (Figuerola et al., 2021). (note that the pH scale is logarithmic.) These rapid change in the natural alkalinity levels is 100 times faster than any change experienced during the last 20 million (Unesco, 2021) to 55 million years (European Environment Agency, 2021). The problem has exacerbated during the past decades, since half of the increase in atmospheric CO₂ concentration

compared to pre-industrial levels (from 280 to 400 ppm), took place since the 1980s leading to a 30% increase in ocean acidity (from 8.11 to below 8.06 (**Fig. 6.2.1**)) in the same reference period (European Environment Agency, 2021). More alarmingly, oceans' mean pH value is expected to further drop by ~0.3 by 2100 (Figuerola et al., 2021). These rapid changes in seawater's mean pH level have a huge impact on marine ecosystems (Doney et al., 2020) and particularly on calcifiers (e.g., stony corals, bryozoans, bivalves, sea urchins and asteroids, along with coccolithophores, foraminiferans, and pteropods (Figuerola et al., 2021)) and surface-ocean plankton (e.g., diatoms (Petrou et al., 2019)), which will strive to survive if the natural alkalinity level continues to decrease at these paces (Ridgwell and Schmidt, 2010).

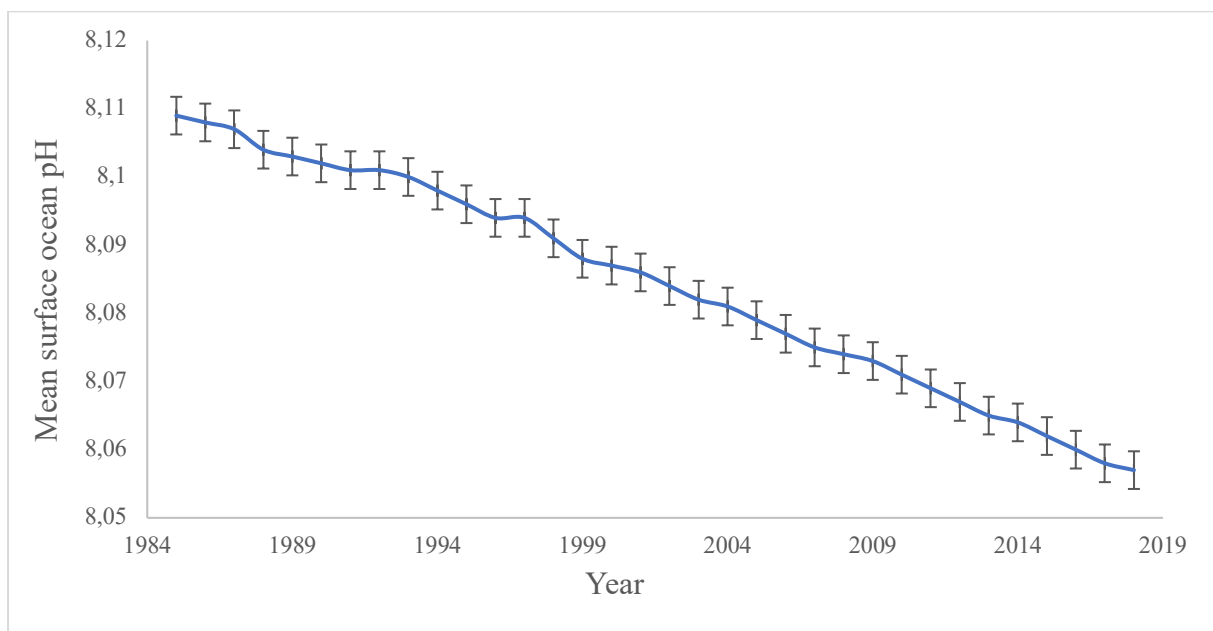


Figure 6.2.1: The global yearly mean surface seawater pH variations for the reference period 1985 – 2018, along with the lower and upper uncertainty (data adapted from (European Environment Agency, 2021)).

To counter both climate change and ocean acidification, the spreading of pulverised (to increase their reactive surface area) silicate-based minerals in the ocean, has been suggested (CEA Consulting, 2019). In this regard, olivine ($(\text{Mg}, \text{Fe}^{+2})_2\text{SiO}_4$), a magnesium and iron bearing silicate mineral, has attracted much attention since it combines widespread abundance with fast dissolution (Meysman and Montserrat, 2017). However, for silicate minerals to be dissolved in the surface oceans water, where CO_2 is taken up from the atmosphere, these have to be pulverised (size $1 \mu\text{m}$ or below), else they will precipitate (Meysman and Montserrat, 2017). Nonetheless, such a high degree of grinding can find little use for practical applications and therefore focused has been placed on using natural forces acting on the coastal zone such as wave and currents action to enhance the rate of silicate minerals dissolution. Depending on

local conditions and initial particle size, fully dissolution in such areas can take from tens to thousands of years (Hangx and Spiers, 2009).

Focus has been also placed on the use of carbonate, instead of silicate, minerals for OAE. The underlying problem with carbonate minerals is that the ocean surface waters, which will uptake the atmospheric CO₂, are supersaturated ($\Omega > 1$) with respect to calcite (CaCO₃) (Cooke and Kepkay, 1984). To address this problem the “activation” of carbonate minerals, i.e., reducing CaCO₃ to calcium oxide (CaO) typically through calcination, before ocean spreading has been proposed (CEA Consulting, 2019). This process is popularly known as ocean liming (OL) and comprise a promising branch of OAE, provided that the generated CO₂ emissions during limestone/calcite activation are captured and stored (Renforth et al., 2013). Apart from thermal processing (calcination) different electrochemical pathways have been also proposed for carbonate minerals used in OAE (Renforth and Henderson, 2017). Furthermore, part of the alkalinity produced in EW will end up in the oceans, mainly through rivers and streams (Bach et al., 2019), however this is outside of the remit of this report. Note that high CO₂ uptake through EW will come at the expense of freshwater natural pH levels, e.g., in a case study in Amazon and Congo river catchments EW could increase river pH from 6.84 (range 6.38–7.89) and 6.71 (range 5.67–7.63) respectively to up to 8.2 (Kohler et al., 2010).

Therefore, for the global scenarios considered here relatively mature and simple to scale up technologies were considered. Specifically, for silicate minerals their direct spreading, after proper grinding, in the coastal environment, as process known as coastal enhanced weathering (CEW) was considered, while for OAE through carbonate minerals OL was considered. Both silicate (CEW) and carbonate (OL) minerals appear promising, since infrastructure for their mining and processing is already in place. Specifically, these minerals are already mined, primarily by the construction aggregates industry, and processed (e.g., limestone by the cement industry) at industrial scales. Therefore, opportunities are available for expanding or employing the spare capacity of the established industries in the fight against climate change. Electrochemical pathways are also be considered, particularly for the silicate minerals since these will enable their rapid dissolution, however, new infrastructure should be built for their large-scale application. Here insight on the quantities and the required infrastructure for the mining, comminution, and spreading of these minerals is given. Wastes or by-products from different industrial processes, such as aggregate mine waste, construction/demolition waste, iron and steel slag, cement kiln dust, and fuel ash could also be used for OAE (Renforth et al.,

2011). However, these are not included in the analysis due to possible contamination concerns, as will be discussed below. In this regard a waste of the desalination industry, i.e., is included in the analysis, since it can be put forward in the electrochemical pathways.

6.2.2 The potential of carbonate and silicate minerals for atmospheric CO₂ uptake through OAE

As a preamble, OAE's CO₂ uptake potential, using silicate and/or carbonate minerals, is high and therefore can be used for lowering atmospheric CO₂ concentrations, provided that OAE was to be applied at industrial scales. For context, the natural weathering of mineral resources in the earth surface (land) annually removes ~1 Gt of atmospheric CO₂ and stores this in the ocean as bicarbonate (CO₃²⁻) and to a lesser extent carbonate (CO₃²⁻) ions (CEA Consulting, 2019). To add to this value, different types of minerals/rock can be used for additional CO₂ uptake. Each mineral has its own CO₂ uptake potential, e.g., 1 t of atmospheric CO₂ can be removed with ~1.8t limestone (calcite) or 1-2 t of olivine-rich rocks (Bach et al., 2019), but these values greatly vary (e.g., limestone deposits can contain dolomite (CaMg(CO₃)₂) and therefore it has been reported that 1.4 t 1.7 t of limestone can remove 1 t CO₂ (Renforth et al., 2013)). Alkaline materials that are already being produced as products or by-products of industrial activities could also be used for OAE and these have the potential of annually remove 2.9–8.5 Gt of CO₂ by 2100 (Renforth, 2019). However, industrial (by)products have economic value, suggesting that alkaline waste materials and legacy wastes are more likely to be used for OAE, at least in the near future.

Considering the above, the production output for alkaline materials (typically carbonate and silicate minerals) should be increased, either by using the spare capacity of the existing industry or more likely by building additional “greener” infrastructure for large scale applications. Opportunities to replace alkaline material with other materials, e.g., aggregates from the construction industry with aggregates produced from carbon capture and storage (CCS) schemes and use the replaced alkaline materials for OAE, could also be considered along with the use of by-product or waste alkaline materials, which have little or no economic value respectively, and legacy wastes.

From the three above pathways the first appears to be the most promising for CO₂ removal rates in the Gt scale, while replaced alkaline materials and alkaline wastes can be used complementary with the first. However, for the Gt scale very large quantities of carbonate and silicate minerals should be mined, crushed, processed, and spread in the ocean. A prerequisite

for increasing the production output of silicate and carbonate minerals would be that ample and readily available reserves of these minerals exists. It has been suggested that this is the case, since the existing natural reserves of rocks containing carbonate and silicate minerals have the potential of sequestering thousands of Gt of CO₂ (Bach et al., 2019) or, in theory, even more (hundreds of trillions of tons of such materials exists (Sverdrup et al., 2017)) as is discussed below.

Therefore, the existing rock reserves cannot be considered as a limiting factor for OAE, but rather the infrastructure for their mining, comminution, processing (calcination or electrochemical processing), and spreading in the oceans. In this regard, it is important to make a distinction between the CO₂ uptake potential of different rock types when used for OAE, which grossly depends on size and composition. For example, in a case study of peridotites (dunite and harzburgite) and basalts (olivine) spreading in seawater it was identified that the CO₂ uptake potential depend both on the rock type (peridotites appeared to be more promising than basalts) and more importantly on their specific surface area (size) (Rigopoulos et al., 2018). Detailed information about alkalinity potential of different minerals can be found elsewhere (e.g., (Renforth and Campbell, 2021). Here, for the sake of brevity, limestone and olivine were considered as the typical minerals of carbonate and silicate rocks, respectively, that can be used for OAE. It was considered that for the uptake of 1 t of CO₂ from the atmosphere 1.6 t (Renforth et al., 2013)) of limestone or ~1 t of olivine (Köhler et al., 2013; Montserrat et al., 2017).

6.2.3 Mining and comminution infrastructure in Europe and further afield

The construction aggregates industry includes the blasting, mining, and crushing of stones/rocks such as limestone, granite, traprock, and sandstone, along with gravel and sand production (Langer, 2001). In Europe (EU 28 and the European Free Trade Association (EFTA) countries) the construction aggregates industry is by far the largest non-energy extractive industry, with 15,334 companies currently employing more than 200,000 people at 26,054 sites (UEPG, 2020). Population growth, along with the need to maintain existing and/or construct new infrastructure, has rendered the construction aggregates industry resilient, even during the past financial crisis and the ongoing COVID-19 pandemic. For example, during the past two decades (reference period 1997-2018) the production output of construction aggregates in Europe (EU member countries, associates, and candidates) has ranged from around 2.2 to 3.1 billion tons (**Fig. 6.2.2**) (BGS, 2019; UEPG, 2020). Currently, more than 3

billion tons of construction aggregates are produced in Europe (EU 28 and EFTA), with the crushed rocks production being 1.43 billion tons (provisional estimates for 2018) (UEPG, 2020). These numbers are on par with corresponding values in USA, where crushed stones production in 2019 amounted to 1.53 billion tons (up from 1.42 in 2018), while sand and gravel production was at 0.97 billion tons in 2019 (up from 0.94 in 2018) (USGS, 2020). Crushed rocks are mainly consumed in road construction and maintenance (road surfaces are made of asphalt and crushed stones) and to a lesser extent in cement and lime manufacturing (e.g., in 2009 72%, 16%, and 8% of USA’s total crushed rock consumption was in roads, cement, and lime respectively (USGS, 2020)). Of prime concern is the cement and lime industries since their spare capacity could be used for OL.

On a global scale, the annual construction aggregates production is estimated at 47-59 billion tons, with the mean value being 50 billion tons (JXSC, 2021). Sand and gravel accounts for the largest share, i.e., 65 - 85% (Sverdrup et al., 2017). Existing estimates also suggest that this number is on the rise with the estimated output in 2030 being 60 billion tons, due to urbanization and population and economic growth (JXSC, 2021). Furthermore, more silicate-based materials are mined than carbonate (limestone), since, for example, from the 52.52 billion tons of primary and secondary resources that were mined in 2012 globally, 66.4% were silicate-based stony materials and the remaining 33.6% was limestone (Sverdrup et al., 2017). Therefore, it appears that a strong and expanding construction aggregates industry is already in place and mainly outside the EU and USA (roughly 5% each (UEPG, 2020; USGS, 2020)).

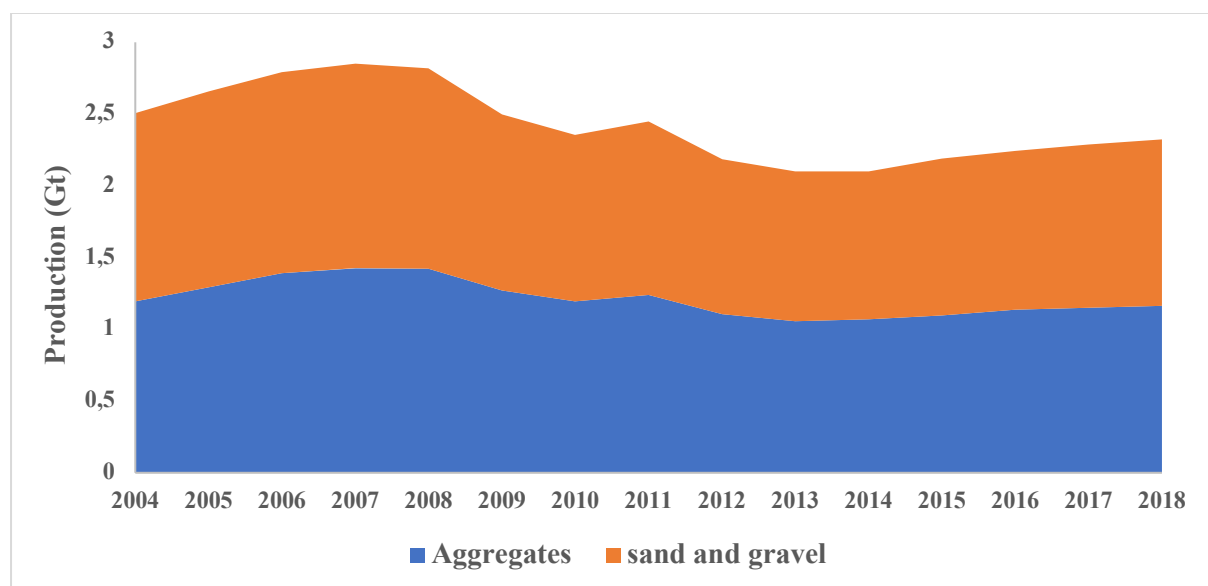


Figure 6.2.2: Construction aggregates production by Europe countries for the reference period 2004-2018. (production data taken from (Minerals4EU, 2021).)

More importantly the global reserves of construction aggregates appear to be vast. Even though the United States Geological Survey (USGS), which provides information on natural resources, does not provide actual estimates, it states that at a global scale the stone resources, along with the limestone and dolomite resources suitable for lime manufacture, are very large, while sand and gravel resources are characterised as plentiful (USGS, 2020). In this regard, (Sverdrup et al., 2017) do provide quantitative estimates for the global reserves, with the sand and gravel resources being 12 trillion ton each and the stone reserves being much larger at 167 trillion tons. Therefore, the global sand, gravel, and stone reserves are more than 190 trillion tons. If part of these vast reserves were to be used for OAE, using methods such as OL and CEW, this could make a huge impact in the fight against climate change.

Furthermore, these massive reserves also suggests that an increase in construction aggregates material is most likely to be feasible and not a limiting factor for OAE. Nonetheless, one should bear in mind that environmental regulations, geographic distribution, and purity might render construction aggregates production impractical and/or uneconomic in some cases (USGS, 2020). For example, even though in the USA abundant limestone reserves are available, cement shortages have been reported, partly due to the need for new suitable quarry sites, which have led to spikes in Portland cement price (Bliss et al., 2012). Furthermore, local communities might not welcome new quarries or even the extension of existing ones, which might hinder OAE application at industrial scale. More importantly, establishing new infrastructure for the processing of the extracted minerals, such as crushing facilities or new kilns for limestone calcination, can be a slow process, e.g., in the permitting process of a new cement plant in USA could take between 8 to 10 years and its construction roughly 2 years (Bliss et al., 2012). Therefore, focus should be placed on the existing infrastructure for the mining, comminution/processing, and spreading of these minerals, since new infrastructure could be considered as a limiting factor for OAE. However, existing infrastructure is ageing and typically energy and carbon intensive, which might render the use of some infrastructure environmentally unsustainable. For this reason, focus should be placed on using the spare capacity of the infrastructure that is environmentally friendly.

6.2.4 Investment in new and environmentally friendly infrastructure

The use of carbonate and silicate minerals for OAE implies that apart from increasing the production output of existing mining sites and/or establishing new mining sites, investment in improved and/or new infrastructure for their low carbon processing is also required.

For silicate minerals to be used for OAE a very high degree of grinding (pulverisation) is typically required. For example, olivine is a promising silicate-based mineral for OAE, since its dissolution rate in ocean water is three orders of magnitude faster than ordinary quartz, with the added benefit that olivine mines are already operating across the globe (Meysman and Montserrat, 2017). However, even at this increase dissolution rate compared to quartz, it will take 700-2100 years for olivine sand (300 μm grain size) to reach the necessary steady state sequestration rate at mean seawater temperatures of 15-25 $^{\circ}\text{C}$, while for 10 μm grain sizes this timespan reduces to 15-20 years (Hangx and Spiers, 2009). Furthermore, using dissolution kinetics it has been calculated that only olivine particles with a grain size of the order of 1 μm or less will sink slowly enough to enable a nearly complete dissolution (Kohler et al 2013). Overall, it appears that coarse grinded silicate-based minerals might have little practical value for OAE, but the silver lining is that coastal zone dynamics (e.g., wave action) could be an important catalyst to enhance their dissolution (Montserrat et al., 2017). In this sense, olivine spreading in the nearshore appears not to directly impact land use, while it can also be integrated into coastal management programmes using existing technology (e.g., dredging) (Meysman and Montserrat, 2017).

However, for large scale OAE the existing mineral grinding infrastructure might not suffice, particularly when considering the need for exceptional fine grinding, and therefore investment in new grinding equipment might be required. Nonetheless, the initial capital expenditure for this infrastructure along the space requirement for their installation is typical not high compared to their overall operating cost (Sayadi et al., 2014) and therefore it does not appear that grinding infrastructure will be main limiting factor for large-scale OAE schemes. Electrochemical approaches that do not require silicate minerals to a high degree can be also employed, however these are typical energy hungry and require additional resources such as brines with high salt concentrations (House et al., 2007). Therefore, the electrochemical pathways can be used to complement OL and particularly CEW, at least in the near future. However, a scenario where CEW is replaced by the electrochemical weathering of olivine was examined, since in this case alkalinity will be readily available while in CEW alkalinity is typically released slowly.

Regarding carbonate minerals, these apart from grinding also need further processing before being used for OAE, since, as mentioned above, surface ocean waters are typically oversaturated with respect to calcite (Caldeira et al., 2005). For OL, limestone needs to be mined, crushed, washed, milled, and then calcined, before being transported and dispersed into the surface ocean waters. However, in this case the dissolution of the calcined carbonate

minerals (lime) is rapid and with proper planning changes in ocean mean pH and CO₂ partial pressure can be miniscule (Rackley 2010).

Therefore, for OL apart from investment in mining activities (e.g., excavators and roads), new investment is required for new grinding mills and calciners. Alternatively, the spare capacity of existing grinding and calcination (the latter in the cement and lime industries) facilities could be explored. Here we assume that existing infrastructure could sustainably absorb up to a 20% increase in construction aggregates mining output, based on historical fluctuations (e.g., lime production in USA fluctuated at this range (**Fig. 6.2.3**)). This means that existing mining sites and infrastructure for limestone calcination are currently not fully utilised at a global scale, i.e., they do not operate 24/7 and/or 24/7/365. We assume that this is the case for mining and comminution infrastructure, both for silicate and carbonates minerals. Therefore, a modest increase in the global construction aggregates material output is most likely to be achieved, at least in the short term, without the need of new mining sites or additional infrastructure. Since the technology readiness levels (TRL) for OAE technologies are low, we assume that existing technology can be used to introduce and test these technologies. However, for higher outputs new and environmentally friendlier, infrastructure will most likely be necessary.

The main problem with existing fine grinding infrastructure pertains to its very high energy demand, which translates to high carbon footprints given the use of fossil fuels in power generation. Therefore, renewable electricity should be used for OAE applications, while future infrastructure should focus on introducing energy efficient grinding mills. For carbonate minerals the aforementioned challenges for their environmentally sustainable grinding should also be addressed, but they affect the system to a lesser extent since the particle size of the spread material in OL is typically in the range of 100s µm (Renforth et al., 2013) so very high grinding is not required. Nonetheless, for OL the main problem pertains to the high thermal energy input of existing calciners, which is required for limestone/calcite (CaCO₃) decomposition to calcium oxide (CaO), and also to the need to capture the relevant CO₂ emissions from limestone decomposition. This suggests that for OAE decarbonised and energy efficient kilns should be used.

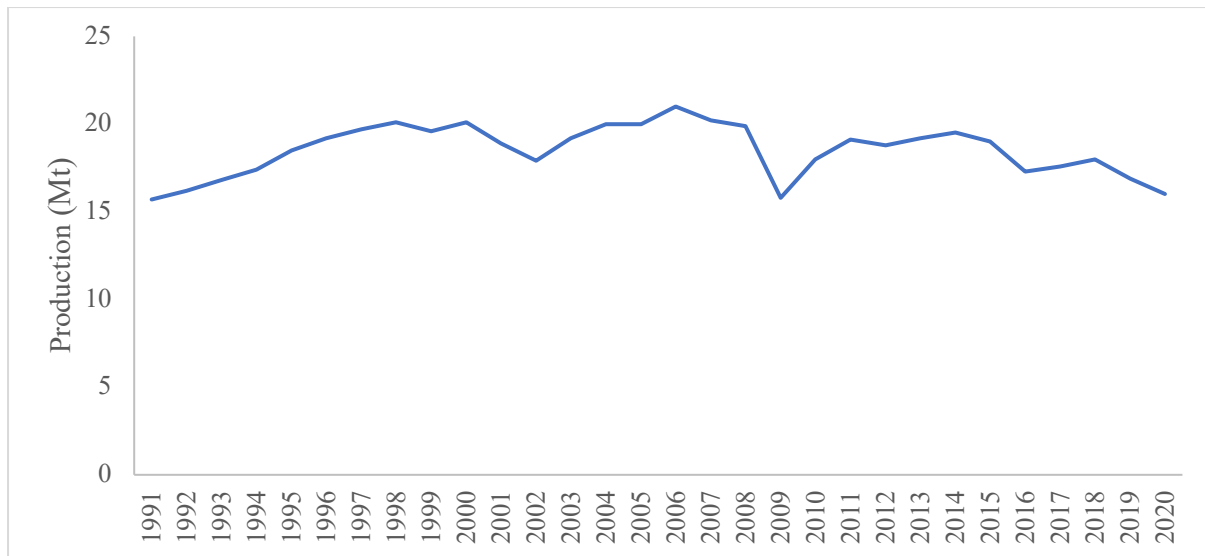


Figure 6.2.3: Lime production fluctuations in USA for the reference period 1991-2019. (production data taken from (USGS, 2020).)

6.2.5 Use of waste and by-product materials for OAE

Each year the global industrial output of alkaline materials amounts to 7 Gt (Renforth, 2019), which suggest that very large quantities of alkaline waste materials are also produced. Specifically, on a global scale it has been estimated that ~2 Gt of alkaline waste/residues are annually produced (Gomes et al., 2016). Others have put this number much higher, at 7-17 Gt of waste silicate minerals (aggregate, mine, construction, and demolition waste, along with iron and steel slag, coal ash, and cement kiln dust) per year (Renforth et al., 2011). Not only this, but these numbers also suggest that already vast quantities of these waste materials are already stockpiled, e.g., only in the UK over 190 Mt of legacy iron and steel slag are available (Riley et al., 2020). However, when waste materials are used for OAE, among other NETs, harmful leachates/wastewater can be produced since these wastes can be enriched with trace (heavy) metals (Gomes et al., 2016). Furthermore, regarding the legacy wastes major management challenges in their extraction and use exists (Riley et al., 2020). Therefore, the direct use of waste materials and legacy waste stockpiles for OAE appears to have little applicability, at least in the near future.

Another promising waste source for OAE, which can be used indirectly to produce alkalinity rather than directly as is the case with alkaline waste/residues is the brine from the desalination industry. On a global scale more than 95 million m³ of desalinated water is daily produced, generating more than 141 million m³ day⁻¹ of brine that is typically discharged into the oceans negatively affecting the receiving ecosystems (Jones et al., 2019). This number is on the rise, since recent estimates suggest that by 2030 the global desalination capacity will be more than

200 million $\text{m}^3 \text{ day}^{-1}$ (Ihsanullah et al., 2021). These very large volumes of reject brines (waste) present certain advantages for use in OAE, since Ca and Mg concentrations in brine are almost twice than in seawater (Bang et al., 2019) as is also the case for salinity (Ihsanullah et al., 2021).

Various pathways for using reject brines in CCS have been proposed, e.g., for CO_2 capture from flue gases (Dindi et al., 2015) or for the mineralisation of Ca and Mg in brine through CO_2 interaction (Bang et al., 2019). When using brines in CCS, apart from capturing CO_2 salinity is also decreased, which is beneficial for receiving ecosystems (Mustafa et al., 2020). In the context of OAE, reject brines could use for acidity removal from the oceans, i.e., hydrochloric acid (HCl) is produced electrochemically and neutralized, valorised, or stored while alkalinity (i.e., sodium hydroxide (NaOH)) is returned to the oceans. In this regard, (House et al., 2007) proposed electrolysis of reject brines for the splitting of salts (sodium chloride (NaCl)) and the use of a fuel cell to combine hydrogen (H) and chlorine (Cl) to HCl production, which can be then neutralised through interaction with silicate rocks, while the produced NaOH can be used for OAE. Alternative electrodialysis, a membrane process, can be used for HCl (which is kept on land) and NaOH (which is returned in the ocean) production (Eisaman and Carter, 2021). Therefore, it appears that reject brines from the desalination industry can be initial used for OAE and if found promising artificial brines can be used to reach the $\text{Gt y}^{-1} \text{ CO}_2$ removal scale.

6.2.6 Potential deployment scenarios

Different scenarios for OAE are proposed and examined focusing on the use of virgin materials, i.e., silicate (CEW) and carbonate (OL) minerals from the construction aggregates industry as well as the use of reject brines from the desalination industry as a proxy scenario to replace CEW in silicate minerals.

6.2.6.1 Use of minerals from the construction aggregates industry

As mentioned above, silicate and/or “activated” carbonate minerals can be used for OAE. However, each mineral may also cause knock-on effects, positive and/or negative, on ocean ecosystems. These effects are greatly dependent on the type of minerals that are used, with silicate-based minerals giving advantages to certain (micro)organisms and carbonate-based minerals to others.

Regarding the silicate-based minerals, these typical contain iron (Fe) and it has been suggested that increased dissolved silicon (Si) and Fe can stimulate primary production and thus lead to additional CO_2 sequestration (Montserrat et al., 2017). Therefore, at first look silicate-based

minerals seems beneficial for ocean ecosystems since they promote ocean primary production, while carbon capture capacity is improved through biological mechanisms. For example, it has been estimated that the relative contributions to total CO₂ uptake by olivine dissolution are 57% for alkalinity, 37% for Fe and 6% silicic acid, a by-product of olivine dissolution (Hauck et al., 2016). Nonetheless, silicic acid could alter marine biology, since in certain areas silicate can be a limiting nutrient for diatoms, and therefore cause a shift in phytoplankton species composition, in this case diatoms, thus also altering the biological carbon pumps (Köhler et al., 2013). Apart from Si and Fe, the dissolution of forsteritic olivine is also known to increase magnesium (Mg), total alkalinity (TA), dissolved inorganic carbon (DIC), and nickel (Ni) concentrations in seawater and cause both biological and physicochemical effects such as increased in suspended particulate matter, sediment pore space clogging, and smothering effects due to the higher specific density of olivine (Montserrat et al., 2017). Furthermore, the release of Si, Fe, and Ni could benefit silicifiers and nitrogen fixing cyanobacteria, which growth rates can rapidly increase, however at the expense of calcifiers and other (micro)organisms, and also turn the blue ocean into a greener shade (Bach et al., 2019). Finally, olivine, as a material, has a green or green shade colour. Therefore, apart from being responsible for leading to greener shade waters, if spread on the coastline it can possibly add to the aesthetic value since the colour of the sand of the beach that is spread would change to a green hue (**Fig. 6.2.4**).



Figure 6.2.4: Example of an olivine beach, where olivine sand has imparted a green hue to the beach. Picture taken from (Project Vesta, 2021).

Regarding the addition of carbonate minerals, in this case CaO or more likely hydrated lime ($\text{Ca}(\text{OH})_2$) these when added at large scales can cause rapid changes in the seawater pH, which can be detrimental for ocean ecosystems. Specifically, when CaO is spread in seawater the pH near the CaO particle surface will rapidly increase from ~ 8 to a theoretical value of ~ 12.5 , then rapidly fall back to ~ 10.5 (the equilibrium pH of magnesium hydroxide), and then reduced to < 9 (due to ion effect of dissolved magnesium in seawater) until returning to background pH (Justnes et al., 2020). Rapid uncontrolled changes in pH, along with changes in carbonate chemistry, may lead to detrimental effects on ocean ecosystems and also affect the rate of carbonate mineral production (Renforth et al., 2013), therefore proper discharge rates should be considered (Caserini et al., 2021). Furthermore, carbonate addition can benefit calcifiers,

e.g., CO_3^{2-} could increase both light and dark calcification and HCO_3^- light calcification in coral reefs (*Porites rus*), while HCO_3^- and particularly CO_3^{2-} can strongly affect certain algal species such as *Hydrolithon onkodes* (Comeau et al., 2013). However, the advantages that calcifiers obtain by carbonate minerals addition can come at the expense of other (micro)organisms such as silicifiers, while a “side effect” is the change of ocean colour into bluer or whiter shades (Bach et al., 2019). An example of ocean water turned into turquoise colour (not by OAE) is shown in **Fig. 6.2.5**, where a rapid growth of coccolithophore population (a calcifier marine algae that sheds white calcium carbonate plates) turned seawater’s colour into bright blue (BBC, 2021).

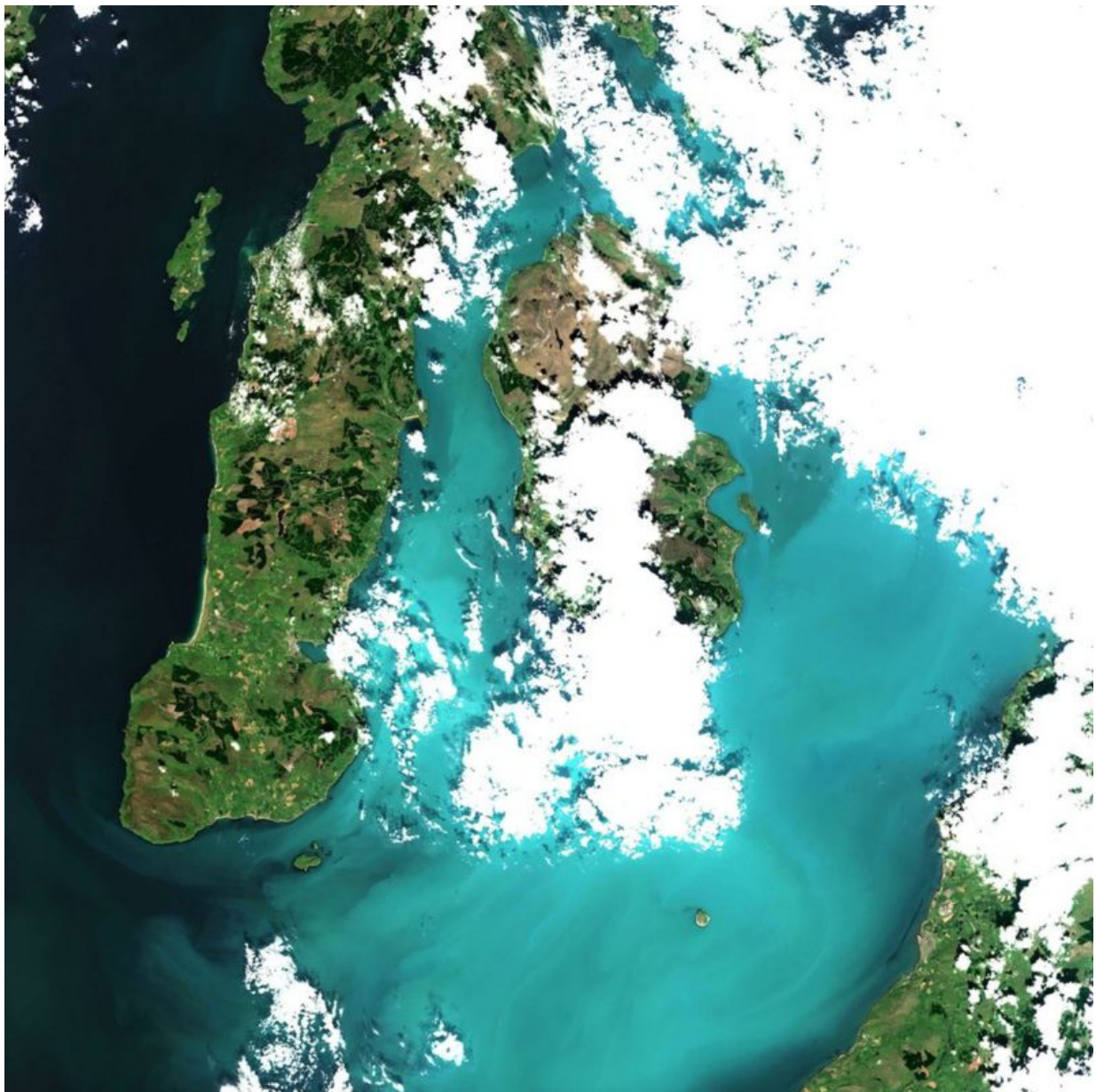


Figure 6.2.5: Changes in the colour of the surface ocean water in Isle of Arran, Scotland, UK caused by coccolithophore rapid bloom. Picture taken from (BBC, 2021).

However, in theory, OAE at a global scale could substantially address climate change, without significantly elevating biogeochemical properties beyond naturally occurring levels (Gattuso et al., 2021). Furthermore, acidification has already caused a large ecological impact, with crabs, shrimps, benthic grazers, and bivalves being directly affected, thus also indirectly affecting specific demersal species that prey on these groups (Doney et al., 2020). Therefore, it appears that OAE might be necessary, not only for removing previously emitted CO₂ but also for protecting ocean ecosystems from acidification. Nonetheless, the aforementioned considerations for silicate versus carbonate minerals addition necessitate the study for the risks and co-benefits of mineral dissolution products on marine ecosystems and environments (Bach et al., 2019; Meysman and Montserrat, 2017), since, for example, the potential secondary effects of olivine dissolution remain a critical issue (Montserrat et al 2017).

Therefore, a “golden ratio” between silicate to carbonate minerals addition should be identified to minimize possible impacts on aquatic ecosystems and at the same time protect them from acidification. This could be greatly affected by local conditions and the species that each ecosystem hosts, however, the exact impacts, negative or positive, of silicate and/or carbonate minerals addition remains grossly unknown. Given that in CEW the dissolution of silicate minerals in the coastal zone is much lower (e.g., tens to thousands of years for olivine sand (Hangx and Spiers, 2009)) than in OL where CaO and/or Ca(OH)₂ rapidly dissolve (Justnes et al., 2020) alkalinity will be released at a much lower pace. (note that as mentioned above for the rapid dissolution of silicate minerals their size should be 1 μm or less (Meysman and Montserrat, 2017), which from the current techno-economic perspective is not practical.)

Therefore, it appears that higher quantities of silicate minerals are required to maintain a balance between silicate vs carbonate minerals dissolution rates and here we guestimate that the existing global extraction pattern of silicate to carbonate materials, i.e., a 2:1 silicate to carbonate ratio (Sverdrup et al., 2017), might be a good starting point for CEW and OL at industrial scales. We assume that the existing industry for the mining, processing, and transportation of the silicate and carbonate minerals, will not be a limiting factor considering both the size of the existing industry (currently at 50 billion tons and 60 billion tons in 2030 (JXSC, 2021)), as well as that opportunities exist to make use of the spare capacity of these industrial processes, e.g., of the cement and lime industry in OL (Renforth et al., 2013).

6.2.6.2 Potential deployment scenario at global scale

Here, the potential CO₂ uptake from proposed global deployment scenarios is analysed and discussed. These scenarios comprise three different sub-scenarios, i.e., OAE through: i) silicate minerals using CEW, ii) carbonate minerals using OL, and iii) HCl removal using desalination brines and/or artificial brines to complement/replace CEW. It is assumed that the amount of silicate minerals that will be used in CEW will be twice as high as the one for carbonate minerals (OL), as to be in agreement with the existing global mining pattern, i.e., 2:1 silicate to carbonate ratio.

6.2.6.2.1 Silicate minerals for coastal enhanced weathering

As mentioned above, a problem with the use silicate minerals for CEW is their persistence in weathering. Specifically, (Hangx and Spiers, 2009) noted that it will take 700 years (range 371-6012 years) and 23 years (range 12-200 years) for 300 µm and 10 µm grain size olivine sand, respectively, to fully dissolve when spread at a beach (25 °C temperature). However, (Meysman and Montserrat, 2017) noted that the dynamics in both beach and shelf coastal zone can further promote olivine dissolution, while (Montserrat et al., 2017) estimated that for 143 µm olivine sand 4% will be dissolved in the first year, 12% in 5 years, 35% in 25 years, 57% in 50 years, 84% in 100 years, and 98% in 200 years. This timespan (200 years) is exceedingly high for OAE that aim at mitigating climate change, it is suggested that lower particle diameters will be required. For the sake of brevity and to account for the effect of beach and shelf coastal zone on silicate minerals dissolution here the 10 µm olivine sand was considered assuming that it will be fully dissolved in 20 years. The dissolution rates were taken from (Montserrat et al., 2017), while the energy input for comminution up to 10 µm, which will determine the carbon penalty for CEW, was taken from (Hangx and Spiers, 2009). It should be noted that 10 µm is very low and most likely will have limited use in practical applications, however it can account for harder minerals such as the ones that contain high amount of quartz and also provide a good estimate for the carbon penalty of CEW when low dissolution times are desirable. Finally, as mentioned above, it was assumed here that 1 t of olivine can remove 1 t CO₂ (Köhler et al., 2013; Montserrat et al., 2017).

Regarding the assumptions for the construction aggregates industry, a 1.85% annual increase was considered up to 2030 when its output will be 60 billion tons (from 50 billion tons currently) (JXSC, 2021) and this increase pattern was extrapolated up to the year 2050. Most likely constant increases up to 2050 are possible, however if OAE schemes were to be introduced, even at pilot scale, these can sustain and multiply the assumed annual increase. The

total construction aggregates industry output for the different starting dates for OAE is shown in **Table 1**. Furthermore, different starting dates were considered for OAE (the application of CEW and OL is assumed to coincide), ranging from 2025 to 2035. Also, a scenario examining 2050 as the starting date of OAE was examined. Different scenarios for initial allocation of minerals from the construction aggregate industry to OAE were considered, ranging from as low as 0.01% to as high as 0.1% and then different annual increase rates were considered (from 2% to 12%). These assumptions reflect the application of OAE at pilot scale initially and with the passing of time its adoption at industrial scale. The carbon capture potential of CEW and OL was capped to a maximum of 2 Gt y^{-1} , while the scenarios were simulated up to 2100.

Specifically, using the data for silicate minerals from **Table 1** the following assumptions were considered. For the starting date of CEW an optimistic (2025), a mean (2030), and a pessimistic (2035) scenario were considered. Furthermore, three different scenarios were considered for the initial share of the total aggregate industry output that would be allocated to CEW, i.e., 0.01%, 0.05%, 0.1%. These very low values provide physical realism since it is expected that initially CEW and OL schemes would be applied at pilot to small industrial scale and therefore only a very small amounts of the construction aggregates industry output would suffice for such applications. However, different scenarios were considered on how fast these technologies are adopted at industrial scale, assuming annual growth rates of 2%, 4%, 6%, 8%, 10%, and 12% over the entire reference period. As mentioned above, in all examined the annual CO₂ uptake rate was capped at 2 Gt to provide physical realism for CEW and OL at scale.

For the carbon penalty for CEW the electricity input for olivine grinding to 10 μm was only considered (173.71 kWh t^{-1} olivine (Hangx and Spiers, 2009)). The average greenhouse gas emission intensity of electricity generation in Europe was considered, where extrapolation suggests that in 2025 around 200 kg CO₂eq per MWh will be emitted and in 2030 as low as 100 kg CO₂eq per MWh (European Environmental Agency, 2021). Therefore, we assume here that each year the total carbon footprint for electricity generation in Europe reduces by 20 kg CO₂eq per MWh for the reference period 2025-2030, then by 10 kg CO₂eq per MWh between 2030-2031 and then gradually by 5 kg CO₂eq per MWh each year, until zero in 2050 where Europe will reach net climate neutrality (European Environmental Agency, 2021). Therefore, after 2050 the carbon penalty for CEW will be zero, which is a likely scenario given the technological advances that will take place in the next 30 years.

For the carbon penalty of OL our preliminary life cycle assessment (LCA) suggests that for the European context a mean of 400 kg CO₂eq per tonne of atmospheric CO₂ removed could be possible. However, we assume that OL could be fully decarbonised in 2050, as is the assumption for CEW, and therefore we extrapolate the carbon penalty of 2025 to 2050 to estimate the yearly carbon penalty of OL. For the electrochemical pathways more research is required to properly estimate carbon penalties and therefore here the carbon penalty for CEW was used as proxy.

Table 1: The total output of the construction aggregates industry for the reference period 2020-2050 (data extrapolated from (JXSC, 2021)).

Year	Silicates (billion tons)	Carbonates (billion tons)	Total output (billion tons)
2020	3.33E+01	1.67E+01	5.00E+01
2021	3.40E+01	1.70E+01	5.09E+01
2022	3.46E+01	1.73E+01	5.19E+01
2023	3.52E+01	1.76E+01	5.28E+01
2024	3.59E+01	1.79E+01	5.38E+01
2025	3.65E+01	1.83E+01	5.48E+01
2026	3.72E+01	1.86E+01	5.58E+01
2027	3.79E+01	1.89E+01	5.68E+01
2028	3.86E+01	1.93E+01	5.79E+01
2029	3.93E+01	1.97E+01	5.90E+01
2030	4.00E+01	2.00E+01	6.01E+01
2031	4.08E+01	2.04E+01	6.12E+01
2032	4.15E+01	2.08E+01	6.23E+01
2033	4.23E+01	2.12E+01	6.35E+01
2034	4.31E+01	2.15E+01	6.46E+01
2035	4.39E+01	2.19E+01	6.58E+01
2036	4.47E+01	2.23E+01	6.70E+01
2037	4.55E+01	2.28E+01	6.83E+01
2038	4.64E+01	2.32E+01	6.95E+01
2039	4.72E+01	2.36E+01	7.08E+01
2040	4.81E+01	2.40E+01	7.21E+01
2041	4.90E+01	2.45E+01	7.35E+01
2042	4.99E+01	2.49E+01	7.48E+01
2043	5.08E+01	2.54E+01	7.62E+01
2044	5.18E+01	2.59E+01	7.76E+01
2045	5.27E+01	2.64E+01	7.91E+01
2046	5.37E+01	2.68E+01	8.05E+01
2047	5.47E+01	2.73E+01	8.20E+01
2048	5.57E+01	2.78E+01	8.35E+01
2049	5.67E+01	2.84E+01	8.51E+01
2050	5.78E+01	2.89E+01	8.67E+01

6.2.6.3 Silicate minerals application coastal enhance weathering

6.2.6.3.1 Optimistic scenario with low allocation of silicate minerals from the construction aggregates industry

As mentioned above in the optimistic scenario it was considered that OAE is adopted as early as 2025. The only downside of early adoption are the increased life cycle carbon emissions for CEW, since in 2025 the energy grid remains fossil fuel dependent and only in 2050 a fully decarbonised energy grid was considered. Results for the life cycle carbon emissions when 0.01% of the construction aggregates are allocated to CEW, and for the six examined growth rates, are shown in **Fig. 6.2.6** (in Mt), where it can be seen that the decarbonisation of grid between 2025 to 2030 takes place at a faster rate than the considered annual growth rates for CEW and therefore the life cycle carbon emissions decrease with time. However, after 2030 the decarbonisation of the energy grid takes place at a much lower pace while the annual growth rates of CEW begin to have a larger impact on the system, particularly in the 6% growth rate scenario and above. Therefore, even though the energy grid decarbonises the increased amounts of silicates minerals that needs processing increases the life cycle carbon emissions of CEW, particularly in the 12% annual growth rate scenario. Starting 2041 the energy grid is largely decarbonised and thereafter the life cycle carbon emissions of CEW decrease until they reach zero in 2050. (note that even though the mining, loading, transportation, and spreading of olivine is outside the system boundary of this report, we assume that these also be decarbonised, e.g., electric trucks).

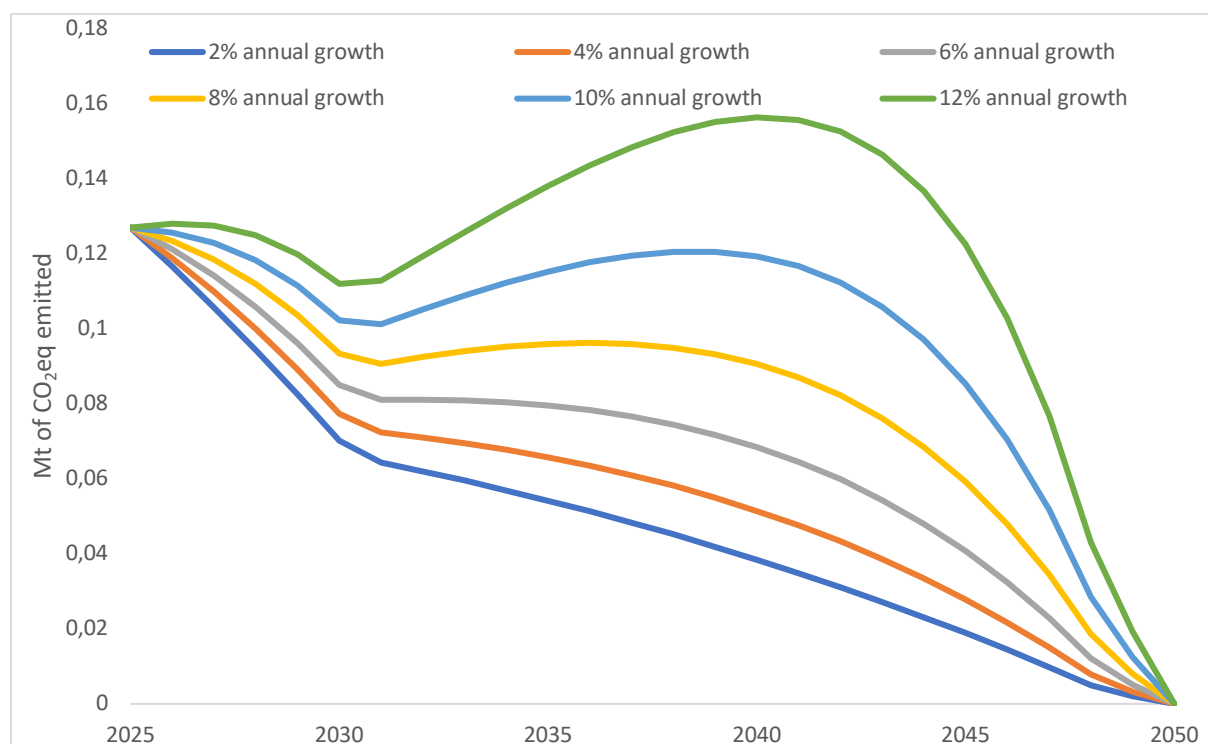


Figure 6.2.6: The life cycle carbon emissions (in Mt) for the 0.01% construction aggregates allocation scenario.

In Fig. 6.2.7 the CO₂ that is taken up from the atmosphere (in Gt) when using the 0.01% construction aggregates allocation scenario is shown. As is observed, due to the relatively slow dissolution of silicate minerals in seawater, even in the optimistic scenario (starting date 2025) when using the 0.01% allocation scenario CEW has a very small impact in the near-term and only after 2075 CO₂ uptake at the Gt scale is achieved in the 12% annual growth rate scenario. The 10% annual growth rate scenario archives the Gt scale only after 2085, while the 8% annual growth rate scenario archives the Gt in 2100. Therefore, if the Gt y⁻¹ is achieved as late as 2075 then CEW will have very little impact in the fight against climate change. Therefore, results suggest that a more aggressive strategy should be in place where CEW is introduced using higher quantities from the early start of its application. The effect of electrochemical pathways for the rapid dissolution of silicate minerals was also examined, since in this case the full amount of alkalinity will be readily available and not in a timeframe of 20 years.

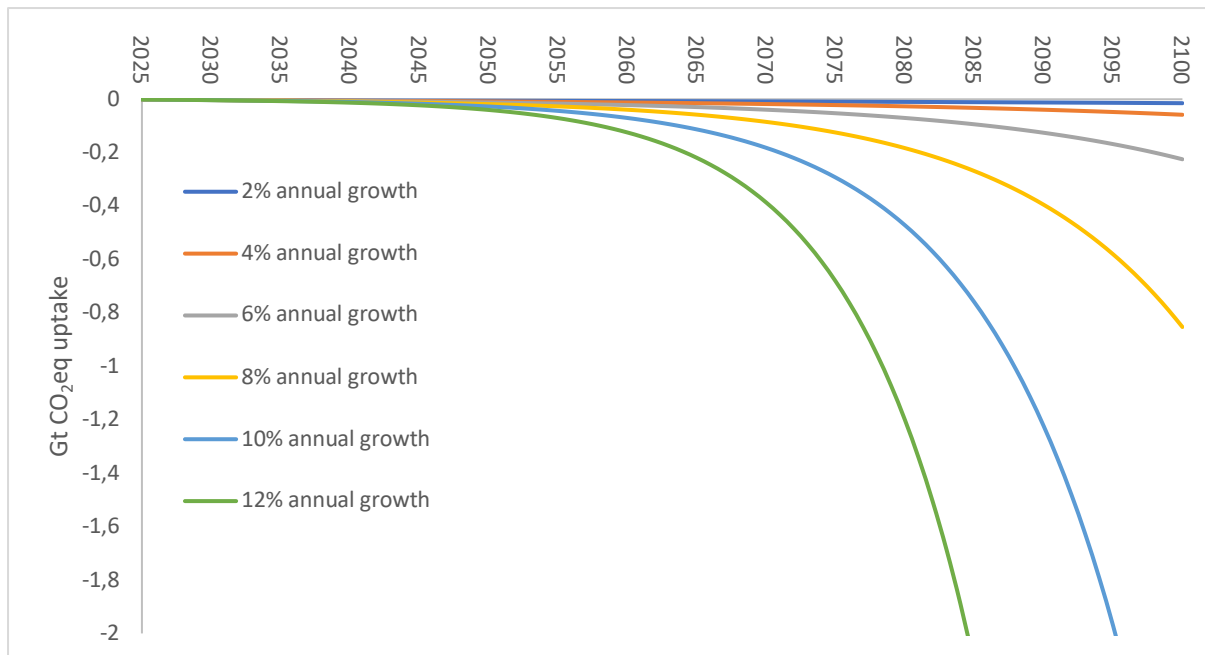


Figure 6.2.76: The CO₂ uptake (in Gt) for the 0.01% construction aggregates allocation scenario.

6.2.6.3.2 Optimistic scenario with mean allocation of silicate minerals from the construction aggregates industry

When higher quantities of silicate minerals from the construction aggregates industry are allocated to OAE, in this case CEW, then results differ significantly. Specifically, in the mean allocation scenario it was assumed that initially 0.05% of silicate minerals from the

construction aggregates industry are allocated to CEW, using the aforementioned constant growth rates, i.e., 2%, 4%, 6%, 8%, 10%, and 12% over the entire reference period.

Results for the life cycle carbon emissions are shown in **Fig. 6.2.8** (in Mt), where, as expected, the same pattern as the one identified in the low allocation scenario is observed but with total higher carbon emissions.

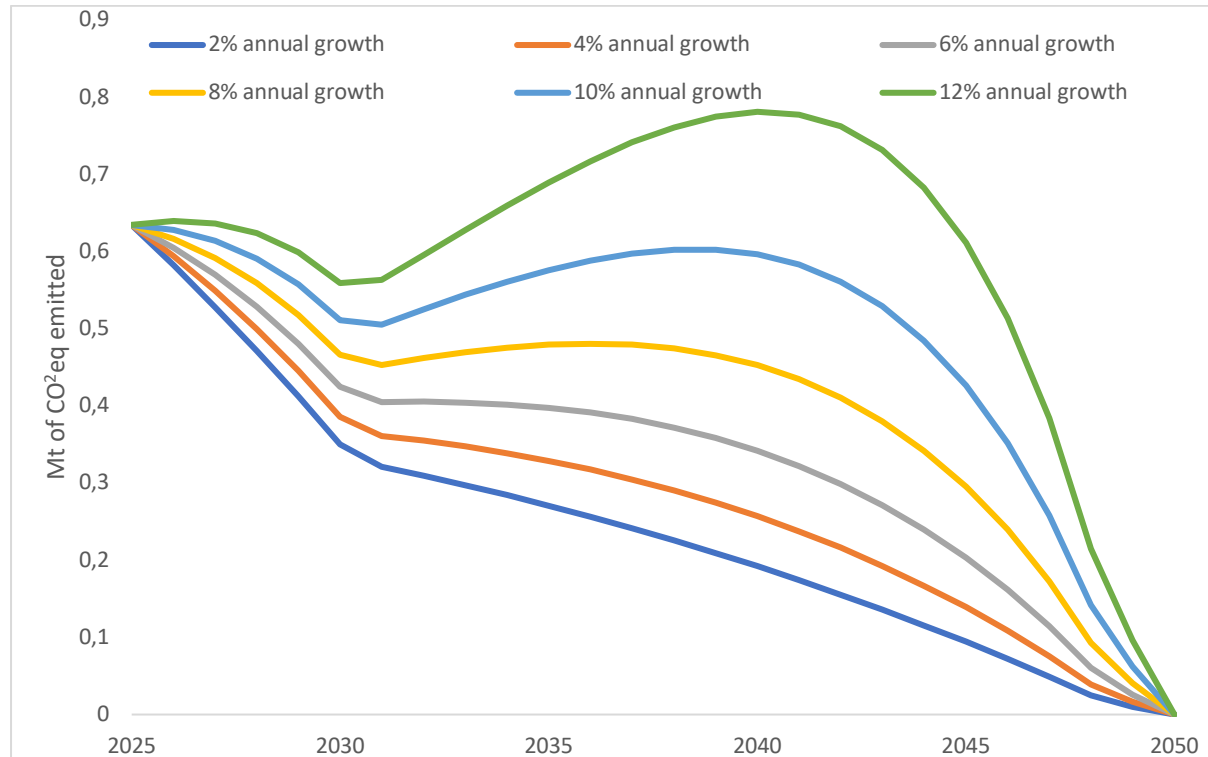


Figure 6.2.8: The life cycle carbon emissions (in Mt) for the mean (0.05%) allocation scenario for silicate minerals from the construction aggregates industry.

Similarly, results for the CO₂ uptake follow the same pattern as in the low allocation scenario, however a much greater amount of atmospheric CO₂ is taken up each year. greatly differ in the mean compared to the low allocation scenario. Specifically, in **Fig. 6.2.9** the CO₂ that is taken up from the atmosphere (in Gt) when initially using the 0.05% allocation of the silicate minerals from the construction aggregates industry is shown. In this scenario the Gt y⁻¹ scales are achieved much earlier than in the low allocation scenario, with the 12% annual growth rate scenario achieving the Gt scale in 2063. Six years later, in 2069, the 10% annual growth rate scenario achieves the Gt scale, while the 8% and 6% annual growth rate scenarios achieve the Gt scale in 2079 and 2095 respectively. Therefore, the mean allocation scenario is more promising than the corresponding low allocation one, but yet it appears that a more aggressive initial allocation quantity is necessary in the fight again climate change, at least in the shorter term.

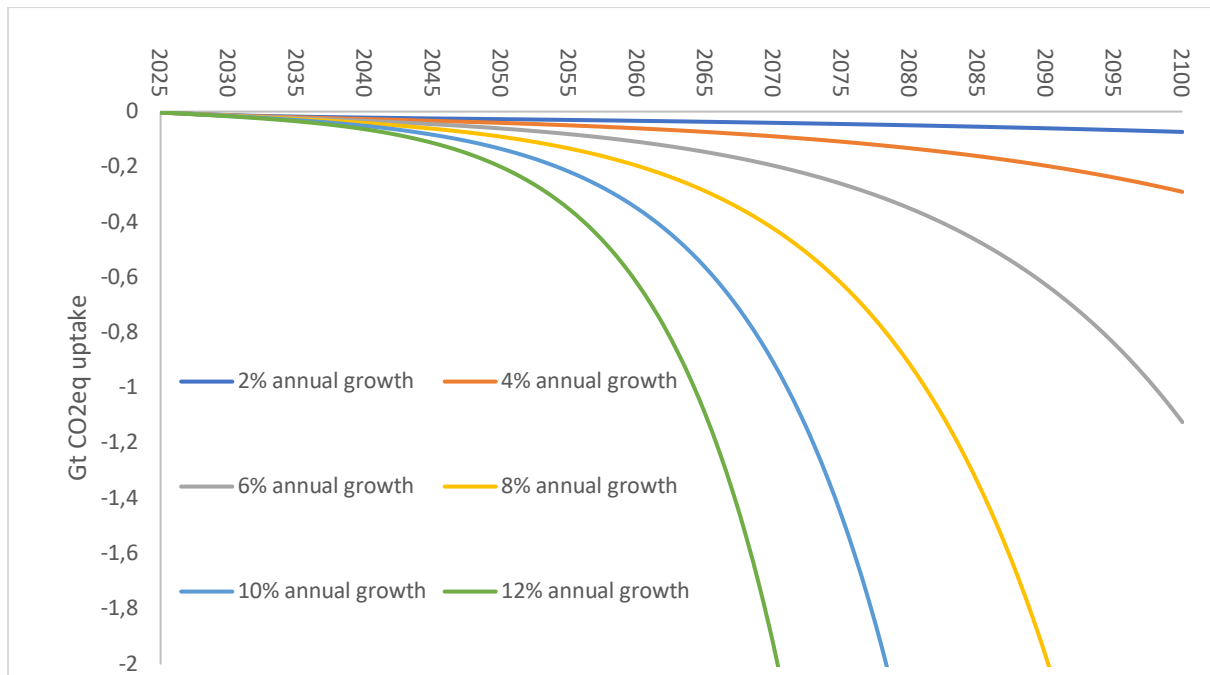


Figure 6.2.9: The CO₂ uptake (in Gt) for the 0.05% construction aggregates allocation scenario.

6.2.6.3.3 Optimistic scenario with high allocation of silicate minerals from the construction aggregates industry

Finally, when a much larger, yet feasible, initial silicate minerals allocation quantity (0.1%) from the construction aggregates industry was considered the Gt scale is achieved even earlier but also the life cycle carbon emissions are higher. Specifically, the results for the life cycle carbon emissions (**Fig. 6.2.10**) follow the same pattern as the one identified in the 0.01% and 0.05% allocation scenarios, with significantly higher total carbon emissions.

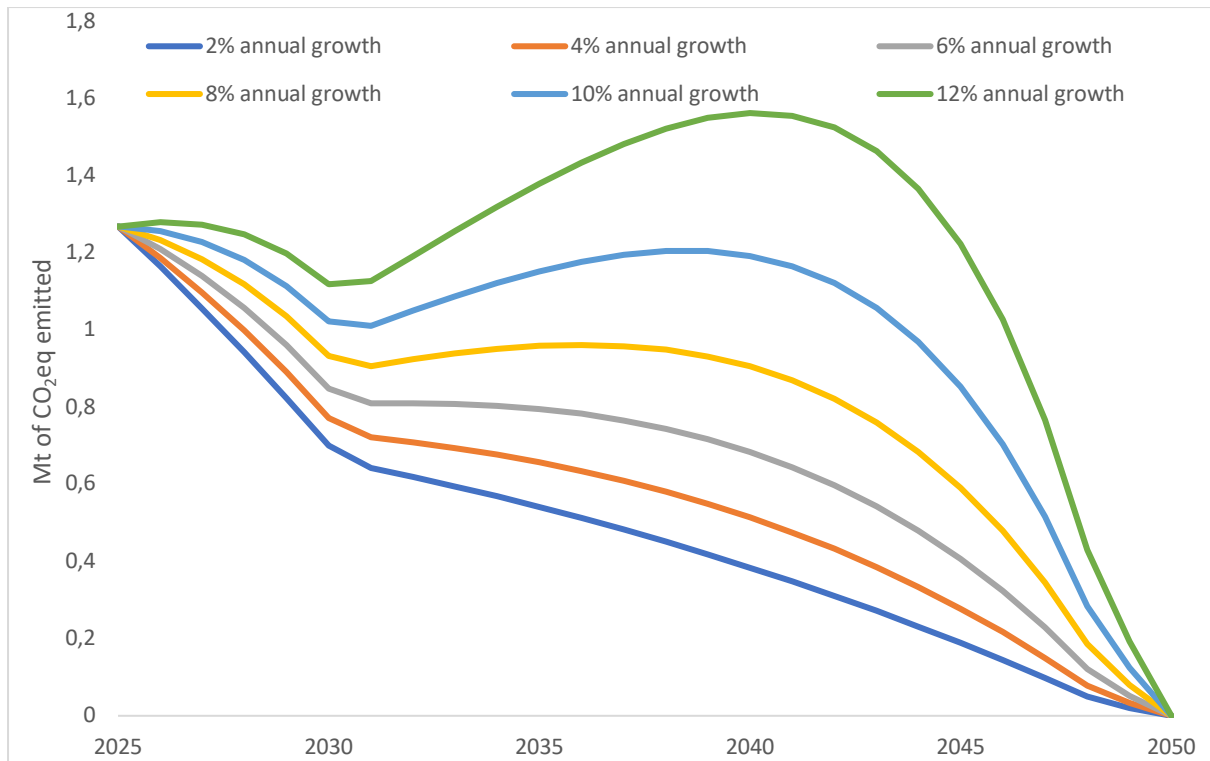


Figure 6.2.10: The life cycle carbon emissions (in Mt) for the high (0.1%) allocation scenario for silicate minerals from the construction aggregates industry.

Nonetheless, the results for the CO₂ uptake are more promising than the previously examined scenarios and suggest the great potential of CEW, and OAE in general, in the fight against climate change (**Fig. 6.2.11**). Specifically, in the high allocation scenario large quantities of CO₂ can be taken up from the atmosphere at a much faster pace with the 12% annual growth rate scenario achieving the Gt y⁻¹ scale as early as 2058. In this scenario even the 6% annual growth seems promising, suggesting that for CEW to provide tangible results in the fight against climate change large amounts of silicate minerals should be spread as soon as possible to the coastal zone to account for the relatively low dissolution rates.

Figure 6.2.12a: The life cycle carbon emissions (in Mt) for the low (0.01%) allocation scenario for silicate minerals from the construction aggregates industry.

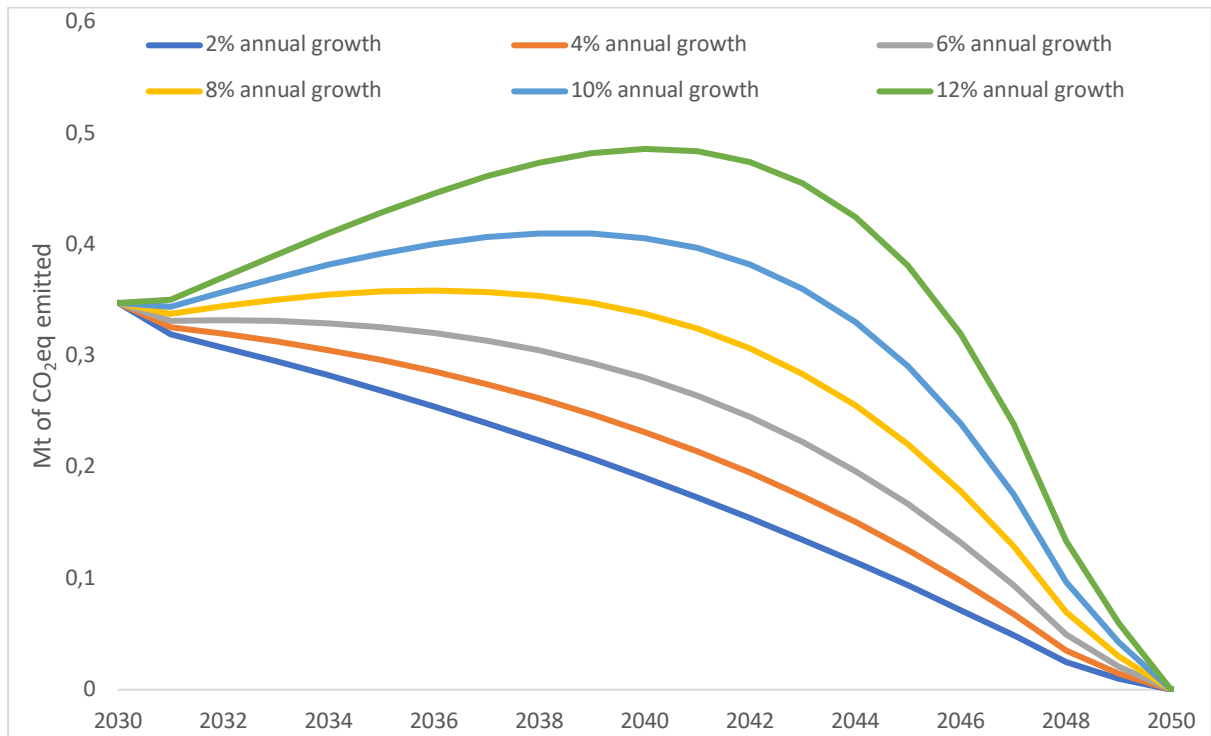


Figure 6.2.12b: The life cycle carbon emissions (in Mt) for the mean (0.05%) allocation scenario for silicate minerals from the construction aggregates industry.

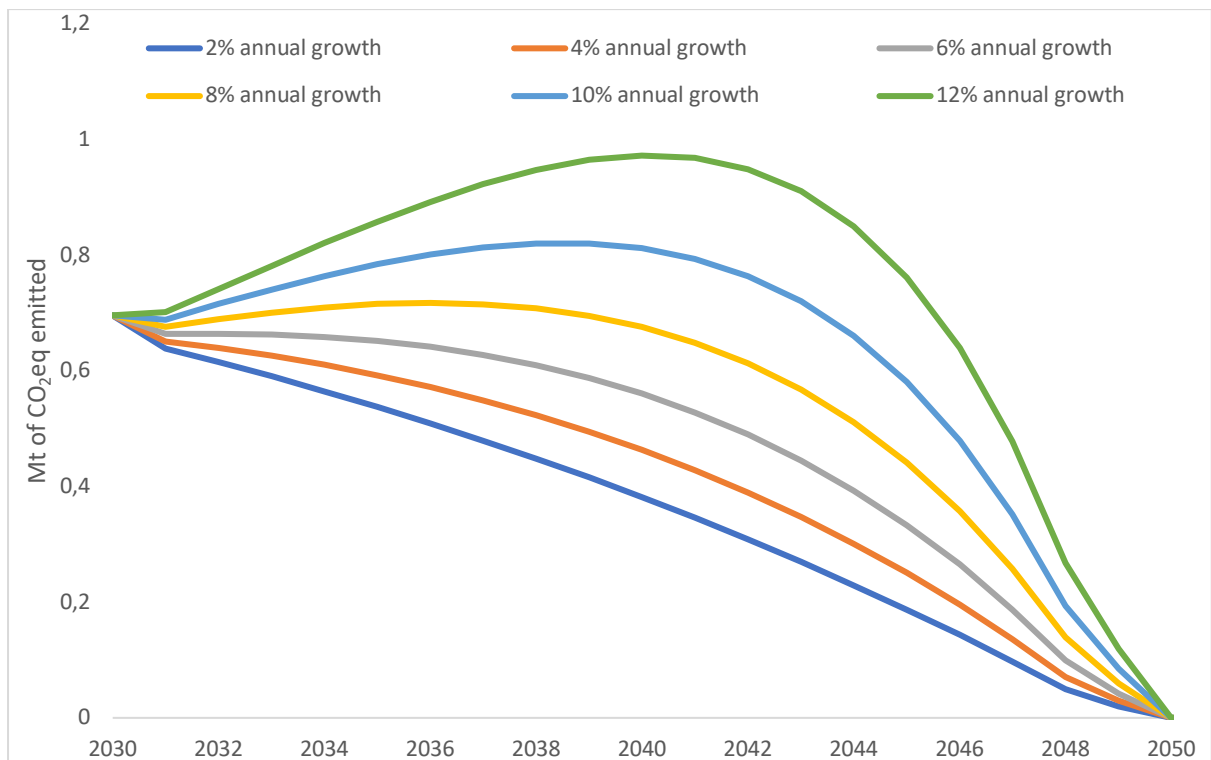


Figure 6.2.12c: The life cycle carbon emissions (in Mt) for the high (0.1%) allocation scenario for silicate minerals from the construction aggregates industry.

The results for CO₂ uptake, when using the three allocation scenarios (0.01%, 0.05%, and 0.1%) and the six annual growth rates (2%, 4%, 6%, 8%, 10%, and 12%) are shown in **Fig. 6.2.13a-c**. Similar CO₂ removal patterns were identified with the optimistic scenario (CEW application in 2025), with the 12% annual growth rate scenario achieving Gt y⁻¹ scale four years later than the optimistic scenario, i.e., in 2067 instead of 2067. The 10%, 8%, and 6% annual growth rate scenarios will achieve the Gt y⁻¹ scale in 2073, 2082, and 2098, i.e., three to four years later than the optimistic scenario.

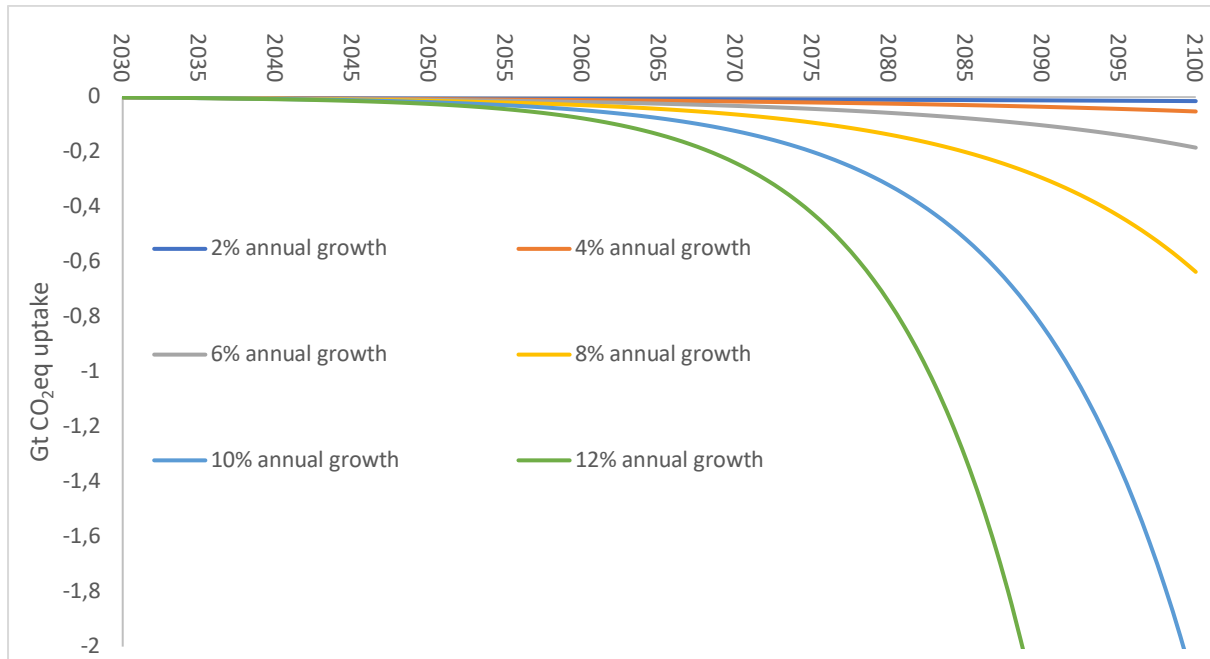


Figure 6.2.13a: The CO₂ uptake (in Gt) for the 0.01% construction aggregates allocation scenario.

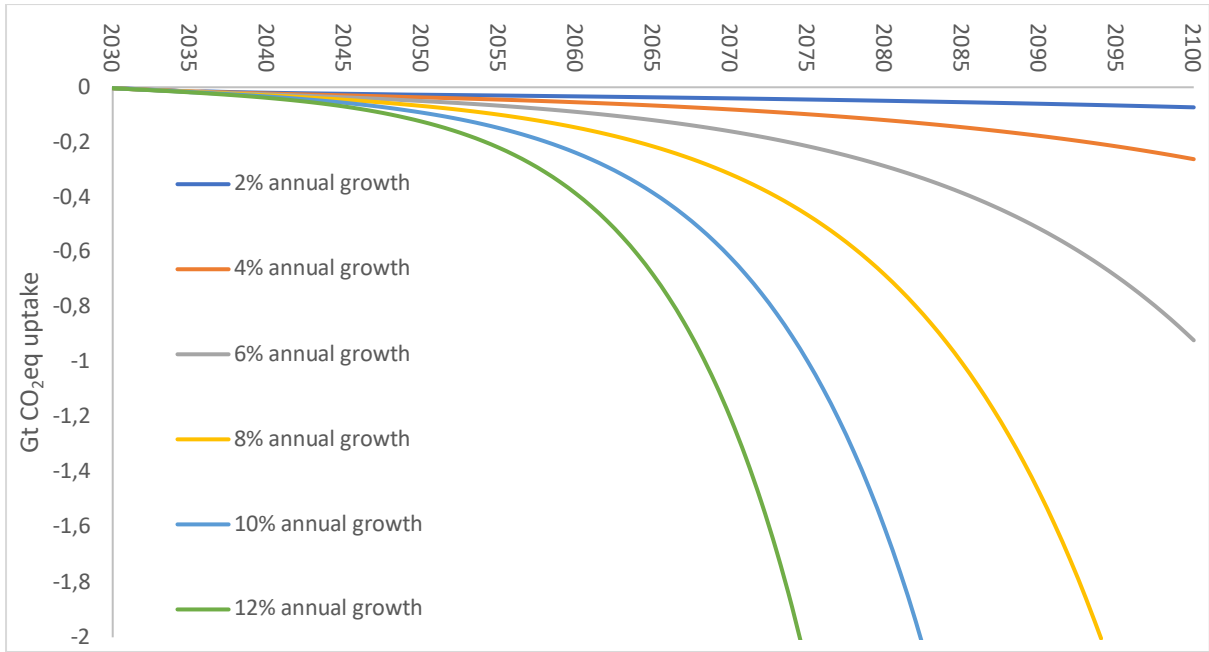


Figure 6.2.13b: The CO₂ uptake (in Gt) for the 0.05% construction aggregates allocation scenario.

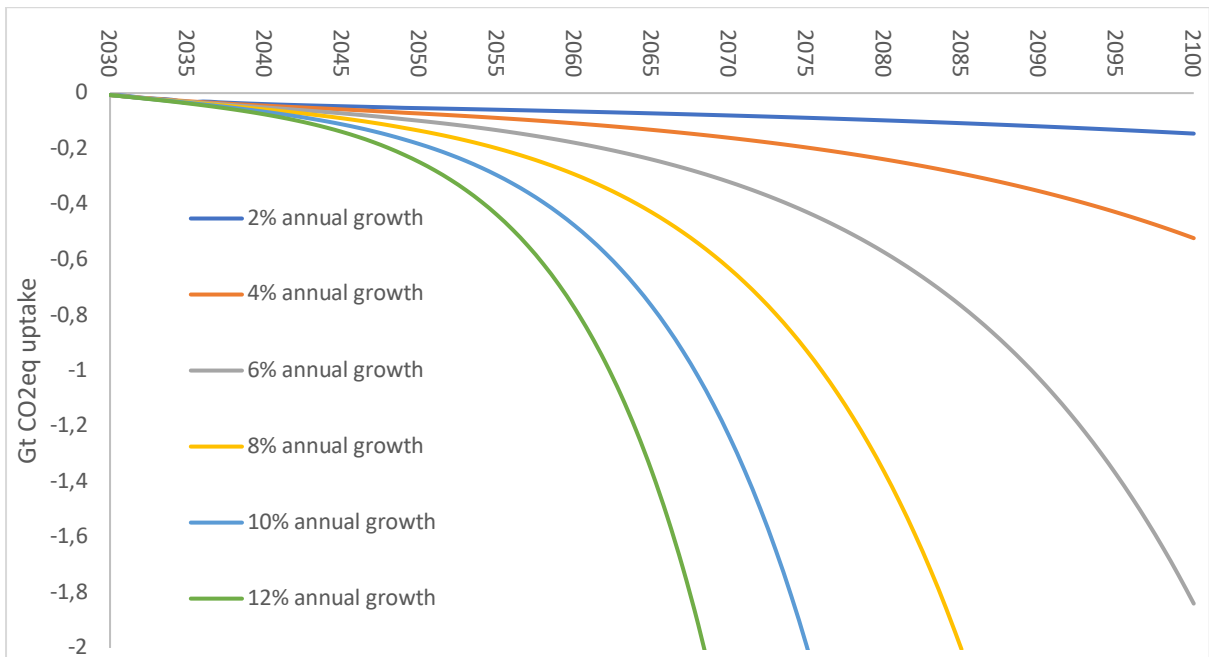


Figure 6.2.13c: The CO₂ uptake (in Gt) for the 0.1% construction aggregates allocation scenario.

6.2.6.2.3 Silicate minerals application pessimistic scenario

In the pessimistic scenario it is assumed that CEW will begin, at pilot or small-scale real-world applications, in 2035. Similar results with the ones that were discussed were obtained and these are shown in **Fig. 6.2.14** (life cycle carbon emissions) and **Fig. 6.15** (CO₂ uptake).

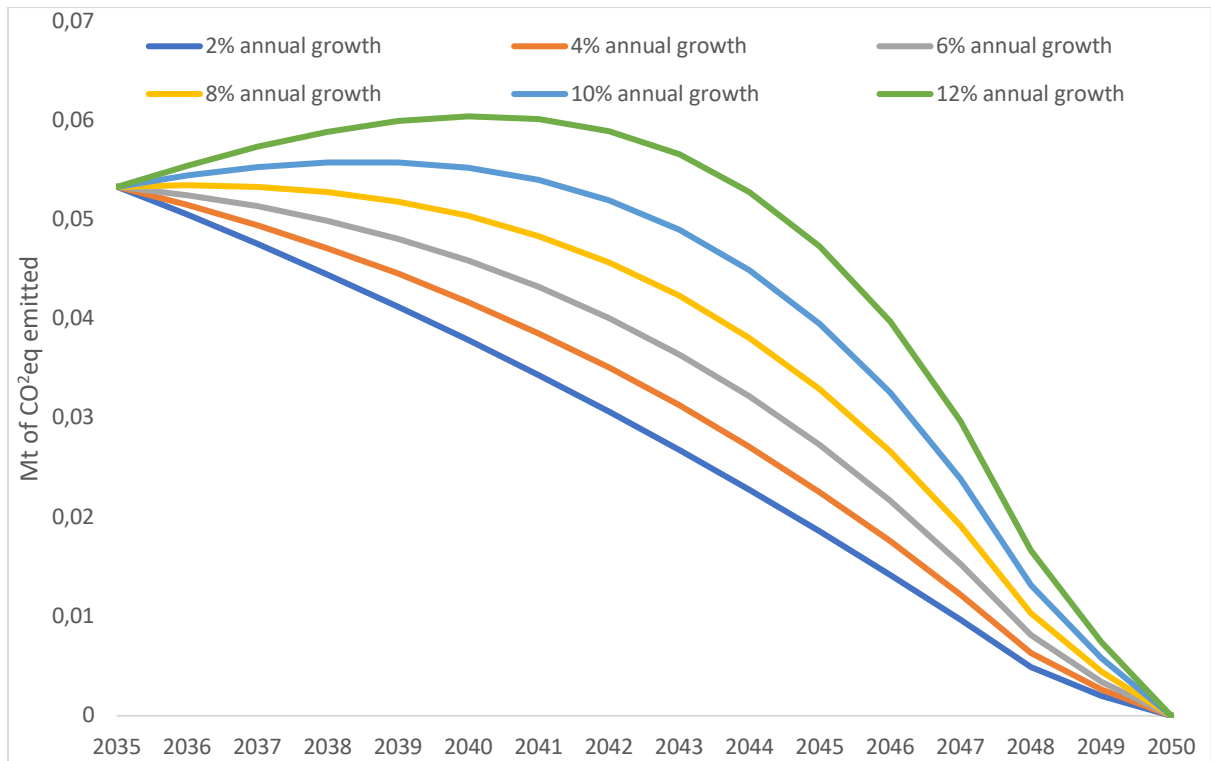


Figure 6.2.14a: The life cycle carbon emissions (in Mt) for the low (0.01%) allocation scenario for silicate minerals from the construction aggregates industry.

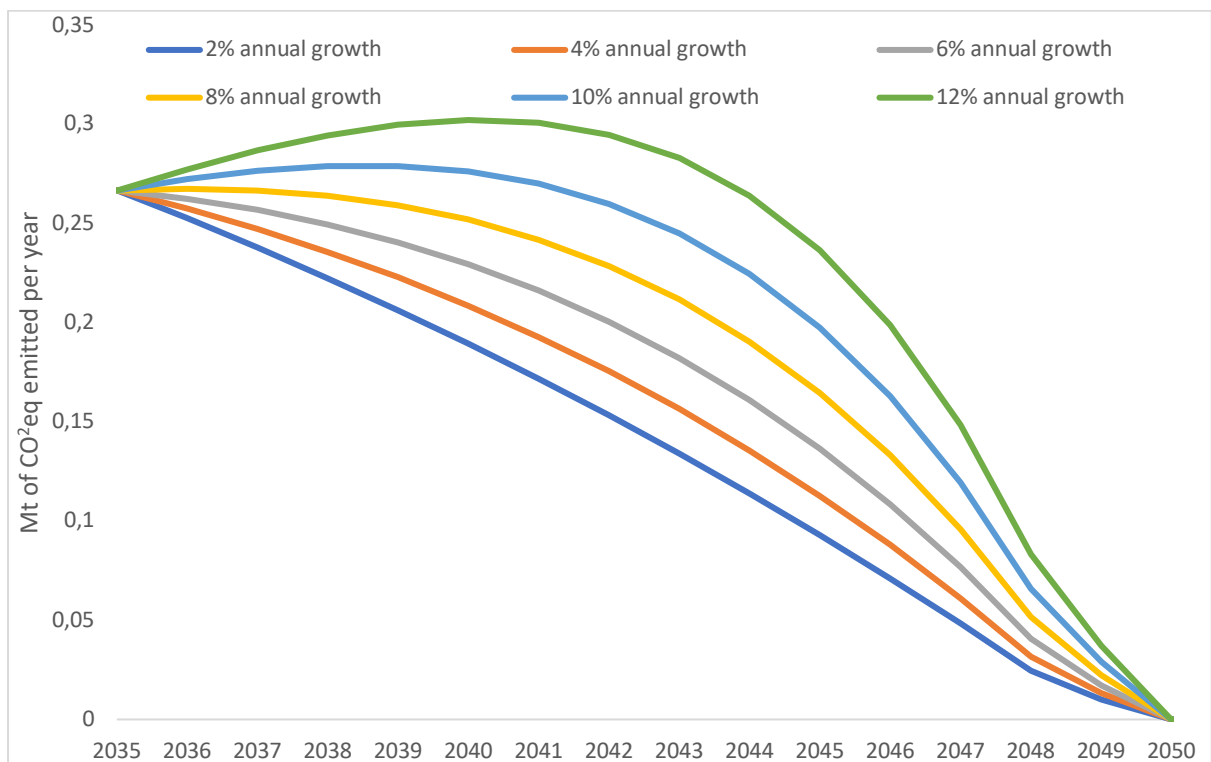


Figure 6.2.14b: The life cycle carbon emissions (in Mt) for the mean (0.05%) allocation scenario for silicate minerals from the construction aggregates industry.

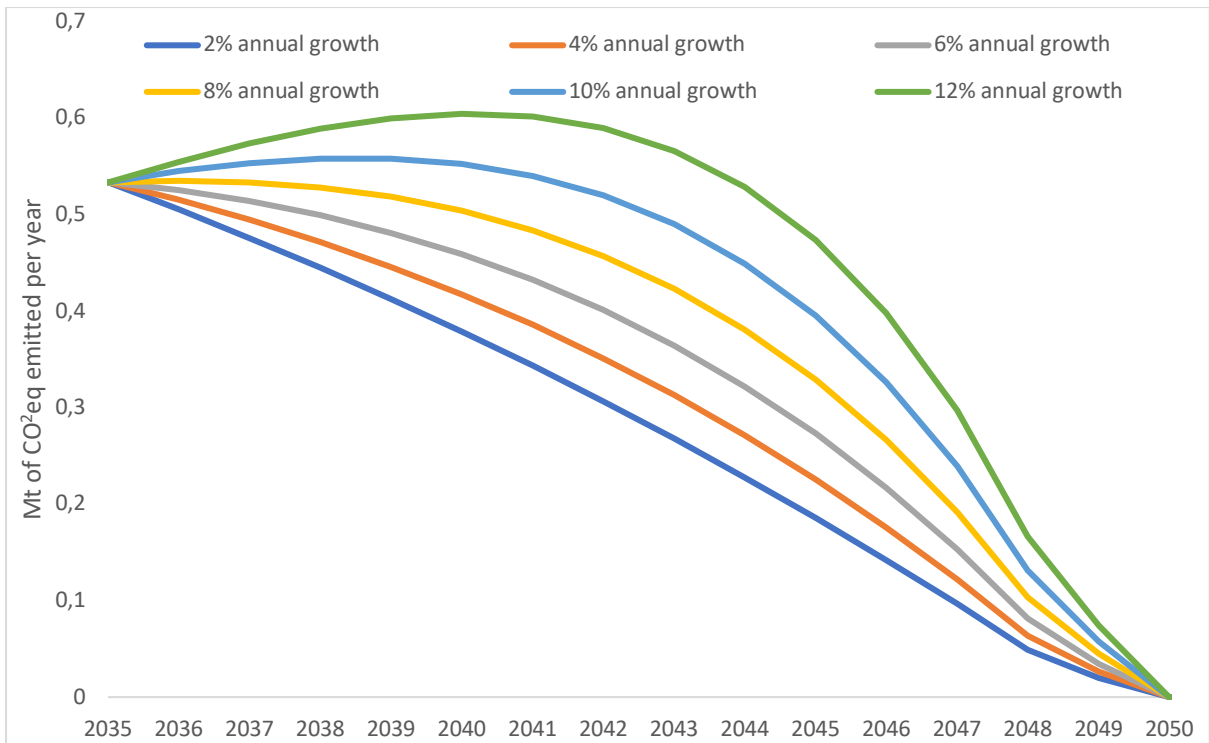


Figure 6.2.14c: The life cycle carbon emissions (in Mt) for the high (0.1%) allocation scenario for silicate minerals from the construction aggregates industry.

The results for CO₂ uptake (**Fig. 6.2.15**) suggest that Gt y⁻¹ will be achieved much latter than the previously examined scenarios.

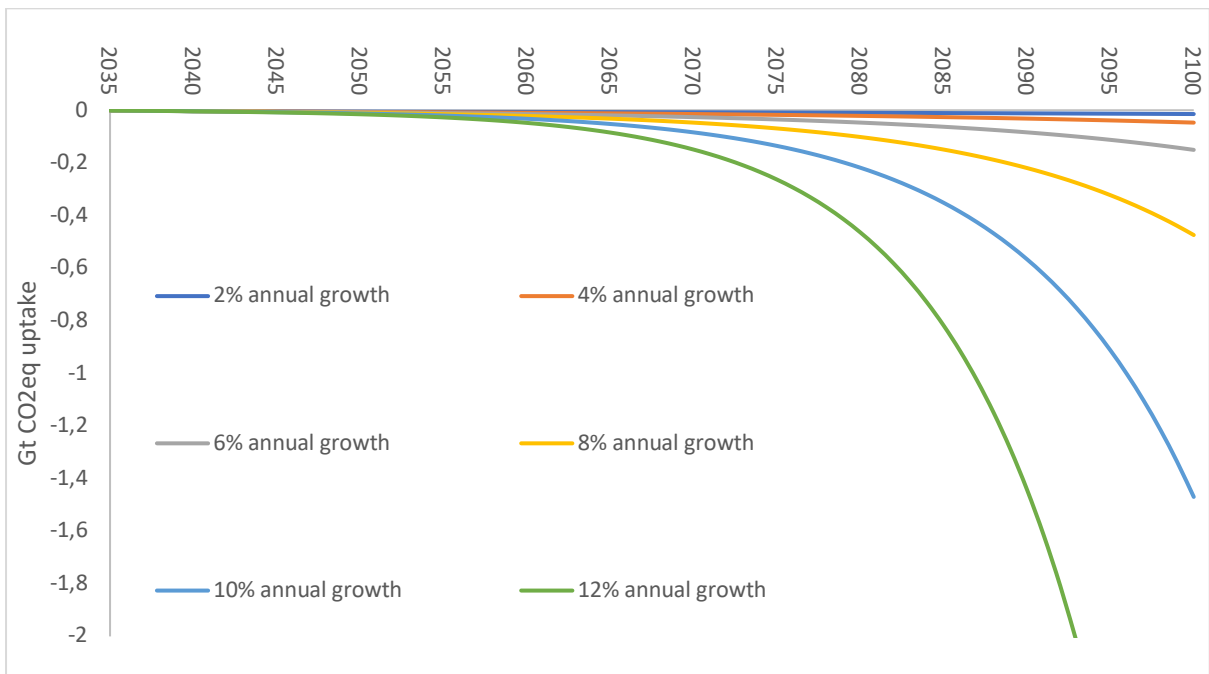


Figure 6.2.15a: The CO₂ uptake (in Gt) for the 0.01% construction aggregates allocation scenario.

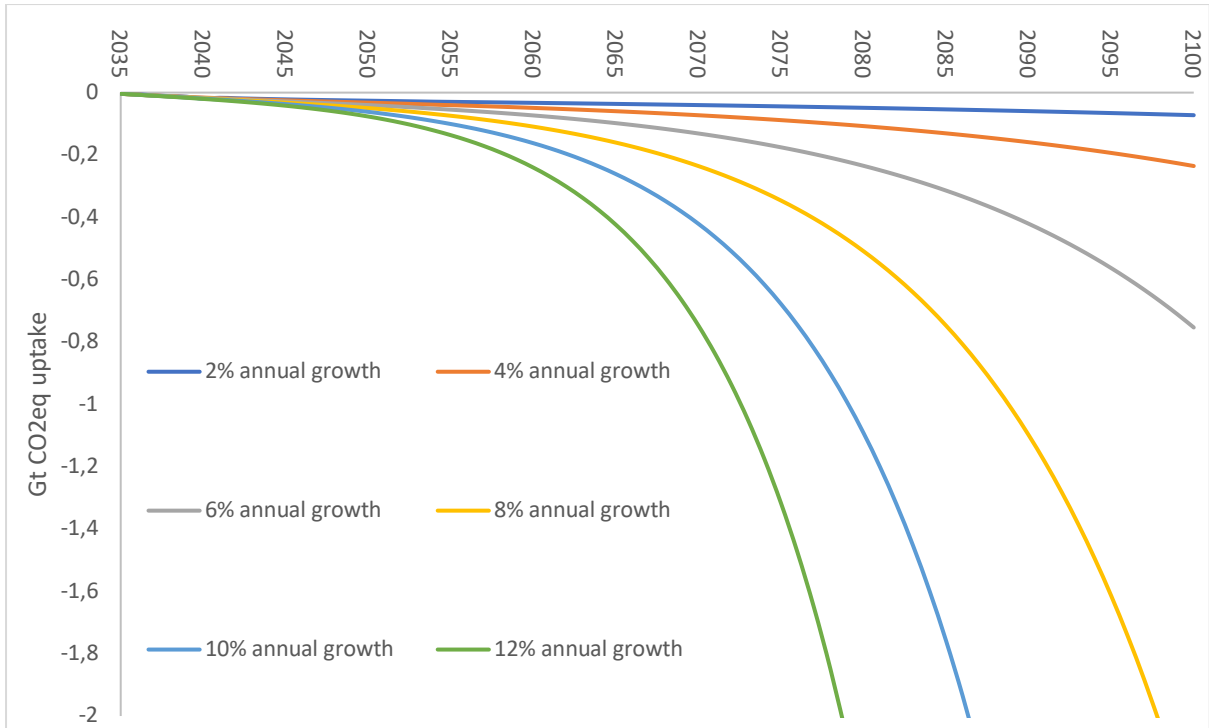


Figure 6.2.15b: The CO₂ uptake (in Gt) for the 0.05% construction aggregates allocation scenario.

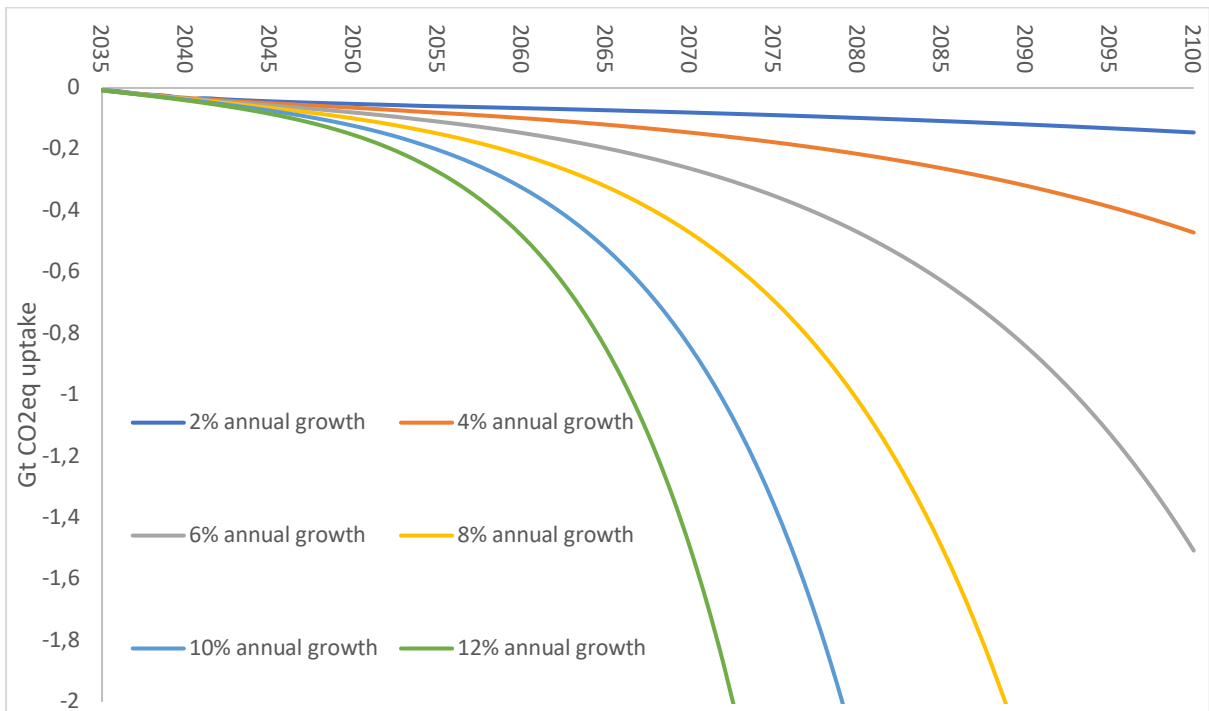


Figure 6.2.15c: The CO₂ uptake (in Gt) for the 0.1% construction aggregates allocation scenario.

6.2.6.3 Silicate minerals application using electrochemistry

As mentioned above, in order to avoid the slow dissolution of silicate minerals in CEW, electrochemical pathways can be used for removing acidity from the oceans and neutralise it

using silicate minerals, in this case olivine. Focus is not given on the life cycle carbon emissions of the process but only on alkalinity addition and by extension atmospheric CO₂ removal. The main difference with CEW is that CO₂ is taken up from the atmosphere within a year after spreading, as is the assumption for OL and therefore results differ.

In Fig. 6.2.16a-ig the results for all examined scenarios are shown.

6.2.6.3.1 Optimistic scenario

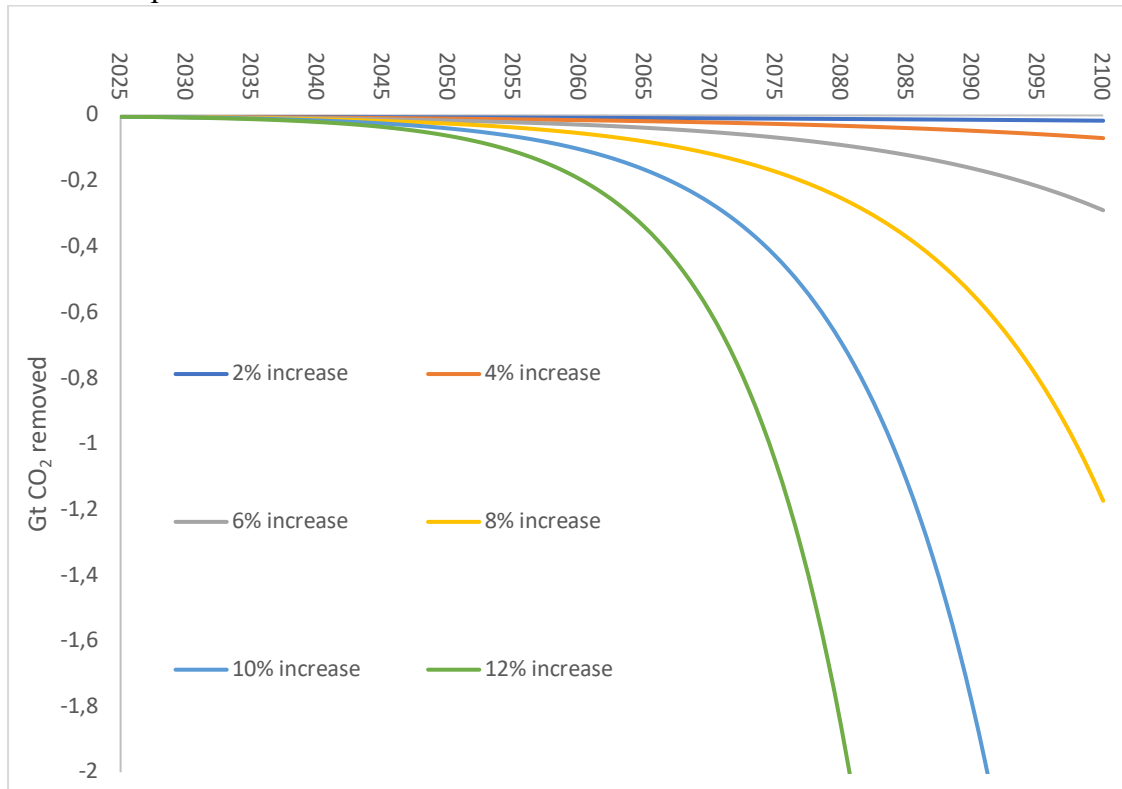


Figure 6.2.16a: The CO₂ uptake (in Gt) for the 0.01% construction aggregates allocation scenario.

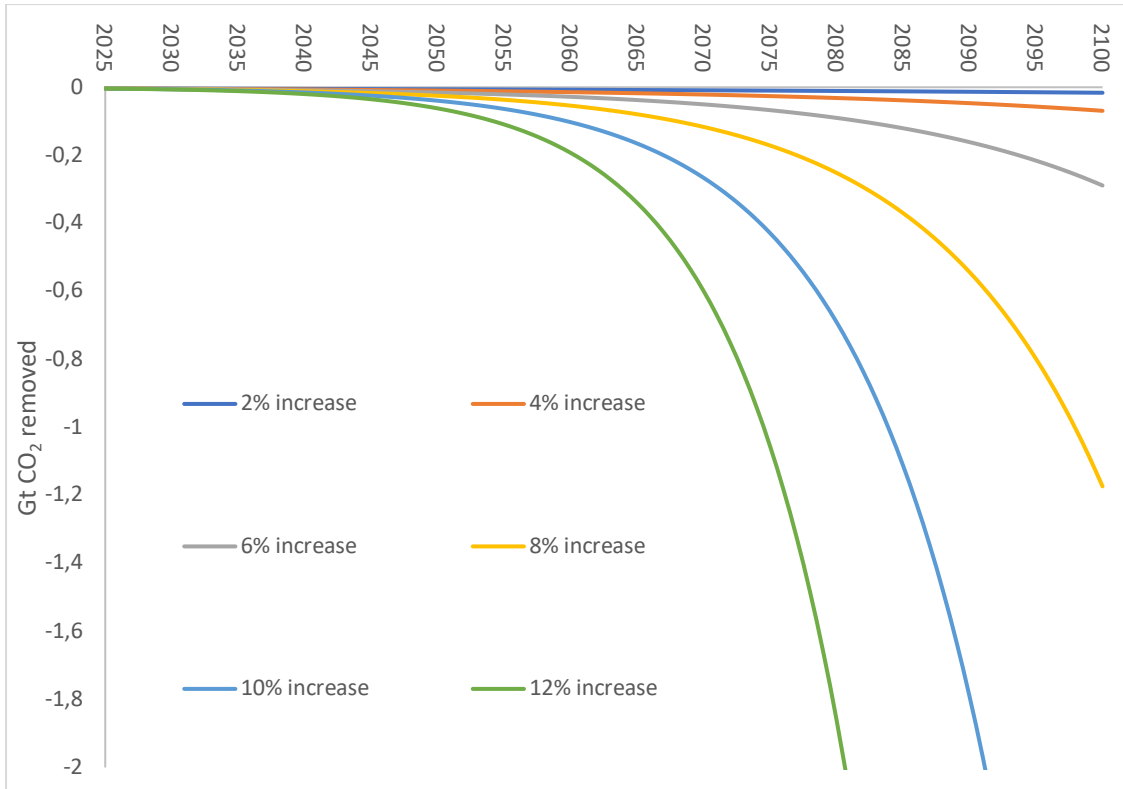


Figure 6.2.16b: The CO₂ uptake (in Gt) for the 0.05% construction aggregates allocation scenario.

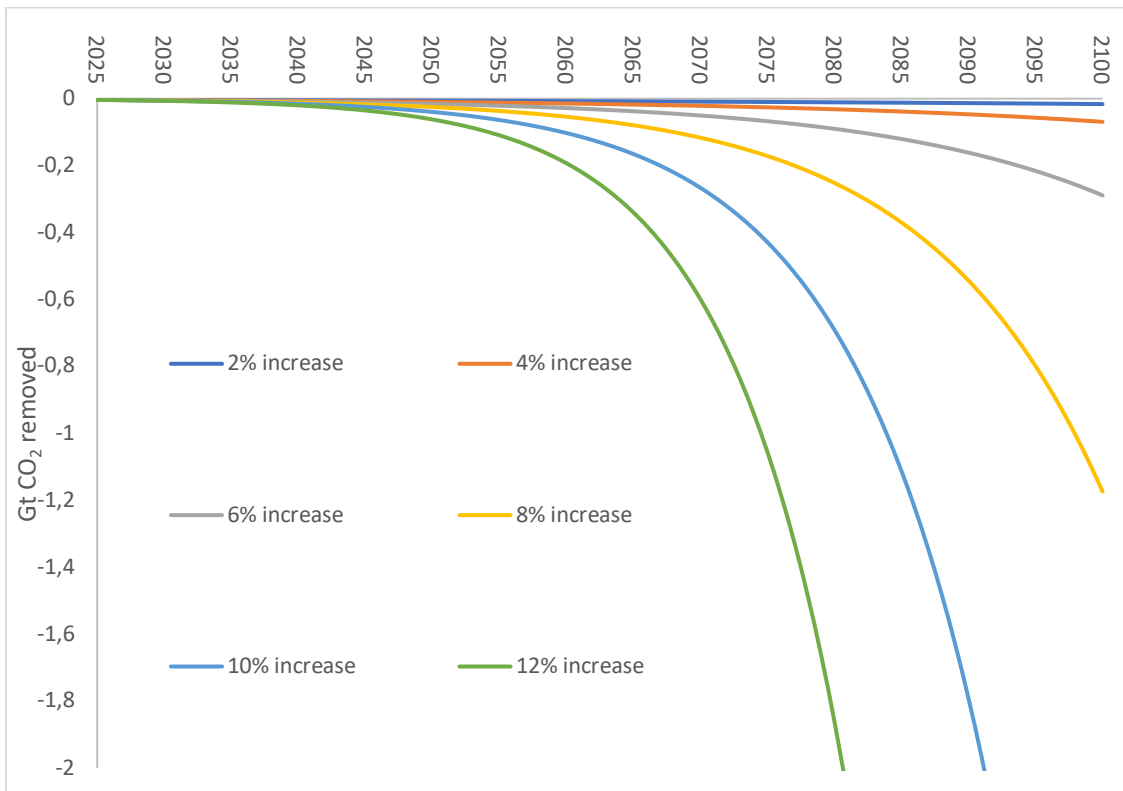


Figure 6.2.16c: The CO₂ uptake (in Gt) for the 0.1% construction aggregates allocation scenario.

6.2.6.3.2 Mean scenario

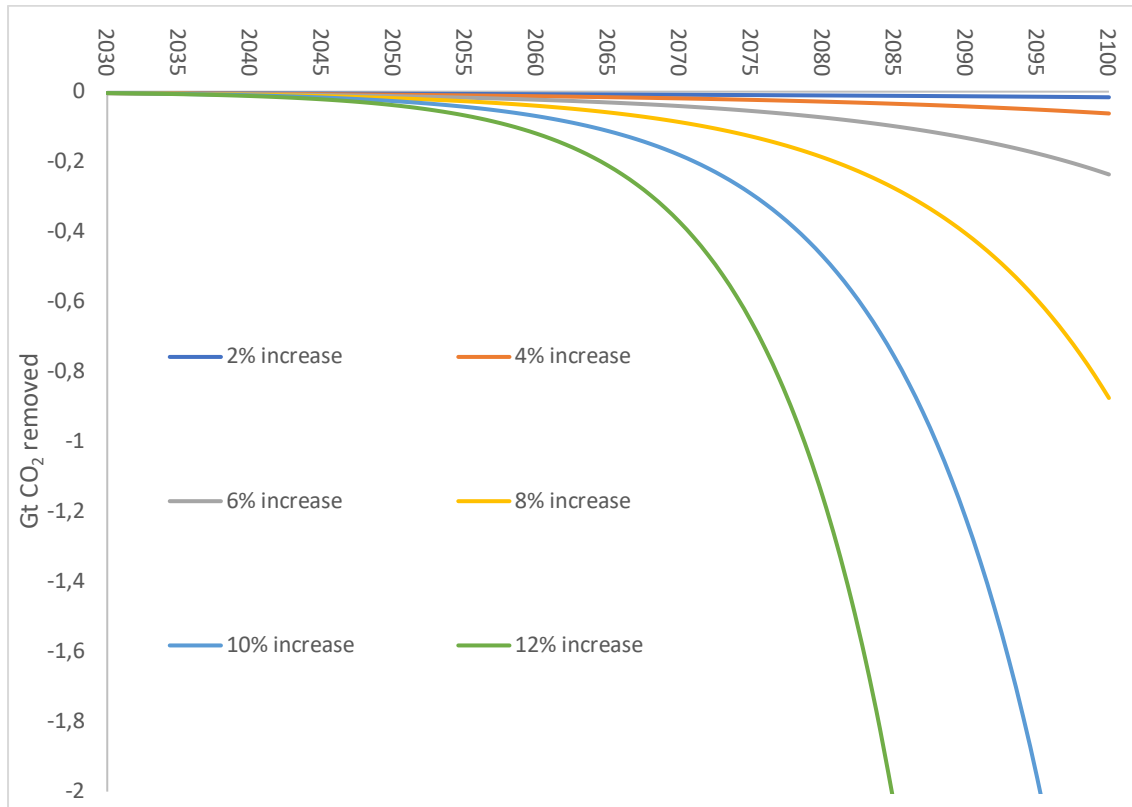


Figure 6.2.15d: The CO₂ uptake (in Gt) for the 0.01% construction aggregates allocation scenario.

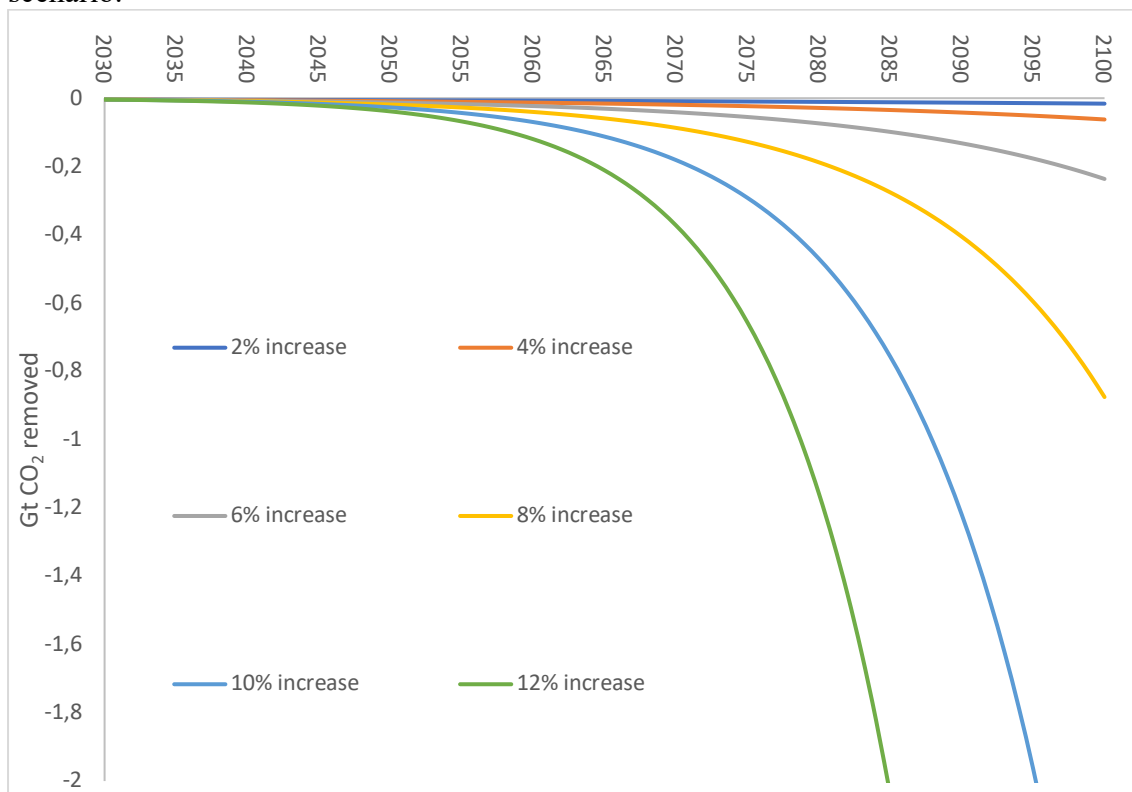


Figure 6.2.15e: The CO₂ uptake (in Gt) for the 0.05% construction aggregates allocation scenario.

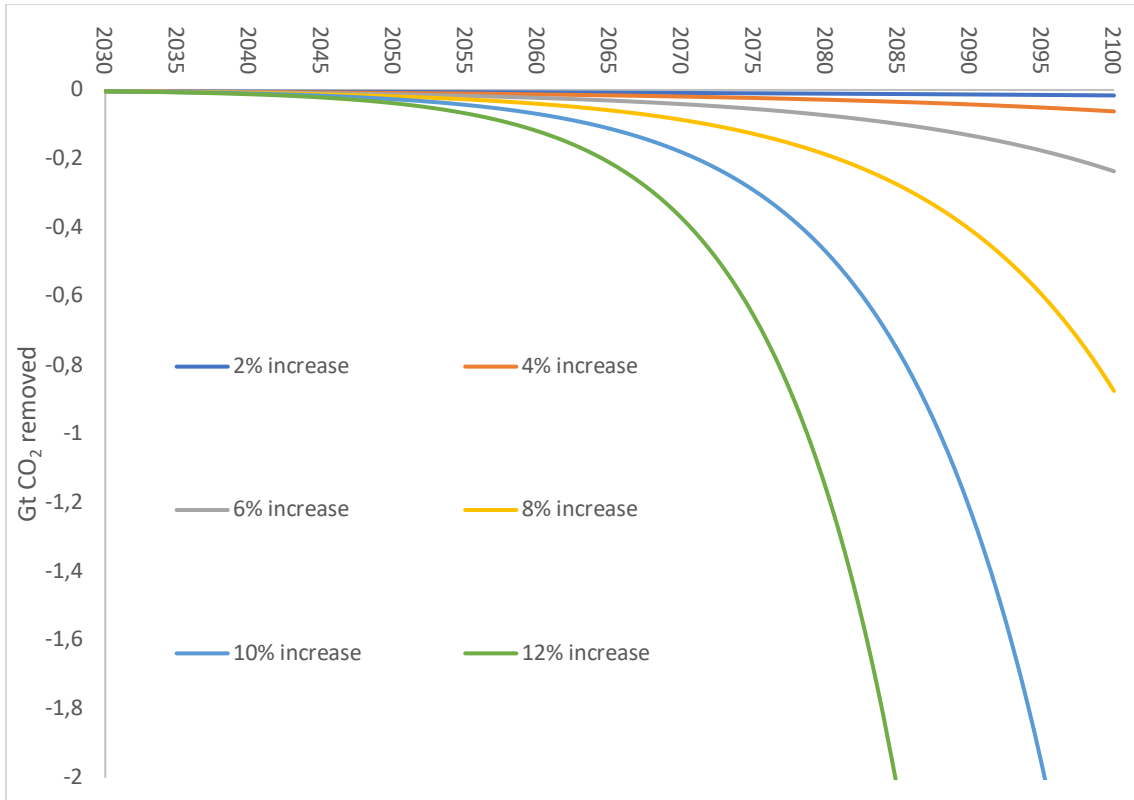


Figure 6.2.15f: The CO₂ uptake (in Gt) for the 0.1% construction aggregates allocation scenario.

6.2.6.3.1 Pessimistic scenario

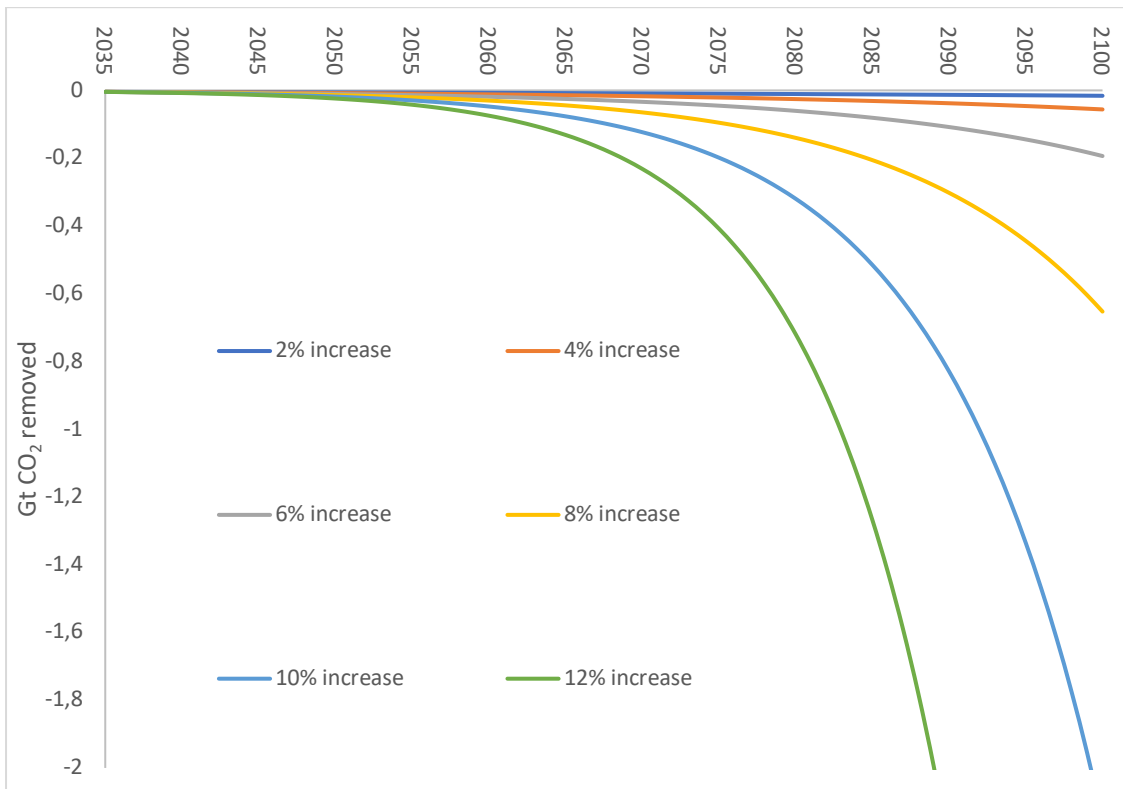


Figure 6.2.15g: The CO₂ uptake (in Gt) for the 0.01% construction aggregates allocation scenario.

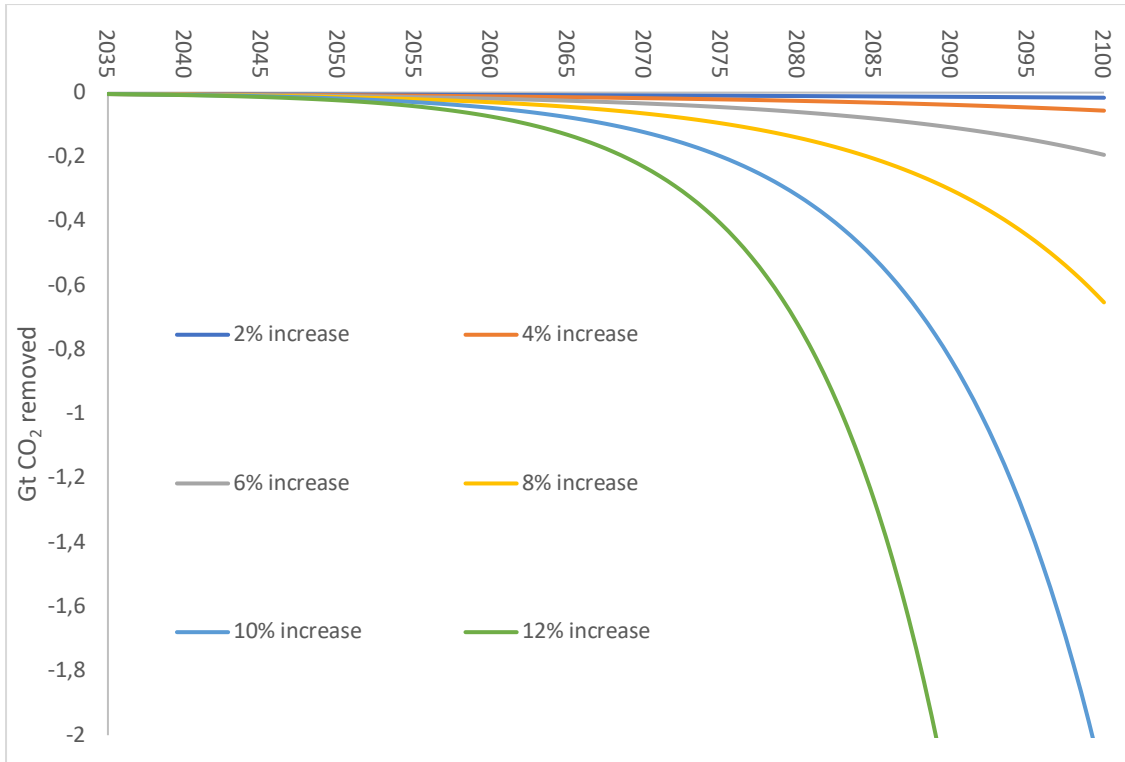


Figure 6.2.15h: The CO₂ uptake (in Gt) for the 0.05% construction aggregates allocation scenario.

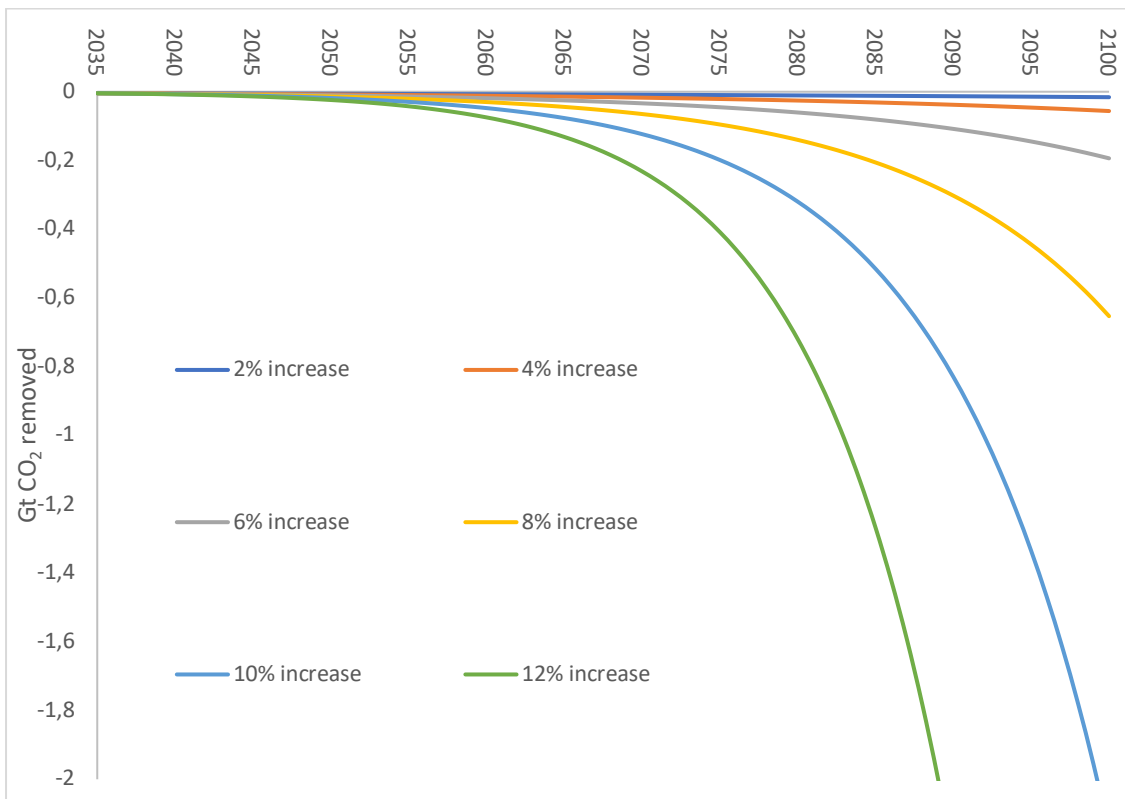


Figure 6.2.15i: The CO₂ uptake (in Gt) for the 0.1% construction aggregates allocation scenario.

6.2.6.4 Carbonate minerals application

As with the silicate minerals scenarios, three different allocation scenarios from the construction aggregates industry were considered for carbonate minerals (OL), i.e., the low (0.01% of the carbonate output is allocated to OL), mean (0.05%), and a high (0.1%), considering the six annual growth rate scenarios, i.e., 2%, 4%, 6%, 8%, 10%, and 12%. However, the main difference with the addition of silicate minerals when using CEW pertains to the rapid dissolution of activated carbon minerals (CaO and/or Ca(OH)_2) in seawater. Therefore, the removal of atmospheric CO_2 will take place shortly after their dissolution and here it is assumed that CO_2 will be captured within a year after their spreading to surface ocean water.

6.2.6.4.1 Carbonate minerals application optimistic scenario

Again, the optimistic scenario assumes that the application of OAE is adopted as early as 2025, with the only downside of early adoption being the increased life cycle carbon emissions. However, the main carbon hotspot in the life cycle of OL was identified in our preliminary LCA as the heat input for limestone calcination. In the context of this report, we assumed that the carbon penalty for OL in 2025 is 40%, i.e., 400 kg are emitted per t of captured CO_2 , and this penalty will cease to be implemented in 2050, as in the case of CEW, since the process is assumed to have been decarbonised by then.

Results for the life cycle carbon emissions are shown in **Fig. 6.2.17a-c** and for the CO_2 uptake in **Fig. 6.2.18a-c**. It is observed that the life cycle carbon emissions are on the rise up until 2042 for the 6% growth scenarios and above, suggesting that in these scenarios the annual increase in the minerals output is greater than the annual decrease in the carbon penalty of the process. However, after 2042 the process has been greatly decarbonised and therefore the life cycle emissions begin to decrease up until 2050 when they are zero (**Fig. 6.2.17a-c**).

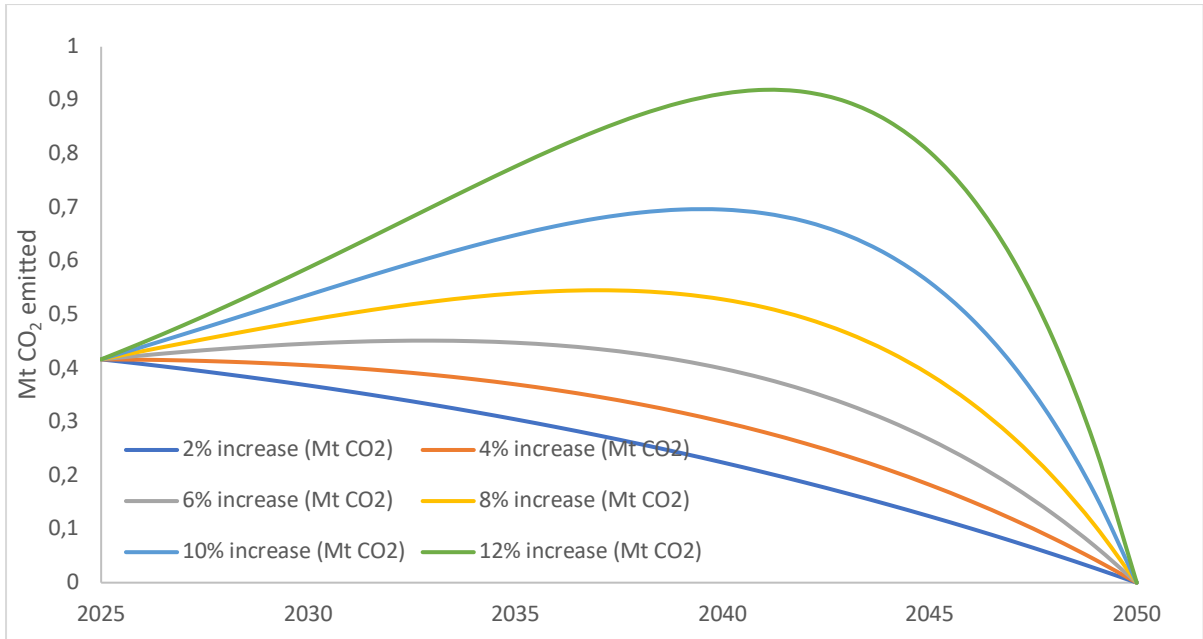


Figure 6.2.17a: The life cycle carbon emissions (in Mt) for the low (0.01%) allocation scenario for carbonate minerals from the construction aggregates industry.

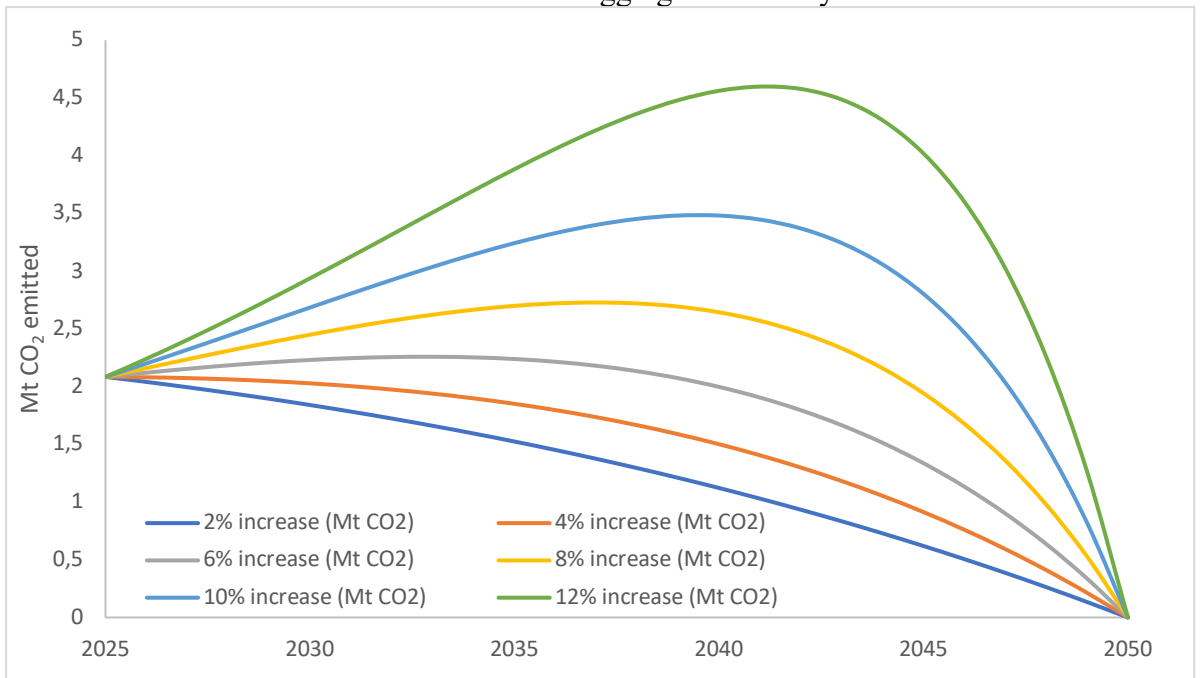


Figure 6.2.17b: The life cycle carbon emissions (in Mt) for the mean (0.05%) allocation scenario for carbonate minerals from the construction aggregates industry.

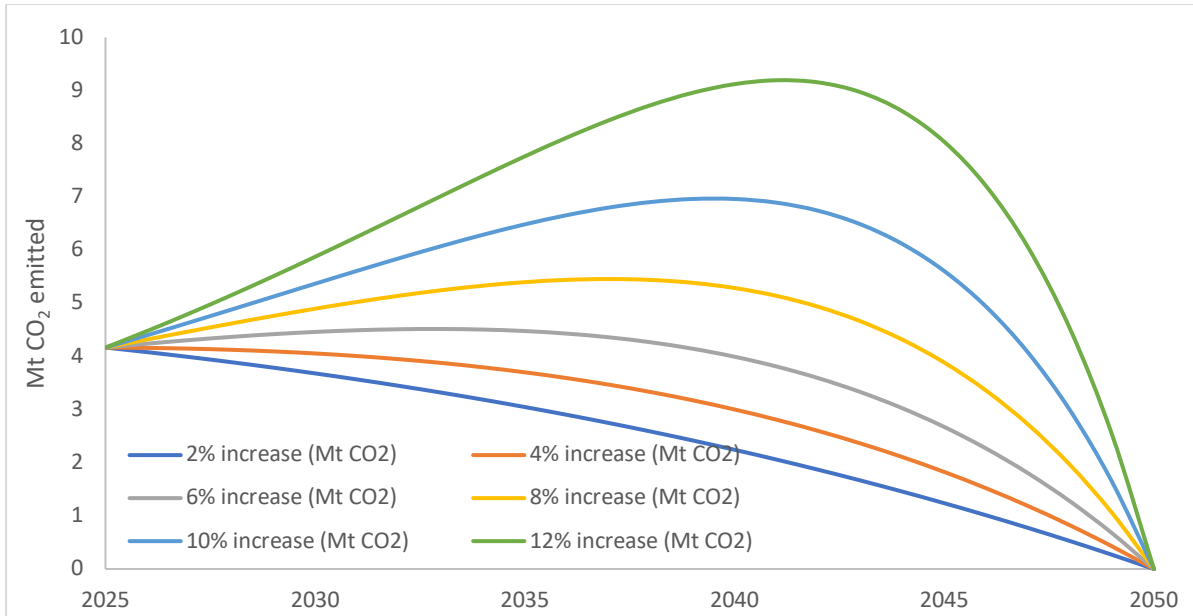


Figure 6.2.17c: The life cycle carbon emissions (in Mt) for the high (0.1%) allocation scenario for carbonate minerals from the construction aggregates industry.

Regarding the CO₂ uptake the results are similar to the ones for the electrochemical pathways for silicate minerals, since in both scenarios alkalinity is assumed to be readily available. The only difference is that in the silicate minerals electrochemical pathways larger quantities are used, which also have a higher alkalinity potential but the observed patterns in CO₂ removal are similar.

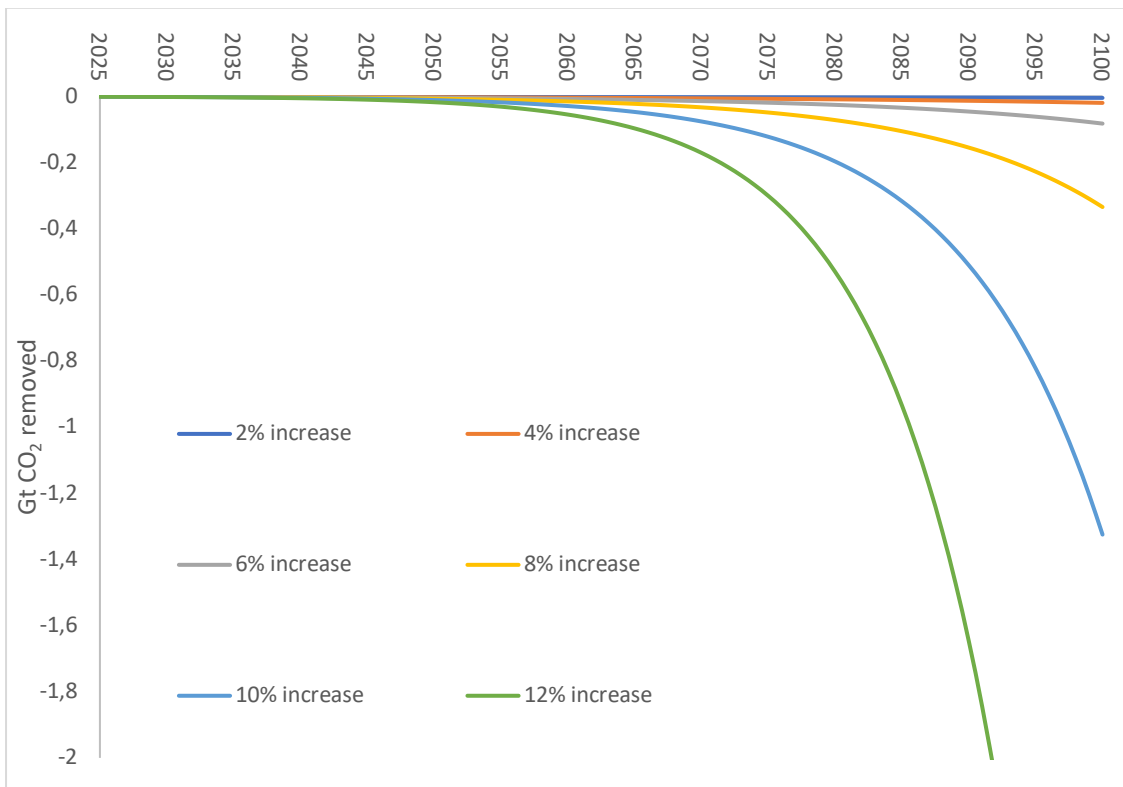


Figure 6.2.18a: The CO₂ uptake (in Gt) for the 0.01% construction aggregates allocation scenario.

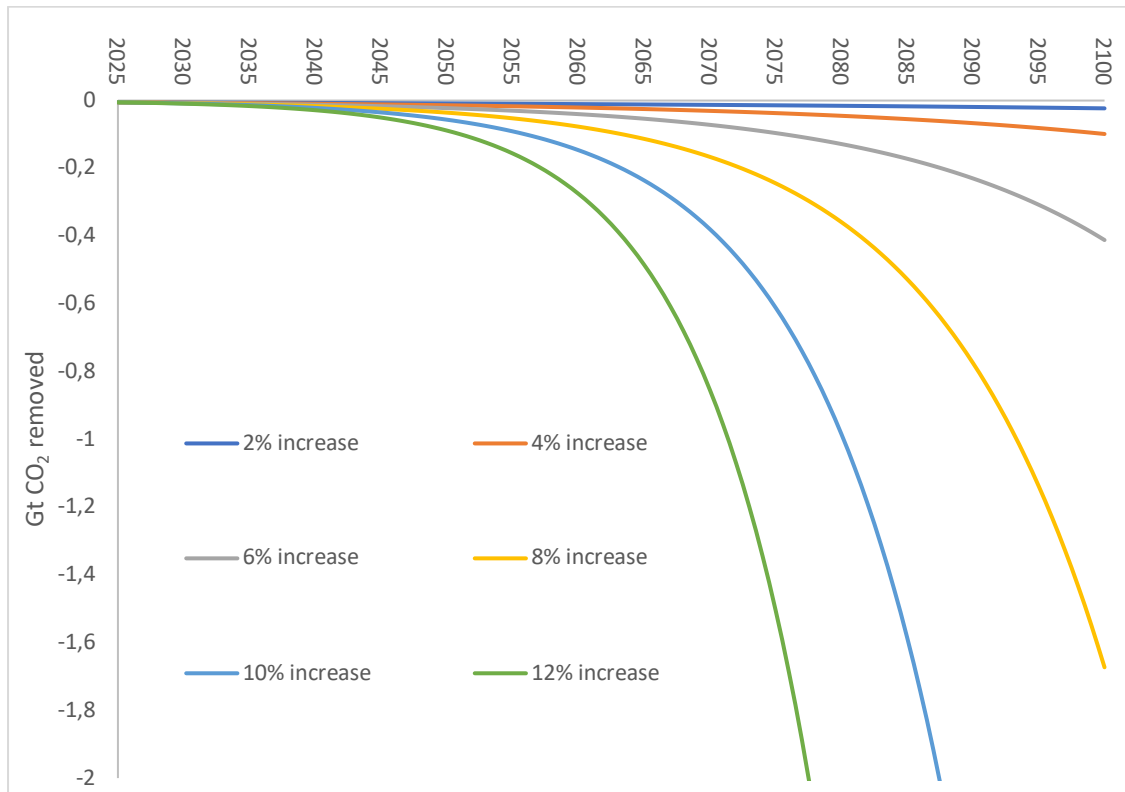


Figure 6.2.18b: The CO₂ uptake (in Gt) for the 0.05% construction aggregates allocation scenario.

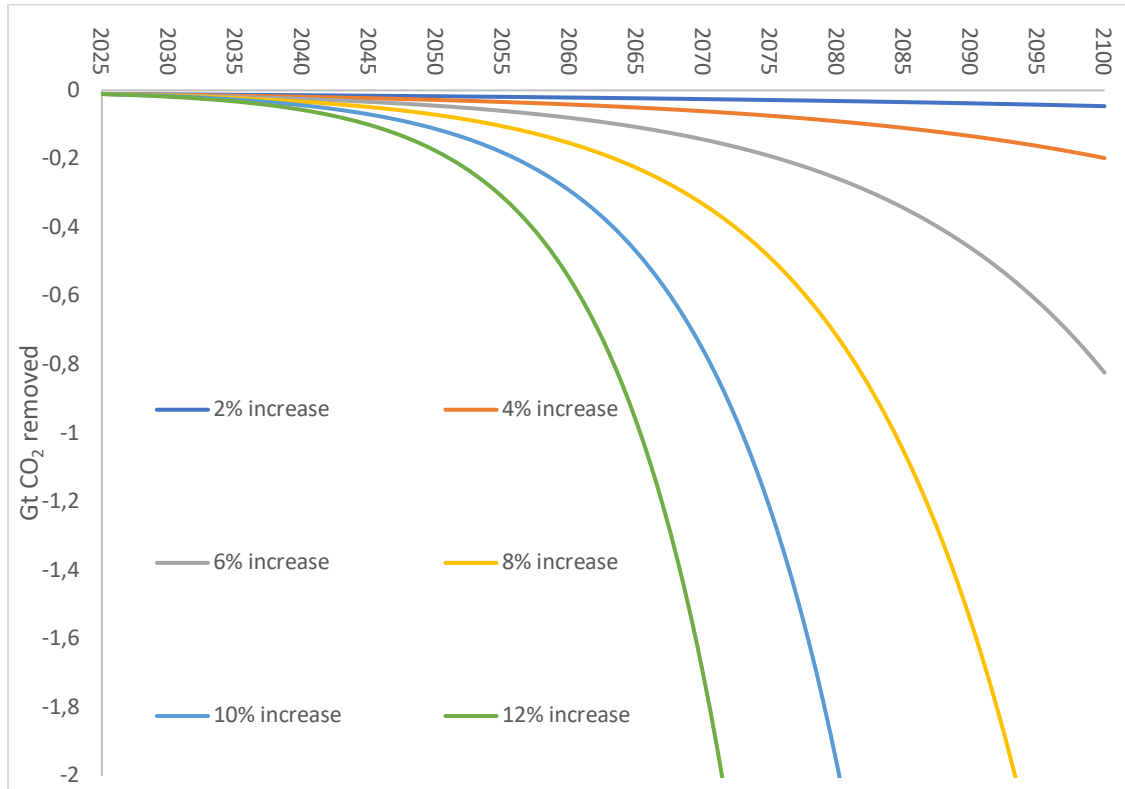


Figure 6.2.18c: The CO₂ uptake (in Gt) for the 0.1% construction aggregates allocation scenario.

6.2.6.4.2 Carbonate minerals application mean scenario

As expected, the same patterns were identified in both the mean and the pessimistic scenarios and results are shown below.

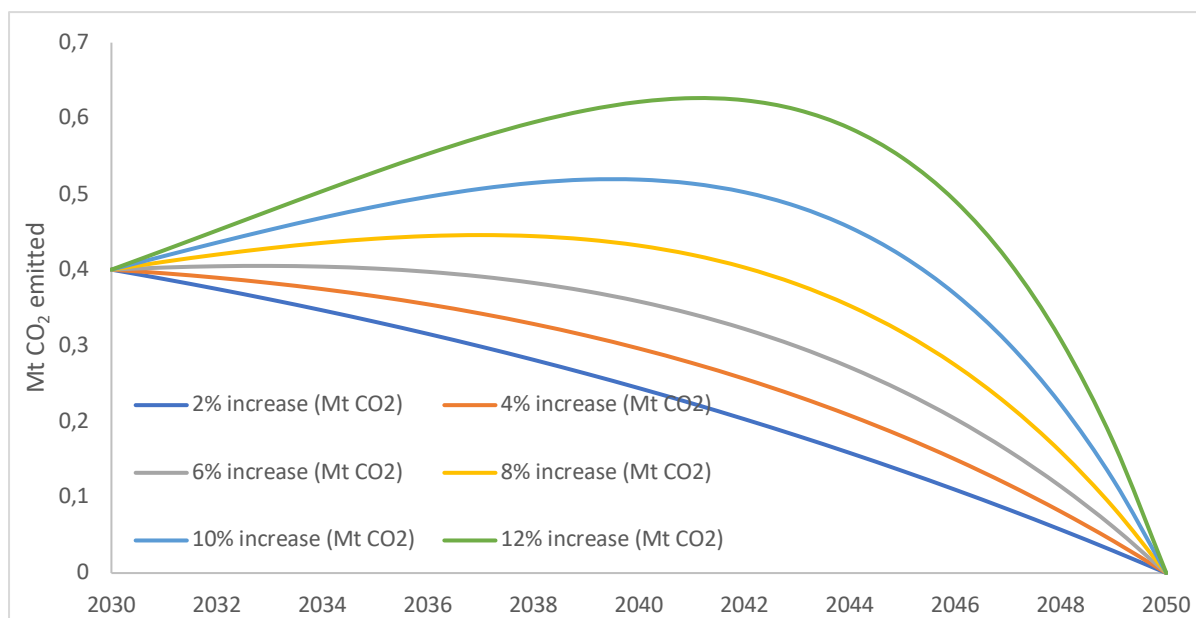


Figure 6.2.19a: The life cycle carbon emissions (in Mt) for the low (0.01%) allocation scenario for carbonate minerals from the construction aggregates industry.

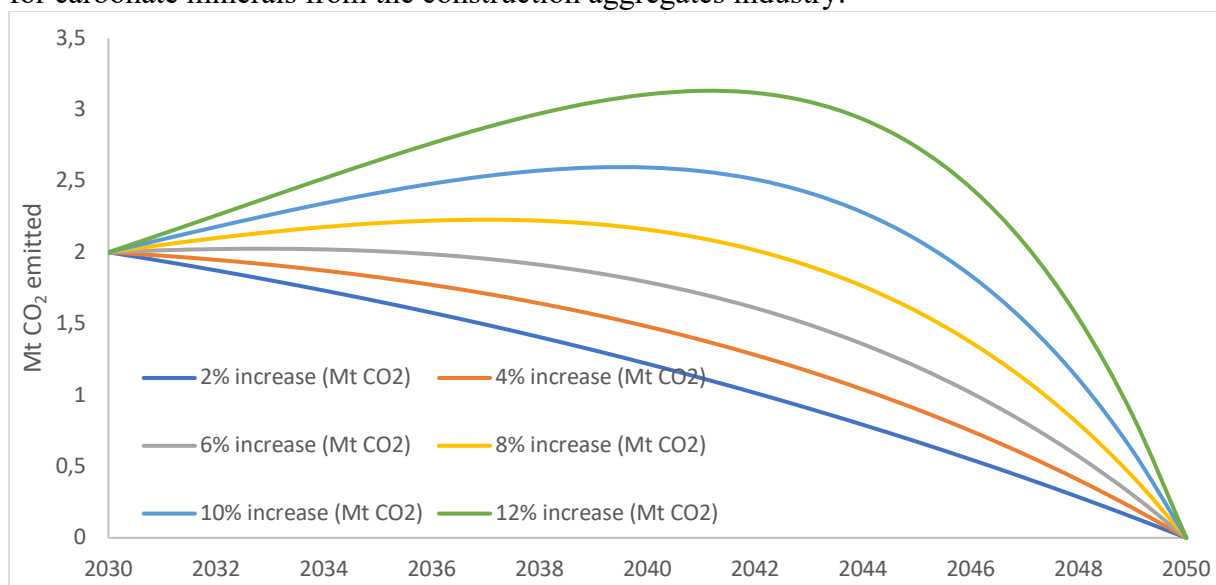


Figure 6.2.19b: The life cycle carbon emissions (in Mt) for the mean (0.05%) allocation scenario for carbonate minerals from the construction aggregates industry.

Figure 6.2.19c: The life cycle carbon emissions (in Mt) for the high (0.1%) allocation scenario for carbonate minerals from the construction aggregates industry.

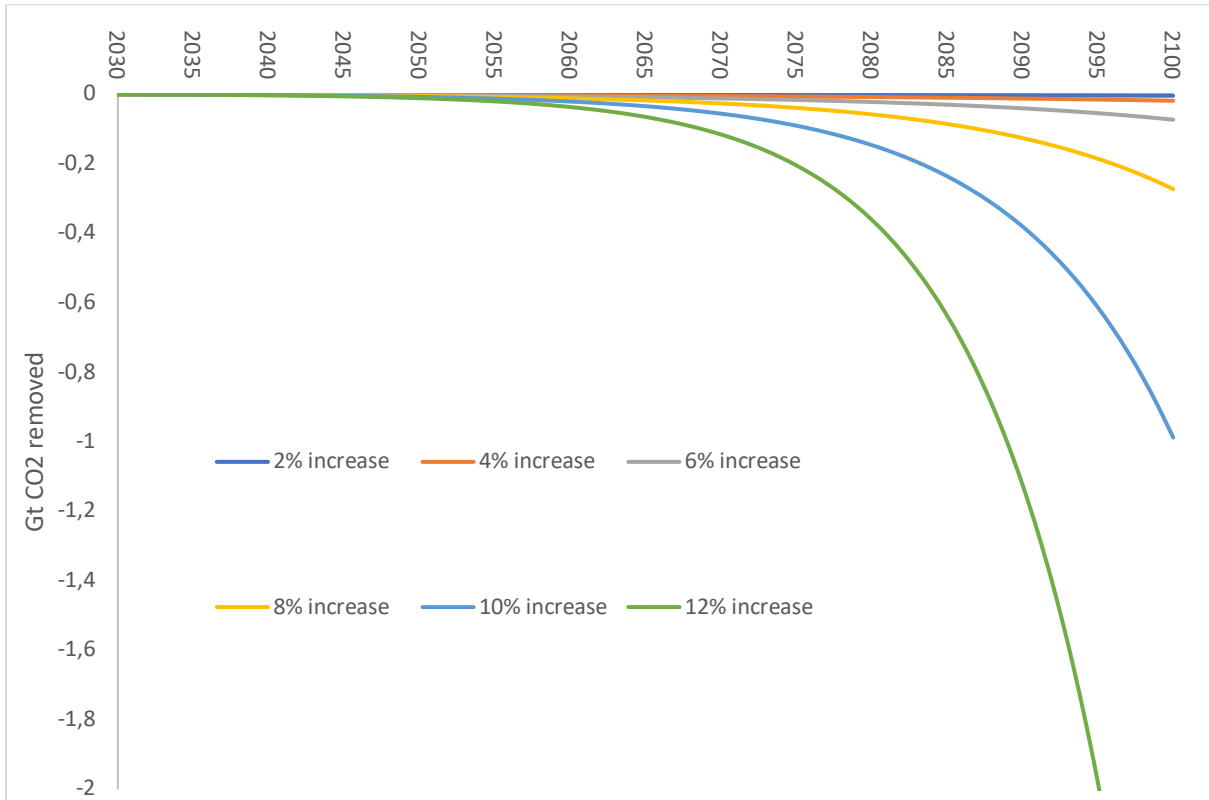


Figure 6.2.20a: The CO₂ uptake (in Gt) for the 0.01% construction aggregates allocation scenario.

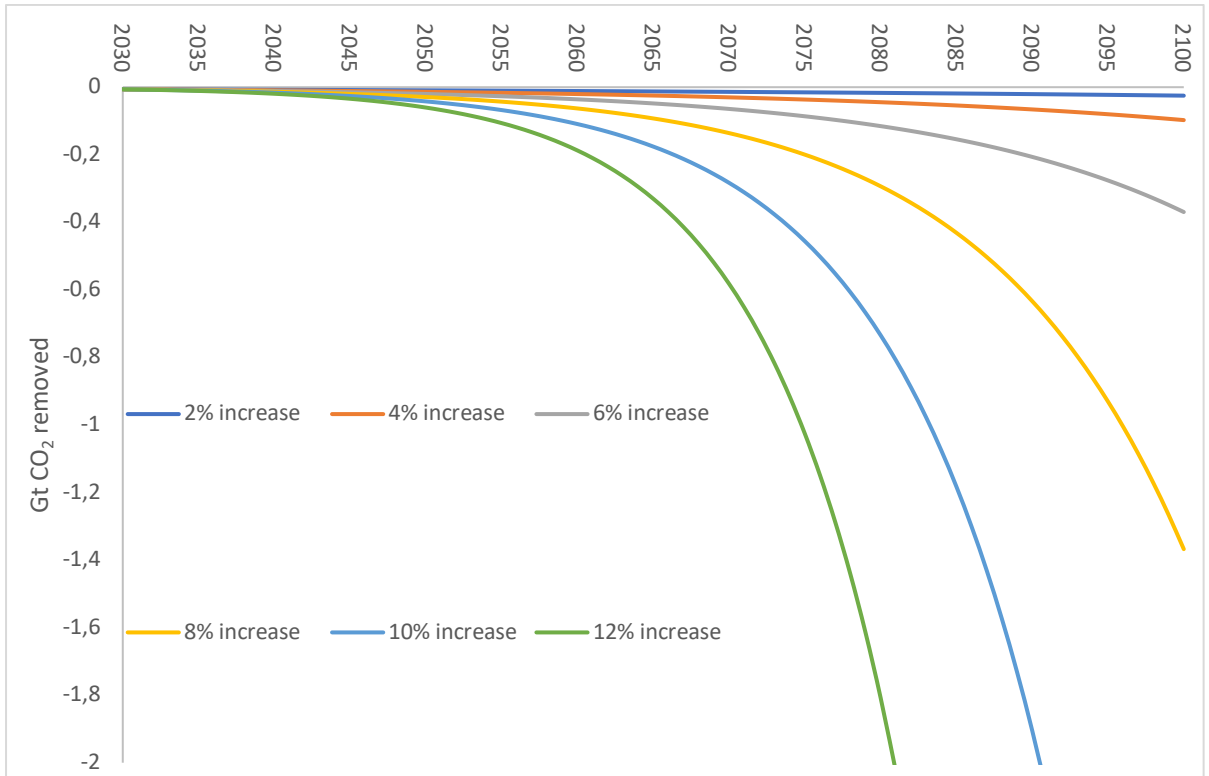


Figure 6.2.20b: The CO₂ uptake (in Gt) for the 0.05% construction aggregates allocation scenario.

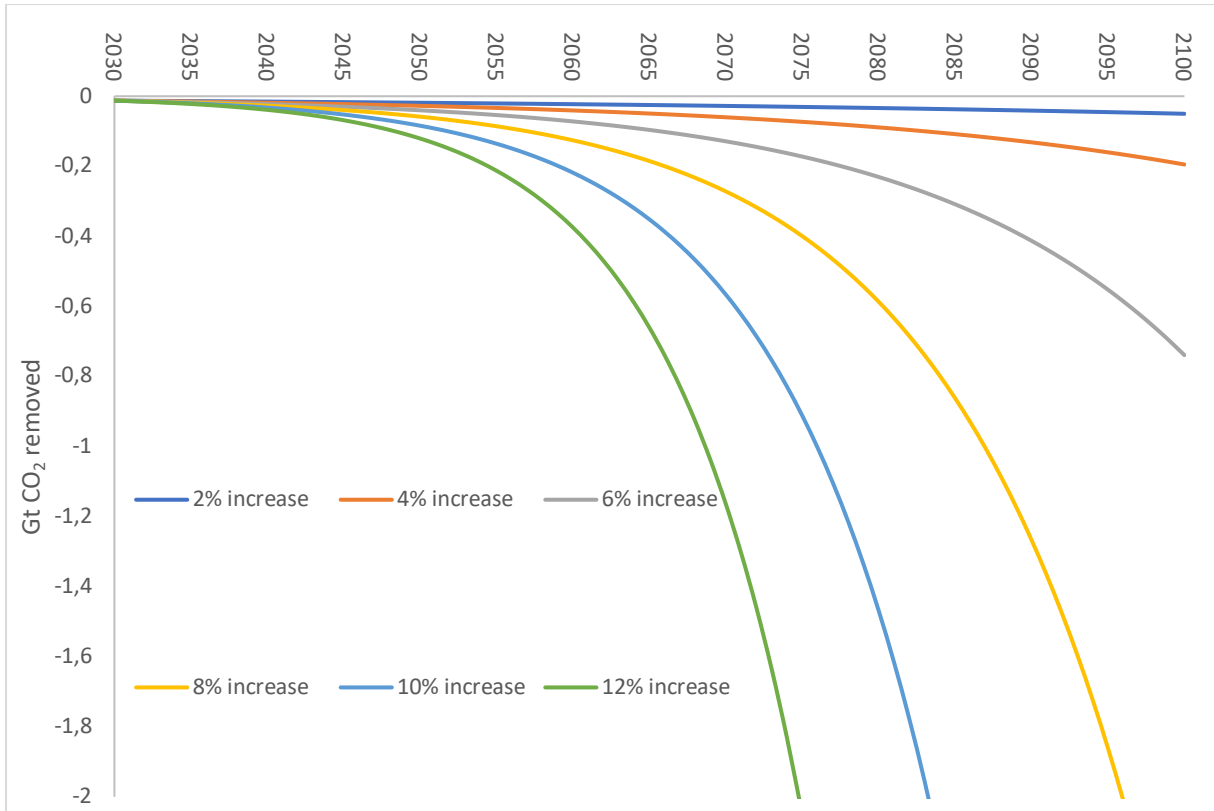


Figure 6.2.18c: The CO₂ uptake (in Gt) for the 0.1% construction aggregates allocation scenario.

6.2.6.4.3 Carbonate minerals application pessimistic scenario

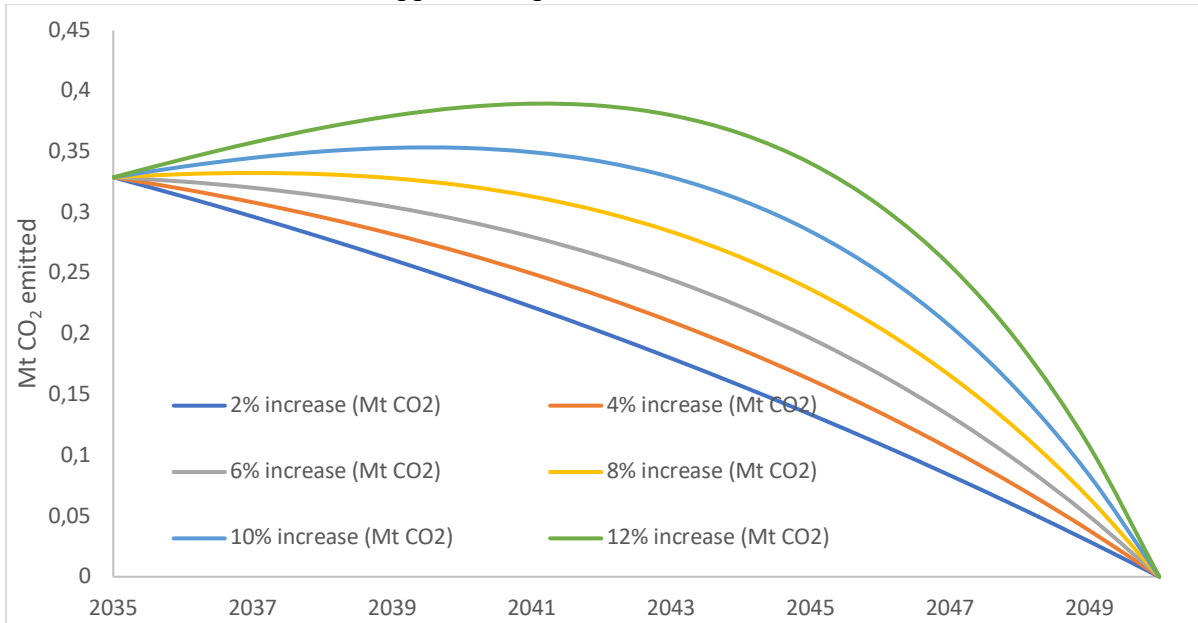


Figure 6.2.21a: The life cycle carbon emissions (in Mt) for the low (0.01%) allocation scenario for carbonate minerals from the construction aggregates industry.

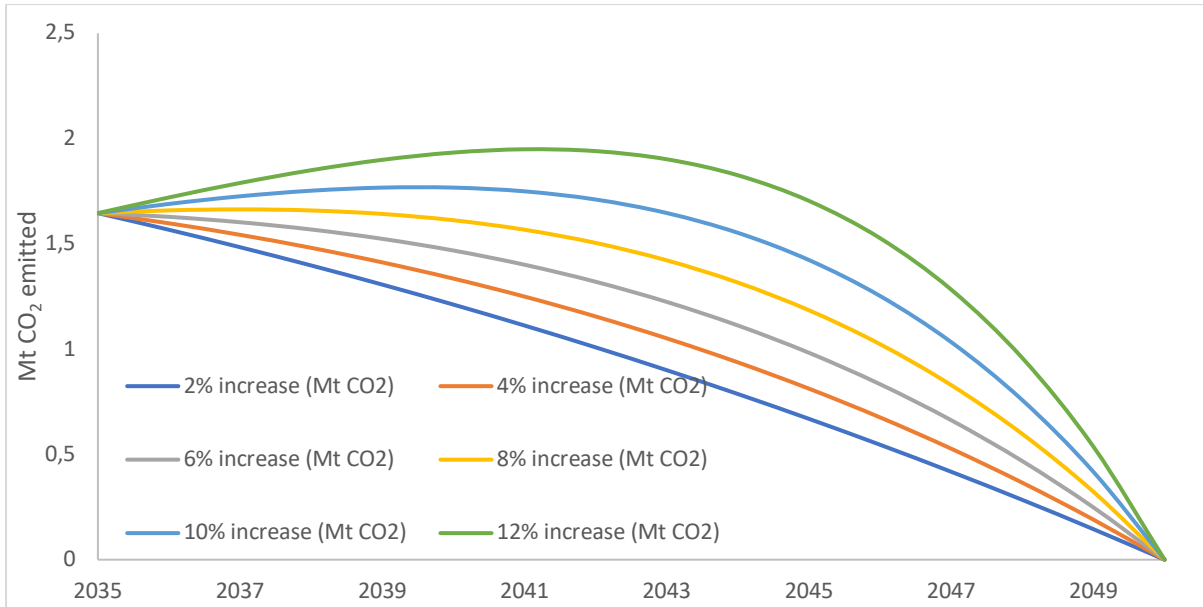


Figure 6.2.21b: The life cycle carbon emissions (in Mt) for the mean (0.05%) allocation scenario for carbonate minerals from the construction aggregates industry.

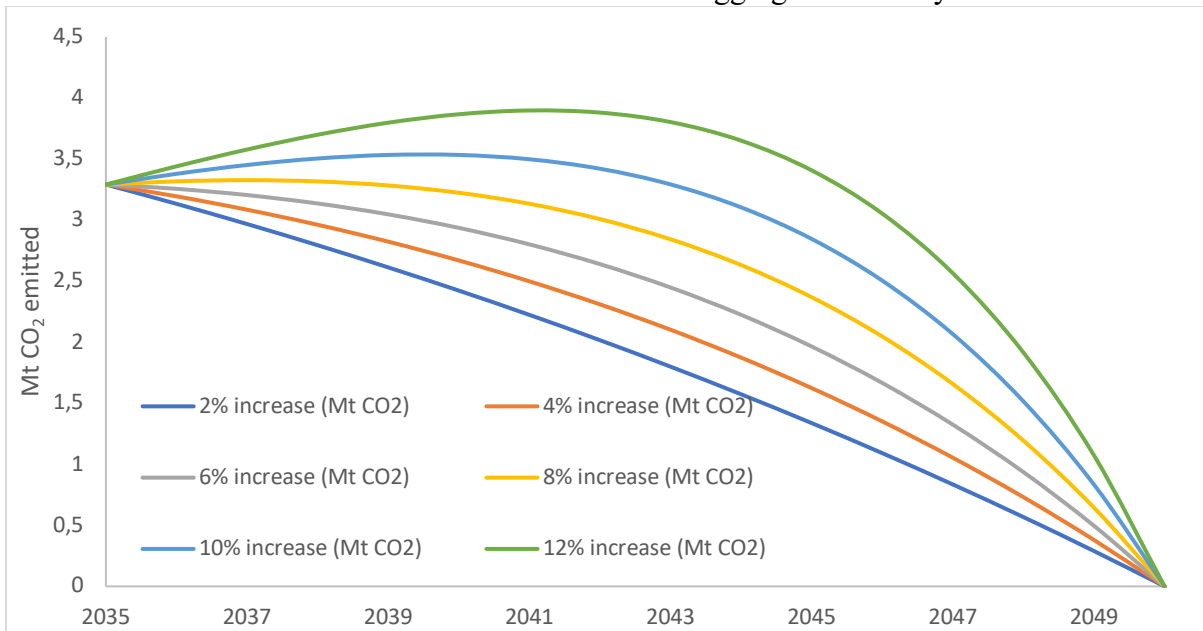


Figure 6.2.21c: The life cycle carbon emissions (in Mt) for the high (0.1%) allocation scenario for carbonate minerals from the construction aggregates industry.

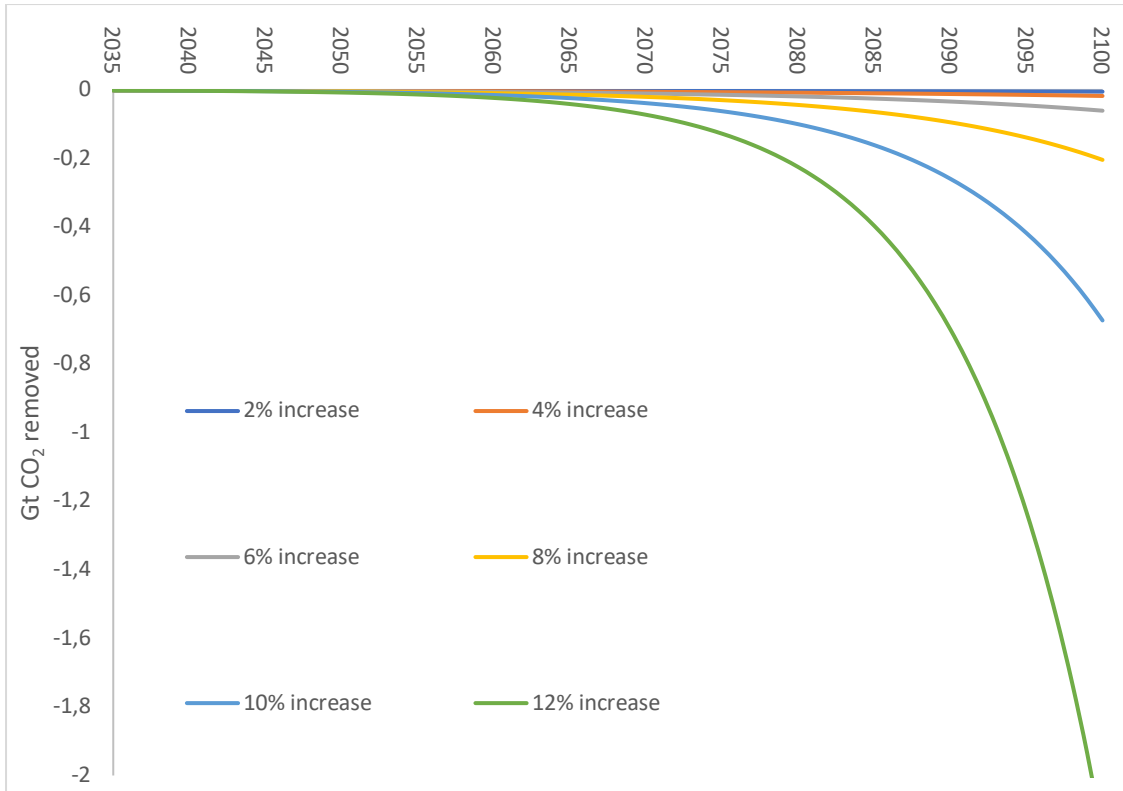


Figure 6.2.22a: The CO₂ uptake (in Gt) for the 0.01% construction aggregates allocation scenario.

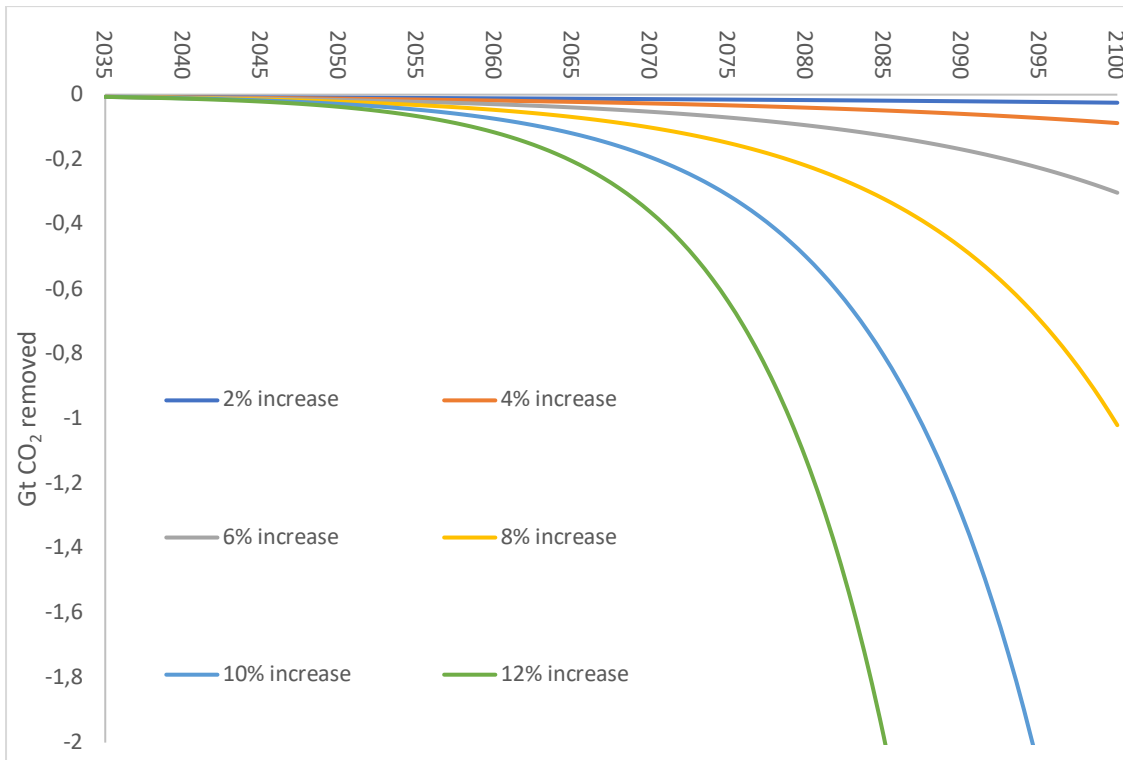


Figure 6.2.22b: The CO₂ uptake (in Gt) for the 0.05% construction aggregates allocation scenario.

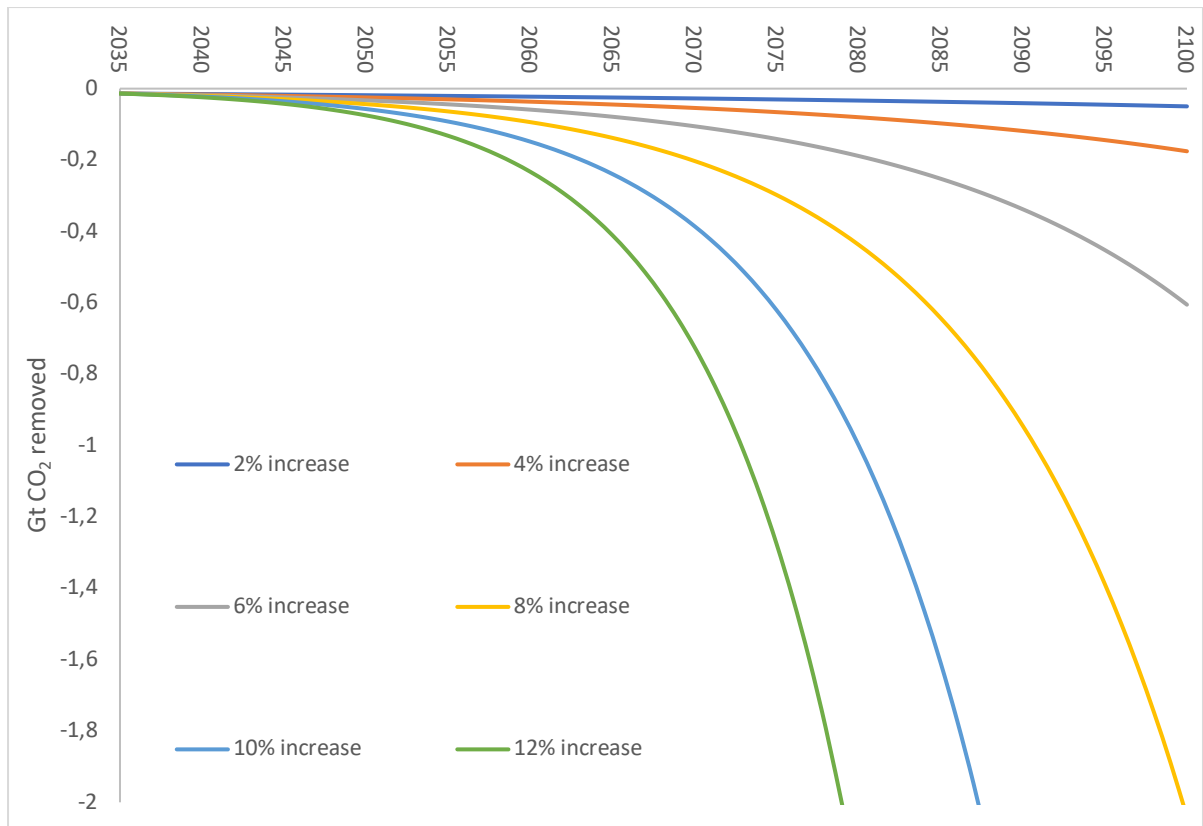


Figure 6.2.22c: The CO₂ uptake (in Gt) for the 0.1% construction aggregates allocation scenario.

6.2.7 Conclusions

From the aforementioned scenarios it appears that OAE has a great potential to remove previously emitted CO₂ from the atmosphere at scale and therefore play an important role in the fight against climate change. Specifically, under the most promising scenario (adoption of this technology as early as 2025, considering a 0.01% initial allocation of carbonate and silicate mineral from the construction aggregates industry and a 12% annual growth rate) the Gt y⁻¹ scale through OAE (OL and CEW in this case) will be achieved as early as 2055. Thereafter, the removal rates steeply increase, achieving the 2 Gt y⁻¹ mark as early as 2061, while in 2072 the assumed maximum removal rate 4 Gt y⁻¹ (2 Gt y⁻¹ for OL and 2 Gt y⁻¹ for CEW) is reached (**Fig. 6.2.23**).

It should be noted that the proposed scenarios can be constrained to different geographies, such as Europe and USA, where the output of the construction aggregates industry is known. Furthermore, specific technical and regulatory constraints, such as the spare capacity of the cement industry, focusing on low carbon kilns, can be further considered. This will provide additional spatial resolution to the proposed scenarios.

to different

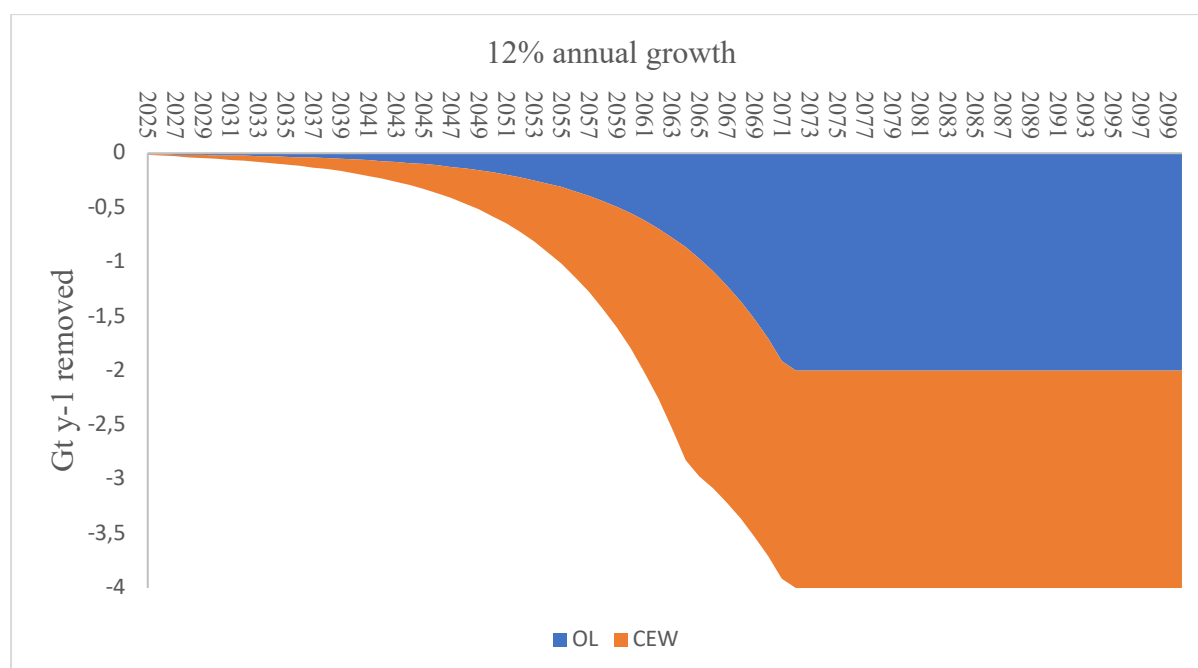


Figure 6.2.23: The total CO₂ uptake (in Gt) for the 0.1% construction aggregates allocation scenario, assuming 2025 as the starting date and 12% annual growth rate.

It should be noted that the aforementioned scenarios provide a preliminary overview of the many possibilities of OAE technologies as promising NETs at scale. However, these scenarios also hold physical realisms, since the adoption of new technologies, such as the ones described here, can take place at a much higher growth rate until they are adopted at full scale. (in this case studies adoption at full scale is the 2 Gt y⁻¹ mark for both OL and CEW or for the electrochemical pathways in the latter case.) For example, the global electric passenger car stock (battery electric vehicles (BEVs)) has followed an exponential growth rate for the reference period 2010-2020 (**Fig. 6.2.24**). Specifically, existing data for BEVs suggest a growth rate of more than 200% from 2010 to 2011, then the growth rate for 2011-2012 is more than 100% while for the next eight years (2012 to 2020) the growth rate reduces, in a stepwise fashion, from around 100% in 2012-2013 to around 45% in 2019-2020 (**Fig. 6.2.24**). If these growth rates were also achieved for the examined OAE technologies, then the Gt y⁻¹ mark might be achieved even earlier than the optimum presented scenario (**Fig. 6.2.23**). However, this will grossly depend on how fast research will progress on the main open questions surrounding OAE, such as the possible side effects on local ecosystems, since this will define the starting date of such technologies at scale. If this starting date was to be known, then one could use the growth rates of new technologies, such as BEVs, and more accurately estimate

the alkalinity that each different examined OAE technology can contribute both at a local but also at a global scale.

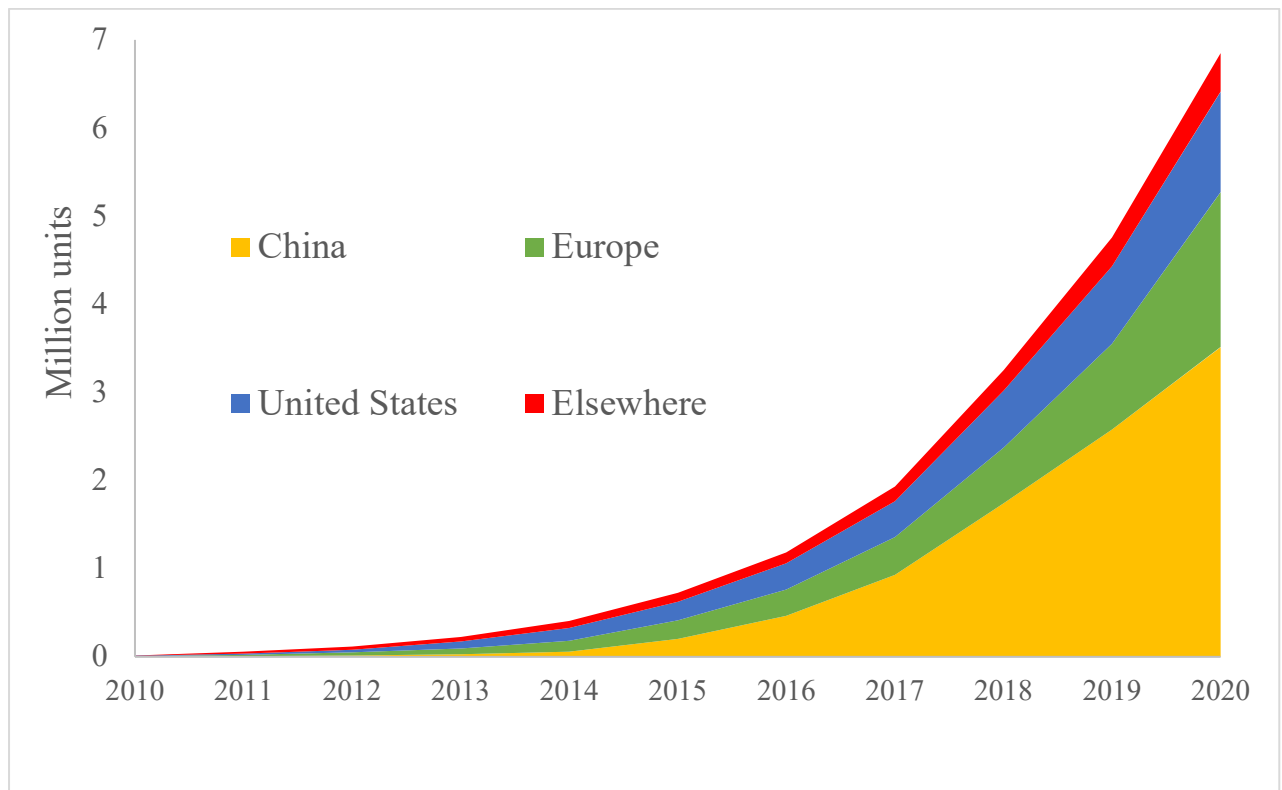


Figure 6.2.23: The total CO₂ uptake (in Gt) for the 0.1% construction aggregates allocation scenario, assuming 2025 as the starting date and 12% annual growth rate. (data adapted from (IEA, 2021).)

6.2.8 Bibliography

- Bach, L.T., Gill, S.J., Rickaby, R.E.M., Gore, S., Renforth, P., 2019. CO₂ Removal With Enhanced Weathering and Ocean Alkalinity Enhancement: Potential Risks and Co-benefits for Marine Pelagic Ecosystems. *Front. Clim.* 1. <https://doi.org/10.3389/fclim.2019.00007>
- Bang, J.-H., Chae, S.C., Lee, S.-W., Kim, J.-W., Song, K., Kim, J., Kim, W., 2019. Sequential carbonate mineralization of desalination brine for CO₂ emission reduction. *J. CO₂ Util.* 33, 427–433. <https://doi.org/10.1016/j.jcou.2019.07.020>
- BBC, 2021. Marine algae turned Scotland's water bright blue [WWW Document]. URL <https://www.bbc.co.uk/news/uk-scotland-57720790> (accessed 11.20.21).
- BGS, B.G.S., 2019. European mineral statistics [WWW Document]. URL <https://www2.bgs.ac.uk/mineralsuk/statistics/europeanStatistics.html>
- Bliss, J.D., Hayes, T.S., Orris, G.J., 2012. Limestone—A Crucial and Versatile Industrial Mineral Commodity (Fs2008-3089).
- Bufe, A., Hovius, N., Emberson, R., Rugenstein, J.K.C., Galy, A., Hassenruck-Gudipati, H.J., Chang, J.-M., 2021. Co-variation of silicate, carbonate and sulfide weathering drives CO₂ release with erosion. *Nat. Geosci.* 14, 211–216. <https://doi.org/10.1038/s41561-021-00714-3>
- Caldeira, K., Akai, M., Brewer, P., Chen, B., Haugan, P., Iwama, T., Johnston, P., Khesgi, H., Li, Q., Ohsumi, T., Portner, H., Sabine, C., Shirayama, Y., Thomson, J., 2005. Ocean Storage, in: *IPCC Special Report on Carbon Dioxide Capture and Storage*. Cambridge University Press, Cambridge, UK and NY (2005), pp. 278–318.
- Caserini, S., Pagano, D., Campo, F., Abbà, A., De Marco, S., Righi, D., Renforth, P., Grosso, M., 2021. Potential of Maritime Transport for Ocean Liming and Atmospheric CO₂ Removal. *Front. Clim.* 3, 1–18. <https://doi.org/10.3389/fclim.2021.575900>
- CEA Consulting, 2019. Ocean Alkalinity Enhancement. Report.
- Comeau, S., Carpenter, R.C.C., Edmunds, P.J., 2013. Coral reef calcifiers buffer their response to ocean acidification using both bicarbonate and carbonate. *Proc. R. Soc. B Biol. Sci.* 280. <https://doi.org/10.1098/rspb.2012.2374>
- Cooke, R.C., Kepkay, P.E., 1984. Apparent calcite supersaturation at the ocean surface: Why

the present solubility product of pure calcite in seawater does not predict the correct solubility of the salt in nature. *Mar. Chem.* 15, 59–69. [https://doi.org/10.1016/0304-4203\(84\)90038-0](https://doi.org/10.1016/0304-4203(84)90038-0)

Dindi, A., Quang, D.V., Abu-Zahra, M.R.M., 2015. Simultaneous carbon dioxide capture and utilization using thermal desalination reject brine. *Appl. Energy* 154, 298–308. <https://doi.org/10.1016/j.apenergy.2015.05.010>

Doney, S.C., Busch, D.S., Cooley, S.R., Kroeker, K.J., 2020. The impacts of ocean acidification on marine ecosystems and reliant human communities. *Annu. Rev. Environ. Resour.* 45, 83–112. <https://doi.org/10.1146/annurev-environ-012320-083019>

Eisaman, M., Carter, B., 2021. Electrochemistry, Decreasing Ocean Acidification via SEA MATE: Safe Elevation of Alkalinity for the Mitigation of Acidification Through Electrochemistry, in: *Ocean Visions Summit*.

European Environment Agency, 2021. Ocean acidification [WWW Document]. URL <https://www.eea.europa.eu/data-and-maps/indicators/ocean-acidification-3/assessment> (accessed 7.7.21).

European Environmental Agency, 2021. Greenhouse gas emission intensity of electricity generation in Europe [WWW Document]. URL <https://www.eea.europa.eu/ims/greenhouse-gas-emission-intensity-of-1> (accessed 11.22.21).

Figuerola, B., Hancock, A.M., Bax, N., Cummings, V.J., Downey, R., Griffiths, H.J., Smith, J., Stark, J.S., 2021. A Review and Meta-Analysis of Potential Impacts of Ocean Acidification on Marine Calcifiers From the Southern Ocean. *Front. Mar. Sci.* 8. <https://doi.org/10.3389/fmars.2021.584445>

Gattuso, J.-P., Williamson, P., Duarte, C.M., Magnan, A.K., 2021. The Potential for Ocean-Based Climate Action: Negative Emissions Technologies and Beyond. *Front. Clim.* 2, 1–8. <https://doi.org/10.3389/fclim.2020.575716>

Gomes, H.I., Mayes, W.M., Rogerson, M., Stewart, D.I., Burke, I.T., 2016. Alkaline residues and the environment: a review of impacts, management practices and opportunities. *J. Clean. Prod.* 112, 3571–3582. <https://doi.org/10.1016/j.jclepro.2015.09.111>

Gore, S., Renforth, P., Perkins, R., 2019. The potential environmental response to increasing

- ocean alkalinity for negative emissions. *Mitig. Adapt. Strateg. Glob. Chang.* 24, 1191–1211. <https://doi.org/10.1007/s11027-018-9830-z>
- Hangx, S.J.T., Spiers, C.J., 2009. Coastal spreading of olivine to control atmospheric CO₂ concentrations: A critical analysis of viability. *Int. J. Greenh. Gas Control* 3, 757–767. <https://doi.org/10.1016/j.ijggc.2009.07.001>
- Hauck, J., Köhler, P., Wolf-Gladrow, D., Völker, C., 2016. Iron fertilisation and century-scale effects of open ocean dissolution of olivine in a simulated CO₂ removal experiment. *Environ. Res. Lett.* 11. <https://doi.org/10.1088/1748-9326/11/2/024007>
- Hönisch, B., Ridgwell, A., Schmidt, D.N., Thomas, E., Gibbs, S.J., Sluijs, A., Zeebe, R., Kump, L., Martindale, R.C., Greene, S.E., Kiessling, W., Ries, J., Zachos, J.C., Royer, D.L., Barker, S., Marchitto, T.M., Moyer, R., Pelejero, C., Ziveri, P., Foster, G.L., Williams, B., 2012. The geological record of ocean acidification. *Science* (80-.). 335, 1058–1063. <https://doi.org/10.1126/science.1208277>
- House, K.Z., House, C.H., Schrag, D.P., Aziz, M.J., 2007. Electrochemical Acceleration of Chemical Weathering as an Energetically Feasible Approach to Mitigating Anthropogenic Climate Change. *Environ. Sci. Technol.* 41, 8464–8470. <https://doi.org/10.1021/es0701816>
- IEA, I.E.A., 2021. Global electric passenger car stock, 2010-2020 [WWW Document]. URL <https://www.iea.org/data-and-statistics/charts/global-electric-passenger-car-stock-2010-2020> (accessed 11.26.21).
- Ihsanullah, I., Atieh, M.A., Sajid, M., Nazal, M.K., 2021. Desalination and environment: A critical analysis of impacts, mitigation strategies, and greener desalination technologies. *Sci. Total Environ.* 780, 146585. <https://doi.org/10.1016/j.scitotenv.2021.146585>
- Jones, E., Qadir, M., van Vliet, M.T.H., Smakhtin, V., Kang, S., 2019. The state of desalination and brine production: A global outlook. *Sci. Total Environ.* 657, 1343–1356. <https://doi.org/10.1016/j.scitotenv.2018.12.076>
- Justnes, H., Escudero-Oñate, C., Garmo, Ø.A., Mengede, M., 2020. Transformation Kinetics of Burnt Lime in Freshwater and Sea Water. *Materials* (Basel). 13, 4926. <https://doi.org/10.3390/ma13214926>
- JXSC, 2021. Global Crushed Stone Aggregate Trends And Market [WWW Document]. URL

<https://www.jxscmine.com/crushed-stone/> (accessed 7.22.21).

Köhler, P., Abrams, J.F., Völker, C., Hauck, J., Wolf-Gladrow, D.A., 2013. Geoengineering impact of open ocean dissolution of olivine on atmospheric CO₂, surface ocean pH and marine biology. *Environ. Res. Lett.* 8. <https://doi.org/10.1088/1748-9326/8/1/014009>

Köhler, P., Hartmann, J., Wolf-Gladrow, D.A., 2010. Geoengineering potential of artificially enhanced silicate weathering of olivine. *Proc. Natl. Acad. Sci.* 107, 20228–20233. <https://doi.org/10.1073/pnas.1000545107>

Langer, W.H., 2001. Construction Materials: Crushed Stone, Sand, and Gravel, in: Buschow, K.H.J., Cahn, R.W., Flemings, M.C., Ilchner, B., Kramer, E.J., Mahajan, S., Veysière, P.B.T.-E. of M.S. and T. (Eds.), . Elsevier, Oxford, pp. 1537–1545. <https://doi.org/https://doi.org/10.1016/B0-08-043152-6/00275-8>

Meysman, F.J.R., Montserrat, F., 2017. Negative CO₂ emissions via enhanced silicate weathering in coastal environments. *Biol. Lett.* 13. <https://doi.org/10.1098/rsbl.2016.0905>

Minerals4EU, 2021. European Minerals Yearbook [WWW Document]. URL <http://minerals4eu.brgm-rec.fr/m4eu-yearbook/pages/bycommodity.jsp?commodity=Aggregates and related materials>

Montserrat, F., Renforth, P., Hartmann, J., Leermakers, M., Knops, P., Meysman, F.J.R., 2017. Olivine Dissolution in Seawater: Implications for CO₂ Sequestration through Enhanced Weathering in Coastal Environments. *Environ. Sci. Technol.* 51, 3960–3972. <https://doi.org/10.1021/acs.est.6b05942>

Mustafa, J., Mourad, A.A.-H.I., Al-Marzouqi, A.H., El-Naas, M.H., 2020. Simultaneous treatment of reject brine and capture of carbon dioxide: A comprehensive review. *Desalination* 483, 114386. <https://doi.org/10.1016/j.desal.2020.114386>

Petrou, K., Baker, K.G., Nielsen, D.A., Hancock, A.M., Schulz, K.G., Davidson, A.T., 2019. Acidification diminishes diatom silica production in the Southern Ocean. *Nat. Clim. Chang.* 9, 781–786. <https://doi.org/10.1038/s41558-019-0557-y>

Project Vesta, 2021. No Title [WWW Document]. URL <https://legacy.projectvesta.org/plan/#phaseI> (accessed 11.19.21).

Renforth, P., 2019. The negative emission potential of alkaline materials. *Nat. Commun.* 10.

<https://doi.org/10.1038/s41467-019-09475-5>

- Renforth, P., Campbell, J.S., 2021. The role of soils in the regulation of ocean acidification. *Philos. Trans. R. Soc. B Biol. Sci.* 376, 20200174.
<https://doi.org/10.1098/rstb.2020.0174>
- Renforth, P., Gore, S., 2017. The Potential of Carbon Storage in the Ocean as Bicarbonate, in: *CO2 Summit III: Pathways to Carbon Capture, Utilization, and Storage Deployment*. Calabria, Italy.
- Renforth, P., Henderson, G., 2017. Assessing ocean alkalinity for carbon sequestration. *Rev. Geophys.* 55, 636–674. <https://doi.org/https://doi.org/10.1002/2016RG000533>
- Renforth, P., Jenkins, B.G., Kruger, T., 2013. Engineering challenges of ocean liming. *Energy* 60, 442–452. <https://doi.org/10.1016/j.energy.2013.08.006>
- Renforth, P., Washbourne, C.-L., Taylder, J., Manning, D.A.C., 2011. Silicate Production and Availability for Mineral Carbonation. *Environ. Sci. Technol.* 45, 2035–2041.
<https://doi.org/10.1021/es103241w>
- Ridgwell, A., Schmidt, D.N., 2010. Past constraints on the vulnerability of marine calcifiers to massive carbon dioxide release. *Nat. Geosci.* 3, 196–200.
<https://doi.org/10.1038/ngeo755>
- Rigopoulos, I., Harrison, A.L., Delimitis, A., Ioannou, I., Efstathiou, A.M., Kyratsi, T., Oelkers, E.H., 2018. Carbon sequestration via enhanced weathering of peridotites and basalts in seawater. *Appl. Geochemistry* 91, 197–207.
<https://doi.org/10.1016/j.apgeochem.2017.11.001>
- Riley, A.L., MacDonald, J.M., Burke, I.T., Renforth, P., Jarvis, A.P., Hudson-Edwards, K.A., McKie, J., Mayes, W.M., 2020. Legacy iron and steel wastes in the UK: Extent, resource potential, and management futures. *J. Geochemical Explor.* 219, 106630.
<https://doi.org/10.1016/j.gexplo.2020.106630>
- Sayadi, A.R., Khalesi, M.R., Khosfarman, M., 2014. A parametric cost model for mineral grinding mills. *Miner. Eng.* 55, 96–102. <https://doi.org/10.1016/j.mineng.2013.09.013>
- Schuiling, R.D., 2012. Olivine and Climate Change, in: *Proceedings of the 10th International Congress for Applied Mineralogy (ICAM)*. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 637–640. https://doi.org/10.1007/978-3-642-27682-8_76

Schuiling, R.D., Tickell, O., 2010. Olivine against climate change and ocean acidification. 2010 1–22.

Sverdrup, H.U., Koca, D., Schlyter, P., 2017. A Simple System Dynamics Model for the Global Production Rate of Sand, Gravel, Crushed Rock and Stone, Market Prices and Long-Term Supply Embedded into the WORLD6 Model. *Biophys. Econ. Resour. Qual.* 2, 1–20. <https://doi.org/10.1007/s41247-017-0023-2>

Taylor, L.L., Quirk, J., Thorley, R.M.S., Kharecha, P.A., Hansen, J., Ridgwell, A., Lomas, M.R., Banwart, S.A., Beerling, D.J., 2016. Enhanced weathering strategies for stabilizing climate and averting ocean acidification. *Nat. Clim. Chang.* 6, 402–406. <https://doi.org/10.1038/nclimate2882>

UEPG, 2020. UEPG Annual Review 2019 - 2020. *Eur. Aggregates Assoc.* 31.

Unesco, 2021. Facts and figures on ocean acidification [WWW Document]. URL unesco.org/new/en/natural-sciences/ioc-oceans/focus-areas/rio-20-ocean/blueprint-for-the-future-we-want/ocean-acidification/facts-and-figures-on-ocean-acidification/ (accessed 7.7.21).

USGS, 2020. Mineral commodity summaries 2020, U.S Department OF The Interior, U.S Geological Survey.