Enhanced weathering and BECCS - are carbon dioxide removal technologies complements or substitutes?

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1 Introduction

In its fifth assessment report, the IPCC stated that "scenarios which are consistent with a likely chance to keep temperature change below 2 °C relative to pre-industrial levels [...] are characterized by near zero $GtCO_2eq$ or below in 2100" (IPCC, 2014). To reach such low CO_2eq emissions, net negative emissions will be necessary in some sectors to compensate for e.g. CH_4 and N_2O emissions from the land-use sector or industry process emissions. There are at least four options to achieve net negative CO_2 emissions: The combination of bioenergy with carbon capture and storage (BECCS), afforestation, direct air capture (House et al., 2011), and enhanced weathering of rocks (Hartmann et al., 2013). BECCS and afforestation are already being studied and are included as mitigation options in some integrated assessment models. The other two possibilities however are only starting to be studied (Tavoni and Socolow, 2013; Chen and Tavoni, 2013). BECCS and afforestation require substantial land areas to grow bioenergy crops or forests, respectively. This might lead to rising food prices due to land competition especially in non-Annex countries (Hussein et al., 2013). Rising food prices, as well as forest protection, water management, or the need to reduce fertilizer input could make it necessary to employ sustainability bounds on the use of bioenergy. CCS, which is needed for BECCS and direct air capture, is not yet available, which leads to uncertainties concerning the extent of its availability and its costs. Even if CCS were technologically feasible, social acceptance is by no means granted.

Chemical rock weathering is an integral part of the carbon cycle and removes about 0.3 TgC per year from the atmosphere (Ciais et al., 2013). Enhanced weathering, the deployment of finely ground minerals over forests and crop lands, could be used to remove CO_2 from the atmosphere. Enhanced weathering faces neither the technological nor the social risks of the other options. However, olivine, the mineral that is best suited, might be contaminated by potentially harmful trace elements. Other sources like basalt can have lower harmful element concentrations, but show lower CO_2 sequestration potential. This could be counterbalanced by increased CO_2 uptake from plants fertilized by nutrient release from these basalt rocks (Van Straaten, 2006). In this paper we discuss the parameterization of enhanced weathering which we implemented in the integrated assessment model REMIND. Our research questions are: What are the optimal design parameters for enhanced weathering? How does enhanced weathering as a mitigation option interact with BECCS?

An important parameter that determines costs as well as carbon removal rate is the grain size. With finer grain sizes, grain surface areas increase, which positively affects the weathering speed and, thus, carbon removal rates. At the same time, grinding costs increase exponentially with finer grain size (Stamboliadis et al., 2009). In this paper we follow a two step approach. In the second section we calculate an optimal grain size that maximizes profits, taking the dependency on carbon removal rate and costs into account. In the third section we use the parameters calculated before for the implementation in the integrated assessment model REMIND and show preliminary results of enhanced weathering as a mitigation option.

2 The optimal grain size

In this chapter we calculate the optimal grain size that maximizes profits per ton of stone. Parameter values are under ongoing research. The parameters depending on the optimal grain size, namely energy demand and weathering rate, are then used for the implementation in the model REMIND.

2.1 Costs

The rocks as the source product are mined and roughly crushed. Afterwards they are finely ground. The ground rocks then have to be transported to and spread on fields.

2.1.1 Mining, crushing, and grinding

Costs for mining, crushing, and grinding C_g consist of specific investment costs, operation and maintenance costs, and energy as given in Brown et al. (2010). Here, only the production costs for rock mining and primary crushing are considered and split by capital expenditures and operation expenditures, which are evaluated as operation and maintenance (O&M) costs. O&M costs are given as costs per ton of capacity. For costs per ton of ground rocks we have to factor in the availability factor per year. The Brown report refers to 5 working days per week. It includes occasional maintenance and site cleaning during nightshifts or Saturdays. 2 days per year are factored in for unplanned maintenance. In total 250 workdays are assumed annually. This would be 69% of the year.
Cost model data from Renforth (2012) are added to account for comminution costs. For a first estimate, the published min and max values were averaged.
Costs for mining and crushing and capital and O&M costs for grinding are a function of mass only $C_f = C_f(m)$. The specific energy demand for mining and crushing is only 0.01-0.03 GJ/t of rock and, thus, negligibly small. The energy demand for grinding E_g is given in [GJ / t] and depends on the output grain size x. This is the decisive share of energy requirement for enhanced weathering.
The electricity price P_e will likely depend on time and the carbon price. For this calculation we only need the electricity at a certain point in time and therefore keep this parameter constant. The energy costs for grinding are $C_e(x) = P_e * E_g(x)$.
The costs for mining, crushing, and grinding in USD per ton are the operation and maintenance costs and the electricity costs

$$C_g(x) = C_f + P_e * E_g(x).$$

2.1.2 Spreading on fields

Costs for spreading the grinded rocks on fields C_s consist of diesel costs and specific costs e.g. for labor. Both are a function of mass only. Diesel costs are much lower than the specific costs and can therefore be neglected.

This yields the Costs
$C(x) = C_g(x) + C_s = C_s + C_f + P_e * E_g(x)$.

2.2 Revenues

Revenues R are the revenues from CO_2 certificates calculated as the amount of carbon removed $co2(t)$ times the CO_2 price $P_{co2}(t)$ discounted and integrated over time.

$$R(x) = \int P_{co2}(t) * co2(t, x) * e^{-rt} dt, \tag{1}$$

where r is the discount rate. The amount of carbon removed is a function of mass of spread rock material and weathering efficiency. Weathering efficiency depends on grain size; all other factors like temperature and moisture are neglected for now. The amount of carbon removed in a given year can be calculated as co2 (t,x) = m * $\Pi * \delta(x) * e^{-\delta t}$ where m is the mass of ground rock spread on fields at time $t = 0$, δ (x) is the specific carbon removal rate and Π is the maximum potential of carbon removal. Under the assumption of an exponentially increasing carbon price $P_{co2}(t) = P_0 * e^{ct}$, this yields the total revenues

$$R(x) = P_0 * m * \Pi * \delta(x) * \int_0^\infty e^{(c-r-\delta)t} dt. \tag{2}$$

The integral converges only for $c - r - \delta(x) < 0$. Under this assumption we can evaluate the integral from 0 to ∞ and get

$$R(x) = -\frac{P_0 * m * \Pi * \delta(x)}{c - r - \delta(x))}. \tag{3}$$

2.3 Profits

The profits P, i.e. revenues minus costs as a function of grain size are

$$\begin{aligned} P(x) &= R(x) - C(x) \\ &= -\frac{P_0 * m * \Pi * \delta(x)}{c - r - \delta(x)} - m * (C_s + C_f + P_e * E_g(x)), \end{aligned} \tag{4}$$

with electricity price P_e, maximum potential of carbon removal Π, start price of CO_2 P_0, mass m, discount rate r, increase rate of carbon price c and carbon removal rate $\delta(x)$. To find the optimal grain size x, we have to maximize the profits.

2.4 Carbon price rising with discount rate

If the carbon price increases exactly with the discount rate, the integrated revenues can simply be calculated as the maximum potential of carbon removal Π times the mass m times the initial carbon price P_0,

$$R = m * \Pi * P_0. \tag{5}$$

We assume that there is a limit to the amount of ground stone that can be spread on fields. If the field is already covered with this maximum amount per square meter G, only the amount that is weathered each year can be replenished each year. This amount equals the maximum potential per square meter times the carbon removal rate δ, which yields

$$R(x) = G * \delta(x) * \Pi * P_0. \tag{6}$$

The costs per square meter are the same as above in eq. 4, again with the mass $m = G * \delta$,

$$C(x) = G * \delta(x) * (C_s + C_f + P_e * E_g(x)). \tag{7}$$

The profits are then equal to

$$P(x) = G * \delta(x) * (\Pi * P_0 - C_s - C_f - P_e * E_g(x)). \tag{8}$$

EW is only profitable if $P(x) > 0$ for some grain size x. To derive the optimal grain size we set the derivative of P to zero, i.e.

$$\begin{aligned}
\frac{\partial P}{\partial x} =& \frac{\partial}{\partial x}\Big(G * \delta(x) * (\Pi * P_0 - C_s - C_f - P_e * E_g(x))\Big) \\
=& G\ (\Pi * P_0 - C_s - C_f - P_e * E_g(x))\frac{\partial \delta(x)}{\partial x} - G * \delta(x) * P_e * \frac{\partial E_g(x)}{\partial x} \\
=& 0.
\end{aligned} \tag{9}$$

This equation can be solved for x numerically, which is then independent of G.

3 Preliminary results

Using the method described in chapter 2 we calculated the optimal parameterization of enhanced weathering (EW) and implemented it as an additional mitigation option in the multi-regional integrated assessment model REMIND (Bauer et al., 2012; Leimbach et al., 2010; Luderer et al., 2013). Each single region is modeled as a hybrid energy-economy system and is able to interact with the other regions by means of trade. Tradable goods are the exhaustible primary energy carriers coal, oil, gas and uranium, a composite good, and emission permits. The economy sector is modeled as a Ramsey-type growth model which maximizes utility, a function of consumption. Labor, capital and end-use energy generate the macroeconomic output, i.e. GDP. The produced GDP covers the costs of the energy system, macroeconomic investments, the export of a composite good and consumption. The energy sector is described with high technological detail. It uses exhaustible and renewable primary energy carriers and converts them to final energies such as electricity, heat and fuels. Various conversion technologies are available, including technologies with CCS. A detailed documentation of the REMIND model is provided in Luderer et al. (2013).

The emissions associated with the technologies are transferred to the reduced complexity coupled climate-carbon cycle model MAGICC6 (Meinshausen et al., 2011) which calculates forcing and temperature. As a climate target we limit total radiative forcing in 2100 to 2.6 Wm^{-2} with overshooting before allowed.

Without enhanced weathering available, this climate target results in a carbon price of around 1000 \$/t CO_2 (Fig. 1). When EW is available as a mitigation option, it provides net negative CO_2 emissions which allow for higher CO_2 emissions earlier in the century (Fig. 2). The slower reduction of CO_2 emissions results in a lower CO_2 price and therefore lower mitigation costs. It is important to note here that the EW parameterization is using conservative assumptions, and neglects totally the release of geogenic fertilizers like P, K, Si, Mg or Ca. Those would replace the demand for industrial fertilizer (cost benefit) and would add to the carbon stock in biomass as well as to the crop and agricultural goods production.

In the scenarios shown here, EW is used as a complement to BECCS. Depending on the exact parameterization of EW, the formulation of the climate target, and on the availability of bioenergy, it might also be used as a substitute for BECCS. This would reduce the dependency on CCS and on the provision of large amounts of bioenergy by the landuse system. In addition, we will analyze scenarios where CCS is not available. In combination with a stringent climate target, these scenarios often show very high mitigation costs or become unachievable (Kriegler et al., 2014). We will investigate to what extent EW can substitute BECCS in this case.

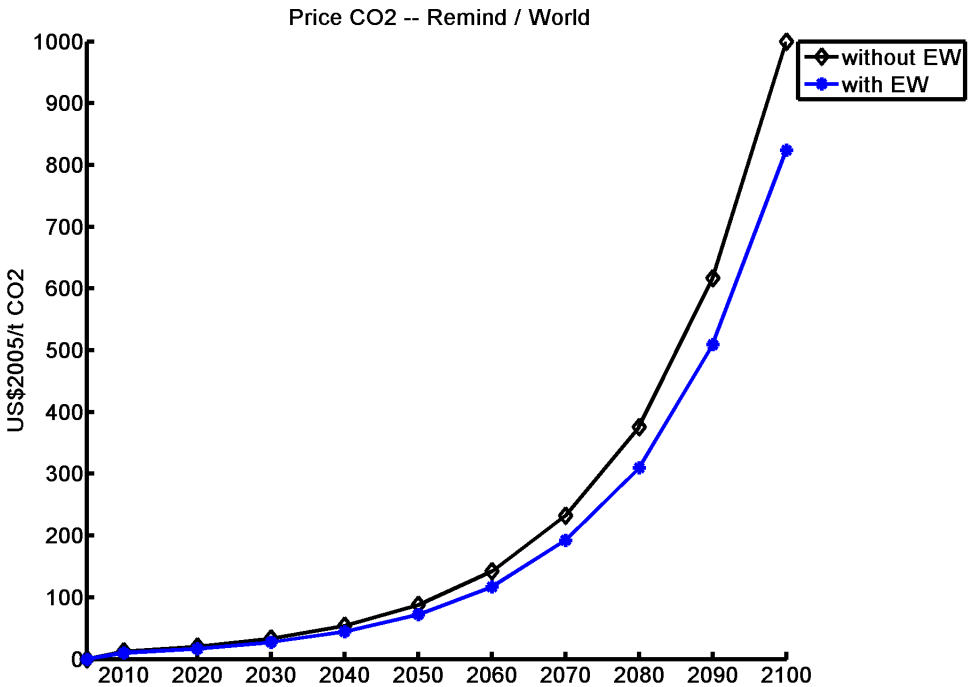
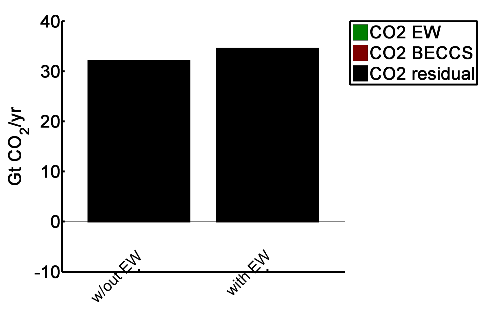
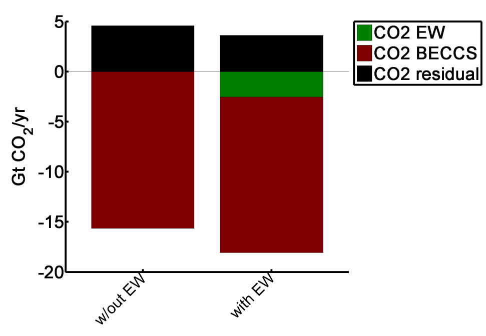


Figure 1: Global CO_2 price in a 2.6 Wm^{-2} overshoot scenario. If enhanced weathering is included as a mitigation option, it reduces the CO_2 price.

Figure 2: Snapshot of global CO_2 emissions in 2.6 Wm^{-2} overshoot scenarios with and without enhanced weathering in



(a) 2030.



(b) 2100.

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