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Letter to the editor

On life-cycle sustainability optimization of enhanced weathering systems

ABSTRACT

Keywords:
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Life-cycle sustainability assessment (LCSA)
Life-cycle sustainability optimization (LCSO)

Enhanced weathering is a simple and scalable negative emissions technology with an estimated carbon dioxide removal potential of multiple gigatons per year. To date, the only life-cycle assessment of enhanced weathering was published by Lefebvre et al. (2019) in this journal. They estimated the carbon dioxide removal potential in Sao Paolo State in Brazil to be 1.3–2.4 Mt/y, examined the penalty from transportation greenhouse gas emissions, and pointed out that using life-cycle assessment can give more reliable estimates of climate change mitigation potential of enhanced weathering systems. In this letter, we discuss the limitations of life-cycle assessment of enhanced weathering, and then propose a more comprehensive life-cycle optimization approach, where the system configuration can be automatically synthesized to maximize environmental performance. This concept can be extended further to life-cycle sustainability optimization by including economic and social dimensions.

1. Introduction

A recent article by Lefebvre et al. (2019) in the *Journal of Cleaner Production* reports the results of the only life-cycle assessment (LCA) of enhanced weathering systems in the scientific literature to date.[1] Enhanced weathering is a negative emissions technology (NET) that has gained the interest of the scientific community due to its simplicity and scalability. The work estimates a carbon dioxide removal (CDR) potential of 1.3–2.4 Mt/y via the application of pulverized basalt on land in Sao Paolo State, Brazil. According to the authors, this result is lower than what is suggested by prior estimates in the literature, due to greenhouse gas (GHG) emissions from various processes and activities in the hypothesized enhanced weathering system. The role of transportation emissions is reported to be particularly important. The authors emphasize the need to use an LCA perspective to provide a holistic, reliable estimate of CDR potential of enhanced weathering systems. Finally, by using the LCA framework, their work provides an important assessment of other environmental impacts that may occur in the effort to curtail GHG emissions.

Lefebvre et al. (2019) assume the use of basalt, which is normally quarried for use as an aggregate for concrete and asphalt. Their estimates are based on an average transportation distance from quarry to application site of 65 km, and an application rate of 1 t/ha/y on 12 Mha of land in the region of interest. Sensitivity analysis is also reported to gauge the effect of parametric assumptions on the LCA results. Despite the importance of this paper as the first LCA study of an enhanced weathering system, there are two main limitations of their work. First, LCA is a fundamentally passive tool for measuring the performance of a fixed system configuration; in LCA, environmental sustainability is measured via different footprint metrics (Čuček et al., 2012). However, the methodology itself has no intrinsic capability to automatically explore alternative system configurations to achieve optimal sustainability targets (Azapagic, 2016). Secondly, LCA focuses only on environmental aspects, while a more comprehensive evaluation of sustainability should include economic and social aspects. These are important research gaps that need to be addressed in order to maximize the potential of enhanced weathering as a CDR technique.

The limitations of the work of Lefebvre et al. (2019) suggest key directions for future research. To address the first gap, an extension of LCA know as life-cycle optimization (LCO) can serve as a powerful tool for planning and designing future enhanced weathering systems. LCO was first proposed by Azapagic and Clift (1998) by combining mathematical programming with LCA. The original single-objective form of LCO was then extended to allow for multiple-objective optimization using the classic ε-constraint algorithm (Azapagic and Clift, 1999). Alternative solution approaches such as fuzzy linear programming have also been developed (Tan et al., 2008). Multiple-objective LCO can be done based on hybrid process-based and economic input-output models (Yue et al., 2016). The capability to synthesize optimal life-cycle systems from component “building blocks” using process graphs has also been demonstrated (Angeles et al., 2017). To address the second gap, an extended life-cycle sustainability assessment (LCSA) framework should be applied. LCSA combines conventional LCA with life-cycle costing (LCC) and social LCA (SLCA) to give a balanced analysis that includes environmental, economic and social dimensions (Guinée, 2015). The improvement can be taken a step further by

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[1] Based on a search in the Scopus database using both “life-cycle assessment” and “enhanced weathering” as queries.

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combining LCO and LCSA into life-cycle sustainability optimization (LCSO).

In this letter, we outline the key research prospects for the development and use of LCO, LCSA, and LCSO models for future enhanced weathering systems. Such models can play an important role in achieving optimal levels of CDR given resource constraints on enhanced weathering systems (Tan et al., 2020a). The rest of this letter is organized as follows. Section 2 gives an overview of enhanced weathering as a NET. Section 3 discusses research gaps and prospects in detail. Finally, Section 4 gives some concluding remarks.

2. Overview of enhanced weathering

Global net GHG emissions will need to be cut to zero by 2050 to prevent catastrophic climate change (IPCC, 2018). CDR and NETs will need to be part of the global carbon management strategy to achieve this goal (Haszeldine et al., 2018). The term NET is used to describe techniques for removing CO_2 from the atmosphere through different physical, chemical, or biological pathways (McLaren, 2012). A review paper by Minx et al. (2018) surveys the NET research landscape, while Fuss et al. (2018) consider the costs, CDR potential, and risks of NET systems. Footprint constraints on NET implementation on a global scale have been estimated by Smith et al. (2016a), and similar studies have been done for specific countries such as the UK (Smith et al., 2016b). Goglio et al. (2020) reviewed LCA studies of different NETs and discussed prospects for future research. Nemet et al. (2018) examined potential roadblocks and enablers for rapid scale-up of NETs to achieve globally significant CDR.

Enhanced weathering is a NET that is based on the acceleration of naturally occurring weathering reactions between alkaline minerals, CO_2, and moisture. According to Köhler et al. (2010), enhanced weathering can also be considered as a form of geoengineering. It was first conceived by Seifritz (1990), who proposed to sequester CO_2 via reaction with silicate minerals. These silicate minerals exist naturally in igneous rocks such as dunite and basalt (Renforth, 2012), or may be found in the by-products of certain industrial processes such as the manufacture of steel, iron, cement, and lime (Renforth, 2019). The alkaline or silicate minerals react with atmospheric CO_2 in the presence of water to form soluble bicarbonates which are then transported to the ocean via run-off water. The bicarbonates also contribute towards mitigating ocean acidification as carbon is sequestered indefinitely in the ocean. Alternatively, the enhanced weathering reactions may form solid carbonates (e.g., $CaCO_3$) which also sequesters the carbon permanently. It is possible to estimate the theoretical CO_2 that can be sequestered using enhanced weathering based on the known reaction stoichiometry of these alkaline and silicate minerals with CO_2. However, caution should be exercised when estimating the sequestration potential of enhanced weathering based on experimental results to large-scale application (Beerling et al., 2020). In addition, a more holistic perspective is needed to account for the GHG emission penalties associated with the enhanced weathering life cycle, which includes grinding, transport, and application of the minerals.

Preliminary studies suggest that the sequestration potential of enhanced weathering is affected by several factors. Variations in the silicate composition and particle size affect dissolution rates, with dissolution time decreasing with reduction in mineral particle size (Renforth, 2012). As such, the minerals have to be pulverized into fine particles in order to achieve significant CDR within reasonable time scales. However, the energy and carbon footprint associated with grinding the mineral into very fine powder (<10 μm) may offset the sequestration benefits of enhanced weathering (Strefler et al., 2018). Other foreseen positive impacts from enhanced weathering include elevating the pH of acidic soil, which can counteract the negative effects of intensive farming practices (Edwards et al., 2017), and the introduction of additional nutrients, which can improve fertility of agricultural land (Hartmann et al., 2013). The scale by which these benefits can be realized is dependent on the ambient temperature, average precipitation (Moosdorf et al., 2014) and soil complexity (Renforth et al., 2015) at the application site. However, adverse effects such as mineral deposition may also be experienced if application rate limits are exceeded (Pullin et al., 2019), and further impacts may occur if the minerals contain any trace amounts of heavy metal contaminants. In addition, health concerns might arise from the generation of particulate matter (PM) emissions during the crushing, transportation and application of the minerals. These concerns may limit the social acceptability of enhanced weathering (Renforth, 2012).

Various studies have attempted to estimate the sequestration potential of enhanced weathering in consideration of resource or application site constraints. Renforth (2012) estimates that a total sequestration potential of 430 Gt CO_2 can be achieved by the UK based solely on available silicate resources. Initial studies estimated a sequestration potential of 0.7–1.2 Gt/y of CO_2 from the use of silicate waste and by-products from industrial processes (Renforth et al., 2011). The estimate was updated more recently to achieve 2.9–8.5 Gt/y of CO_2 until 2100 (Renforth, 2019). The abundance and availability of alkaline and silicate minerals suggests that the limits to enhanced weathering may be dictated by land and water footprint constraints (Strefler et al., 2018). These constraints impact the techno-economic assessment of the technology. McLaren (2012), for example, estimates that sequestering 1 Gt/y of CO_2 using globally available olivine will cost US$ 20–40/t CO_2. Beerling et al. (2020) estimate a cost of US$ 80–180/t CO_2 for the sequestration of 0.5–2.0 Gt/y CO_2 if Brazil, China, India and the US were to implement enhanced weathering on agricultural land. McQueen et al. (2020), on the other hand, estimate a cost of US$ 46–159/t CO_2 for repeatedly capturing CO_2 from the atmosphere using calcined magnesite. This technology is estimated to be capable of sequestering 2–3 Gt/y of CO_2.

In addition to terrestrial enhanced weathering, coastal application of alkaline minerals is a promising alternative (Meysman and Montserrat, 2017). Coastal enhanced weathering relies partly on mechanical agitation and attrition from waves, and thus does not require mineral particles to be as fine as in terrestrial enhanced weathering. According to Meysman and Montserrat (2017), coastal enhanced weathering also avoids land use issues associated with terrestrial enhanced weathering, and can be implemented using existing dredging technology. The concept has been verified in laboratory tests using olivine (Montserrat et al., 2017); field tests are currently in progress to get better estimates of *in situ* enhanced weathering performance for large scale applications (Project Vesta, 2020).

3. Research gaps and prospects

Despite the extensive body of literature on enhanced weathering systems, including studies that estimate CDR potential, only Lefebvre et al. (2019) have done an LCA, and no LCO, LCSA, or LCSO results have been reported. Models for optimizing enhanced weathering networks have been reported using linear programming (Tan and Aviso, 2019) and fuzzy mixed-integer linear programming (Aviso and Tan, 2020); however, these formulations are based on supply chain network models that are structurally based on process integration problems (Tan et al., 2020a). A new class of models based on LCA core formulation (Heijungs and Suh, 2002) will need to be developed. The main challenges in the development and use of LCSO models for enhanced weathering systems are discussed here.

The computational structure of all LCA models is described comprehensively by Heijungs and Suh (2002). The framework relies on linear models that can be implemented easily via matrix algebra, and is compatible with economic input-output models. The basic structure can be extended into an LCO model that allows automated exploration of different system configurations (Azapagic and Clift, 1998). In the context of enhanced weathering, this capability will allow automated comparison of alternatives, such as the choice between terrestrial and coastal application. Extensions of the basic LCO model allow for consideration of multiple objectives (Azapagic and Clift, 1999), parameter uncertainties (Wang and Work, 2014), and hybridization with economic input-output models (Yue et al., 2016). The basic LCA model can also be applied with minimal modification to an extended LCSA framework (Hejiungs et al., 2013). These developments suggest that there are no serious mathematical impediments to the formulation of a generic LCSO model. However, in the case of enhanced weathering, such an LCSO model must also deal with two system characteristics that are discussed here: epistemic uncertainties and the presence of multiple agents.

Epistemic uncertainties are inherent in novel, emerging technologies; these uncertainties arise from lack of fundamental knowledge about a process, in contrast to stochastic uncertainty that results from variations in parameters. An example of stochastic uncertainty as discussed by Lefebvre et al. (2019) is the potential variation in transportation distance in enhanced weathering systems. Such variations can be dealt with using techniques such as sensitivity analysis or stochastic programming. The nature of epistemic uncertainties, particularly in the context of enhanced weathering, is different from such variations. The basic chemical reactions that occur in enhanced weathering are well-understood, but in practice, the true dissolution rate of pulverized minerals is a complex function of environmental factors such as soil conditions, ambient temperature, and precipitation level. There has been limited field-test data to make more reliable estimates of true CDR potential (Beerling et al., 2020). The variations in the estimates for CO_2 sequestration potential of enhanced weathering result from epistemic uncertainties in the system since the real mechanisms determining dissolution rates are still not fully understood.

Another source of epistemic uncertainty is the rock application limit per unit area of land, which may be constrained by the adverse effects of mineral residue deposition (Aviso and Tan, 2020). Estimation of local PM emissions from application sites is also a significant challenge. The uncertain effects of localized pH elevation in terrestrial and marine environments due to the products of enhanced weathering chemical reactions also needs to be considered. These effects may manifest as co-benefits (e.g., improved soil fertility due to reduced acidity) or as adverse impacts on flora and fauna. In a comprehensive LCSO, quantification of social acceptability also brings additional epistemic uncertainty during optimization (Renforth, 2012). The “soft” aspects that arise in SLCA present a very difficult modelling challenge due to their fundamentally subjective nature. To address such issues, the previous use of fuzzy set theory in LCO (e.g., Tan et al., 2008) should be extended to LCSO.

It is important to consider that real-life macro-scale systems involve the presence of multiple stakeholders and decision-makers (Nemet et al., 2018). Tools such as game theory and agent-based modelling can allow potentially conflicting perspectives of multiple players to be accounted for. Ren et al. (2018) developed a multi-agent, multi-criterion decision analysis technique for SLCA. The role of government regulations and economic instruments is also a critical factor in commercializing enhanced weathering. As carbon credits will be the main source of revenues for future enhanced weathering networks, there will need to be an existing framework for economic valuation of CDR. Interactions between government and industry can be modelled using a Stackelberg or leader-follower game theoretic framework; such games can then be implemented as bi-level mathematical programming models (Yue and You, 2017). Models of this form can be used to calibrate a regulator’s economic instruments (e.g., taxes or incentives) in order to incentivize sustainable practices in industrial systems (Aviso et al., 2010). Cooperative game models will also be needed to ensure fair allocation of costs and benefits among the different parties involved in enhanced weathering systems (Gutiérrez et al., 2018).

These two main challenges leads to interesting prospects for the development of LCSO models for enhanced weathering. In addition to models based purely on mathematical programming, hybrid techniques can be developed to complement equation-based models. For example, process graph models can enhance LCSO by adding network synthesis capability (Friedler et al., 2019), while pinch analysis can give the capability to identify optimal system-level sustainability targets independently of the actual system configuration (Klemeš et al., 2018). New process graph techniques can also be used to model the interaction of physical and intangible elements (e.g., regulations, policies, or economic instruments) in enhanced weathering systems (Tan et al., 2020b). Use of Big Data to calibrate these models will also be an important step to achieving verifiable CDR in the future (Wu et al., 2016).

4. Conclusions

The paper of Lefebvre et al. (2019) is an important initial step in the application of life-cycle principles to the evaluation of future enhanced weathering systems. In this letter, we propose to extend this area of research further by using an LCSO framework. This improved approach will have two important advantages. First, with LCSO it will be possible to synthesize an optimal system configuration, while LCA only allows a passive evaluation of a fixed, pre-defined one. Secondly, LCSO will broaden the scope of evaluation to cover environmental, economic, and social dimensions. The latter two aspects will play a critical role in determining the success of enhanced weathering as a NET. Other research prospects can also be incorporated in LCSO, particularly the presence of epistemic data uncertainties and multiple decision-making agents in enhanced weathering systems.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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