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Perspective

The role of process integration in managing resource constraints on negative emissions technologies

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Global greenhouse gas (GHG) emissions need to be cut to zero by mid-century in order to keep mean global temperature rise to about 1.5 °C by 2100. To achieve this goal, *negative emissions technologies* (NETs) will be a necessary to offset positive GHG emissions that will continue to be released elsewhere by other technologies and anthropogenic activities. These NETs will remove carbon dioxide (CO_2) from the atmosphere through different chemical pathways, leading to a permanent storage of the sequestered carbon in different environmental compartments. Examples of NETs include bioenergy with carbon capture and storage (BECCS), direct air capture (DAC), enhanced weathering, and biochar application to soil. In addition, other low-tech carbon sequestration techniques such as afforestation, reforestation, and soil carbon management are also classified as NETs. There is extensive literature discussing different NET concepts at various levels of technological maturity. Estimates of the scalability of different NETs based on resource constraints can also be found in recent papers (e.g., Fuss et al., 2018; Fajardy et al., 2019).

Resource constraints may impose limits on the scale-up of many much-needed decarbonization technologies. For example, modern low-carbon energy technologies such as storage batteries and photovoltaic cells are highly mineral-intensive. In addition to absolute limits on the availability of such resources on a global scale, the uneven geographic distribution of such resources poses the risk that future energy supply chains will become vulnerable to political tensions, in the same way that unequal distribution of fossil fuel resources has caused so much historical unrest (de Koning et al., 2018). In the context of large-scale deployment of NETs, such resource constraints may create problems as well. For example, recent work has studied the land, water, energy, economic, and nutrient constraints on a range of alternative NETs (Fajardy et al., 2019). In addition, both BECCS and DAC require geological pore space – itself a finite resource – for storage of captured CO_2. The central gap in the literature is the prevalent emphasis on the evaluation of NETs in parallel, as if the available options are mutually exclusive. There is a lack of a holistic outlook that considers how a range of NET options can be integrated along with other carbon management technologies in an optimal manner to maximize total CO_2 removal while minimizing the use of shared global resources. This research gap can be addressed by *process integration*.

Process integration is a specialized branch of chemical engineering that was initially developed in the 1970s as a set of thermodynamically rigorous computational techniques for designing heat recovery systems to optimize the thermal energy efficiency of manufacturing industries. After an initial lag in scientific and industry interest, the global oil crises of the 1970s provided the impetus for the growth in popularity of process integration. The computational techniques of process integration consist of a family of algorithms (e.g., pinch analysis) and models (e.g., mathematical programming models and process graphs) based on the general principle of allocating energy while accounting for both quantity (e.g., heat load in heat recovery systems) and quality (e.g., temperature for heat transfer). Process integration places emphasis on system-level interactions that occur among components in order to determine optimal energy resource consumption budgets, or *targets*. These methods also provide valuable physical insights for engineers to examine design options needed to achieve system targets prior to implementation.

In the late 1980s, process integration was extended to industrial applications for reducing the use of *mass separating agents* (e.g., process solvents); this diversification was based on the natural analogy between the underlying heat and mass transfer principles. Further diversification of process integration followed in the ensuing decades. Examples include hydrogen integration in refineries to produce cleaner petroleum-based fuels; water integration to reduce freshwater consumption and wastewater generation; and integration of renewables for planning low-carbon energy systems. A broad overview of process integration history, covering both methodology and industrial applications, can be found in the handbook of Klemeš (2013).

While process integration was originally developed for the purpose of economizing on the use of physical resources, it has since been generalized to apply to the systematic conservation of resources in general. For example, process integration techniques have been developed for optimizing the use of human, equipment, or financial resources in industry; many of these non-conventional applications are

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discussed by Tan et al. (2015). Hence, it is highly plausible that process integration principles can be creatively directed at the urgent problem of minimizing the use of natural resources when deploying NETs throughout the world. Averting a climate crisis will require using NETs at the scale of multiple gigatons per year, which makes it imperative to find ways to effectively cope with the resource limitations on their use. It will be important to determine what percentage of the estimated global potentials of NETs can be achieved when the uneven geographic distribution of resources is considered. Likewise, the possibility of relieving resource bottlenecks through synergistic integration of multiple NETs should be examined. Decisions will also need to be made in the face of data uncertainties that naturally come with such novel technologies. Further diversification of the process integration toolbox can help to address these research challenges; new techniques can be developed to identify how, when, and where NETs should be used in consideration of both decarbonization goals and resource limits.

Conflict of interest statement

The authors have no conflict of interest to declare.

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