Decarbonizing steel production

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Integrating industrial sectors in the transition to more sustainable chemicals

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Transitioning to more sustainable chemicals will require the challenging replacement of fossil resources with renewable carbon and energy sources in their production. Now, integrating industrial sectors offers an interim solution to mitigate emissions in the chemical industry until technologies for closing the carbon loop can be deployed at scale.

The chemical sector is essential for covering the global demand for goods and services, yet it consumes large amounts of fossil resources employed as carbon and energy sources, resulting in substantial carbon emissions (2.0 $GtCO_2$ from the global annual production of ammonia, methanol and plastics in 2020[1]). Defossilizing chemicals to close the carbon loop in their production will require replacing fossil carbon with renewable carbon feedstock, such as captured CO_2 from the air, biomass and recycled chemical products. However, many renewable carbon-based technologies have not yet reached a sufficient maturity level, are still too expensive or could even lead to burden-shifting when attempting to combat climate change (that is, one environmental impact improves at the expense of worsening others)[1,2]. Hence, until such technologies become more competitive, and the socio-political landscape is ready to embrace them broadly, alternative mitigation strategies still based on fossil carbon could be deployed and coexist with current infrastructure with minor adjustments, thereby smoothening the transformation of the chemical sector.

Now, writing in *Nature Chemical Engineering*, Yang Guo, Denise Mauzerall and co-workers[3] report the deployment in China of a technologically ready, short-term mitigation strategy based on integrating industrial sectors. In essence, the proposed integration would be enabled by replacing syngas from coal (used as feedstock in chemicals production) with excess steelmaking off-gas, which is currently burnt to generate electricity (Fig. 1). While chemicals would still be produced from fossil carbon, integrating both sectors could lead to overall savings of up to 7% in greenhouse gas emissions and 1% in cost for today's market in China[3]. The authors also discuss the role of carbon trading markets in this context, concluding that a sufficiently large carbon price could lead to even larger environmental and economic benefits (more specifically, reductions of 22% and 10% in greenhouse gas emissions and cost, respectively, relative to the current decoupled production of steel and chemicals).

Identifying mitigation solutions based on integrating industrial sectors like the one above could be challenging, particularly given the large number of activities in the global economy and processes within the chemical sector. Here we argue that the process systems engineering and industrial ecology communities could greatly assist engineers and policymakers in this task. Mass and energy integration

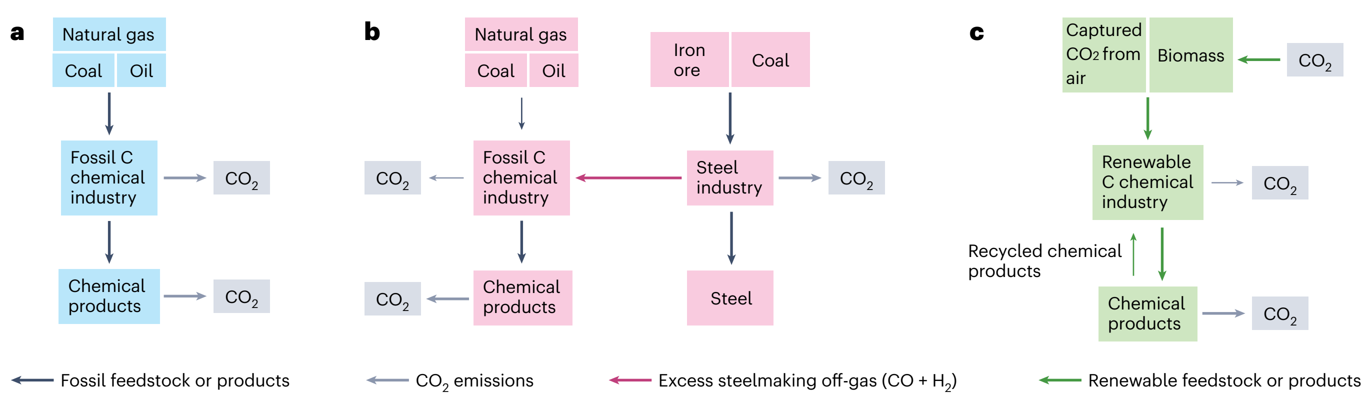

Fig. 1 | Today's fossil-based chemical industry, mitigation strategy based on integrating industrial sectors, and pathways toward closed carbon-loop chemicals. a, The business-as-usual chemical industry relies on fossil resources (coal, oil and natural gas) as energy sources and feedstock. Transforming fossil feedstock into platform chemicals, intermediates and final products can emit CO_2 and requires energy, primarily generated from fossil fuels, which leads to additional CO_2 emissions. Moreover, in the end-use phase, most chemicals degrade in landfills or are combusted, thereby releasing their fossil carbon as CO_2 into the atmosphere. **b**, Now, Yang Guo, Denise Mauzerall and co-workers propose integrating steel and chemicals production in China to mitigate CO_2 emissions by using excess off-gas from coal-based steelmaking, rich in CO and H_2, as feedstock for chemicals production, thereby reducing the overall carbon footprint and cost. **c**, In the long term, sustainable chemicals production might require closing the carbon loop by replacing fossil resources with renewable energy and carbon (that is, captured CO_2, biomass and recycled chemical products), as discussed in ref. 1. We omit here carbon capture and storage coupled with fossil infrastructure as it does not rely on renewable carbon feedstock.

in industrial sites is a topic long considered in the process systems engineering literature, which was primarily investigated at the plant rather than sector level. In particular, connected to the latter, the concept of eco-industrial park can be seen as a manifestation of industrial symbiosis that seeks to reduce mass and energy inputs and waste by integrating diversified clusters of firms[4,5]. Optimization approaches were applied to design eco-industrial parks based on superstructures (mathematical representations embedding all alternatives of interest from which the optimal one should be selected)[5]. At a higher scale, integrated assessment models (IAMs)[6] investigate exploratory prospective scenarios based on socio-economic pathways by modeling the entire economy and its links to the environment. These models offer a limited technological representation of the chemical industry, which hinders the identification of specific cross-sectoral integration opportunities potentially arising in the global economy. The need for including industrial ecology system linkages into IAMs to find mitigation scenarios has been recently pointed out[7], yet work in this area is still limited.

Due to inherent trade-offs between sustainability goals, it is highly unlikely that a single technological silver bullet to produce chemicals sustainably will ever be found. Instead, region-specific optimal portfolios of technologies to be deployed over time should be identified to shape the future chemical sector, including fossil and renewable carbon-based routes accompanied by integration opportunities to enhance circularity. Computer-aided approaches such as process modeling, optimization, machine learning, life-cycle assessment and IAMs could be combined within a unified modeling framework to support decision-making in this complex endeavor. Even after identifying appealing technological portfolios, socio-political barriers will still have to be overcome, so quantitative studies on the global implications of deploying technologies at scale will be more necessary than ever to make better informed decisions toward sustainable chemicals. Interim solutions like that studied by the authors could help in this transition, yet closing the carbon loop will very likely become a prerequisite in the long term to stay within planetary boundaries[2]. In this journey, modeling and experimental groups, policymakers and industrial practitioners should join forces to tackle this grand challenge effectively and ensure sustainable development for many centuries to come.

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Competing interests

The authors declare no competing interests.