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# Co-production of steel and chemicals to mitigate hard-to-abate carbon emissions

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Hard-to-abate sectors emitted ~30% of global $CO_2$ emissions in 2018. As the world's largest producer of chemicals and steel, China's mitigation efforts in these sectors are crucial. Here we examine the greenhouse gas mitigation and costs of co-producing steel and chemicals in China by extracting $H_2$ and CO from steelmaking off-gas for chemical production and using a customized optimization model with a life-cycle assessment. Without carbon pricing, co-production reduces greenhouse gas emissions by 36 $MtCO_2eq\ yr^{-1}$ (−7%) and costs by 1.5 billion CNY per year (−1%) relative to independent production. A carbon price of 350 CNY per $tCO_2$ enhances emissions and cost reductions to 113 $MtCO_2eq\ yr^{-1}$ (−22%) and 25.5 billion CNY per year (−10%), respectively. Furthermore, 60% of total emissions and cost reductions can be achieved via 24% of connections, ~50% of which are in Hebei, Henan, Shanxi and Shandong provinces. This study demonstrates the cost-effectiveness of using co-production to mitigate these hard-to-abate emissions and the importance of targeting critical connections to obtain the majority of reductions.

Hard-to-abate sectors, including steel, chemicals and cement, accounted for ~30% of global annual $CO_2$ emissions in 2018 (ref. 1). These emissions must be dramatically reduced for a net-zero emissions future. The steel and chemical sectors manufacture bulk materials fundamental to the economy and globally contribute about one-third of hard-to-abate emissions[1]. In steel and chemical plants, greenhouse gas (GHG) emissions mainly result from onsite use of fossil fuels for feedstocks and high-temperature heat generation[2]. The challenge in reducing these emissions lies in carbon-intensive chemical reactions integral to their production processes, including reduction of iron ore ($Fe_3O_4 + 2C \rightarrow 3Fe + 2CO_2$) for steelmaking and coal-based hydrogen production ($2C + O_2 \rightarrow 2CO$, $CO + H_2O \rightarrow CO_2 + H_2$) for chemical syntheses. In addition, producing high-temperature heat from electricity at scale is not feasible in the near term[2]. Thus, transitioning to carbon-free electrification alone is not sufficient to address these hard-to-abate emissions. China is the world's largest producer of steel and chemicals, both of which are heavily dependent on coal[3,4]. The coal chemical sector, in particular, has experienced a rapid growth over the past decade, representing ~25% of China's coal consumption in 2020 (ref. 5). The steel and coal chemical sectors contributed to 14% and 9% of China's 2020 GHG emissions, respectively[6,7]. To decarbonize these two sectors, China has enhanced production efficiency[4,8] and is starting to deploy emerging technologies, such as green hydrogen and carbon capture, utilization and storage (CCUS)[9]. However, the potential for carbon mitigation through efficiency measures is limited[4,8] while green hydrogen and CCUS are expected to remain costly through 2040 (refs. 10,11). Therefore, co-production of steel and chemicals is emerging as a critical strategy to reduce hard-to-abate emissions in the near future.

During co-production of steel and chemicals, $H_2$ and CO from steelmaking off-gas (including coke oven gas (COG), blast furnace gas (BFG) and basic oxygen furnace gas (BOFG)) are extracted and purified to produce chemicals, such as methanol and olefins[12,13]. China's steel plants annually generate ~1.2 trillion $m^3$ of off-gas, primarily composed of CO, $H_2$, $CH_4$, $CO_2$ and $N_2$ (refs. 13–15). Specifically, COG has a

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high concentration of $H_2$ (55–60%) while BFG and BOFG are rich in CO (23–27% and 50–70%, respectively)[13,15]. Currently, ~50% of steelmaking off-gas is returned to steelmaking processes for reductants and fuels, and the rest is used in situ for electricity generation[12,15–17]. Producing electricity from off-gas is carbon intensive because CO is a main component of off-gas and CO-to-electricity has a carbon intensity of 1,940 $gCO_2eq\ kWh^{-1}$, which is higher than that of China's grid electricity (590 $gCO_2eq\ kWh^{-1}$) and even coal-to-electricity (930 $gCO_2eq\ kWh^{-1}$) (Supplementary Table 1). In addition, using steelmaking off-gas for electricity generation overlooks the opportunitiy to use off-gas derived $H_2$ and CO to replace coal-based $H_2$ and CO. To produce $H_2$ in coal chemical plants, coal is first gasified to produce CO and a portion of CO then undergoes the water–gas shift reaction ($CO + H_2O \rightarrow CO_2 + H_2$) to produce $H_2$. This process contributed to about one-third of total GHG emissions from China's coal chemical sector in 2020 (ref. 6). Therefore, redirecting steelmaking off-gas to chemical production can substantially reduce GHG emissions from both the steel and chemical sectors by avoiding carbon-intensive CO-to-electricity and coal-based $H_2$ production.

Co-production of steel and coal chemicals has been demonstrated to be technologically viable and ranked highly on the net-zero agenda in China[12,13,15,18,19]. Since 2009, China has deployed approximately ten co-production projects that use steelmaking off-gas to produce chemicals such as methanol, ethanol and ethylene glycol (Supplementary Table 2). In 2021, China's national decarbonization strategies highlighted the co-production of steel and chemicals as a critical pathway to decarbonize the steel sector, in parallel with other pathways such as improving efficiency, adopting carbon-free energy and using scrap steel via electric arc furnaces[19]. Because of this policy spotlight, it is now crucial to explore how to widely and cost-effectively deploy co-production of steel and chemicals.

Co-production between industrial sectors (for example, using coal ash and steel slag for cement production) is beneficial for carbon mitigation, resource conservation and the environment[20–22]. Only a few case studies have evaluated the environmental and economic implications of steel–chemical co-production in China[13,15], the European Union[23], Canada[24], Finland[25] and South Korea[26] (see Supplementary Table 3 for a list of case studies). For example, Ghanbari et al.[25] and Kang and Han[26] reported that steel–chemical co-production can lead to carbon mitigation relative to current practices in Finland and South Korea, respectively. In addition to carbon mitigation, Shangguan et al.[15] documented lower energy costs of a co-production project than those of independent production in China, and Arvola et al.[23] found that cost reductions of the co-production depend on electricity and carbon prices. Although these studies shed light on the co-production benefits, they cannot be generalized to inform national or regional policy because they are individual cases of co-production. These studies also overlooked some critical processes in co-production, such as gas purification and transport, which can substantially influence feasibility and cost-effectiveness. More importantly, existing projects and studies mostly focus on building new chemical facilities in steel plants rather than connecting existing plants. However, holistically, bridging these two types of existing plants is needed to fully utilize current coal chemical production capacity and avoid over-capacity for chemical production, as well as reducing national coal consumption and GHG emissions.

In this Article, we examine the carbon and cost implications of deploying co-production of steel and chemicals across China via establishing connections between existing steel and chemical plants. Our study includes plant-level characteristics of steel and coal chemical production in China, and models GHG emissions and costs of associated industrial processes from a life-cycle perspective. We identify opportunities where co-production of steel and chemicals can reduce GHG emissions and lower costs compared with maintaining independent production.

# Results

First, we develop a geodatabase of 272 steel plants and 187 coal chemical plants (2022 data) with plant-level characteristics in China (Source data). We spatially quantify the supply of $H_2$ and CO from steel plants and the demand for these compounds in coal chemical plants. Second, we customize an optimization model to match supply with demand at the plant level to maximize the GHG mitigation of the entire co-production system while not increasing costs relative to independent production of steel and chemicals. We use a baseline scenario where steel and chemicals are produced separately: excess steelmaking off-gas is combusted for electricity generation in steel plants, and coal is used for $H_2$ and CO production in coal chemical plants. We use a counterfactual co-production scenario where $H_2$ and CO purified from excess steelmaking off-gas is transported via pipelines to coal chemical plants for chemical syntheses. Scenario configurations are shown in Supplementary Fig. 1. Third, we apply a life-cycle assessment to quantify the GHG mitigation and cost reductions of the co-production scenario relative to the baseline scenario under different carbon prices and pipeline length limits. See details in Methods and Supplementary Notes 1–5.

## Changes in GHG emissions and cost per tonne of $H_2$ or CO

We estimate changes in GHG emissions and costs per tonne of $H_2$ or CO for co-production relative to independent production by individual process shown in Fig. 1. We exclude emissions and costs of pipelines because they mainly depend on pipeline lengths, which are determined by the optimization model for plant connections. However, we include pipeline-related processes (manufacturing, construction and installation, operation and maintenance, and decommissioning) in analyzing overall GHG emissions and costs of co-production at the national, provincial and plant levels. See details in Supplementary Information Note 3.

We first quantify changes in GHG emissions per tonne of $H_2$ or CO for co-production relative to independent production. Using $H_2$ from COG, CO from BFG and CO from BOFG reduces GHG emissions by 18.3 $tCO_2eq$ per tonne of $H_2$, 1.1 $tCO_2eq$ per tonne of CO and 1.2 $tCO_2eq$ per tonne of CO, respectively. GHG mitigation of using $H_2$ for co-production primarily results from replacement of coal-based $H_2$ with $H_2$ from steelmaking off-gas (−22.0 $tCO_2eq$ per tonne of $H_2$). For coal-based $H_2$ production, coal is first gasified to produce CO ($2C + O_2 \rightarrow 2CO$) and a portion of CO then undergoes the water–gas shift to produce $H_2$ ($CO + H_2O \rightarrow CO_2 + H_2$). GHG mitigation of using $H_2$ for co-production also results from reducing energy use in supporting processes such as producing steam for the water–gas shift (−3.6 $tCO_2eq$ per tonne of $H_2$) and producing $O_2$ and electricity for coal gasification (−2.5 and −1.0 $tCO_2eq$ per tonne of $H_2$, respectively). Reductions in coal for chemical feedstocks also decrease GHG emissions by 2.3 $tCO_2eq$ per tonne of $H_2$. GHG mitigation of using CO for co-production substantially results from avoiding the carbon-intensive CO-to-electricity (−1.57 $tCO_2eq$ per tonne). Additional GHG mitigation of using CO for co-production occurs due to reductions in coal, $O_2$ and electricity used for coal gasification (−0.14, −0.15 and −0.06 $tCO_2eq$ per tonne of CO, respectively). However, using $H_2$ and CO for co-production leads to an increase in GHG emissions from grid electricity generation (7.90 $tCO_2eq$ per tonne of $H_2$ and 0.47 $tCO_2eq$ per tonne of CO, respectively) needed for steel plant operations. Furthermore, gas purification increases GHG emissions by 2.58 $tCO_2eq$ per tonne of $H_2$ from COG, 0.27 $tCO_2eq$ per tonne of CO from BFG and 0.19 $tCO_2eq$ per tonne of CO from BOFG, respectively; gas compression (for transport) increases GHG emissions by 0.59 $tCO_2eq$ per tonne of $H_2$ and 0.04 $tCO_2eq$ per tonne of CO, respectively.

We then quantify cost changes per tonne of $H_2$ and CO for co-production relative to independent production. Using $H_2$ from COG for co-production yields a net cost reduction of 1,278 CNY per tonne of $H_2$. However, using CO from BFG and BOFG increases costs by 251 and 134 CNY per tonne of CO, respectively. Since coal-based $H_2$ and CO are replaced, cost reductions mainly result from reductions in coal

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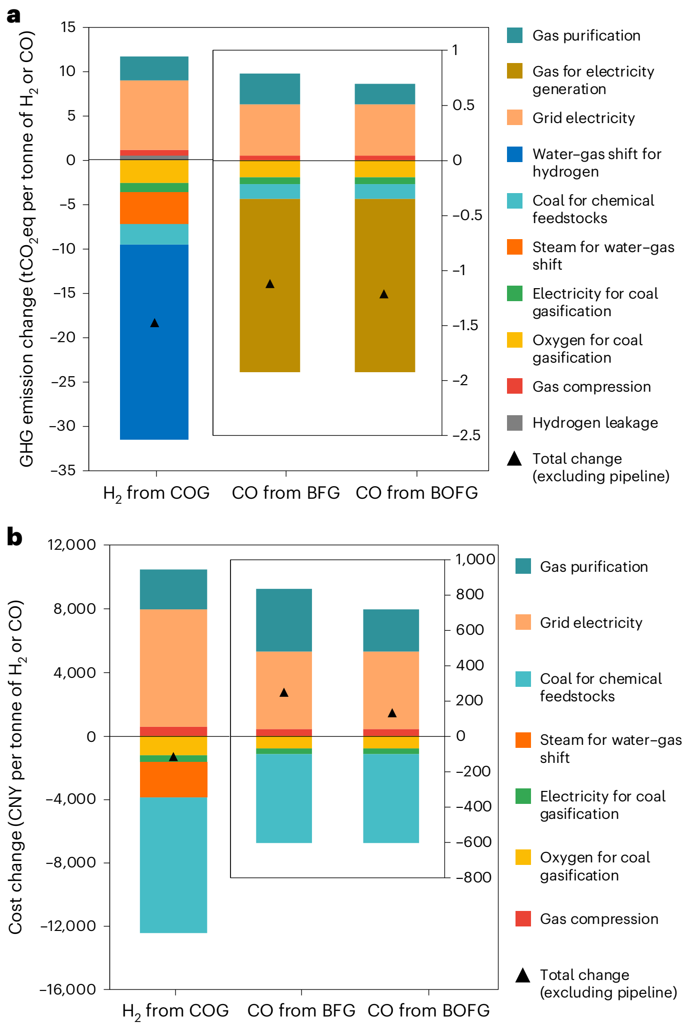


**Fig. 1 | Changes in GHG emissions and costs per tonne of $H_2$ or CO used for co-production relative to independent production.** **a**, Changes in GHG emissions. **b**, Changes in costs. Inner plots use the same metrics as outer plots. Costs use the metric of 2022 CNY.

production for chemical feedstocks (−8,540 CNY per tonne of $H_2$ and −502 CNY per tonne of CO), steam production for the water–gas shift (−2,186 CNY per tonne of $H_2$), $O_2$ production for coal gasification (−1,199 CNY per tonne of $H_2$ and −71 CNY per tonne of CO) and electricity generation for coal gasification (−484 CNY per tonne of $H_2$ and −28 CNY per tonne of CO). However, purchasing additional grid electricity results in major cost increases by 7,410 CNY per tonne of $H_2$ and 444 CNY per tonne of CO. Purifying $H_2$ and CO from steelmaking off-gas brings additional costs of 2,551 CNY per tonne of $H_2$, 351 CNY per tonne of CO from BFG and 234 CNY per tonne of CO from BOFG. Purified $H_2$ and CO requires compression before transport, which increases costs by 549 CNY per tonne of $H_2$ and 39 CNY per tonne of CO. Thus, decreasing grid electricity prices can lead to substantial cost decreases for co-production.

Pipelines are the most practical option to transport large volumes of gas over medium and long distances[27]. Our analysis includes pipeline manufacturing, installation, operation and maintenance, and decommissioning. GHG emissions per kilometer of pipelines is small relative to emissions from other individual processes (0.24 $kgCO_2eq$ per tonne per kilometer for $H_2$ and 0.017 $kgCO_2eq$ per tonne per kilometer for CO). However, costs per kilometer of pipelines are notable (4.4 CNY per tonne per kilometer for $H_2$ and 0.16 CNY per tonne per kilometer for CO; Methods). Therefore, incorporating pipelines results in an insignificant increase in GHG emissions of co-production but notably increases costs. The maximum cost-effective length for $H_2$ pipelines is 290 km without a carbon price for the steel and chemical sectors. However, CO pipelines require a carbon price or other alternative incentives to be cost-effective. The carbon price must be at least 240 CNY per $tCO_2$ for using CO from BFG and 120 CNY per $tCO_2$ for CO from BOFG, and higher for longer pipelines. For example, when using pipelines of 100 km, a carbon price of at least 260 and 130 CNY per $tCO_2$ is needed for cost-effectively transporting CO from BFG and from BOFG, respectively. In addition to carbon prices, we consider technical limits for pipeline lengths due to engineering and leakage concerns. See further discussions about pipelines in Methods and Supplementary Note 3.

## GHG mitigation and cost savings of co-production

We quantify the national and provincial GHG mitigation potential and costs of steel–chemical co-production relative to independent production. In doing so, we develop an optimization model that includes distances between existing steel and coal chemical plants, supply–demand matching of $H_2$ and CO, pipeline length limits and projected carbon prices when the steel and chemical sectors are covered in the national carbon trading market. The model derives the plant-level connections that maximize GHG mitigation of the co-production scenario relative to the baseline. Cost constraints require that no connection increases costs of paired steel and coal chemical plants relative to their independent production costs. See details in Methods and Supplementary Note 5.

Based on our geodatabase of China's steel and coal chemical plants, we estimate plant-level supply of $H_2$ and CO on the basis of production of blast furnace–basic oxygen furnace (BF–BOF) steelmaking. We also estimate plant-level demand for $H_2$ and CO on the basis of production of various chemical products (methanol, oil, natural gas, olefins, ethylene glycol and ethanol). The results are shown in Fig. 2, and calculations are clarified in Methods and Supplementary Notes 1 and 2. The spatial proximities of steel and coal chemical plants indicate that purified $H_2$ and CO from steelmaking off-gas can be transported via short-distance pipelines, especially in Shandong, Hebei, Shanxi, Jiangsu and Xinjiang. Overall, China's steel plants can supply 3.5 Mt $yr^{-1}$ of purified $H_2$ from steelmaking off-gas, which is equal to 19% of $H_2$ demand in coal chemical plants (18 Mt $yr^{-1}$). The steel plants can supply 218 Mt $yr^{-1}$ of CO (85% from BFG and 15% from BOFG), which is 180% of CO demand in coal chemical plants (121 Mt $yr^{-1}$). Thirty-seven percent of steel plants do not generate COG, from which $H_2$ is extracted, because they are not equipped with coking facilities and instead purchase coke from independent coking plants.

We then apply our optimization model to identify the plant-level connections that maximize the GHG mitigation of the co-production scenario and do not increase costs for any connection, relative to the baseline scenario (Methods and Supplementary Note 5). Figure 3 shows the overall rates of GHG mitigation and cost reductions under various pipeline length limits and carbon prices. We set a pipeline length limit ranging from 100 to 500 km based on existing studies[28], with a step length of 100 km. We use a range of 0–350 CNY per $tCO_2$ for carbon prices with an increment of 50 CNY per $tCO_2$, based on analyses of carbon pricing when both steel and chemical sectors are covered by China's carbon trading market[29]. China's national carbon trading market started operating for the electricity sector in 2021 and is expected to include the steel sector by 2025 and the chemical sector later, though the schedule has not been announced[29]. The carbon price is currently 40–60 CNY per $tCO_2$ (ref. 30) and is estimated to reach 326–459 CNY per $tCO_2$ when the steel and chemical sectors are covered[31]. Consistent with current practices, the carbon price in our study applies only to $CO_2$, excluding other GHGs. Figure 3 indicates that a higher pipeline length limit or a higher carbon price result in larger GHG mitigation and cost reductions. Thus, for a given pipeline length limit, the lower and upper limits of GHG mitigation rates and cost reduction rates are those derived with a carbon price of 0 and 350 CNY per $tCO_2$, respectively;

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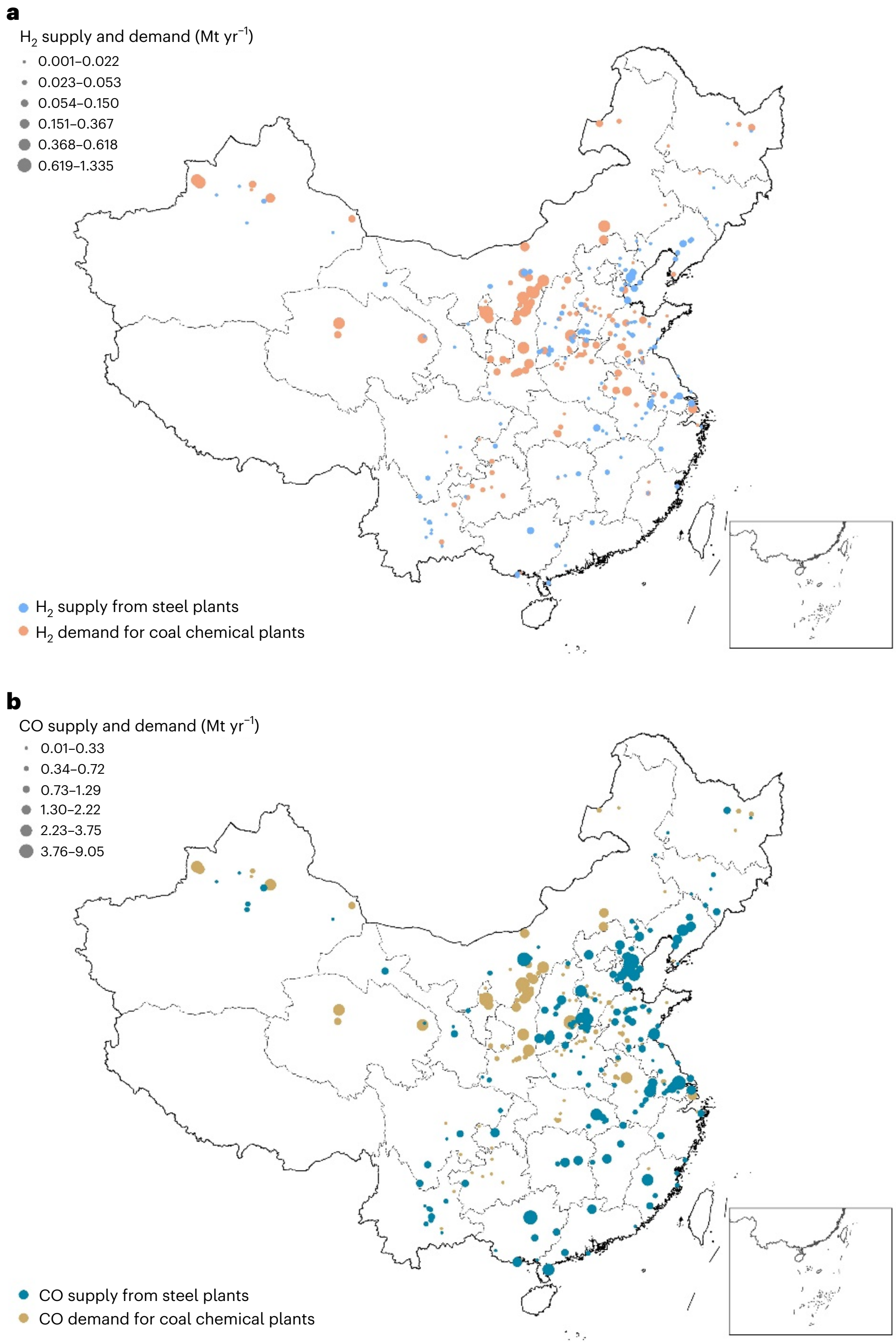


**Fig. 2 | Supply of $H_2$ and CO from steel plants and demand for $H_2$ and CO in coal chemical plants in China. a**, Supply. **b**, Demand. The China map is drawn by importing publicly released geographic data by the Ministry of Natural Resources of China[41] into ArcGIS software.

for a given carbon price, the lower and upper limits of GHG mitigation rates and cost reduction rates are those derived with a pipeline length limit of 100 and 500 km, respectively. As the pipeline length limit increases from 100 to 500 km, the GHG mitigation rate ramps up from 3.1–6.9% to 7.2–22% and the cost reduction rate increases from 0.4–3.4% to 0.6–9.8%. When there is no carbon price for the steel and chemical sectors, the GHG mitigation rate will be 3.1–7.2% and the cost reduction rate will only be 0.4–0.6%. A carbon price of 350 CNY per $tCO_2$ increases the GHG mitigation rate to 6.9–22% and the cost reduction rate to 3.4–9.8%. This is because a higher carbon price leads to larger carbon trading benefits to enable longer pipelines cost-effective, which brings additional co-production opportunities.

Without a carbon price, 2.0 $MtH_2\ yr^{-1}$ from steelmaking off-gas can be cost-effectively used for co-production, which reduces GHG emissions by 36 $MtCO_2eq\ yr^{-1}$ (−7.2%) and reduces costs by 1.5 billion CNY per year (−0.6%) relative to independent production. With a carbon price of 350 CNY per $tCO_2$, 2.8 $MtH_2\ yr^{-1}$ and 54 $MtCO\ yr^{-1}$ can be cost-effectively used for co-production, which reduces GHG emissions by 113 $MtCO_2eq\ yr^{-1}$ (−22%) and reduces costs by 25.5 billion CNY per year (−9.8%) relative to independent production. A carbon price of

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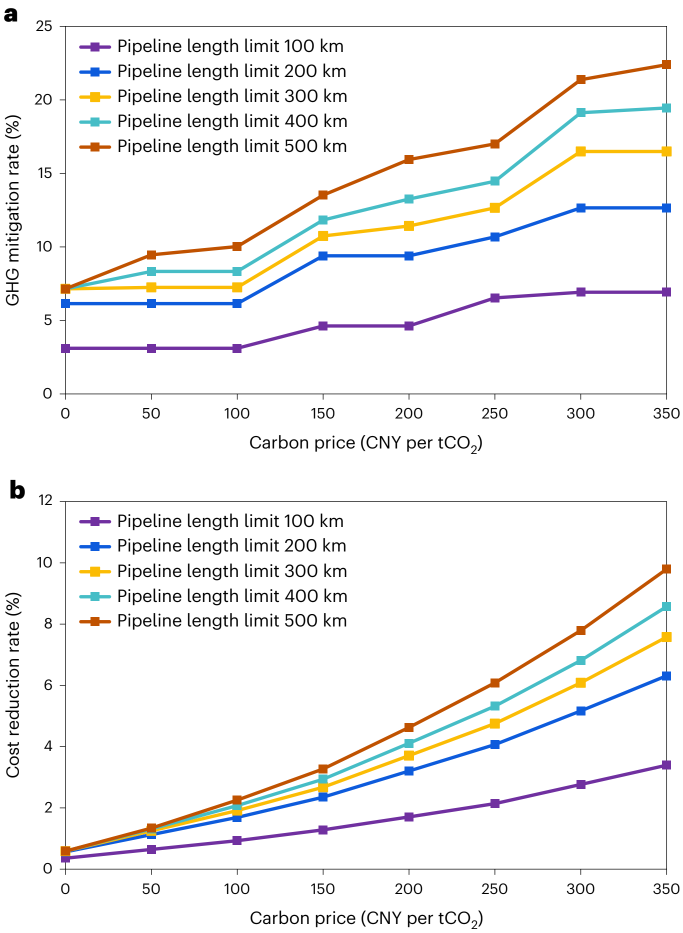


**Fig. 3 | GHG mitigation rates and cost reduction rates in co-production relative to independent production across carbon prices and pipeline length limits. a**, GHG mitigation rates. **b**, Cost reduction rates. GHG mitigation rates = differences in GHG emissions between the co-production and baseline scenarios/baseline emissions from coal chemical plants. Cost reduction rates = differences in costs between the co-production and baseline scenarios/baseline production costs of coal chemical plants. See details in Supplementary Table 4 for cost analyses in the baseline and co-production scenarios. The GHG metric is $CO_2$eq that convert $CO_2$, $CH_4$ and $N_2O$ emissions using 100-year global warming potential (GWP) of 1, 28 and 265, respectively[42]. See Supplementary Note 3 for discussions about results when using 100-year GWP and 20-year GWP. Carbon prices use the metric of 2022 CNY. Lines are used for illustrating the trends.

350 CNY per $tCO_2$ leads to an economically break-even pipeline length longer than 500 km (maximum pipeline length limit). Therefore, a carbon price higher than 350 CNY per $tCO_2$ cannot bring additional co-production opportunities. However, it could motivate more aggressive implementation of co-production connections due to increasing cost savings at the plant level.

For further analysis, we use a pipeline length limit of 500 km and a carbon price of 350 CNY per $tCO_2$ because this combination yields the maximum GHG mitigation and cost reductions in the co-production scenario relative to the baseline. Under these conditions, the co-production scenario results in total GHG mitigation of 113 $MtCO_2$eq $yr^{-1}$ (−22%) and total cost reduction of 25.5 billion CNY per year (−9.8%). We further decompose these changes by industrial process at both national and provincial levels, as shown in Fig. 4. At the national level, co-production results in additional GHG emissions from grid electricity generation and gas purification by 47 $MtCO_2$eq $yr^{-1}$ and 20 $MtCO_2$eq $yr^{-1}$, respectively (Fig. 4a). Gas compression, $H_2$ leakage and pipeline-related processes (including pipeline manufacturing, installation, maintenance and decommissioning) contribute small additional GHG emissions of 3.9, 1.5 and 0.3 $MtCO_2$eq $yr^{-1}$, respectively. However, these additional GHG emissions can be more than offset by emission reductions in CO-to-electricity (−85 $MtCO_2$eq $yr^{-1}$) and the water–gas shift for $H_2$ production (−58 $MtCO_2$eq $yr^{-1}$). Production of coal, $O_2$, steam and electricity for coal gasification and/or the water–gas shift reaction collectively account for a reduction of 43 $MtCO_2$eq $yr^{-1}$.

We find similar patterns in cost changes. In the co-production scenario, grid electricity generation and gas purification substantially increase costs by 45 and 23 billion CNY per year (Fig. 4b), while cost increases in pipelines and gas compression are small (4.4 and 3.6 billion CNY per year, respectively). Cost savings are primarily due to using less coal for chemical feedstocks, leading to a cost reduction of 49 billion CNY per year. Reduction in supporting processes, including $O_2$ and electricity generation for coal gasification and steam production for the water–gas shift, collectively result in a cost saving of 15 billion CNY per year. In addition, reduced $CO_2$ emissions can be sold in the trading market and offer remarkable benefits of 37 billion CNY per year.

Furthermore, comparable GHG mitigation of 51 or 62 $MtCO_2$eq $yr^{-1}$ is obtained by using $H_2$ or CO from steelmaking off-gas for chemical production, respectively. However, using $H_2$ for co-production reduces costs by 18 billion CNY per year, which is more than twice the cost savings obtained by using CO for co-production (7.7 billion CNY per year). Such cost disparity between using $H_2$ and CO mainly results from more coal is required to produce one tonne of $H_2$ (8.0 tonnes of coal per tonne $H_2$) than CO (0.47 tonnes of coal per tonne of CO). Consequently, using $H_2$ for co-production leads to larger coal cost savings. See details in Supplementary Fig. 2.

At the provincial level, changes in onsite GHG emissions are attributed to provinces where they physically occur, and changes in upstream GHG emissions of grid electricity generation, pipeline-related processes and coal production are allocated to provinces on the basis of provincial production of thermal electricity, crude steel and coal (see details in Supplementary Table 5). Among the 31 provinces studied (excluding Hong Kong, Macau and Taiwan due to data unavailability), 21 achieve a net GHG emission reduction and 16 achieve a net cost reduction in the co-production scenario relative to the baseline scenario (Fig. 4c,d). We find that Shanxi, Hebei, Inner Mongolia and Shandong collectively account for 67% of total GHG mitigation. Such dominance is due to their spatial proximities of steel and coal chemical plants, enabling large volumes of $H_2$ and CO to be transported via pipelines for co-production.

We find that cost reductions mainly occur in Shandong, Shaanxi, Inner Mongolia and Anhui. Some steel-intensive provinces observe net cost increases via co-production though they exhibit substantial GHG mitigation, such as Hebei and Jiangsu. This implies the imbalanced cost–benefit allocation between the supply and demand sides. On the demand side, coal chemical plants use byproduct $H_2$ and CO from steel plants and thus reduce their coal costs for feedstocks and fuels. However, on the supply side, steel plants must purchase additional grid electricity since they redirect off-gas from electricity generation to chemical production. In Fig. 4d, we attribute cost changes to either steel or coal chemical plants on the basis of where they physically occur. Carbon trading benefits are attributed to where $CO_2$ mitigation occurs. Such location-based cost–benefit allocation, though intuitive in practice, might compromise the economic benefits for steel plants even though they facilitate the GHG mitigation in coal chemical plants. Therefore, a win–win cost–benefit allocation is required to foster the co-production. Specifically, steel plants can price byproduct $H_2$ and CO on the basis of the revenues they would have gained if they used off-gas for electricity generation. In doing so, coal chemical plants can share coal cost savings and carbon trading benefits with their paired steel plants.

We identify the provincial flows of cost-effective $H_2$ and CO supply from steel plants to coal chemical plants, as shown in Fig. 5. Total cost-effective supply in steel plants is 2.8 Mt $yr^{-1}$ for $H_2$ and 54 Mt $yr^{-1}$ for CO, equal to 14% and 43% of total $H_2$ and CO demand in coal chemical plants, respectively. On the supply side, Hebei, Shanxi, Inner

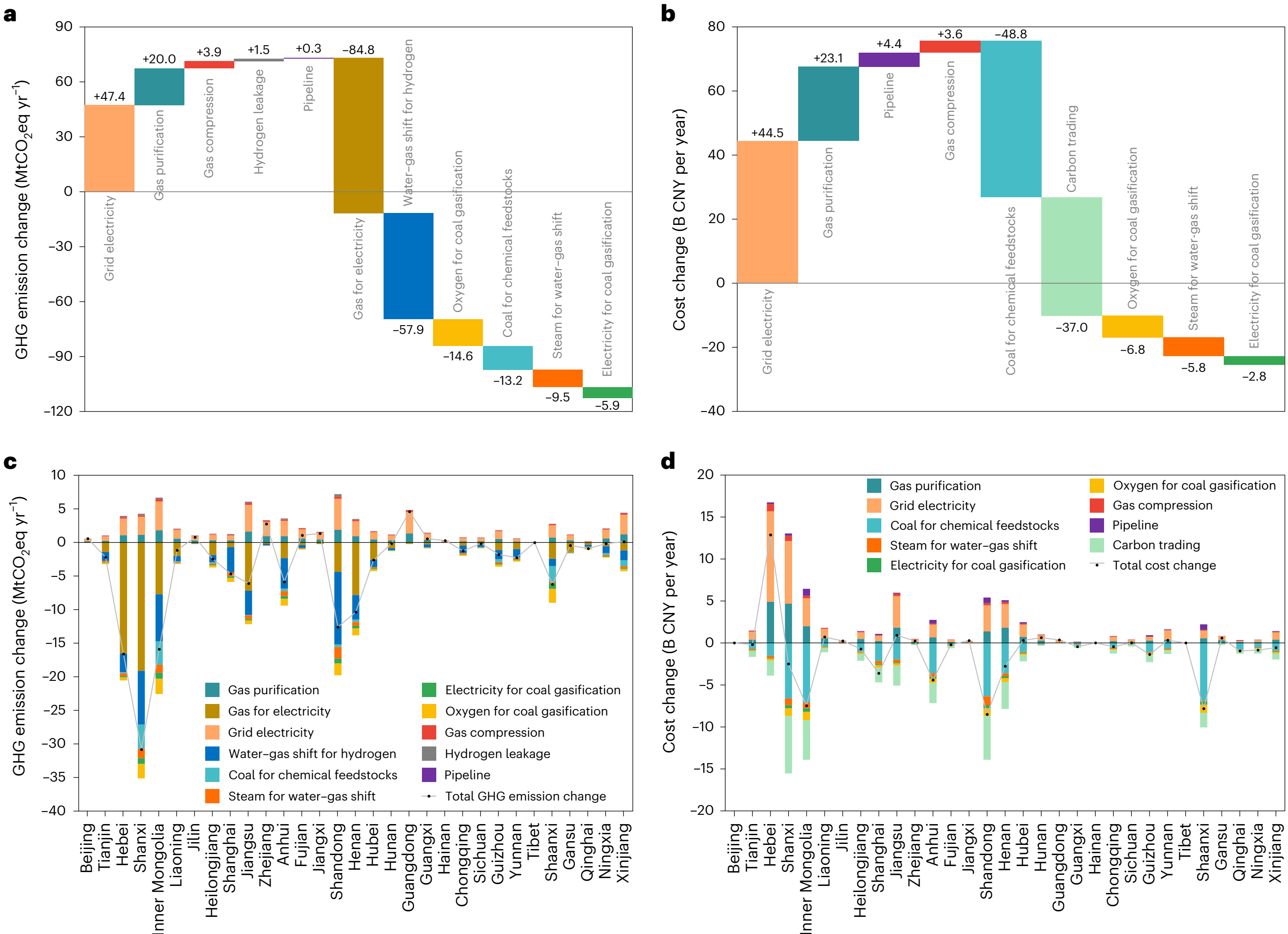


**Fig. 4 | Changes in GHG emissions and costs by industrial process in co-production relative to independent production.** **a**, National GHG emission changes. **b**, National cost changes. **c**, Provincial GHG emission changes. **d**, Provincial cost changes. We use a pipeline length limit of 500 km and a carbon price of 350 CNY per $tCO_2$. Costs use the metric of 2022 CNY.

Mongolia, Jiangsu, Shandong and Henan collectively provide 66% and 74% of cost-effective $H_2$ and CO supply, respectively. On the demand side, Shanxi, Inner Mongolia, Anhui, Shandong, Henan and Shaanxi collectively receive 61% and 78% of cost-effective $H_2$ and CO supply, respectively. Most provinces have intra-province flows, accounting for 48% and 42% of total cost-effective $H_2$ and CO supply, respectively. Inter-province flows constitute 52% and 58% of total cost-effective $H_2$ and CO, respectively. Provinces that have intensive steel plants, such as Hebei and Jiangsu, supply $H_2$ and CO to surrounding provinces due to extensive short-distance transport opportunities for the co-production.

## Connection-level analysis of co-production

Based on our optimization model, we obtain 599 cost-effective co-production connections between existing steel and coal chemical plants (Source data). Among all, 34% of connections use $H_2$ from COG, 16% use CO from BFG and 50% use CO from BOFG. Figure 6 shows the locations where onsite GHG mitigation occurs due to reductions in onsite fuel combustion and chemical reactions, using 0.25° resolution grid boxes. We find that onsite GHG mitigation of CO connections is more extensive across the country than that of $H_2$ connections. This is because CO connections reduce onsite emissions in both steel and coal chemical plants by reducing onsite electricity generation from CO and coal, respectively. $H_2$ connections only reduce onsite emissions in coal chemical plants by reducing coal-based $H_2$ production. Hebei, Shanxi, Shandong and Henan are hotspots for co-production connections because they have many steel plants in proximity to coal chemical plants. These four provinces include 54% and 49% of all connections from the supply and demand sides, respectively.

We further examine the connection-level characteristics to identify critical connections. Supplementary Fig. 3a shows that cost reductions go up with GHG mitigation, and for a given quantity of GHG mitigation, the order of cost reductions is $H_2$ from COG > CO from BOFG > CO from BFG. On average, these connections result in GHG mitigation of 0.25, 0.10 and 0.33 $MtCO_2eq\ yr^{-1}$, respectively, and cost reductions of 86, 19 and 22 million CNY per year, respectively. Connections using CO from BOFG exhibit a better economic performance than those using CO from BFG due to a lower purification cost per tonne of CO produced (at a purity level of at least 98.5% (ref. 32)). Supplementary Fig. 3b shows that unit cost reductions go down with pipeline lengths due to an increase in pipeline costs, and the order of unit cost reductions is $H_2$ from COG > CO from BOFG > CO from BFG. The average unit cost reductions for these connections are 6,400 CNY per tonne of $H_2$, 224 CNY per tonne of CO and 76 CNY per tonne of CO, respectively, and their average pipeline lengths are 206, 215 and 227 km, respectively. Notably, 54% of connections have a pipeline length less than 200 km and they account for 53% of total GHG mitigation. Although shorter pipeline lengths are preferrable to obtain higher unit cost reductions, many cost-effective connections have longer

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pipelines because additional costs of pipelines constitute only a minor portion of total costs (Fig. 4b).

Furthermore, we rank all cost-effective connections on the basis of the magnitude of GHG mitigation from highest to lowest, and find that 24% of the connections can achieve 60% of both total GHG mitigation and total cost reduction (Supplementary Fig. 4). This highlights the importance of prioritizing these critical connections to obtain most of carbon mitigation and cost savings. By leveraging a plant-level geodatabase with our optimization model, this study offers policymakers granular insights into these critical connections.

## Discussion

Decarbonizing hard-to-abate sectors is a critical yet challenging step toward a net-zero emissions future. The steel and coal chemical sectors are the largest hard-to-abate emitters in China, collectively accounting for about one-fourth of national GHG emissions[6,7]. GHG mitigation potential of efficiency measures is limited[4,8], and green hydrogen and CCUS might remain costly over the next two decades[10,11]. However, our study demonstrates that co-production of steel and chemicals can reduce these hard-to-abate emissions in the near future. By using a plant-level geodatabase and a life-cycle-based optimization model, this study examines the GHG mitigation and costs of co-production between China's steel and coal chemical sectors, considering a range of possible carbon prices and pipeline length limits. This study extends previous studies by analyzing existing steel and coal chemical plants across China, including all relevant industrial processes in co-production, and prioritizing connections between existing plants rather than the construction of new chemical facilities. Therefore, our findings can directly inform co-production policymaking at the national, regional and plant levels and pinpoint the most feasible and beneficial connections for pilot projects.

We find that, without a carbon price in the steel and coal chemical sectors, using $H_2$ for co-production reduces costs even for long-distance connections relative to independent production. However, using CO for co-production increases costs, and thus, carbon pricing is needed to unlock the GHG mitigation of byproduct CO-to-chemicals. Under a carbon price of 350 CNY per $tCO_2$ and a pipeline length limit of 500 km, cost-effective $H_2$ supply accounts for 79% of total supply of $H_2$ from COG while cost-effective CO supply accounts for 16% and 77% of total supply of CO from BFG and from BOFG, respectively. These cost-effective connections deliver a total GHG mitigation of 113 $MtCO_2eq\ yr^{-1}$ (−22%) and a total cost reduction of 25.5 billion CNY per year (−9.8%). The majority of GHG mitigation results from reductions in coal-based $H_2$ production and CO-to-electricity, while cost savings are mainly from reductions in coal for feedstocks and fuels and additional benefits in carbon trading. In particular, reductions in coal used for $H_2$ and CO production amount to 21 $Mt\ yr^{-1}$ and 25 $Mt\ yr^{-1}$, respectively, collectively equal to 1.1% of China's annual coal consumption. In addition, spatial proximity of a subset of steel and coal chemical plants allows for most of the GHG mitigation and cost reductions. About 50% of the connections occur within several neighboring provinces, including Hebei, Shanxi, Shandong and Henan. We find that 60% of GHG mitigation and cost reductions can be achieved via only 24% of all possible connections. Thus, these cost-effective high-mitigation connections should be prioritized for demonstration.

We also suggest an equitable allocation to balance expenses and gains between steel and coal chemical plants. Attributing costs and benefits to plants on the basis of where they physically occur (Fig. 4d) might compromise the economic benefits for steel plants. This is because most cost reductions occur in coal chemical plants due to coal cost savings and carbon trading benefits. Steel plants, in contrast, incur the majority of cost increases because they need to purchase additional grid electricity when redirecting steelmaking off-gas from electricity generation to chemical production. In China's national strategies to peak carbon emissions, steel–chemical co-production is highlighted as a vital approach to decarbonize the steel sector only. Our findings suggest a cross-sector policy framework to facilitate the co-production between steel and chemical sectors. Policymakers can help price byproduct $H_2$ and CO to incentivize steel plants to adopt co-production, and such pricing can be based on off-gas-to-electricity revenues and carbon prices.

We use a counterfactual approach to quantify the GHG mitigation and cost changes of co-production compared with independent production. Our model is built on current configurations of steel and coal chemical plants, which can offer valuable insights to inform immediate policy decision. However, it has limitations since it does not include future changes in energy parameters (for example, grid electricity mixes and prices) or in these plants (for example, technology updates and capacity expansions). To partly address the limitations, we analyze the sensitivity of the results to critical parameters, including grid electricity, pipeline parameters, coal production, and $H_2$ and CO concentrations in steelmaking off-gas (Supplementary Note 6 and Supplementary Table 6).

This study uses a recent national average grid electricity price of ~0.55 CNY $kWh^{-1}$, and the price is projected to decrease to below 0.3 CNY $kWh^{-1}$ in the near future[33] due to the electricity market reform and increased utilization of renewable electricity. A reduction in the grid electricity carbon intensity reduces both GHG emissions and costs, while a reduction in grid electricity price only reduces costs. This indicates that additional carbon and economic benefits of co-production can be achieved by reducing the carbon intensity and price of grid electricity. When we reduce grid electricity carbon intensity by 95% and grid electricity price by 20% to simulate green power trading, GHG mitigation and cost reductions are substantially increased relative to the original results (60% and 50%, respectively). Thus, expansion of the green power trading market has a large potential to motivate steel–chemical co-production.

Existing studies suggest that Chinese steelmaking plants will continue to use the BF–BOF route and, thus, will generate off-gas through 2040 (ref. 8), which has led to our assumption of a 20-year lifetime for gas pipelines in this study. In response to the possibility of accelerated technological transition in steelmaking, we examine the impacts of a shortened pipeline lifetime in co-production, as shown in Supplementary Table 6. We find that a reduced pipeline lifetime slightly reduces annual GHG mitigation and cost reductions of co-production. This indicates that, on an annual basis, co-production is a cost-effective way to mitigate GHG emissions even with conservative assumptions about the pipeline lifetime. However, a shortened pipeline lifetime will reduce cumulative GHG mitigation and cost savings. Given the limited time window of roughly two decades before $H_2$ and scrap steel become dominant in steelmaking[8], we recommend fast-tracking demonstration projects of the most cost-effective connections identified by our plant-level modeling. In addition, a 50% increase in pipeline unit costs slightly increases both GHG emissions and costs of co-production while a 50% decrease in pipeline unit costs slightly reduces costs of co-production. This indicates that, if pipeline unit costs decrease with pipeline capacities as a result of economies of scale, co-production can achieve additional cost reductions compared with the current results.

To analyze the impacts $H_2$ and CO concentrations in steelmaking off-gas on co-production, we reevaluated the outcomes using the upper and lower limits of the three specified ranges (55–60% for $H_2$ concentration in COG, 23–27% for CO in BFG and 50–70% for CO in BOFG[15]) (Supplementary Note 6). We find that higher $H_2$ and CO concentrations further reduce the GHG emissions and costs of co-production relative to independent production, due to an increase in $H_2$ and CO supply. However, even using the upper/lower limits of the concentration ranges, variations in the results are not notable, which demonstrates the robustness of our conclusions.

We also recognize the uncertainty of including steel and chemical sectors in China's national carbon trading market. The carbon trading

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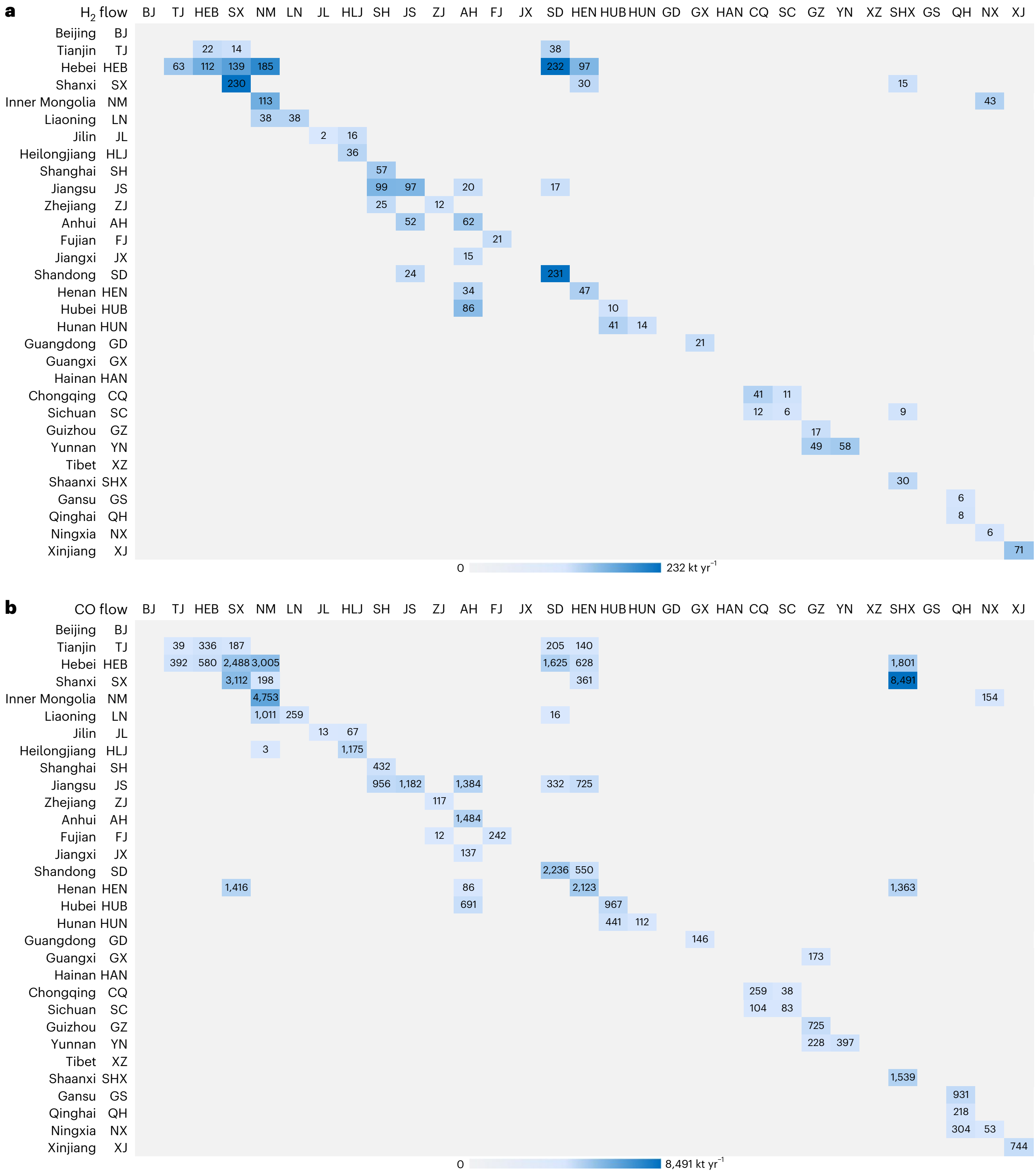


**Fig. 5 | Cost-effective supply of $H_2$ and CO in the co-production from origin provinces (rows) to destination provinces (columns). a**, $H_2$ flows. **b**, CO flows.

market currently covers only the coal- and natural gas-fired electricity sector and is likely to expand to the steel sector by 2025 and the coal chemical sector later[29]. The feasibility of connections is notably affected by carbon prices and pipeline length limits. We analyze the sensitivity of GHG emission mitigation and cost reductions of the co-production to carbon prices and pipeline length limits (Fig. 3). We apply a range of 0–350 CNY per $tCO_2$ for carbon prices and a range of 100–500 km for pipeline length limits based on real cases and literature[28,31]. We find that, with higher carbon prices and pipeline length limits, co-production can achieve larger GHG mitigation and cost reductions relative to the baseline. However, the timely integration of the steel and chemical sectors into the national carbon trading market remains uncertain due

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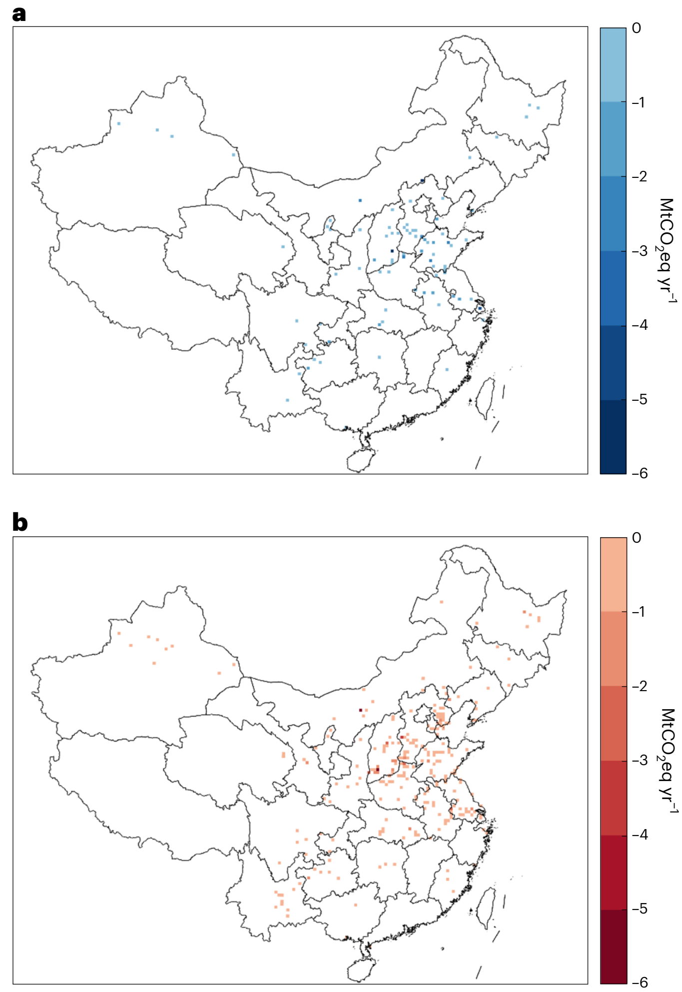


**Fig. 6 | Onsite GHG mitigation of $H_2$ and CO connections in co-production relative to independent production. a**, $H_2$ connections. **b**, CO connections. Onsite GHG mitigation results from reductions in onsite fuel combustion and chemical reactions, presented in 0.25°-resolution grid boxes. Onsite GHG mitigation of $H_2$ connections occurs in coal chemical plants due to reductions in coal-based $H_2$ production. Onsite GHG mitigation of CO connections occur in steel plants due to reductions in CO-to-electricity and in coal chemical plants due to reductions in coal gasification. The China map is drawn by importing publicly released geographic data by the Ministry of Natural Resources of China[41] into ArcGIS software.

to the complexity of GHG emissions accounting (for example, onsite GHG emissions result from both fuel combustion and chemical reactions in steel and chemical plants). However, these uncertainties do not overshadow the contributions of our study. First, this study indicates notable GHG mitigation potential of steel–chemical co-production even without economic incentives for carbon reductions. We find a GHG mitigation rate of 3.1–7.2% in the absence of carbon pricing (Fig. 3), which is still considerable. Second, national carbon prices analyzed in this study can be a benchmark for sectoral alternative incentives such as subsidies, tax credits and grants. Therefore, our findings offer crucial insights into how co-production can achieve GHG mitigation in a cost-effective way.

We provide a comprehensive analysis of the carbon and cost implications of steel–chemical co-production. We demonstrate that co-production is a feasible way to mitigate GHG emissions from the steel and chemical sectors. Our findings highlight the importance of targeting cost-effective high GHG mitigation connections between steel and chemical plants to achieve the majority of carbon and cost reductions. They also emphasize the need for a balanced cost–benefit allocation mechanism between steel and coal chemical plants to incentivize co-production.

## Methods

### Geodatabase development

We develop a geodatabase for China of 272 steel plants that generate off-gas from the BF–BOF steelmaking route and 187 coal chemical plants that require $H_2$ and/or CO for chemical syntheses (2022 data). We integrate the Global Steel Plant Tracker and AnyChem Coal Chemical Dataset[34,35] with technical and cost parameters obtained from national/sectoral statistics, technical reports, government documents and literature (Supplementary Note 1). Total crude steel production of these 272 steel plants is ~830 Mt $yr^{-1}$ in 2022. Each of these plants may have several units consisting of coke ovens, BFs and BOFs. To estimate the generation of COG, BFG and BOFG in each steel plant, we use the BF–BOF steel production data, coking capacity data and the generation factors of COG, BFG and BOFG (Supplementary Note 1). In practice, of the off-gas produced, approximately 55% of COG, 50% of BFG and 52% of BOFG, is currently used for electricity generation, and the rest is returned to steelmaking systems as reductants and fuels[12,15–17]. COG is rich in $H_2$, and BFG and BOFG are rich in CO. We then use the volume of steelmaking off-gas used for electricity generation and its concentrations of $H_2$ and CO to derive the $H_2$ and CO volumes that each steel plant can supply for chemical production. The 187 Chinese coal chemical plants include coal-based production of methanol, oil, natural gas, olefin, ethylene glycol and ethanol, with a total capacity of ~90 Mt $yr^{-1}$ and a total production of ~75 Mt $yr^{-1}$. We use plant capacities, capacity factors and chemical reaction parameters to derive the $H_2$ and CO demand of each coal chemical plant. See Supplementary Note 1 for our method for estimating plant-level supply and demand of $H_2$ and CO. We further clarify the data reliability for steel and coal chemical plants in our analysis, as in Supplementary Note 2.

We collect the geographic coordinates of steel and coal chemical plants from the Global Steel Plant Tracker[35] and Baidu Map[36], respectively. We derive a matrix (272 × 187) of roadway distances from steel plants to coal chemical plants via geographic techniques using the open application programming interface of Baidu Map[36]. The road distances are used for gas pipeline lengths because pipelines are generally deployed along roads according to national guidelines[37]. We detail the geodatabase and parameters in Source data and supplementary notes and tables.

Given the small quantity of methane in steelmaking off-gas, purification and chemical utilization of methane is less cost-effective than for $H_2$ and CO due to limited economies of scale. In addition, coal chemical plants require additional costs for equipment retrofits if they utilize methane for chemical production. Thus, our analysis focuses on bridging steel and coal chemical plants via utilizing $H_2$ and CO from steelmaking off-gas for chemical production.

### Optimization model

We adopt a counterfactual method and use 2022 data for the baseline and co-production scenarios. In the baseline scenario, steel and chemicals are produced separately: excess steelmaking off-gas is combusted for electricity generation in steel plants, and coal is used to produce $H_2$ and CO for coal chemical plants. In the co-production scenario, $H_2$ and CO are purified from excess steelmaking off-gas and then transported via pipelines to coal chemical plants for chemical syntheses. Compared with the baseline scenario, the co-production scenario requires additional gas purification, gas compression and pipeline-related processes. Steel plants must purchase additional grid electricity due to reductions in use of CO for electricity generation. Coal chemical plants reduce coal used for $H_2$ and CO production as well as reduce coal used for supporting processes (such as production of $O_2$, steam and electricity) due to use of byproduct $H_2$ and CO from steel plants. Accordingly, we identify differences in GHG emissions and costs between the baseline and co-production scenarios that have the same output of steel and coal chemicals. We detail the estimations for changes in GHG emissions and costs per tonne of $H_2$ and CO used for co-production in Supplementary Note 3.

We use a life-cycle assessment[38,39] that incorporates onsite and upstream processes to quantify GHG emission changes of the co-production scenario compared with the baseline scenario. The functional unit is defined as the production of 1 tonne of steel and $x$ tonnes of coal chemicals, where $x$ depends on the type of coal chemical product (methanol, natural gas, oil (direct or indirect liquefaction), olefin, ethylene glycol and ethanol). Therefore, the two scenarios produce the same amounts of steel and chemicals. We apply a broad system boundary to analyze the GHG emissions from all critical processes relevant to the co-production, such as gas purification and compression, pipeline-related processes, gas leakage, CO for electricity generation, steelmaking, chemical reactions (coal gasification and the water–gas shift), coal for electricity generation, air separation for $O_2$ production, steam production and upstream production processes of grid electricity, coal, iron ore and limestone. We present the functional unit and system boundary of our analysis in Supplementary Fig. 1.

We develop an optimization model that matches the plant-level supply and demand of $H_2$ and CO between steel plants and coal chemical plants considering their spatial proximities. The model derives the solution of cost-effective connections that maximize the GHG mitigation of the co-production scenario and simultaneously do not increase costs for any connection, relative to the baseline scenario (equation (1)). We coded the optimization model in C++.

$$\begin{aligned}&\text{Maximize GHG mitigation in co-production scenario}\\&\text{relative to baseline scenario}\\&\text{Subject to (co-production cost} - \text{baseline cost)}\\&\text{of each connection} \le 0\end{aligned} \quad (1)$$

We detail the estimations for changes in GHG emissions and costs per tonne of $H_2$ and CO used for co-production in Supplementary Note 3. We clarify the $CO_2$ mitigation per tonne of $H_2$ and CO used for co-production that can be used in carbon trading in Supplementary Note 4. We then model the cost-effective connections between plants as follows (see details in Supplementary Note 5). We also consider possible carbon prices and pipeline length limits to include the uncertainty of future carbon trading market and pipeline engineering constraints (Fig. 3).

In particular, pipelines are the most practical option to transport large volumes of $H_2$ and CO over medium and long distances for continuous coal chemical production. There are two demonstration projects of $H_2$ pipeline transport in China[40], whose parameters are used as references in our analysis. $H_2$ and CO from steel plants should be transported to nearby coal chemical plants as much as possible to reduce pipeline costs and pipeline-related emissions. We optimize $H_2$ and CO connections separately to allow $H_2$ and CO from each steel plant to be transported to different coal chemical plants depending on demand. Steel plants can also provide $H_2$ or CO to multiple coal chemical plants in our model. We describe the optimization model step by step in Supplementary Note 5. We further analyze the sensitivity of the results to critical parameters, including those for pipelines, grid electricity, coal production and $H_2$ and CO concentrations in steelmaking off-gas (Supplementary Note 6).

### Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

## Data availability

Source data are provided with this paper. All data and parameters used for this study are provided in Source data and Supplementary Information.

## Code availability

Each component of our model is detailed in Supplementary Information with parameterizations provided for each step. The codes for the optimization algorithms and mapping of grid boxes are available via GitHub at https://github.com/indsyn/Steel-chemical (ref. 43).

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## Author contributions

Y.G. and D.L.M. conceived the research idea. Y.G., J.L. and D.L.M. designed the study procedures; Y.G. and J.L. compiled the database and configured the scenarios; Y.G. conducted the parameterizations and modeling; Y.G. and J.L. made the figures and tables; J.L., Q.Z., Y.C. and L.C. contributed to parameterizations; Y.G., J.L., Q.Z., Y.C., L.C. and D.L.M. analyzed the results; Y.G., J.L. and D.L.M. wrote the paper with contributions from all authors.

## Competing interests

The authors declare no competing interests.

## Additional information

**Supplementary information** The online version contains supplementary material available at https://doi.org/10.1038/s44286-024-00061-1.

**Correspondence and requests for materials** should be addressed to Yang Guo or Denise L. Mauzerall.

**Peer review information** *Nature Chemical Engineering* thanks the anonymous reviewers for their contribution to the peer review of this work.

nature research

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Denise L. Mauzerall

Last updated by author(s): Oct 27, 2023

# Reporting Summary

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| ☒ | ☐ | The statistical test(s) used AND whether they are one- or two-sided<br>*Only common tests should be described solely by name; describe more complex techniques in the Methods section.* |
| ☒ | ☐ | A description of all covariates tested |
| ☒ | ☐ | A description of any assumptions or corrections, such as tests of normality and adjustment for multiple comparisons |
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| ☒ | ☐ | For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings |
| ☒ | ☐ | For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes |
| ☒ | ☐ | Estimates of effect sizes (e.g. Cohen's *d*, Pearson's *r*), indicating how they were calculated |

*Our web collection on statistics for biologists contains articles on many of the points above.*

## Software and code

Policy information about availability of computer code

| | |
|---|---|
| Data collection | No software was used for data collection. |
| Data analysis | 1) We design an optimization algorithm to identify the connections between steel plants and coal chemical plants using C++.<br>2) We assess life-cycle environmental impacts and economic costs of steel-chemical connections using Excel 2019.<br>3) We conduct geographic data analyses and present spatial data using MATLAB R2023a and ArcGIS V10.4.1. |

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☐ Life sciences ☐ Behavioural & social sciences ☒ Ecological, evolutionary & environmental sciences

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# Ecological, evolutionary & environmental sciences study design

All studies must disclose on these points even when the disclosure is negative.

| | |
|---|---|
| Study description | Here we examine the carbon and cost implications of deploying co-production of steel and chemicals across China, via establishing connections between existing plants. Our study includes plant-level characteristics of steelmaking and coal chemical production across China, and models GHG emissions and costs of associated industrial processes from a life-cycle perspective. We identify opportunities where co-production of steel and chemicals can reduce GHG emissions and lower costs compared to maintaining separate production. |
| Research sample | 272 steel plants and 187 coal chemical plants (2022 data) in China |
| Sampling strategy | No sampling strategy |
| Data collection | We integrate the Global Steel Plant Tracker and AnyChem Coal Chemical Dataset with technical and cost parameters obtained from national/sectoral statistics, technical reports, government documents, and literature.<br>We collect the geographic coordinates of steel and coal chemical plants from the Global Steel Plant Tracker and Baidu Map, respectively.<br>We derive a matrix (272×187) of roadway distances from steel plants to coal chemical plants via geographic techniques using the open application programming interface of Baidu Map.<br>We refer to all data sources in the main text and Supplementary Information. |
| Timing and spatial scale | 2022 data in China |
| Data exclusions | No data exclusion |
| Reproducibility | We provide all the input and output data of our model in the Source Data file. All the codes are also available. Other parameterizations and detailed results are described in Supplementary Information. |
| Randomization | The data are not from a random sampling, and randomization is not involved. |
| Blinding | Blinding methods are not involved in this study. |

Did the study involve field work? ☐ Yes ☒ No

# Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

## Materials & experimental systems

| n/a | Involved in the study | |
|---|---|---|
| ☒ | ☐ | Antibodies |
| ☒ | ☐ | Eukaryotic cell lines |
| ☒ | ☐ | Palaeontology and archaeology |
| ☒ | ☐ | Animals and other organisms |
| ☒ | ☐ | Human research participants |
| ☒ | ☐ | Clinical data |
| ☒ | ☐ | Dual use research of concern |

## Methods

| n/a | Involved in the study | |
|---|---|---|
| ☒ | ☐ | ChIP-seq |
| ☒ | ☐ | Flow cytometry |
| ☒ | ☐ | MRI-based neuroimaging |