Journal of Cleaner Production 384 (2023) 135550

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Steel decarbonization in China – a top-down optimization model for exploring the first steps

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ARTICLE INFO

Handling Editor: Jing Meng

Keywords:
China
Steel industry
Decarbonization
Air pollution impact
Provincial allocation

ABSTRACT

The steel industry is a major contributor to emissions of CO_2 and key air pollutants. Reducing air pollution has since long been a policy priority in China. Reducing CO_2 emissions has more recently also become a key priority partially manifested through the signing of the Paris Agreement in 2015. Although there are often synergies between reducing CO_2 emissions and air pollution, it may have implications for the geographical location if one is prioritized over the other, with subsequent effects on local economies and overall policy efficiency. Therefore, we build a top-down optimization model to assess the provincial allocation of steel production, air pollution impact and the cost for meeting the target of peaking CO_2 emissions in 2025 and reducing them by 30% in 2030. This short-term reduction target can be regarded as the first steps for China's steel industry to meet the national net zero target and the Pairs agreement. We analyze a scenario to minimize air pollution impact and compare this with a scenario to minimize CO_2 mitigation costs. The results show that it is possible to peak CO_2 emissions in 2025 and reduce them by 30% in 2030 but the resulting scrap demand requires increased quality scrap collection or imports. The total cost for different scenarios is similar but optimizing on abatement cost leads to lower cumulative CO_2 emissions 2021–2030 compared to optimizing on pollution impact. If reducing pollution impact is the main objective, it leads to 22–26% lower pollution impact than when optimizing on abatement costs, and less primary production in densely populated areas. This implies that policy must handle trade-offs between cost optimal mitigation and pollution impact, as well as effects on local economies. Policy must also balance the accelerated introduction of Electric Arc Furnaces while simultaneously reducing overcapacity in primary production.

1. Introduction

The steel industry is one of main emitters of global greenhouse gas emissions and it accounts for approximately eight percent of global CO_2 emissions (McKinsey and Company, 2020). China is the largest steel producer in the world, accounting for 57% of global production. In terms of CO_2 emissions, the Chinese steel industry accounts of 15% of all emissions (Shen et al., 2021). Reducing emissions from the steel industry is an important Chinese policy target. In September 2020, the government announced that China's CO_2 emissions should peak before 2030 and reach carbon neutrality by 2060 (National Development and Reforming Commission, 2021). For the steel industry, towards the end of 2021, the initial signal from the Chinese government was to peak emissions already in 2025 and to reduce them by 30% in 2030 (Economic Information Daily, 2021). However, in February 2022, the formal policy, *Guidance on Promoting High-quality Development of Iron and Steel Industry* (Ministry of Industry and Information Technology, 2022), scaled down the ambition: the new target is to peak emissions by 2030 instead of 2025. Nevertheless, major steelmakers in China have adopted higher ambition levels than the government. For example, the HBIS steel group, Baowu steel group, and Angang steel group have all set targets to peak emission by 2022, 2023 and 2025, respectively (Baowu steel group, 2021; HBIS steel group, 2021; Angang steel group, 2021), well ahead of the official 2030 target. Those companies are all state-owned enterprises, and these higher ambitions at the company level signal that the government see them as important in leading the development towards lower emissions.

In addition to being a major contributor to CO_2 emissions, the steel industry is also a large contributor to air pollution (Dai et al., 2016; Tang et al., 2020; Zheng et al., 2018), notably sulfur dioxide (SO_2), nitrogen

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https://doi.org/10.1016/j.jclepro.2022.135550
Received 4 July 2022; Received in revised form 23 November 2022; Accepted 6 December 2022
Available online 8 December 2022

oxides (NO_X) and particulate matter (PM) (Zheng et al., 2018; Coudon et al., 2019). It accounted for 14.5% of SO_2, 24.5% of NO_X, 21.7% of PM in 2016 (Wang et al., 2019a). Areas with a large steel industry, such as around Beijing and Tianjin, and the Hebei province (Yang et al., 2019; Mele and Magazzino, 2020) face a severe pollution problem. To tackle this problem and safeguard people's health, a set of policies have been introduced (Ministry of Ecological Environment, 2019; Ministry of Ecology and Environment, 2019; State Council, 2018). For the steel industry, the policy aim is to upgrade the steel industry to achieve ultra-low emission standards with even stricter standards than in the European Union and the United States (China Economic Net, 2021). The air pollution policy (Ministry of Ecology and Environment, 2019) states that more than 80% of the steel capacity should achieve ultra-low emission by 2025. To meet these objectives, the state offers differential electricity prices, tax preference, and financial support.

In the context of reducing CO_2 emissions and the level of air pollution, it is important to understand the geographical distribution of the steel industry. First, the impact of air pollution is dependent on where the emissions occur (i.e., human exposure depends on population density) whereas the impact of CO_2 emissions is not dependent on where geographically the CO_2 emissions occur. Second, the geographical location of steel industry is also of economic importance for various provinces. The steel industry brings considerable tax revenues for provincial governments, as well as employment. If provinces lose production, it may hurt them economically in the short term unless compensatory measures are taken. Thus, the geographical distribution of the steel industry is not just about environment but also economics. Last but not least, studying the steel industry at the provincial level also may help to balance and achieve political goals more efficiently. In China, the central government sets national targets, but implementation is mainly done at provincial and lower levels, where the contribution to meeting national targets may differ depending on local circumstances. If the provinces do not have specific targets, there is a risk of an implementation gap. A top-down policy is needed to allocate each province individual targets in order to secure that the national target is met.

Strategies for reducing carbon emissions and pollution must also be understood in the context of the current overcapacity and the implications of switching to scrap-based secondary steelmaking. The overcapacity is currently estimated at 130–350 Mt in China (Peterson Institute for International Economics, 2017), and reducing overcapacity naturally makes the CO_2 and air pollution problem easier to solve. The government has released a set of policies (Ministry of Industry and Information Technology, 2022; State Council, 2016; The National Development and Reform Commission, 2017; Ministry of Industry and Information Technology, 2021) to phase out obsolete production capacity that cannot meet governmental technical standards (The National Development and Reform Commission, 2013). These policies should also be seen in light of the overarching Chinese economic development strategy to change into a "new normal" and transform from high-speed to medium-high speed economic growth, and thus a slowdown in steel demand.

In addition to reducing overcapacity, a key measure in the short term to reduce both carbon emissions and air pollution is to switch to scrap-based secondary steelmaking through electric arc furnaces (EAFs). The secondary scrap based route produced by EAF accounted for 26.3% of world output in 2020, but in China this figure was a mere 9.2%, far lower than many other areas such as 42.4% in EU and 70.6% in the United States (World Steel Association, 2021). In 2022, China adopted a policy target to increase the share of EAF to 15% in 2025 (Ministry of Industry and Information Technology, 2022). Since steel products have a life-time between 10 and 30 years before being recycled (Wang et al., 2014) and China's steel consumption has grown tremendously the past 20 years, more scrap will become available on the domestic market (Chen et al., 2014) thus enabling a transition to more secondary steel.

Most studies in this field have focused on one problem at a time; either air pollutants (Tang et al., 2020; Yang et al., 2019; Mele and Magazzino, 2020; Wang et al., 2016; Zhang et al., 2019) or carbon dioxide emissions in steel industry (Shen et al., 2021; Ren et al., 2021a; Zhang et al., 2022; Li et al., 2019; Tan et al., 2019; Long et al., 2020; An et al., 2018). Few consider the two simultaneously (Wang et al., 2019a; Long et al., 2020; Yang et al., 2018), and none consider the problem within a geographical context or the recent CO_2 peaking and reduction targets. For meeting the short-term decarbonization targets, which can be regarded as the first step for meeting the national carbon neutrality target, switching to secondary steel combined with reducing overcapacity have been identified as key components. For example, Li et al. (2019) have predicted short-term reductions of the carbon emissions of the Chinese steel industry by building a nonlinear environmental-economic model, and examined emissions reduction effects of technology upgrades, EAF expansion, and energy efficiency. They found that the decrease in crude steel production is essential for the carbon emissions reduction of the steel industry. An et al. (2018) have built a NET-IS model to predict energy consumption and CO_2 emissions in China's iron and steel industry from the perspective of the steel production process. They concluded that the existing policy of phasing out obsolete production capacities can contribute greatly to energy savings and CO_2 emission reduction. They also found that structural changes to promote EAFs would be very important in the long run. None of these studies included consideration of changes at the provincial level and where future production may be located.

To fill this gap, we build a top-down optimization model to assess the future provincial allocation of production capacities and secondary steelmaking in China. The model is based on the assumption that emissions shall peak in 2025, in line with the steel industry's commitment, and decline by 30% by 2030. To explore synergies and trade-offs between the CO_2 mitigation target and pollution target, we analyze a strategy to minimize costs for reaching the climate target and compare this with a strategy of minimizing air pollution impact (measured as air pollution multiplied by population density in each province). We define scenarios to see whether the shares of EAF can meet the 15% and 20% targets in 2025. From this we draw some insights for policy that may help the Chinese steel industry reach their climate and air pollution targets.

This paper is outlined as follows. Section 2 is an overview of China's steel industry and relevant policies. In section 3, we present the model in detail and data used, and in section 4, the results are presented and discussed. Section 5 concludes and highlights the main policy implications.

2. Overview and policies of China's steel industry

2.1. Overview of steel production in China

Steel is produced via the following two main routes: primary steel via the BF-BOF route and secondary scrap-based steel via the EAF route (Sun et al., 2020a). In primary steel making, iron ores are reduced to iron in the BFs using coal for energy and as reduction agent, and then converted to steel in the BOFs. The EAF route produces steel using recycled steel scrap that is melted in the EAF as the major raw material and electricity as the major form of energy. About 75% of steel in the world is produced by using the BF–BOF route, and about 25% is produced via the EAF route (Sun et al., 2020b).

Compared with BF-BOF, EAF has lower emissions of CO_2 emissions and air pollutants. The GHG emission intensity of the BF-BOF route is 2.6 times greater than that of the EAF route (Li et al., 2018). EAF steel production can reduce SO_2 emissions by 55%, and PM emissions by 89% compared to that of BF-BOF primary steel production (Zhang et al., 2019).Therefore, switching to EAFs is a good option both for short-term CO_2 reduction and for improving air quality.

China produced 1033 Mt crude steel in 2021 (World Steel Association, 2022). BF-BOF is the most common production method while EAF production is relatively low. Limited availability of scrap and recycling infrastructure, as well as high scrap and electricity prices constitute the main barriers to the expansion of EAF production in China (Ren et al., 2021b; Zhou and Yang, 2016; Wübbeke and Heroth, 2014).

To promote the development of EAF, *Guidance on Promoting High-quality Development of Iron and Steel Industry (Exposure Draft)* (Ministry of Industry and Information Technology, 2020) was issued at the end of 2020. The guidance asks for an increase in the share of EAF steel to at least 15% of total steel production by 2025 with an ambition to try to reach 20%. In the more recently published *Guidance on Promoting High-quality Development of Iron and Steel Industry* (Ministry of Industry and Information Technology, 2022), the 15% target remains but the 20% target is no longer mentioned.

Even so, scrap based EAF steel has a big development potential in the coming years. First, availability of domestic steel scrap will increase considerably in the future (Chen et al., 2014). Second, EAF is less polluting and less energy intensive (Zhang et al., 2019). Last but not least, scrap-based steel can substitute for BF-BOF, so China can reduce its dependence on imported iron ore and coking coal. Around 83% of the iron ore is imported from other countries, mainly Australia and Brazil (Ministry of Commerce of People's Republic of China, 2020; Sina, 2021), with associated concerns for resource supply security and steel production security. Replacing iron ore-based BF-BOFs with EAFs could reduce such risks. Increasing the share of EAFs could also decrease the reliance on imported coking coal. Imported high-quality coking coal is an important supplement to China's partly lower quality domestic coking coal. In 2020, the apparent consumption of coking coal in China was 556 Mt (Chyxx, 2021), of which 73 Mt was imported. Most of the import came from Australia (35 Mt), Mongolia (24 Mt), Russia (7 Mt) and Canada (5 Mt). Because of geopolitics, China banned importing coking coal from Australia in late 2020. In addition, mainly due to Covid, Mongolia could only export 14 Mt coking coal to China in 2021. Even though China has increased imports from other countries, the resulting gap has not been filled (Zhongtai Security, 2022).

2.2. Geographical production distribution and steel policy in China

Steel production in China is clustered in specific regions. Fig. 1 shows provincial steel capacity in Mt in 2020. Data come from the Global Steel Plant Tracker (Global Energy Monitor, 2021). The provinces and places with numbers are included in the assessment. In 2020, the total steel capacity was 1124 Mt (only plants with a capacity over 1 Mt are considered), including the Northern (444 Mt), Eastern (329 Mt), Central (91 Mt), Southern (86 Mt), Northeast (78 Mt), Southwest (54 Mt) and Northwest (42 Mt) regions. The province of Hebei has the largest amount of crude steel capacity with 299 Mt in 2020, which accounts for 27% of China's steel capacity. The second and third ranking provinces are Jiangsu and Shandong, with 119 Mt and 83 Mt capacity respectively. These three provinces together account for 45% of steel production capacity in China.

The steel industry has been important for the industrialization and economic development of China. As the economy is maturing with decreasing steel demand and higher environmental ambitions, the government has developed different policies to help in the restructuring of steel industry. Those targets can be summarized into several parts: eliminating overcapacity and prohibiting newly built capacity, reducing air pollution and CO_2 emissions, and promoting the deployment of other technologies such as EAFs. Details on policies are summarized in Table 1.

2.3. Scrap imports to China

China's scrap imports have fluctuated widely in recent years (World Metal Guide, 2021). In 2017, the government introduced a regulation to decrease the imports of solid waste (where scrap is included) from 2017

Fig. 1. Provincial steel capacity (unit: Mt).

Table 1
Policies and signals for the steel industry in China.

Year	Policy or signal	Main information
2022	Guidance on Promoting High-quality Development of Iron and Steel Industry (Ministry of Industry and Information Technology, 2022)	① Peak emissions by 2030 ② Increase the production of EAF to more than 15%
2021	Signal communicated in interview published online (Economic Information Daily, 2021)	Peak emissions in 2025 and to reduce them by 30% in 2030
2021	Measures for the Implementation of Capacity Replacement in Steel Industry (Ministry of Industry and Information Technology, 2021)	① Phase out obsolete capacity ② Net new capacity is prohibited ③ Capacity replacement method: If 1 tonne new EAF capacity is built, 1–1.5 tonnes old BF-BOF capacity should be phased-out
2020	Guidance on Promoting High-quality Development of Iron and Steel Industry (Exposure Draft) (Ministry of Industry and Information Technology, 2020)	① Increase the production of EAF to more than 15% and try to reach 20% by 2025 ② Net new capacity is prohibited
2019	Opinions on Promoting the Implementation of Ultra-low Emissions in the Steel Industry (Ministry of Ecological Environment, 2019)	① Net new capacity is prohibited ② Ultra-low emission transform
2018	A Three-year Action Plan to Win the Battle for Protecting the Blue Sky (State Council, 2018)	① Control air pollution ② Net new capacity is prohibited ③ Encourage railway instead of road to transport bulk commodities such as steel
2016	Eliminating Excess Capacity and Getting Out of Difficulties of the Iron and Steel Industry (State Council, 2016)	Phase out 100-150 Mt overcapacity from 2016 to 2020
2016	Plan for Adjustment and Upgrading of the Steel Industry (2016–2020) (The National Development and Reform Commission, 2017)	Phase out overcapacity

and stop all imports of solid waste by the end of 2020 (State Council, 2017). As a result, scrap import declined from 2326 kt (thousand tonnes) in 2017 to 184 kt in 2019 (Statista, 2022), and almost stopped with only 27 kt being imported in 2020 (Fastmarkets, 2022). This created a big shortage in scrap supply. A new guideline (Ministry of Ecological Environment, 2020) was published in late 2020 that no longer defined high-quality scrap as solid waste and gave it a new name: “renewable steel”. Since “renewable steel” with high quality is no longer regarded as the waste, it can be imported from 2021 but faces strict customs inspections for quality. As a result in 2021, scrap imports increased again to 553 kt (Fastmarkets, 2022).

Increasing scrap imports may affect regional scrap trade, and sourcing large quantities of high-quality scrap may be a challenge in the short term. Japan was the biggest scrap exporter to China (389 kt in 2021 or 70.4% of total imported scrap) (Fastmarkets, 2022) followed by South Korea (96 kt in 2021 or 17%) (S&P Global Commodity Insights, 2022). In 2020, total scrap exports of Japan amounted to roughly 9.37 Mt and its biggest scrap buyer is Vietnam (Statista, 2020). In addition, South Korea exported only 253 kt of scrap in 2020 in total (Fastmarkets, 2021). This may point to a need for China to improve and increase the amount of high-quality domestic scrap collection and also diversify imports to include scrap from a wider range of countries.

3. Method and data

3.1. Model description

In this study, a top-down optimization model was developed to investigate possible short-term pathways for reducing CO_2 emissions from the Chinese steel industry. Since CO_2 is a global problem while air pollution mainly harms local population, we run the model with two different optimization objectives, first to minimize total cost including annualized investment cost, production, transportation and carbon costs, and second to minimize air pollution impact (measured as population density exposed to air pollution). By doing this, we can compare how the two different objectives affect provincial steel capacity distribution and secondary steelmaking capacity. Motivated by that major Chinese steel companies like Baowu steel group and HBIS steel group who have made their own peak emissions and reduction roadmaps, and the earlier indicated signal that steel industry should peak emissions in 2025, we use “peak emissions in 2025 and reduce by 30% in 2030” as modeling constraints, to explore how these targets can be achieved and what is necessary for achieving them. The model optimizes the geographical distribution of production to the Chinses provinces taking into consideration (i) the CO_2 emission reduction target of peak emission in 2025 and 30% reduction target in 2030, (ii) the targets to reduce national overcapacity, and (iii) the targets for increasing the share of EAFs. The time period in this study is 2021–2030 which allows us to assume that no other or new technologies (such as hydrogen direct reduction) will be widely introduced. That is, we consider changing from BF-BOF to scrap-based EAF as the only technical option. Fig. 2 shows the model framework.

3.2. Objective function

3.2.1. Economic objective (EO)

The objective function of this model is to minimize the total cost (TC) of the steel industry from 2021 to 2030. The total cost is the sum of total annualized investment cost, energy and material cost, transportation cost and carbon cost, as shown in Eq. (1).

$$\min TC = \min(\text{total annualized investment cost} + \text{energy and material cost} + \text{transportation cost} + \text{carbon cost}) \tag{1}$$

where

$$Total\,annualized\,investment\,cost = \sum_{t=1}^{T}\sum_{j=1}^{j}\sum_{i=1}^{i=2} AIC_{i,t}\times X_{t,i,j}\times U\times(1+r)^{-t} \tag{2}$$

$X_{t,i,j}$ is the first optimization variable and denotes steel capacity in year t ($t=1,2,\ldots T$, $T=10$). i is the technology, $i=1,2$ represent BF-BOF and EAF. j indicates province ($j=1,2,\ldots J$, $J=30$) that we assess. AIC is the annualized investment cost (Yuan/(t *year)), which is calculated by total initial investment cost based on literature data (Ren et al., 2021a).

In this paper, we assume the steel industry is integrated, meaning that the entire steel production process includes sintering, pelletizing, coking, iron making, and steel making processes. For energy and material cost, four kinds of energy and material (iron ore, coking coal, scrap and electricity) are considered, productions shown in Eq. (3).

$$Energy\,and\,material\,cost = \sum_{t=1}^{T}\sum_{j=1}^{J}\sum_{i=1}^{i=2}\left(\alpha_i\times X_{t,i,j}\times P_{t,j}^{electricity} + \beta_i\times X_{t,i,j}\times P_t^{ironore} + \gamma_i\times X_{t,i,j}\times P_t^{scrap} + \delta_i\times X_{t,i,j}\times P_t^{coal}\right)\times U\times(1+r)^{-t} \tag{3}$$

$\alpha,\beta,\gamma,\delta$ is the amount of electricity, iron ore, scrap and coking coal needed in producing one unit of steel, P is the price. r is the discount rate, U is the capacity utilization rate.

For transportation cost, it contains two parts: the transport of iron ore as well as coking coal, and provincial steel transportation for satisfying demand. Transportation is assumed by rail in line with the government published guidelines (State Council, 2018; State Council, 2018) to promote bulk rail transportation. Those policies are motivated by energy efficiency and reduced air pollution.

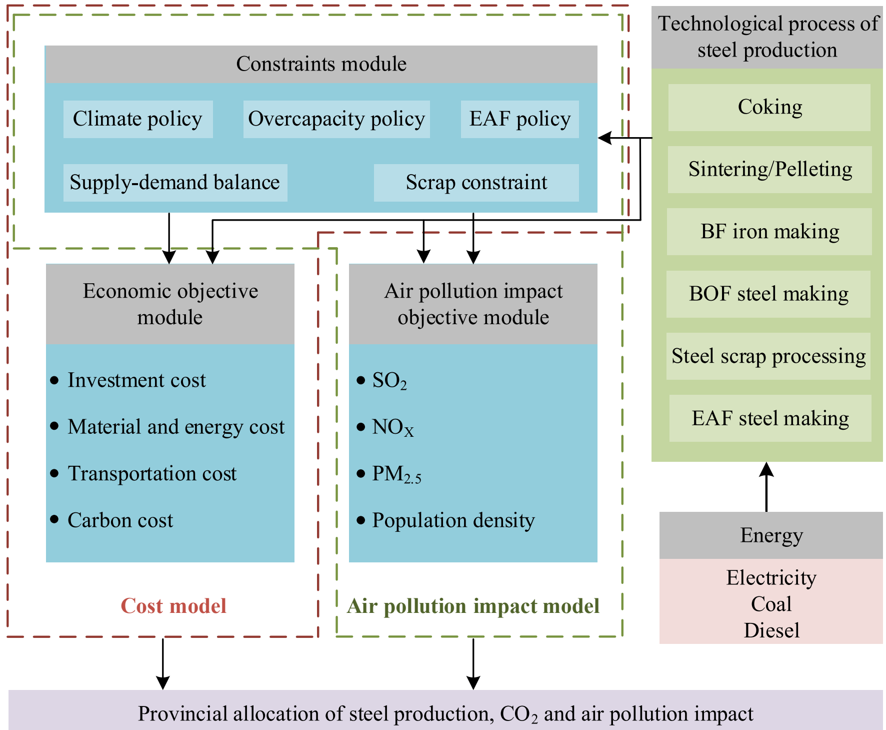


Fig. 2. Model framework.

$$Transportation\ cost = \sum_{t=1}^{T}\left[\sum_{j=1}^{J}\sum_{i=1}^{i=2}\left(D_j^{ironore}\times TP_t^{ironore}+D_j^{coal}\times TP_t^{coal}\right)\times X_{t,i,j}\times U+\sum_{j=1}^{J}\sum_{j'=1}^{J}Y_{t,j,j'}\times TP_t^{steel}\times D_{j,j'}^{steel}\right]\times(1+r)^{-t} \quad (4)$$

TP is the unit transport cost (Yuan/(t*km)). $Y_{t,j,j'}$ is another optimization variable and is the transported steel from province *j* to *j'* in year *t*. *D* is the transport distance; for iron ore, we assume that all iron ore is imported, through nine major ports in China (Rizhao, Qingdao, Tangshan, Tianjin, Yantai, Qinhuangdao, Jinzhou, Yingkou, and Dalian). The reason behind this simplifying assumption is that 83% of iron ore consumption in China is imported (Ministry of Commerce of People's Republic of China, 2020; Sina, 2021) with 75% of this import entering China through these nine ports (Souhu, 2017). Therefore, the distance $D_j^{ironore}$ is the minimum distance between these ports and the capital of province j; for coking coal, the distance D_j^{coal} is the average transportation distance of coking coal because it is difficult to know the specific source of coking coal in each province.

For the inclusion of a carbon cost, the steel industry has been involved already in most of the pilot carbon markets (Tianjin, Shanghai, Hubei, Guangdong and Chongqing). With the completion of nation carbon market in the near future, we assume that the steel industry will face a carbon price of 50–93 Yuan from 2021 to 2030 (Center for Strategic and International Studies (CSIS), 2021) and the carbon cost for a steel plant can thus be calculated according to Eq. (5).

$$Carbon\ cost = \sum_{t=1}^{T}E_t\times P_t^{carbon}\times(1+r)^{-t} \quad (5)$$

and

$$E_t = \sum_{j=1}^{J}\sum_{i=1}^{i=2}a_i\times X_{t,i,j}\times U \quad (6)$$

Where *a* is the emission factor of producing one unit of steel; E_t is the CO_2 emission in year *t*. Like said before, the steel industry is assumed to be integrated, so CO_2 emissions are calculated from the entire steel production process including sintering, pelletizing, coking, iron making, and steel making processes. Emissions of air pollutants are also included from the entire production process.

3.2.2. Air pollution impact objective (AO)

Steel making is always accompanied by air pollution. It is important to analyze how minimizing air pollution impact will affect how to reach the climate target, especially in terms of geographical industrial structure and secondary steelmaking. It is also important to compare geographic differences when having cost minimization as the target versus pollution impact minimization as the target since air pollution harms local populations whereas CO_2 emissions are a global problem. Therefore, we run our model also with an objective to minimize air pollution impact, and present what is named AO scenarios. The sum of SO_2, $PM_{2.5}$ and NO_X emissions, multiplied by population density is used to express the pollution impact in each province.

$$min\ air\ pollution\ impact = min\sum_{t=1}^{T}\sum_{j=1}^{J}\sum_{i=1}^{i=2}\mu_i\times X_{t,i,j}\times U\times L_{t,j} \quad (7)$$

Where μ is the amount of pollution emission in producing one unit steel.

L is the population density.

3.3. Constraints

(1) Climate policy constraints

Here we assume that the target is to peak CO_2 emissions in 2025 and reduce them by 30% in 2030:

1) Peak emissions in 2025

$$E_{t=5} \geq E_{t \neq 5} \tag{8}$$

2) Emissions in 2030 are equal to 70% of the peak emission

$$E_{t=10} = 70\% \, E_{t=5} \tag{9}$$

(2) EAF share policy constraint

The EAF share in China is low compared to the world average and we also consider the newly published policy target of increasing the share of EAF to 15% of total steel production in 2025 (Ministry of Industry and Information Technology, 2022). Based on that, we make the constraint that the share of EAF is equal to 15% in 2025.

$$\sum_{j=1}^{J} X_{t=5,i=2,j} \times U = 15\% \sum_{i=1}^{i=2} \sum_{j=1}^{J} X_{t=5,i,j} \times U \tag{10}$$

(3) Capacity policy constraints

According to the policy, no province can build net new steel capacity (Ministry of Industry and Information Technology, 2022). If one province wants to build 1 tonne new EAF capacity, then 1–1.5 tonne of old BF-BOF capacity should be eliminated (Ministry of Industry and Information Technology, 2021). In addition, it is not economical to eliminate newly built EAF capacity. Therefore, for each province, BF-BOF capacity cannot increase according to the above polices and, provincial EAF capacity cannot decrease.

Furthermore, to give an upper limit for capacity in 2021 and to make sure the 2021 capacity is reasonable, we adopt the constraints that the 2021 total capacity does not exceed the 2020 total capacity on both the national and provincial levels, that the 2021 BF-BOF capacity is not higher than in 2020, and that the 2021 EAF capacity is not less than that of 2020. According to the above, we have the following constraints:

1) For each province, BF-BOF will not increase each year in the time period

$$X_{t-1,i=1,j} \geq X_{t,i=1,j} \tag{11}$$

2) For each province, EAF will not decrease each year in the time period

$$X_{t-1,i=2,j} \leq X_{t,i=2,j} \tag{12}$$

3) For each province, total capacity in the time period is less than that of 2020 and do not increase annually.

$$\sum\nolimits_{i=1}^{i=2} X_{t+1,i,j} \leq \sum\nolimits_{i=1}^{i=2} X_{t,i,j} \leq \sum\nolimits_{i=1}^{i=2} X_{t_0,i,j} \tag{13}$$

Where t_0 means time is 2020.

4) For the whole nation, the totally national capacity will not increase from 2020

$$\sum\nolimits_{j=1}^{J} \sum\nolimits_{i=1}^{i=2} X_{t+1,i,j} \leq \sum\nolimits_{j=1}^{J} \sum\nolimits_{i=1}^{i=2} X_{t,i,j} \leq \sum\nolimits_{j=1}^{J} \sum\nolimits_{i=1}^{i=2} X_{t_0,i,j} \tag{14}$$

(4) Demand -supply constraints

1) To satisfy the balance of demand and supply, for each province, the production plus import minus by export should no less than demand. Where M is the steel demand.

$$\sum\nolimits_{i=1}^{i=2} X_{t,i,j} \times U + \sum\nolimits_{j'=1}^{J} \sum\nolimits_{i=1}^{i=2} Y_{t,i,j',j} - \sum\nolimits_{j'=1}^{J} \sum\nolimits_{i=1}^{i=2} Y_{t,i,j,j'} \geq M_{t,j} \tag{15}$$

2) For each province, the steel transported to other provinces is less than steel produced in this province.

$$\sum\nolimits_{j'=1}^{J} \sum\nolimits_{i=1}^{i=2} Y_{t,i,j,j'} \leq \sum\nolimits_{i=1}^{i=2} X_{t,i,j} \times U \tag{16}$$

(5) Scrap constraints

Scrap is the major raw material for producing steel in an EAF, but scrap can also be added and mixed with pig iron into the basic oxygen furnace when producing steel via the BF-BOF route (Ryman and Larsson, 2006). According to a new policy from 2020 (Ministry of Ecological Environment, 2020), only scrap of high quality can be imported to China, and the quality is strictly checked during customs inspection. This quality requirement may limit the availability of scrap that can be imported to China. Steel can be in use for decades before being recycled (World Steel Association, 2022) and China, whose big steel expansion started only in the early 2000s (He et al., 2020), still has a limited availability of domestic scrap. In addition, the total capacity of scrap handling enterprises approved by the Chinese government is only about 100 Mt (Ren et al., 2021b).

Therefore, we set a constraint to make sure that total scrap used is less than total scrap available in the time period. S is the scrap available.

$$\sum_{j=1}^{J} \sum_{i=1}^{i=2} X_{t,i,j} \times U \times \gamma_i \leq S_t \tag{17}$$

3.4. EAF-scenarios

As noted earlier, the share of EAF in 2020 is 9% and policy documents have signaled both 15% and 20% shares as targets for 2030. To assess how different EAF target can be met, and see how those EAF targets affect cost, air pollution, and the geographical distribution of steel capacity, we employ two scenarios for the share of steel production via EAFs. In the Business as usual (BAU), the share of EAF will be equal to 15% in 2025; in the Higher EAF Shares (HES) scenario, we assumed the share of EAF to be 20% in 2025. Each scenario is optimized both on the cost minimum objective (EO) and on the air pollution impact minimum objective (AO), so that implications for the geographical location and timing of measures can be compared when one objective is prioritized over the other. To summarize, four scenarios are considered in this paper: BAU-EO, BAU-AO, HES-EO, HES-AO. See Table 2 for details.

Table 2
Four scenarios.

	Minimizing costs	Minimizing air pollution impact
The share of EAF is 15% in 2025	BAU-EO	BAU-AO
The share of EAF is 20% in 2025	HES-EO	HES-AO

3.5. Data

For calculating CO_2 emissions, our system boundaries include seven processes: coking process, sintering, pelleting, BF iron making, BOF steel making, steel scrap processing and EAF steel making. We also consider indirect emissions from purchased electricity. Provincial electricity emission factors for calculating indirect emissions come from the National Center for Climate Strategy (Ministry of Ecology and Environment, 2020). Data for CO_2 emissions from different steel processes and the materials needed in the production of one tonne of steel are taken from (Ren et al., 2021a, 2021b; Jing et al., 2014; Xuan and Yue, 2016). We calculate that producing one tonne of BF-BOF steel will release 1.9–2.1 tonne of CO_2, and that producing one tonne of EAF steel emits 0.037–0.36 tonne, depending on provincial emission factors. For the system boundary of air pollution, we follow Wang's research (Wang et al., 2019b). Air pollution data are taken from (Yang et al., 2019; Wang et al., 2019b), and about 26.9 and 10 tonnes of air pollution (the sum of SO_2, NO_X, $PM_{2.5}$) are released when producing one tonne of BF-BOF and EAF steel, respectively. Annualized investment cost comes from (Ren et al., 2021a). Detailed data can be found in Appendix A.

The prices of provincial electricity and iron ores are forecasts based on the Electricity Statistics Yearbook and the Steel Statistics Yearbook. The national steel demand projection comes from Net Zero Steel (Net Zero Steel, 2021) and provincial steel demands are calculated based on their population shares and the national steel demand projection. Transport costs for steel and raw materials come from (National Development and Reform Commission, 2017). Scrap price is assumed based on historical data (My Steel Net, 2020; Sina, 2019). Capacity utilization rate is set to 90% from IEA (International Energy Agency, 2020) and the discount rate is 10% (Ren et al., 2021a).

There are many projections of domestic scrap availability (Xuan and Yue, 2016; McKinsey & Company, 2017; Reuters, 2021; World Steel Association, 2018; Zhang et al., 2018; Li and Hanaoka, 2020), but here we rely on a projection from Worldsteel (World Steel Association, 2018) which is close to the middle of different projections. When first solving the model, we found that with the set domestic scrap amount assumed from Worldsteel, the model had no feasible solution. This means that if only domestic scrap is considered, the two policy targets of 30% emission reduction in 2030 and 15% EAF shares in 2025 cannot be met together. Meeting the 15% and 20% targets requires 1.2 and 1.25 times more scrap, respectively, than in the Worldsteel's projection. We assume 1.25 times more scrap in both EAF scenarios. This means that imports are needed.

4. Results and discussion

In this section, we first present the results related to the two objectives of the model: cost and air pollution impact. This is followed by the results regarding capacity, it's geographical distribution and provincial steel trade in the four scenarios. CO_2 emission and scrap demand are then presented, both at national and provincial levels. Finally, the results of a sensitivity analysis are presented to demonstrate the robustness of the model.

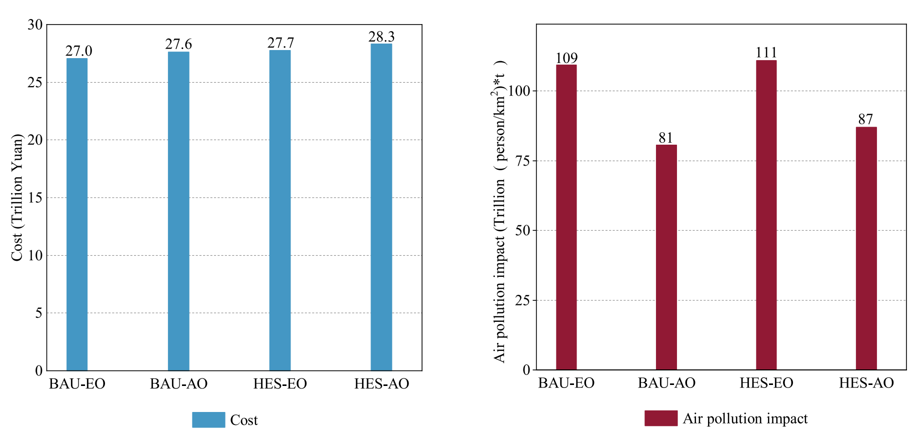
4.1. Total cost and air pollution impact

Fig. 3 compares the four scenarios when optimizing on cost and pollution impact, respectively. As shown in Fig. 3(a), the total costs for the four scenarios are similar. The cost in BAU-EO is the lowest, 27 trillion Yuan. The other three scenarios are 2% (BAU-AO), 3% (HES-EO), and 5% (HES-AO) more expensive respectively. This is within the margin of error of the model but suggests that focusing on air pollution impact or on increasing EAF shares may only slightly increase the total cost.

The air pollution impact in Fig. 3(b) shows a very different trend compared to that in Fig. 3(a). The air pollution impact in the cost optimization BAU scenario is 1.3 times higher than in the minimized the air pollution impact scenario. The results are similar when comparing the scenarios with higher EAF shares. If reducing pollution impact is the main objective, it would lead to 22–26% less pollution impact than when optimizing on CO_2 abatement costs at the national level. The pollution impact in the BAU-EO is almost the same compared with that of HES-EO. Therefore, a target of higher shares of EAF in 2025 will not significantly affect air pollution impact and costs. These results indicate that policy may give priority to reducing air pollution impact as the difference in total cost between the optimization options is almost negligible in the case where only costs and pollution impact are considered.

4.2. National steel capacity and geographical distribution

In this section, we first present results for the national steel capacity and then its geographical distribution at provincial levels. Fig. 4 shows the result of total steel capacity in 2025 and 2030 compared to the capacity in 2020. From 2020 to 2030, the total capacity is reduced by 122 Mt in all scenarios, but they differ in terms of when the reduction occurs. From 2020 to 2025, 59 Mt (EO) and 50 Mt (AO) capacity is reduced in the BAU scenarios, but in the HES scenarios the capacity is reduced only



a) Comparison of cost

b) Comparison of air pollution impact

Fig. 3. Cost and air pollution impact in four scenarios.

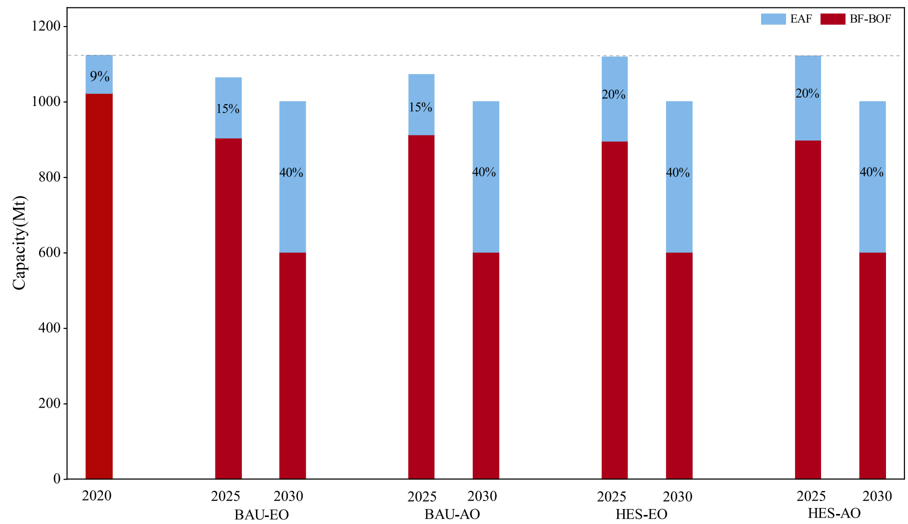


Fig. 4. Total capacity in 2020,2025 and 2030 in four scenarios.

by 3 Mt (EO) and 0.5 Mt (AO) in the same time period. However, from 2025 to 2030, capacity is reduced by 63 Mt (BAU-EO), 72 Mt (BAU-AO), 119 Mt (HES-EO), and 122 Mt (HES-AO). The above means that focusing on higher EAF shares target in 2025 implies small reductions in overall steel capacity 2021–2025, followed by a higher reduction target in the period 2025–2030. To sum up, it is difficult to accelerate the introduction of scrap based EAF steelmaking and simultaneously reduce overcapacity in the 2021–2025 period. Therefore, policy must strike a balance between accelerating the introduction of scrap based EAF steelmaking versus reducing overall capacity.

Fig. 4 also shows the shares of EAF in different scenarios. Higher shares of EAF (20%) in 2025 is possible in terms of cost and air pollution impact but necessitates, as stated before, that China imports scrap or substantially increase domestic high quality scrap collection. For the four scenarios, the shares of EAF reach 40% in 2030, which implies that the share of EAF in 2030 should be at least 40% to meet the 30% peak emissions reduction target. The high share of EAF can substitute BF-BOF steel production, and thus reduce the dependence on imported iron ore and coking coal.

Fig. 5 shows the combination of BF-BOF and EAF capacity at the provincial level in 2020, 2025 and 2030 in EO (right) and AO (left) in BAU scenarios. The geographical capacity layout in the future will differ depending on whether we minimize cost or air pollution impact. Taking the Jiangsu province in east region as an example, to minimize cost, Jiangsu had 101 Mt BF-BOF capacity (in light gray) and 18 Mt EAF capacity (in dark gray) in 2020, and that remains stable in 2025 and 2030. However, if we minimize air pollution impact, Jiangsu's BF-BOF will decrease to 42 Mt (in light red) and EAF will increase to 78 Mt (in light blue) in 2025, but the total capacity remains the same as in 2020. By 2030, Jiangsu has phased-out all its BF-BOF capacity whereas EAF capacity remains at 78 Mt (in dark blue) as in 2025.

Different objectives will lead to different levels of total capacities and different combinations of BF-BOF and EAF. In 2030, assuming cost minimization, the BF-BOF capacities become concentrated in provinces near ports due to the transport costs of iron ore. Results from minimizing air pollution impact gives a different geographical pattern. Most EAFs

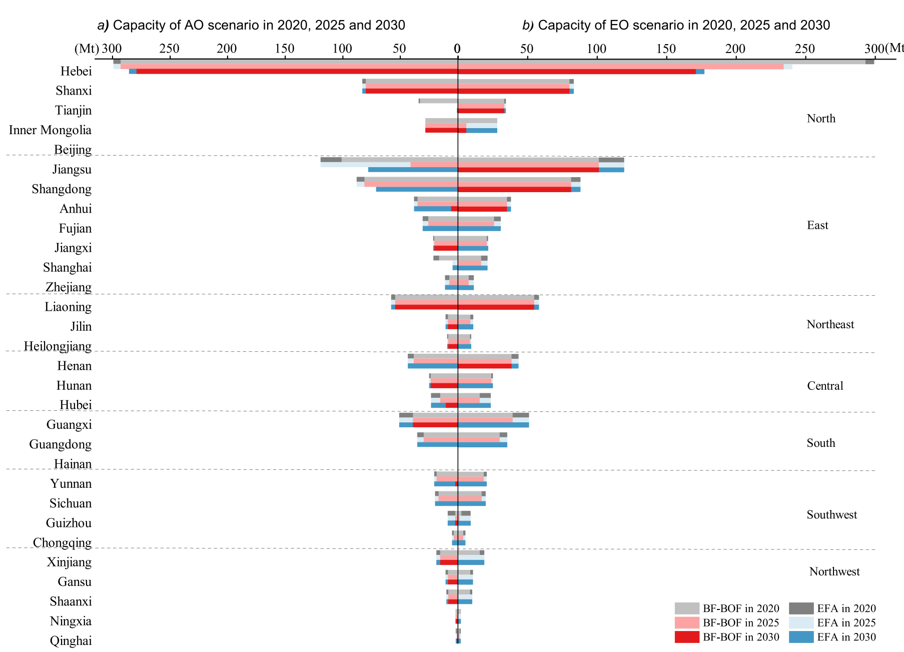


Fig. 5. Comparison of capacity in 2020, 2025 and 2030 in EO and AO of BAU.

concentrate in provinces with high population density, e.g., Jiangsu, Shandong, Guangdong, and Henan. To sum up, provinces with shorter distance to ports will have more BF-BOF capacity if the policy is focused on low mitigation cost; provinces with high population density will have more EAF capacity if policy is focused on reducing pollution impact.

The reduction of overcapacity will be distributed differently across provinces depending on the optimization objective. For the EO scenarios (both BAU and HES), Hebei province is the only province that reduces steel capacity from 2020 to 2030 (i.e., 122 Mt). The reason for the drastic reduction in Hebei in the EO scenarios is that Hebei has a substantial overcapacity and presently exports steel to other provinces. The cost efficiency restriction in the EO scenarios suggests that Hebei overcapacity is the capacity that should be reduced first. For the AO scenarios, more provinces will reduce capacities. Specifically, Jiangsu (42 Mt), Tianjin (33 Mt), Shandong (17 Mt), Shanghai (17 Mt), Hebei (14 Mt) decrease their capacities in BAU-AO scenario; while Shandong (81 Mt), Henan (26 Mt), Hebei (14 Mt), Shanghai (5 Mt) decrease their capacities in HES-AO scenario. The differences between the EO and AO scenarios are explained by differences in the population densities. In the AO scenarios, the results show that capacity reduction should focus on the provinces with the highest population density, e.g., Jiangsu and Shandong with currently a large fleet of BF-BOFs. To sum up, capacity should be reduced in Hebei if cost minimization is the main objective, whereas Jiangsu, Shandong and others should reduce capacity if reduced air pollution is the main objective.

4.3. Provincial trade

Fig. 6 shows steel imports and exports (from/to other provinces) for the EO-BAU and AO-BAU scenarios in 2030. Steel exporters (provinces in blue) are mainly in the northern part, with Hebei as the biggest exporter. Steel importers (provinces in pink) are mainly in the central and southern parts, with Guangdong as the biggest importer. Three places (Shanghai, Shandong and Tianjin indicated with red borders in Fig. 6(b)) change from being steel exporters (in the EO scenario) to being steel importers (in the AO scenario). These are provinces with high population density and steel production leads to high exposure to air pollution which is why they become importers if reduced exposure is the main objective.

4.4. CO_2 emissions

Fig. 7 shows CO_2 emissions in different scenarios. Fig. 7 (a) shows total cumulative CO_2 emissions for 2021–2030 in the four scenarios. The emissions in the BAU-EO and HES-EO scenarios are 14663 Mt and 14465 Mt of CO_2, respectively. The emissions in the BAU-AO and HES-AO scenarios are 148 Mt and 68 Mt higher, respectively, than in the BAU-EO and HES-EO. In the AO-scenarios, many BF-BOFs are in provinces with low population density (e.g., Inner Mongolia, Jiangxi, and Xinjiang) but high electricity emission factors leading to higher CO_2 emissions.

Fig. 7(b) shows average CO_2 emission of per unit steel (total CO_2 emissions divided by total steel production 2021–2030) in our four scenarios. The CO_2 emission per unit of steel in BAU are about 1.41 t/t (EO) and 1.42 t/t (AO). These emissions are about 3% higher than in the two scenarios with higher share of EAFs (HES-EO and HES-AO). Increasing the share of EAFs will decrease the carbon intensity of steel production in general, even though Chinese grid emission factors are relatively high.

Fig. 7(c) shows how annual CO_2 emissions change in the BAU-EO scenario. From 2020 to 2021, emissions are reduced by 410 Mt CO_2. From 2021 to 2025, annual CO_2 emission remain at 1680 Mt before declining 2026 to 2030. Total emissions in 2030 are 1176 Mt, which corresponds to about 504 Mt reduction thus meeting the 30% reduction target.

Fig. 8 shows the provincial cumulative CO_2 emissions and air pollution impact for 2021–2030 in a BAU scenario. According to the distribution of provinces, the whole area can be divided into to four quadrants. Quadrant I means higher CO_2 emissions and higher air pollution impact area, quadrant II is the area with lower CO_2 emissions and higher air pollution impact, quadrant III is lower CO_2 emissions and lower air pollution impact area, and finally IV is higher CO_2 emissions and lower air pollution impact area. Many provinces gather in the third quadrant in the two scenarios, but Hebei and Jiangsu behave differently. In both EO and AO scenarios, Hebei is in the first quadrant, which means that Hebei is the more vulnerable compared with other provinces. However, Hebei's CO_2 emissions and air pollution impact will be less in EO scenario, meaning Hebei may prefer a minimized mitigation cost strategy. Jiangsu is also sensitive with different strategies. In EO scenario, Jiangsu is in the second quadrant with higher air pollution; while in AO scenario, Jiangsu is in the third quadrant with lower air pollution. Therefore, Jiangsu may prefer a pollution impact minimization target. Apart from Tianjin, other five provinces (Shandong, Shanghai, Zhejiang, Anhui and Henan) also will emit less CO_2 and face less air pollution impact when reducing air pollution impact is the objective and prefer air pollution impact minimization strategy, while the other 24 provinces may prefer a cost optimal target. The above demonstrates that policy should balance the trade-off between cost optimal CO_2 mitigation and reduced pollution impact, and it may also consider measures to compensate disadvantaged provinces.

4.5. Scrap demand

Fig. 9 shows the demand for and availability of scrap. Fig. 9(a) shows the total scrap demand 2021–2030 for the different scenarios. The total amount of scrap needed in the BAU scenarios is around 2921 Mt to 2931

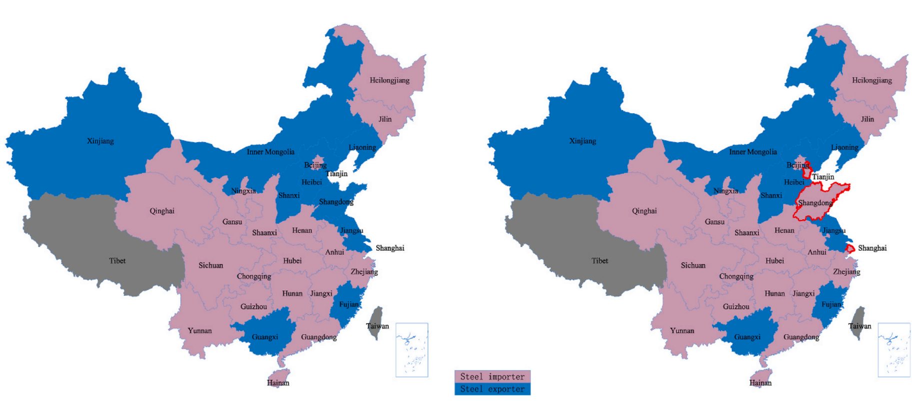


Fig. 6. Provincial steel trade of EO and AO in BAU scenario in 2030.

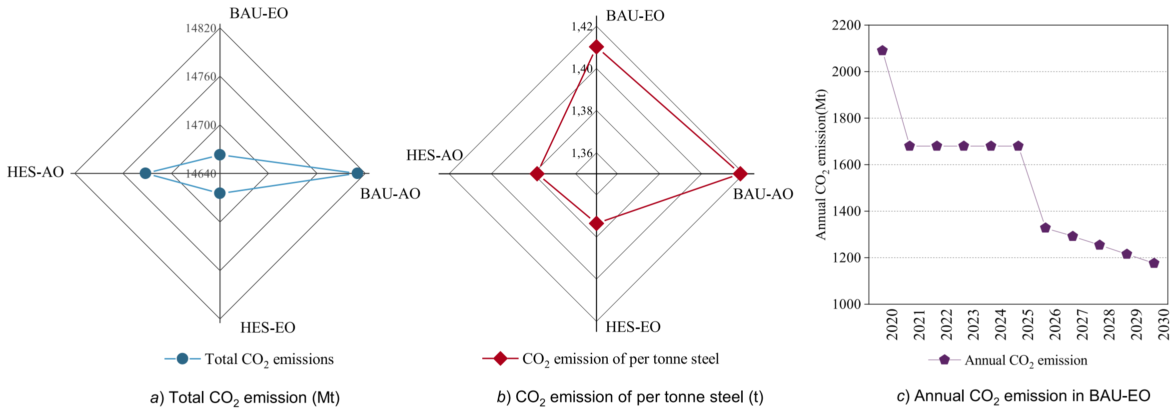


Fig. 7. CO_2 emissions in four scenarios.

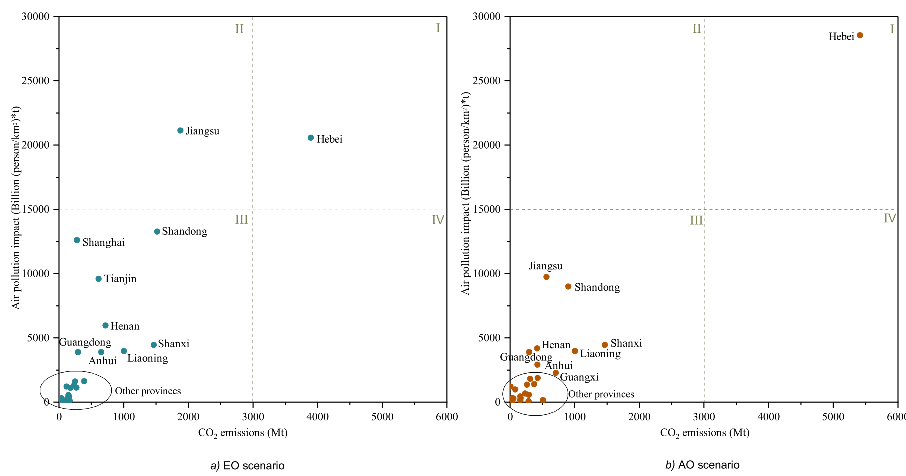


Fig. 8. Provincial CO_2 emissions and air pollution impact in BAU.

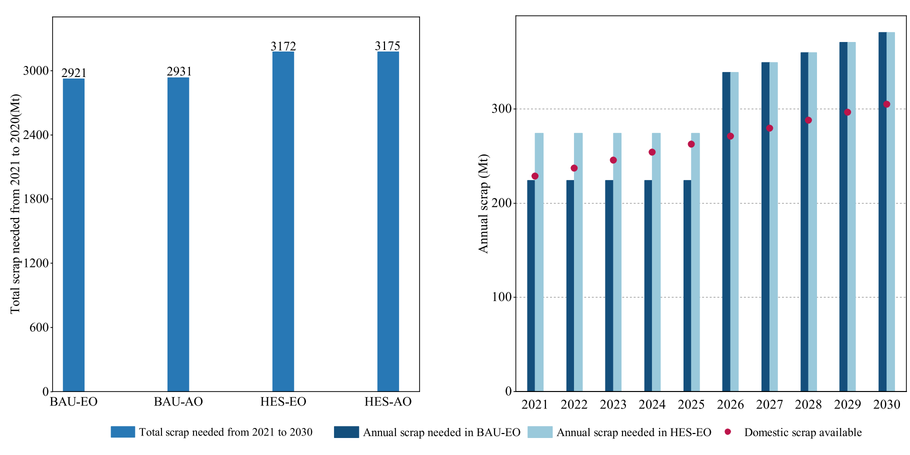


Fig. 9. Scrap demand in four scenarios.

Mt, and about 244–251 Mt higher in the HES scenarios. However, the amount of scrap needed does not differ significantly between the EO and the AO scenarios. Minimizing air pollution impact will only require 3-10 Mt more scrap compared with those strategies focusing on reducing the total cost.

Fig. 9(b) shows the annual scrap needed and the domestic availability for the BAU-EO and HES-EO scenarios. For the BAU-EO scenario, domestic scrap can meet the demand from 2021 to 2025, but from 2026 to 2030 between 68 and 76 Mt needs to be imported annually. For the HES-EO scenario, the demand is higher than what is available domestically already in 2021 and between 12 and 76 Mt needs to be imported annually 2021–2030. Scrap availability becomes an important concern if high shares of EAFs is a policy priority. Therefore, if the government wishes to achieve a high share of EAFs, scrap availability should be considered carefully.

Importing high quality scrap and strengthening the scrap collection industry in China are important steps but may present challenges. In 2019, the total amount scrap traded internationally was 99 Mt, while China imported only 0.2 Mt. The main exporters to China historically are Japan and South Korea whose total exports were 7.7 Mt and 0.2 Mt respectively in 2019 (World Steel Association, 2021). Even if China would buy all the scrap exported by Japan and South Korea there would still be a large shortage. This means that China must import large amounts of scrap also from other countries. Improved domestic scrap collection will also be important but developing infrastructures and markets for this may take time.

Different strategies will also cause different provincial scrap demand. Fig. 10 describes provincial cumulative scrap demand for 2021–2030. Provinces in northern and eastern China will need more scrap, especially Jiangsu, Hebei and Shandong. For some provinces, like Jiangsu, Shandong and Anhui, scrap demand in AO scenario is two times more than that in EO scenario; vice versa, like in Inner Mongolia, scrap demand in EO scenario is two times more than that in AO scenario. Thus, provincial scrap demand is very sensitive to the policy priority and different provinces will have to take measures to secure scrap supply depending on this.

4.6. Sensitivity analysis

A sensitivity analysis was done to identify how different input parameters affect the results. Shifting to EAFs is an important strategy but high electricity and scrap prices, as well as low scrap availability, may hinder the expansion of EAFs. Therefore, we test the sensitivity to changes in scrap availability, scrap price and electricity price. We also test for the impact of changes in steel demand, which is a very important exogenous parameter. We performed the sensitivity analysis by varying the value of selected parameters within the range of ±25% and tested how this affects the total cost and cumulative CO_2 emissions in the BAU-EO scenario. The results are shown in Table 3.

Steel demand and scrap availability are the parameters that have the highest effect on both total cost and cumulative CO_2 emissions, whereas the result is not sensitive to changes in scrap and electricity prices. When steel demand decreases by 25%, the total cost and cumulative CO_2 emissions decrease by 26% and 29%, respectively. If steel demand is increased by 25%, the model cannot provide a solution, mainly due to limited scrap availability. Correspondingly, the model does not have a solution when scrap availability decreases by 25%. When scrap availability increases by 25% the total cost and cumulative CO_2 emissions decrease by 2% and 5%, respectively. Changes in scrap and electricity prices have relatively small effects on the total cost and do not affect CO_2 emissions.

5. Conclusions and policy recommendation

For achieving the net zero target in 2060 and at the same time safeguard people's health, the Chinese steel industry needs to start with a great short-term effort to bend the trend and reduce both CO_2 emissions and air pollution this decade. Although they are largely synergistic, different emphasis on CO_2 versus air pollution will have implications for where primary as well as secondary steelmaking is located geographically. This paper presents a top-down optimization model where we assess the future provincial allocation of production capacities and secondary steelmaking if CO_2 emissions are to peak in 2025 and then decrease by 30% in 2030, while at the same time reducing overcapacity and increasing the share of EAFs. We developed four scenarios that compare a strategy focused on minimized mitigation costs with a strategy focused on reduced air pollution impact. For each strategy, one scenario is "business as usual" and one scenario is "higher EAF share". The results reveal synergies and conflicts between these strategies and show that there are large differences in the geographical location of steelmaking capacity depending on strategy. Our main findings and associated policy insights are as follows.

(1) China's steel industry can peak CO_2 emissions in 2025 and reduce them by 30% in 2030 (about 504 Mt CO_2), but scrap availability will be a challenge. At least 68-76 Mt scrap needs to be imported annually from 2026 to 2030. The share of EAFs in total steelmaking should be 40% in 2030 to achieve the 30% reduction target. This makes it important that China develops infrastructures and markets for domestic scrap collection as well as increases imports.
(2) The total cost is nearly the same across the four scenarios. If reduced pollution impact is the main objective, it leads to 22–26% less air pollution impact compared to a minimized mitigation cost strategy. However, a minimized mitigation cost

Table 3
Sensitivity analysis.

Parameter	Changing rage (%)	Total cost (%)	Cumulative CO_2 (%)
Steel demand	−25	−26	−29
	+25	NA	NA
Scrap availability	−25	NA	NA
	+25	−2	−5
Scrap price	−25	−5	0
	+25	6	0
Electricity price	−25	−1	0
	+25	1	0

Note: NA (Non available result) means the model don't have available results.

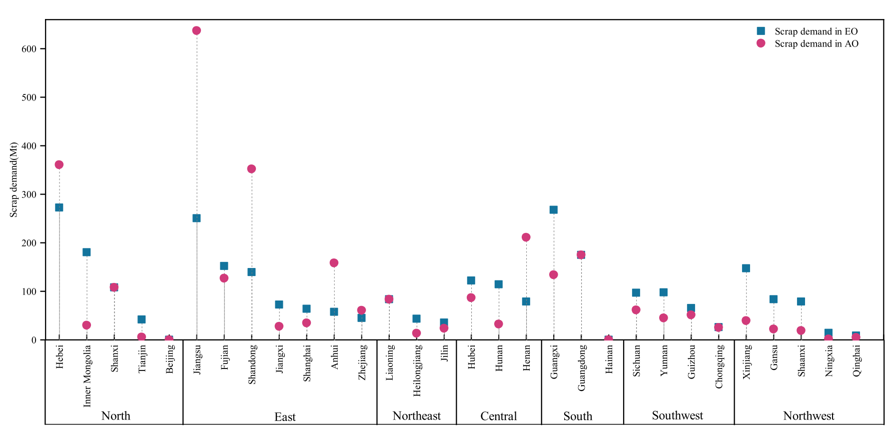


Fig. 10. Provincial steel scrap demand in BAU.

strategy will reduce CO_2 emissions by an additional 68–148 Mt compared to focusing on air pollution impact. Provinces such as Hebei may prefer a prefer a minimized air pollution target, while provinces such as Jiangsu may prefer a cost optimal strategy. Hence, policy must balance the trade-off between cost optimal CO_2 mitigation and reduced pollution impact.

(3) Different scenarios lead to different geographical distributions of primary and secondary steelmaking. If the focus is on minimized mitigation cost, provinces with shorter distance to ports will have relatively more BF-BOFs in 2030. If the focus is on reduced pollution impact, provinces with high population densities will have relatively more EAF capacity. Capacity should be reduced in Hebei if cost minimization is the main objective, whereas Jiangsu, Shandong and others should reduce capacity if reduced air pollution is the main objective.

(4) It may be a challenge to accelerate the introduction of scrap based EAF steelmaking and simultaneously reduce overcapacity in the 2021–2025 period. Focusing on higher EAF shares target in 2025 implies small reductions in overall steel capacity 2021–2025, followed by accelerated capacity phase-out in the period 2025–2030. Therefore, policy must strike a balance between accelerating the introduction of scrap based EAF steelmaking versus reducing overall capacity.

CRediT authorship contribution statement

Zhenxi Li: Methodology, Software, Writing – original draft. **Fredrik N.G. Andersson:** Methodology, Supervision. **Lars J. Nilsson:** Supervision, Writing – review & editing. **Max Åhman:** Conceptualization, Writing – review & editing.

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.

Data availability

I have shared the data used in my "supplement data" part in my paper.

Acknowledgements

This work was supported by the China Scholarship Council under Grant Number: 202006410002 and the CAST-project financed by the Swedish Energy Agency.

The computations were enabled by resources provided by the Swedish National Infrastructure for Computing (SNIC) partially funded by the Swedish Research Council through grant agreement no. 2021/22–939.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2022.135550.

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