Exploring selected pathways to low and zero CO_2 emissions in China's iron and steel industry and their impacts on resources and energy

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Abstract

The increasing energy and material consumption associated with global economic growth has resulted in the need for more severe efforts at mitigating global climate change. The iron and steel industry consumes 8% of energy and emits 7% of total CO_2 globally. China's iron and steel industry contributes to 15% of that country's total CO_2 emissions. Therefore, there is an urgent need to explore the possibility of net zero emissions in the iron and steel industry in China to meet China's goal of carbon neutrality before 2060. In the study presented in this paper, the MESSAGEix–China iron and steel model was developed by integrating the process-based technology of the sector into the IIASA's MESSAGEix framework to explore zero CO_2 emission pathways and their associated impacts on resources, energy, and water in China's iron and steel industry up to 2100. We found that there are multiple pathways to achieving zero CO_2 emissions in the Chinese iron and steel industry by the end of the 21st century. More specifically, in all the pathways developed in this study, CO_2 emissions decreased significantly between 2030 and 2060 due to the rapid application of 100% scrap-based Electric Arc Furnaces (EAFs) and hydrogen-based Direct Reduced Iron (DRI)-EAFs steel-making technologies. However, by 2060, there will still be 70–360 Mt of CO_2 emissions from China's iron and steel industry; consequently, carbon sink or negative emission technologies are required to offset this and achieve the country's carbon neutrality goal. Furthermore, technologies for achieving zero emissions differ widely in terms of their impacts on the consumption of materials and energy. Compared to the electric (ELE) scenarios, 25–40% of extra iron ore is consumed in the current and new national policy (NPS) scenarios and the DRI scenarios, but 25–220% of scrap is required. At the same time, 20–150% more energy will be saved in the ELE scenarios than in the NPS and DRI scenarios. Finally, we recommend that policy makers design a cross-cutting strategy to achieve zero CO_2 emissions and enhance efforts for material recycling and the provision of clean energy and water.

Keywords: Iron and steel industry, MESSAGEix, net zero emissions, energy and water

Highlights:

1) There are multiple pathways to achieving net zero emissions in China's iron and steel industry.

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2) Steel outputs are essential for reducing CO_2 emissions and conserving materials, energy, and water.

3) Hydrogen-based DRI and 100% scrap-EAFs technologies are key to achieving zero emissions.

4) CO_2 mitigation measures have limited impacts on water consumption.

Nomenclature	
MESSAGE	The Model for Energy Supply Strategy Alternatives and their General Environmental Impact
GAINS	The Greenhouse Gases and Air Pollution Interactions and Synergies
EAFs	Electric Arc Furnaces
DRI	Direct Reduced Iron
NPS	Current and New National Policy Scenarios
ELE	Electric-based scenarios
IAMs	Integrated Assessment Models
BECCS	Bioenergy Carbon Capture and Storage
IEA	International Energy Agency
IRENA	The International Renewable Energy Agency
KIC	The Climate-Knowledge and Innovation Community
EU	European Union
CCUS	Carbon Capture, Utilization and Storage
TIMES	The Integrated MARKAL-EFOM System
BF-BOF	Blast Furnaces - Basic Oxygen Furnaces
IIASA	International Institute for Applied Systems Analysis
O&M costs	Operation and Maintenance costs
IMAGE	Integrated Model to Assess the Global Environment
STEPS	Stated Policies Scenario
SDS	Sustainable Sevelopment Scenario
NZE	Net Zero Emission
GLOBIOM	Global Biosphere Management Model
GDP	Gross Domestic Product
HSD	High Steel Demand
LSD	Low Steel Demand
HC|GAS_DRI	Fossil-fuel-based DRI scenarios
H2_DRI	Hydrogen-based DRI scenarios
CECA	China Energy Conservation Association
Sinter_prod_bf_bof	Sinter production in BF-BOF process
Pellets_prod_bf_bof	Pellets production in BF-BOF process
Iron_ore_extr_open_pit	Iron ore extraction by open pit mining technology
Iron_ore_extr_underground	Iron ore extraction by underground mining technology
Iron_ore_benefication	Iron ore production by iron ore processing/benefication technology using primary iron ore to secondary iron ore-used in sinter/pellets plants

Crudesteel_prod_bof	Crude steel production in basic oxygen furnace route
Crudesteel_prod_eaf_prim	Crude steel production in pig iron based electric arc furnace with DRI process
Crudesteel_prod_eaf_sec	Crude steel production in 100% scrap based electric arc furnace process
Steel_hot_rolling_prod	Hot rolled steel production by hot rolling from cast steel
Steel_cold_rolling_prod	Cold rolled steel production by cold rolling from cast steel
Steel_finishing_prod	Steel production by finishing process (including coating, painting, etc.) from rolling steel
Steel_cast_prod	Cast steel production in casting process from crude steel
Pigiron_prod_bf	Pig iron production in blast furnace process and will be used in BOF route
Pigiron_prod_h2_dri	Pig iron production by hydrogen-based DRI process and will be used in EAF route
Pigiron_prod_coal_dri	Pig iron production by coal-based DRI process and will be used in EAF route
Pigiron_prod_coal_dri_ccus	Pig iron production by coal-based DRI process with CCUS and will be used in EAF route
Pigiron_prod_gas_dri_ccus	Pig iron production by natural gas-based DRI process with CCUS and will be used in EAF route
Pigiron_prod_gas_dri	Pig iron production by natural gas-based DRI process and will be used in EAF route
Pigiron_prod_smelt	Pig iron production in oxygen-rich smelting reduction process and will be used in BOF route
Pigiron_prod_smelt_ccus	Pig iron production in oxygen-rich smelting reduction process with CCUS and will be used in BOF route
Coke_prod_coal	Coke making by coal
lime_prod	Lime production from limestone

1. Introduction

The carbon cycle includes short-term processes (e.g., photosynthesis, respiration, exchanges between air and sea, etc.) and long-term processes (exchanges between the oceans, atmosphere, biosphere, and soils) (Berner, 2003). The consumption of fossil fuels has rapidly increased, resulting in the emission of a large amount of CO_2 disturbing the global carbon cycle (The Royal Society, 2021). Because CO_2 is the main driver of climate change, it is essential to limit global warming by reducing CO_2 emissions. During the past 20 years, the effort to combat climate change has increased. For example, the 2015 Paris agreement pledged to limit global warming to less than 2°C and to pursue the goal of a 1.5°C cap to avoid the worst impacts. In line with the Paris agreement, a growing number of countries (e.g., Sweden, France, Germany, the United Kingdom, Canada, Japan, and South Korea) have pledged to achieve net zero emissions or carbon neutrality before the second half of the 21st century (Megan and Isabelle, 2019). Consistent with this, in September 2020, China, one of the world's largest CO_2 emitters (accounting for around 28% of the global total), announced that it will achieve a peak in CO_2 emissions before 2030 and become carbon neutral before 2060. These goals are crucial for tackling climate change and for avoiding a 0.2–0.3 °C temperature increase this century, relative to the pre-industrial level (Cai et al., 2020; Climate Action Tracker, 2020; Hector, 2020; Normile, 2020). It also means that all sectors of the economy have to rapidly take action to reduce emissions in the next several decades. However, China has not yet revealed details on how it intends to reach its carbon neutrality target, including what efforts are required and the associated realistic timelines by industry sector.

Many integrated assessment models (IAMs) are widely used to explore long-term climate change mitigation pathways and the associated impacts on energy use, the economy, and the environment. Yet, most IAMs analyses tend to focus on supply-side mitigation options on global and regional scales. For example, IAMs studies have found that energy efficiency improvement, energy transition from coal to clean energy, and bioenergy carbon capture and storage (BECCS) in energy supply systems are essential for achieving the 1.5°C cap (Grubler et al., 2018; Rogelj et al., 2018; Vuuren et al., 2018). However, solutions for demand-side sectors are not given the same level of attention due to economic and technical challenges (e.g., complexity of industrial sectors) (Creutzig et al., 2018, 2016). The latest analysis from the International Energy Agency (IEA) summarized four main challenges (i.e., long lifetime, high temperature requirement, process emissions, and trade within the global market) for achieving higher decarbonization levels in energy-intensive sectors, especially the iron and steel, cement, aluminum, and chemicals sectors (Hana et al., 2020). The International Renewable Energy Agency (IRENA) provides a ranking of the best potential efforts for reaching zero emissions in the iron and steel, chemical and petrochemicals, cement and lime, aluminum, and transportation sectors by 2060 (IRENA, 2020). In the European Union (EU), the Climate-Knowledge and Innovation Community (KIC) found that material efficiency improvement, material reuse, new production processes, and carbon capture and storage/use are essential for achieving net zero emissions in heavy industrial sectors by 2050 (Material Economics, 2019). Moreover, the reduction in material demand, the use of good quality recycling methods, and the decarbonization of production by using CO_2-free hydrogen and electricity and Carbon Capture, Utilization and Storage (CCUS) could lead to zero emissions in the cement and steel sectors (Chris, 2019).

In China, current studies have mostly focused on cost-effective decarbonization measures in the manufacturing sector, especially in the iron and steel industry, which accounts for 15% of energy and CO_2 emissions in China (Hasanbeigi et al., 2013; Sun et al., 2020; Wen et al., 2019, 2014; Yue et al., 2018; Zhang, 2016). Many researchers have developed process-based tools to estimate the potential for energy conservation and CO_2 emissions mitigation in the Chinese iron and steel industry; they have reported that the application of the currently available technologies to achieve energy efficiency would only result in a 8–27% decrease in those emissions (Zhang et al., 2014, 2019a). Similarly, the China-TIMES model, developed by Ma et al. (2016), was employed to quantify the key efforts that were being made, including the application of energy-efficient measures, reductions in steel demand, and the replacement of blast oxygen furnaces with electric arc furnaces (EAFs), that contribute to CO_2 reductions and their associated impacts on the reduction of air pollution in the Chinese iron and steel industry. They found that such measures will not only reduce CO_2 emissions by around 20% in 2050, but will significantly reduce air pollution (Ma et al., 2016). However, the latest studies show that there is a lack of knowledge on how to achieve net/near zero emissions in China's iron and steel industry. Therefore, the study presented in this paper fills this gap by exploring the pathways to achieving net zero emissions in the Chinese iron and steel industry by the end of the 21st century and by quantifying how technology options affect the consumption of energy and resources. The model for energy supply strategy alternatives and their general environmental impact (MESSAGEix)–China for iron and steel was developed and used to assess the potential for CO_2 reduction using different process-based steel making routes and to quantify the associated impacts on energy and water by the end of the 21st century.

More specifically, this study first builds on Zhang et al. (2019) by extending the study period from 2050 to 2100 to reflect the-state-of-art studies of steel demand projections. Then, the technologies (e.g., iron ore extraction through open pit and underground technologies, iron ore processing through beneficiation technology, coal-based Direct Reduced Iron (DRI) with and without CCUS, natural gas-based DRI with and without CCUS, and hydrogen-based DRI technologies for pig iron production, secondary-based EAFs technologies for crude steel production, and post-process of crude steel through casting, hot rolling, cold rolling, and finishing technologies, etc.) are employed to improve the technology database that was developed by Zhang et al. (2019). The extended timeframe and process-based technology database of the present study provide two important elements and insights. First, the developed MESSAGEix – China iron and steel industry model allows for narrowing the pathways for low and zero emissions in China's iron and steel industry and determining the associated impacts on consumption of resources, energy, and water under the selected target (e.g., carbon neutrality). The technology selection and the relevant capacity and activity will also be identified. Second, under China's carbon neutrality goals, carbon sink or negative emission technologies will be needed to offset 70–360 Mt of CO_2 emissions from the Chinese iron and steel industry by 2060.

This paper is organized as follows. Section 2 presents a brief overview of the iron and steel industry. Section 3 describes the MESSAGEix–China iron and steel model that we employed to develop the scenarios we used to explore the low and zero emissions pathways in China's iron and steel industry. Section 4 presents a discussion of the results of raw material, energy, and water consumption in relation to the CO_2 mitigation pathways. Section 5 presents the uncertainties analysis for the key modelling parameters. Section 6 presents the conclusions and recommendations for further research.

2. Overview of the iron and steel industry

Global crude steel production has been rising steadily in the last 70 years, especially in the last two decades, due to rapid urbanization and economic development. The global crude steel production was nine-times higher in 2020 than in 1950 (see Figure 1). Rapid global development occurred during two periods; the first period was between 1950 and 1970 due to the construction of infrastructure in developed countries (e.g., the United States, Japan, and countries in the EU), while the second period occurred after 2000, due to the key contribution of China (He and Wang, 2017). Pig iron is a key intermediate product in crude steel production. In blast furnaces - Basic Oxygen Furnaces (BF–BOF) route of steel making, pig iron production accounts for over 62% and 50% of the total energy consumption and total CO_2 emissions in the iron and steel industry, respectively (Zhang et al., 2014). Similar to the trend of crude steel, the global production of pig iron rose from 381 Mt in 1968 to more than 1300 Mt in 2020. In China, crude steel production has increased nearly 14-fold, from 66 Mt in 1990 to 1064 Mt in 2020, and pig iron production has increased at the same rate.

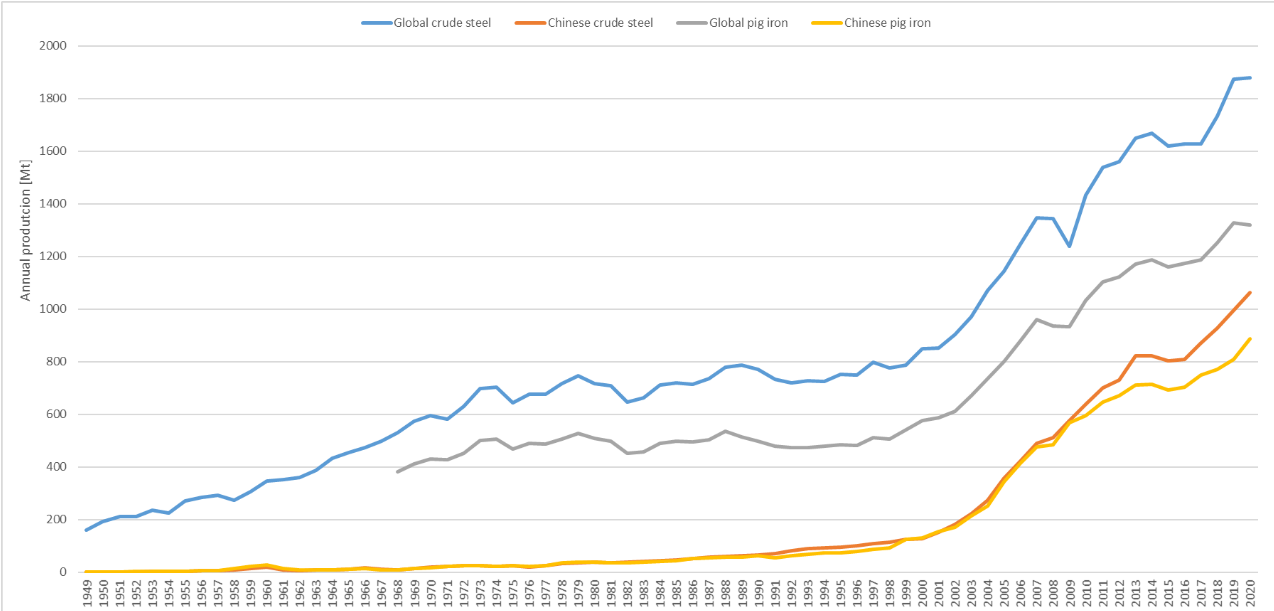


Figure 1: Pig iron and crude steel production globally and in China

Data source: CSDRI (2016), National Bureau of Statistics (2019, 2016), and the World Steel Association (2017). Calculations done by the authors.

The iron and steel industry is one of the most energy- and material-intensive of all industries; it accounts for 8% of global energy consumption and 7% of CO_2 emissions in the energy sector (including energy combustion and processes emissions) (IEA, 2020a). In the iron and steel industry, energy consumption is related to production volume, type of products, production processes, and technological change (Song et al., 2018). Similar to that of crude steel production, the total energy consumption in the global and Chinese iron and steel industries has risen significantly in the last 30 years (see Figure 2). However, energy consumption has not increased as much in the iron and steel industry as it has in the crude steel production process. For example, in China, crude steel production has increased 14-fold over the past 30 years, while energy consumption has only increased seven-fold during the same period as a result of the use of advanced technology. However, the ratios of different sources of energy used in the iron and steel industry have been fairly constant between 1990 and 2019 both globally and in China. Importantly, coal plays a dominant role in steel production; it accounts for 50% of the fuel used in steel production globally and 74% in China. In China, if the sources of electricity generation are considered, direct coal consumption and electricity generated from coal[2] account for over 90% of the total energy in that country's iron and steel industry.

[2] In 2015, coal electricity generation accounted for 67% of China's total electricity production (China Electric Power Yearbook Editorial Committee, 2015).

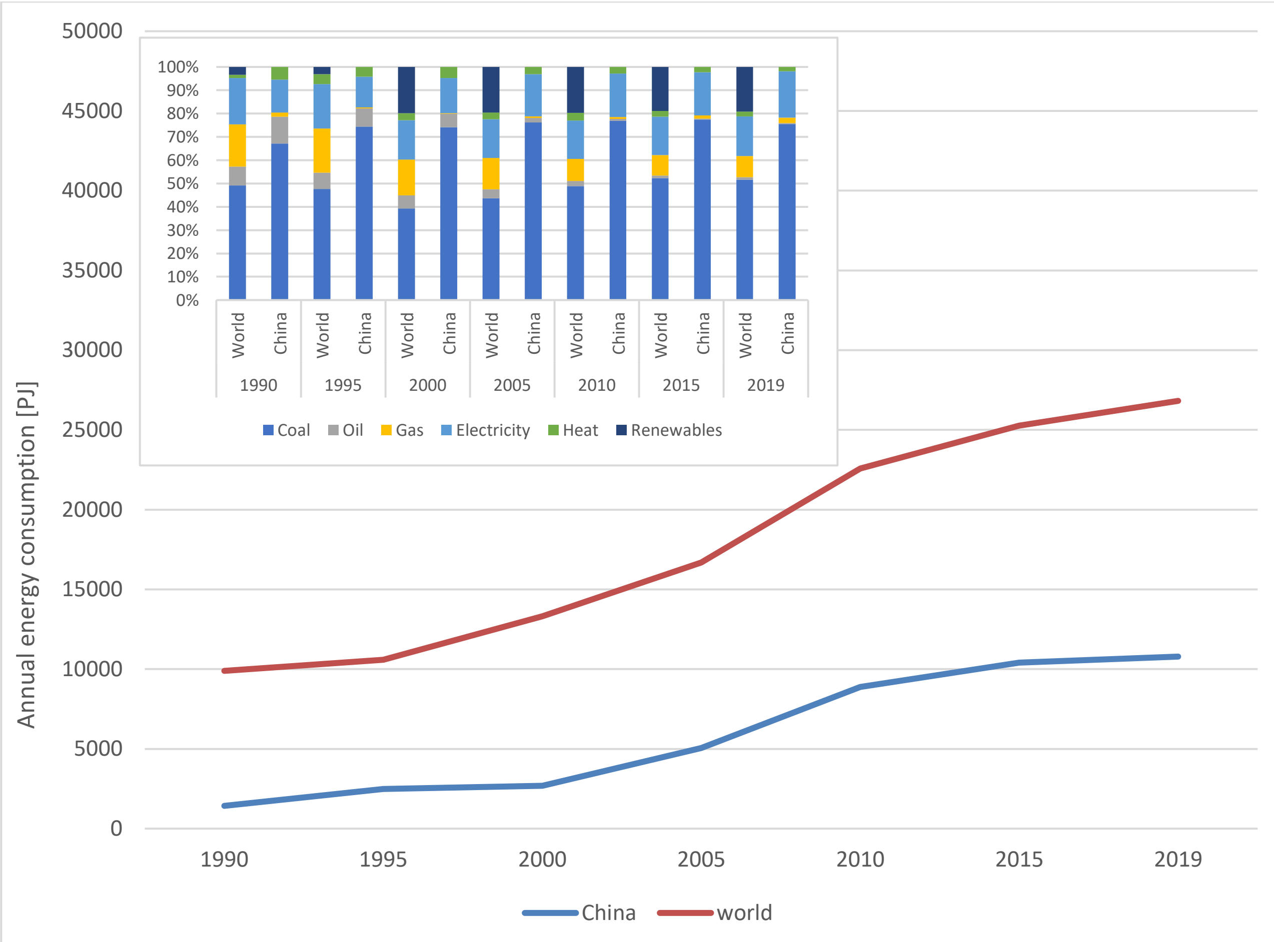


Figure 2: Energy consumption in the iron and steel industry by fuel type

Data source: IEA (2020b). Calculations done by the authors. Note: The boundary of iron and steel industry from IEA's data does not cover the extraction and processing of raw materials (e.g., iron ore and limestone); thus, the total energy consumption of China's iron and steel industry presented in Figure 2 is 18% lower than the data presented in Figure 8 in this paper.

A similar phenomenon is observed with CO_2 emissions in the iron and steel industry (see Figure 3). As shown in Figure 3A, CO_2 emissions increased rapidly between 1990 and 2019, both globally and in China, by two- and eight-times, respectively. Globally, between 1990 and 2005, the percentage of the contributions of different fuels to CO_2 emissions vary slightly. Using the year 2000 as a reference point, the contribution of coal to total CO_2 emissions was 1% higher in 1990 and 5% higher in 2005. In 2019, the global emissions from coal increased by 11% due to the coal consumption and the fossil-based electricity generation in China. In China, no real improvement can be seen in the sources contributing to CO_2 emissions during the same period. Specifically, the largest CO_2 emitter in China's iron and steel industry is coal, accounting for 64–70% of all emissions, followed by electricity (27%). CO_2 emissions from other sources (e.g., gas, oil, heat, and renewable sources) remained nearly constant (Figure 3B).

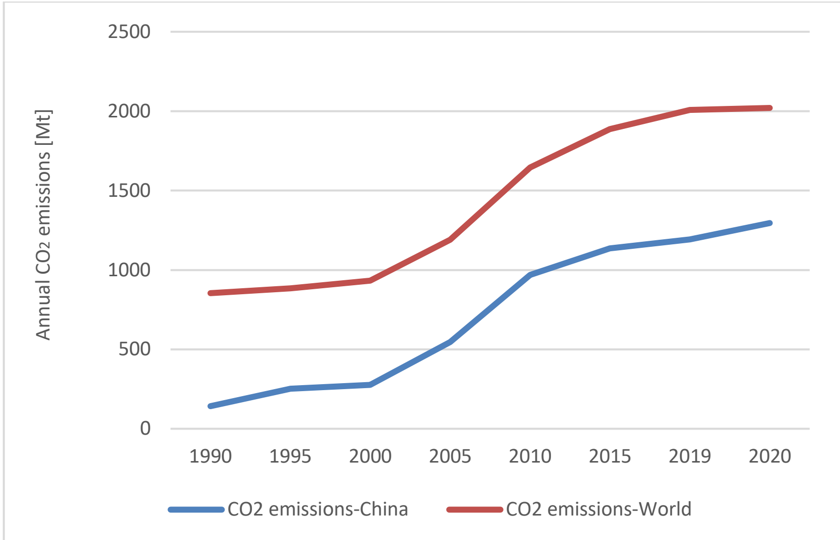


Figure 3A: Total CO_2 emissions in China and the world

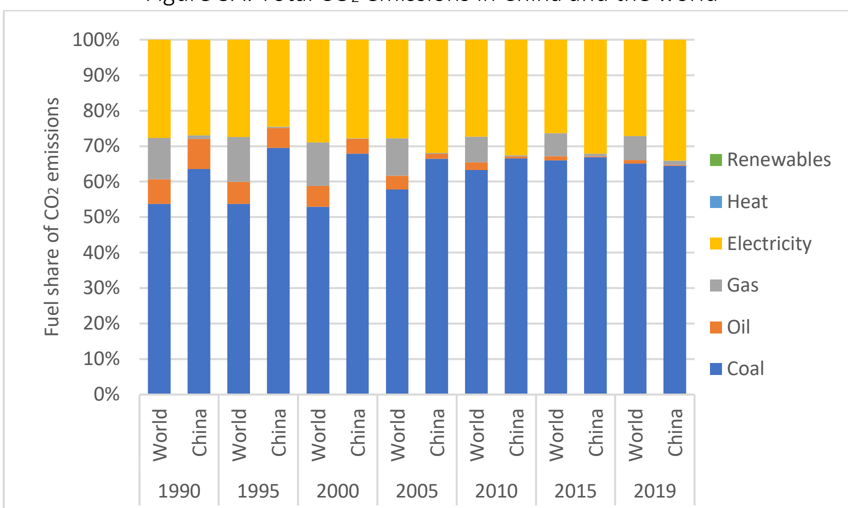


Figure 3B: The CO_2 emissions by fuel types in China and the world

Figure 3: CO_2 emissions and their sources in China's iron and steel industry

Data source: IEA (2020b). Calculations by the authors. Note: The boundary of the iron and steel industry from the IEA's data does not cover the extraction and processing of raw materials (e.g., iron ore and limestone); thus, the CO_2 emissions from China's iron and steel industry presented in Figure 3 is 15% lower than the data presented in Figure 10 in this paper.

3. Methodology

3.1 The MESSAGEix-China iron and steel model

MESSAGE, an energy-environment-economy systems integrated assessment model, was developed by the International Institute for Applied Systems Analysis (IIASA) over the past 40 years (Messner and Strubegger, 1995). Many versions of the model have been developed to investigate topics, such as energy transition, climate change mitigation, and the policy analysis of selected sectors/regions (Dagnachew et al., 2020; Ghadaksaz and Saboohi, 2020; Sullivan et al., 2013; Zhao et al., 2021). The key advantages of the latest MESSAGEix model are: 1) it allows modelers to easily extend the structure or add new formulations and parameters for specific case analyses; 2) it offers efficient workflows (including data processing and reporting) and the ability to interact with other models, such as the greenhouse gas-air pollution interactions and synergies (GAINS) model (Fricko et al., 2017; Ghadaksaz and Saboohi, 2020; Huppmann et al., 2019). MESSAGEix combines technologies and commodities to develop energy and material flows, aiming to visualize the energy and resource footprints from extraction, beneficiation, conversion, distribution, and consumption. The model is mostly used to design long- and medium-term energy and climate strategies by optimizing energy systems with a specified demand at the lowest system costs. The costs include investment costs, operation and maintenance (O&M) costs for selected technologies, and environmental constraints (Huppmann et al., 2019).

MESSAGEix-China is an energy-resource system integrated assessment model that was developed based on the open-source MESSAGEix modeling framework. In this model, the specific features of China's energy and resource systems and the associated policies are included in and expanded to the energy demand modules of the building, transportation, and industrial sectors (e.g., iron and steel). Thus, the MESSAGEix–China iron and steel model developed in this study is a sub-model of MESSAGEix–China. The MESSAGEix–China iron and steel model has a more detailed description of the steel-making process. Specifically, a new energy, material, and water system for China's iron and steel industry was developed to capture the interactions between process technologies through inflows and outflows of the activity of intermediate products (see Figure 4). The model includes six different energy commodities (i.e., coal, coke, electricity, fuel oil, gas, and hydrogen) and 16 materials and water carriers (e.g., iron ore, limestone, sinter, sinter flux, pellets, pellet flux, lime, pig iron, crude steel, cast steel, rolled steel, scrap, slag, steel products, fresh water, and water withdrawal). On the basis of our previous study (Zhang et al., 2019a), seven new steel-making technologies are investigated to enable the exploration of zero emission pathways (Hana et al., 2020; IEA, 2020a; Material Economics, 2019). Therefore, the current MESSAGEix–China iron and steel model consists of 22 process technologies from resource extraction to intermediate material production and product manufacturing. More information on the description of the technology can be found in the Appendix, Table 1. The physical and economic modelling parameters of each technology consist of input/output efficiency, investment and O&M costs, historical capacity and activity, capacity factor, bound of capacity, and future activity. Note that the system boundary of this study is focused on exploring the CO_2 emissions pathways in the iron and steel industry; thus, the indirect emission effect, production and transportation of energy and water carriers, and the leaked emissions due to implementation of CCUS technologies are beyond the scope of this study. This approach is consistent with the emission calculations of current process-based integrated assessment models (e.g., Integrated Model to Assess the Global Environment (IMAGE) and the GAINS model (Tanzer et al., 2020; van Sluisveld et al., 2021; Wang et al., 2017).

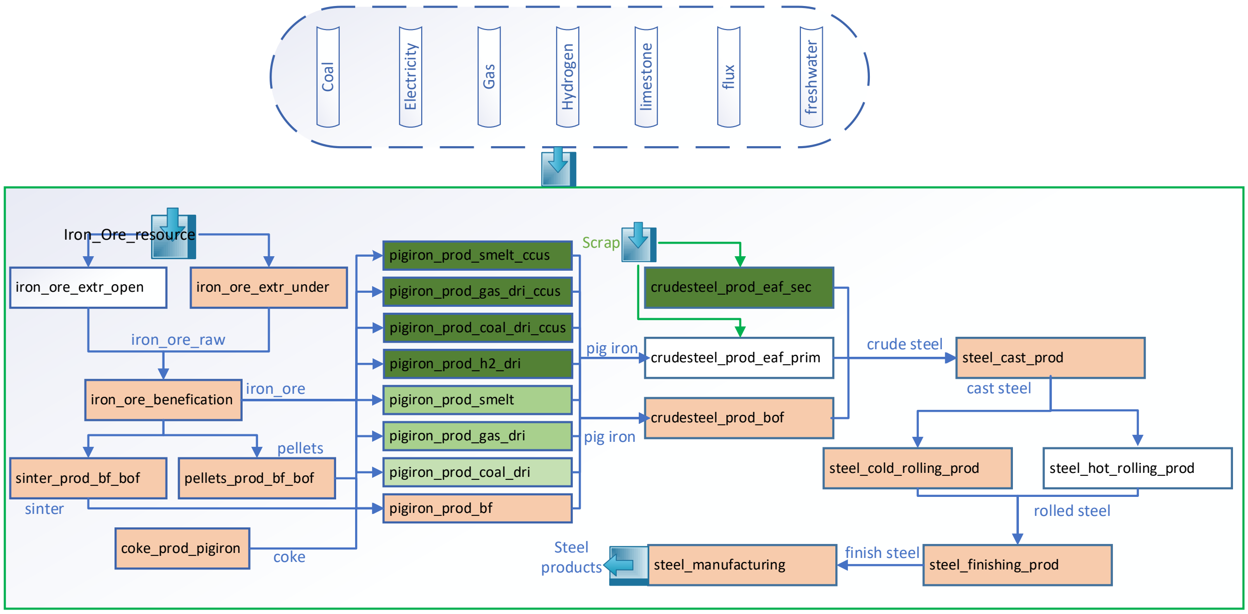


Figure 4: The MESSAGEix–China iron and steel model framework and the associated technology interactions

The model period used in this study is 1990–2100, and the time intervals are the 5 years before 2060 and the time intervals are the 10 years between2060 and 2100. The year 2015 was selected as the first model year to ensure that the modeling results were consistent with the current situation. The historical constraints/status (e.g., total capacity, new capacity, and total activity in the specific year) of each technology and their associated technical lifetimes were used to determine when the technologies would be phased out and what new processes would be implemented. Finally, according to the constraints of technologies, energy source, materials, and resources of China's iron and steel industry, the model will determine the most cost-efficient pathways to satisfy the steel demand.

3.2 Data sources and scenarios

3.2.1 Data sources

The historical activity of the energy commodities (e.g., coal, coke, and electricity) and material commodities (e.g., iron ore, pig iron, sinter, pellets, crude steel, steel products) were obtained from the China Steel Yearbook (CSDRI, 2019, 2016). The consumption levels of historical steel products by end-use sector (e.g., building, transportation, machinery, and domestic appliances) and their associated usage levels were obtained from previous studies (China Industry Information Network, 2015; China Metallurgical Mining Enterprises Association, 2014; Ma et al., 2016; Zhang et al., 2019a).

Investment and O&M costs, fuel efficiency, material efficiency, water efficiency, historical total capacity, and the annual growth capacity for current adopted process technologies were obtained from the China Steel Yearbook and a review of relevant literature (CSDRI, 2019; IEA, 2010; Zhang et al., 2019a). The above parameters for new steel-making technologies—scrap-based EAFs, coal-based DRI with and without CCUS, gas-based DRI with and without CCUS, hydrogen-based DRI, and oxygen-rich smelting reduction with and without CCUS—were obtained from recent studies and communication with Chinese experts (Battle et al., 2014; IEA, 2020a; IRENA, 2020; Material Economics, 2019; University of Groningen, 2020).

As the production and transportation of energy, raw materials, and water carriers are beyond the scope of this study, the energy-related CO_2 emissions of the iron and steel industry are calculated based on the emission factor estimated in previous studies. The CO_2 emission factors for fossil fuel were obtained from the GAINS model (https://gains.iiasa.ac.at/models/index.html) and calibrated based on previous studies (Hasanbeigi et al., 2013; Zhang et al., 2014). The average CO_2 emission factors for electrolytic hydrogen before 2050 were calculated based on the associated power structure from the Stated Policies Scenario (STEPS) by the IEA's World Energy Outlook 2020, the sustainable development scenario (SDS) of the GAINS model, and the work by Rapier (2020). The average CO_2 emission factor of hydrogen was assumed to be zero after 2050, based on the latest analysis by Lauri (2020), the assumption of the low energy demand scenario of the MESSAGEix-GLOBIOM model (Grubler et al., 2018), and the Net Zero Emission (NZE) scenario by the IEA's Net Zero by 2050 (IEA, 2021).

3.2.2 Scenario design

Steel is the fourth-most widely used metal that has had the largest impact on global economic development; it accounted for 10.7% of the annual gross domestic product (GDP) of global total in 2017 (Doug, 2019; FocusEconomics, 2018). In this study, the physical-based intensity use curve was employed to estimate future steel production based on the activity of the steel end-use sectors (e.g., building, transport, machinery, and domestic appliances). The physical-based intensity use is defined as the amount of steel per unit of activity measured in physical terms. For example, a unit of activity is a vehicle that is produced or a square meter building area that is constructed.

We provide two patterns of steel production projections: high steel demand (HSD) and low steel demand (LSD) (see Figure 4). These two patterns, using the same socio-economic projections, were obtained from the Integrated Policy Model for China, the Integrated Model of Economy, Energy and Environment for Sustainable Development/Computable General Equilibrium model, and IEA's World Energy Outlook (IEA, 2020b), as well as our previous study (Zhang et al., 2019a). Specifically, the urbanization rate in China, as an example, increased from 36.22% in 2000 to 63.89% in 2020. During this period, the number of cars owned per 100 households increased from 13 to 173 and the housing area per capita increased from 15 m^2 in 2000 to 40 m^2. Combing the socio-economic projections (e.g., population and GDP per capita), we assume that the space area of new buildings will increase slightly, due to saturation effects. However, the number of transport vehicles will continue to increase because the replacement of fossil-based vehicles by electric vehicles is considered. Moreover, the share of import and export of total steel products in these two patterns is assumed to remain the same in the future, which is consistent with the situation in previous decades. For the HSD projections, we assume that the material intensity of steel demand per activity (e.g., steel consumption per vehicle and steel consumption per space area of building) will be the same during the study period, while the impacts on extending the lifetime of buildings with high retrofit rates, using light weight vehicle, and the material substitution from steel to aluminum in vehicles are considered in the LSD projections. As shown in Figure 5, both steel production projections are higher in the current study than in Ma et al. (2016) and the IEA's projection before 2035. The main reason is that China's rapid transition and its rapid economic development will still require a large amount of steel consumption over the next 15 years. Note that this study also provides the projection of steel products based on the steel manufacturing technology and we used the steel products to analyze the low and zero emissions pathways and the associated impacts on energy and resource. More information of the future activity of steel end-users can be found in appendix Tables 2-3.

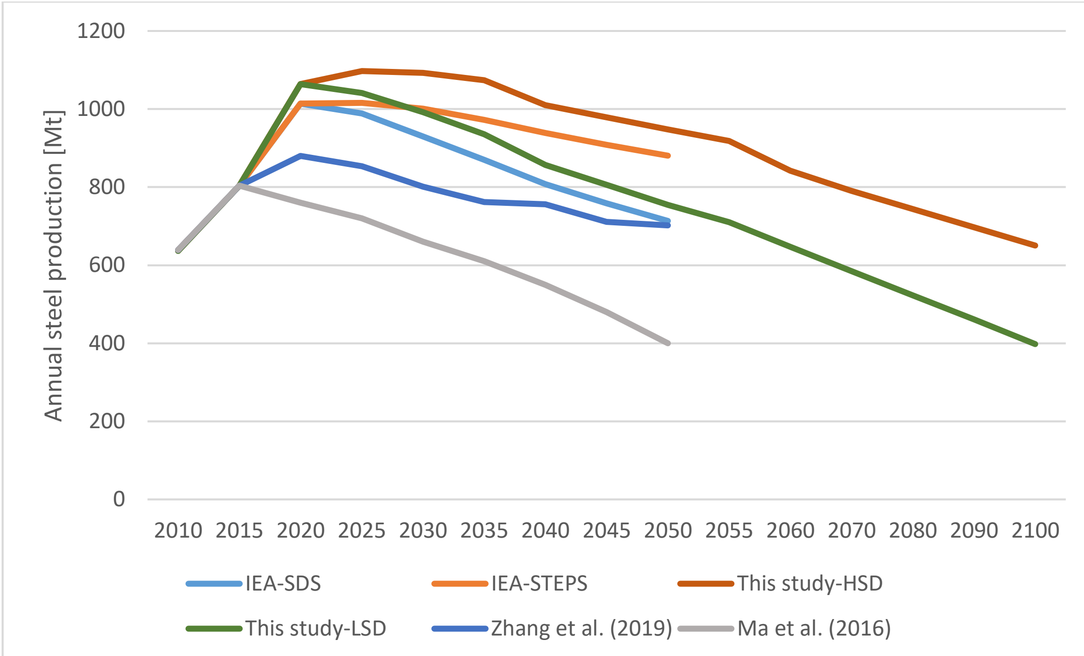


Figure 5: Projection of steel production in China

In this study, two groups were investigated: the HSD group and the LSD group. Each group consists of four scenarios: current and new national policy (NPS), electric (ELE)-based, fossil-fuel-based DRI (HC|GAS_DRI), and hydrogen-based DRI (H2_DRI). These scenarios differ with respect to the key drivers and technologies that affect CO_2 mitigation and their contributions toward reaching zero emissions, under the specific steel demand. Current Chinese energy and climate policies, national commitments, the 14th five-year plan and 2035 goals, and Chinese iron and steel development planning are considered in the NPS with HSD (NPS_HSD) and NPS with LSD (NPS_LSD) scenarios. These two scenarios allow for estimating the impact of current and future policies on energy, resources, and CO_2 emissions. Coal is the dominant fuel in China's iron and steel industry, and it will still play a major role in the future. This is mainly because China has large quantities of low-cost coal. Therefore, two other fossil fuel-based scenarios were developed, (HC|GAS_DRI_HSD and HC|GAS_DRI_LSD), to assess substantial emission reductions relative to the current situation. Under these two scenarios, the iron-making technologies through coal-based DRI with and without CCUS and natural gas-based DRI with and without CCUS are included, while the other process technologies remained the same in comparison to the NPS scenarios. The electrification options and pathways for China's iron and steel industry are described in the ELE_HSD and ELE_LSD scenarios to assess how electrification measures affect CO_2 mitigation. The key feature of the ELE_HSD and ELE_LSD scenarios is that primary-based (40% scrap plus 60% pig iron) EAFs technology and secondary-based (100% scrap) EAFs technology are used for crude steel production. The primary-based EAFs technology represents the current feature of EAFs-based steel making in China, while the secondary-based EAFs technology represents the maximum technology possibility for crude steel production from scrap. Last, but not least, we developed the hydrogen-based DRI (H2_DRI) with different demand scenarios (i.e., H2_DRI_HSD and H2_DRI_LSD) to provide the maximum potential for CO_2 emission reductions and to determine the impacts on energy and water consumption, due to the application of zero carbon electrolytic hydrogen in hydrogen-based DRI for pig iron production.

Table 1: Overview of the scenarios

<table>
<tr><th colspan="3">Scenarios</th><th>Definitions</th></tr>
<tr><td colspan="2" rowspan="2">NPS</td><td>HSD</td><td rowspan="2">Current and new national policies and commitments introduced (e.g., Chinese determined contribution target, 14th five-year plan and 2035 goals) and planning for China's iron and steel industry.</td></tr>
<tr><td>LSD</td></tr>
<tr><td colspan="2" rowspan="2">ELE</td><td>HSD</td><td rowspan="2">High electrification will be employed in the future using EAF technologies for crude steel production.</td></tr>
<tr><td>LSD</td></tr>
<tr><td rowspan="4">DRI</td><td rowspan="2">HC|GAS_DRI</td><td>HSD</td><td rowspan="2">Coal- and gas-based DRI with and without CCUS technologies will be used for pig iron production after 2035.</td></tr>
<tr><td>LSD</td></tr>
<tr><td rowspan="2">H2_DRI</td><td>HSD</td><td rowspan="2">Low-carbon hydrogen (H2) will be used in hydrogen-based DRI route for pig iron production after 2035.</td></tr>
<tr><td>LSD</td></tr>
</table>

4. Results and discussion

4.1 CO_2 emissions and their sources

The projected CO_2 emissions and their associated sources in China's iron and steel industry are shown in Figure 6. As shown in the top section of Figure 6, multiple efforts have been made to achieve zero emissions by the end of the 21st century. Overall, based on all the scenarios, the CO_2 emissions in China's iron and steel industry are projected to peak in 2020 and then decrease at a high rate until 2070. By 2030, the CO_2 emissions with NPS_HSD will be 7% higher than they were in 2015 but 9% lower in comparison to peak levels. By 2030, the CO_2 emissions with NPS_LSD will be 1% higher than they were in 2015 but 13% lower in comparison to peak levels. Within the two scenarios, the current routes, which consist of BF-BOF and crudesteel_prod_eaf_prim (40% scrap + 60% pig iron) technologies, would continue to be used for steel production because most steel plants in China were constructed after 2010. Between 2030 and 2050, although all the scenarios have a trend of reducing emissions, the ELE_LSD scenario showed the largest emission reductions; this scenario is assumed to have the largest implementation of crude_steel_prod_eaf_sec technology, where we assume 100% of scrap is used in the EAFs for steel making. In comparison to 2015, by 2060, emissions are projected to decrease by 73% with HSD and 91% with LSD, most notably in the shift from the BF-BOF route to the scrap- and DRI-based EAFs routes. Moreover, by 2060, emissions with NPS_HSD are only expected to be 5% higher than those with NPS_LSD, while the production gap in the two scenarios is 77%. Only the ELE_LSD scenario achieved zero emissions by 2070; the other five scenarios (NPS_HSD, NPS_LSD, ELE_HSD, H2_DRI_HSD, H2_DRI_LSD) achieved zero emissions at the end of the 21st century. In the HC|GAS_DRI scenario, 24-35 Mt and 16–25 Mt of CO2 will be emitted by 2070 and 2100 due to the use of coal- and gas- based DRI with CCUS technology for pig iron production; the emissions from the other process technologies would stay constant in the NPS scenarios (e.g., basic oxygen furnace for crude steel production and cold rolling for rolled steel production). As mentioned in Section 2, together, coal and electricity account for over 98% of the CO_2 emissions in China's iron and steel industry; thus, the MESSAGEix-China iron and steel model developed in this study only explores the CO_2 emissions by type of fossil fuel (coal and gas) and electricity, as well as the capture potential of CCUS (see the lower section of Figure 6). The negative number in the HC|GAS_DRI scenario represents the percentages of emissions that are captured using CCUS with a CO_2 removal efficiency of 90%. Notably, in the process of iron making, CCUS technology is adopted rapidly in the HC|GAS_DRI scenario, resulting in an emissions reduction of 20–30% by 2050 and 90% by 2070. The other fossil-related emissions (e.g., coal, gas, and electricity) in all the scenarios are mostly generated from the processing of intermediate products of sinter, coke, pig iron, and casting, rolling, and finishing.

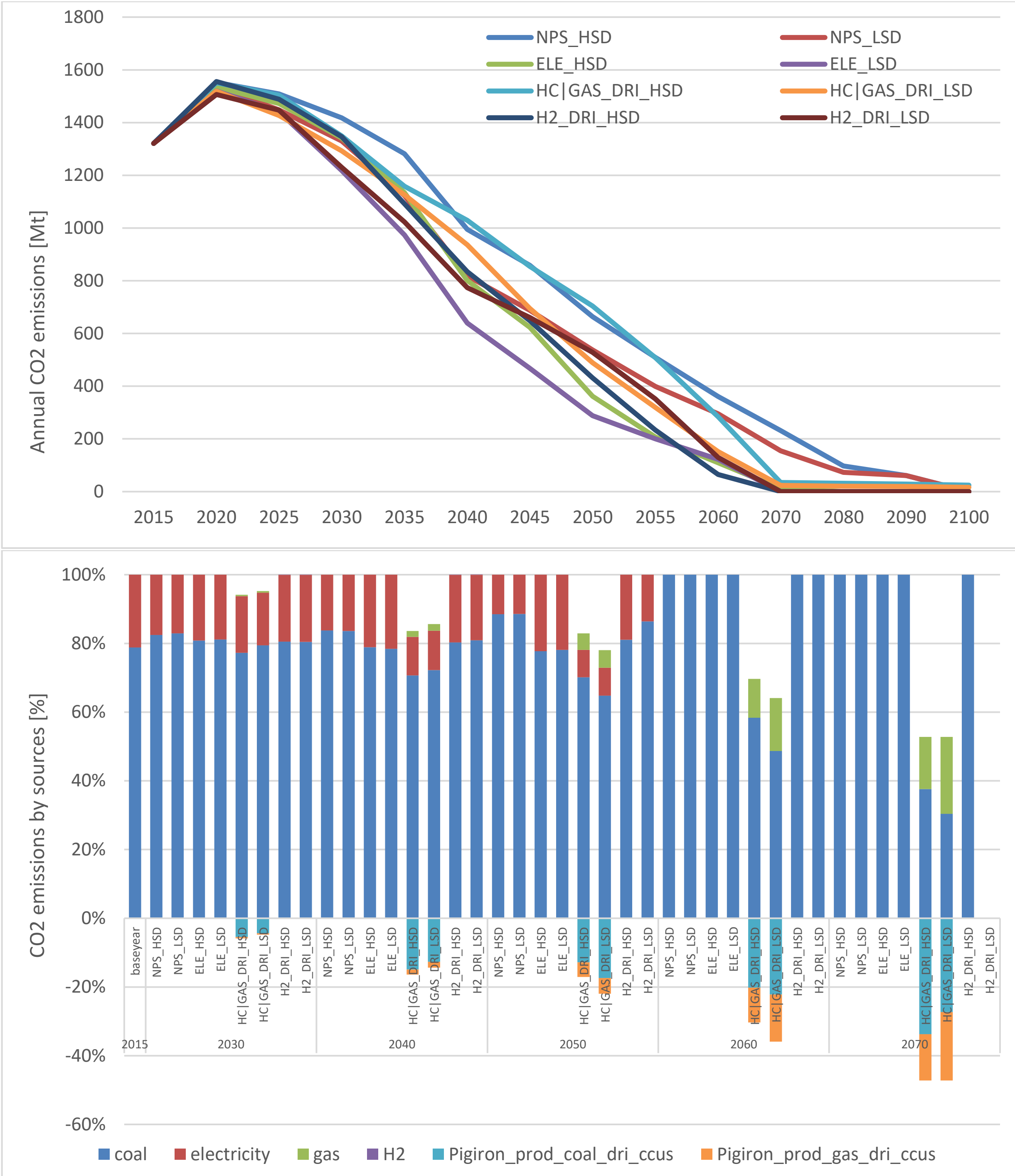


Figure 6: CO_2 emissions (top) and their sources (bottom) in China's iron and steel industry under different scenarios

Note: The x-axis represents the name of the scenarios developed in this study; for example, HC|GAS_DRI_HSD and HC|GAS_DRI_LSD represent the coal-based DRI with and without CCUS and the natural gas-based DRI with and without CCUS that are employed for iron making, while the other process technologies remained the same in comparison to the NPS scenarios. A similar definition is used for the information presented in Figure 7 through Figure 11.

4.2 Material consumption by type

Iron ore is one of most important raw materials in the steel manufacturing process. For China, the iron ore demand rose 11% per year starting in 1990; it went from 179 Mt in 1990 to 763 Mt in 2018, similar to the increase in China's steel production. Overall, the iron ore demand in China's iron and steel industry peaked in 2020; it declines afterwards (see Figure 7). In comparison to 2015, the annual iron ore demand in the NPS_HSD scenario declines by 42% in 2050 and 63% in 2060, due to the shift from BF-BOF technology to 100% scrap-based EAFs technology for crude steel production. Specifically, in the NPS_HSD scenario, the crude steel production from BF-BOF technology declines by 40% from 53 Mt by 2050 to 33 Mt by 2060, while the crude steel production increases by 24% during the same period. If the low steel demand is adopted (NPS_LSD scenario), the iron ore consumption would decrease by 7–11% during the period 2050–2060. The cumulative iron ore consumption declines by 20–25% in the ELE scenarios (i.e., ELE_HSD and ELE_LSD) in comparison to the NSP scenarios. The main reason for this is that there is no iron ore consumption after 2070 due to the full implementation of the 100% scrap-based EAFs for crude steel production (see Figure 8). However, the cumulative iron ore consumption in the DRI-based scenarios (HC|GAS_DRI and H2_DRI) increase by 17–30%, which is a greater increase than in the NPS scenarios, during the entire study period. The main reason is that the material efficiency of pig iron production from DRI technologies is 25% higher than the blast furnaces (BFs) technology. In short, the characteristics of iron ore (e.g., iron content, sulfur content, and fineness of iron ore) determine the process-based technology that will be used in the future. For example, to make pig iron, only iron ore with a fineness of less than 50 mm can be used in BFs.

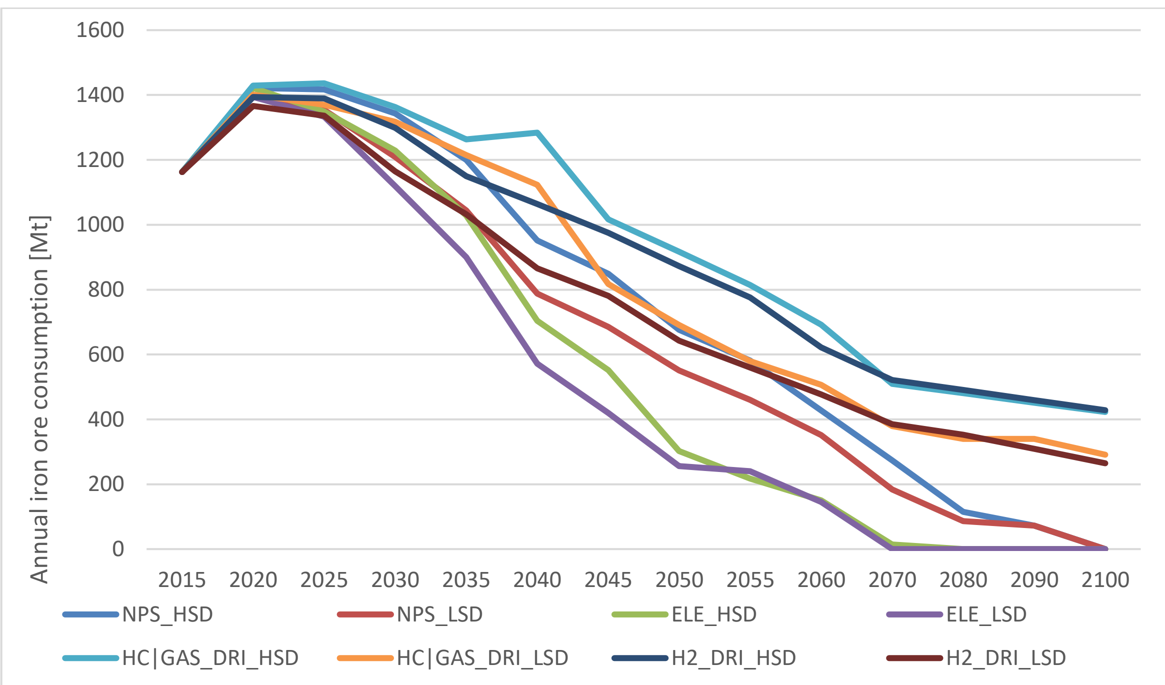


Figure 7: Raw material consumption in China's iron and steel industry

Scrap has been used for steel production over the past 30 years. The use of scrap in EAFs in place of pig iron in basic oxygen furnaces can reduce the consumption of iron ore and coking coal. With the increasing volumes of available scrap, it is essential to use scrap-based EAFs technology in the iron and steel industry to reduce CO_2 emissions and improve the quality of the environment (Chris, 2019; Steven et al., 2017). In this study, we assume that China will have sufficient volumes of scrap to meet the future demand because China has utilized the largest amount of steel products in its building, infrastructure, and machinery sectors in the last 40 years, and Chinese scrap production is projected to increase by 10% per year by 2050 (Energy Transitions Commission and Rocky Mountain Institute, 2021). The analysis indicates that scrap consumption varies; for example, it is projected to be,254–750 Mt in 2060 and 184–674 Mt in 2100 (see Figure 8). This difference stems partly from activity outputs and the adoption of different steel-making methods. Specifically, in the NPS scenarios, by exploring the development pathways under the assumptions of current policies and commitments, the annual scrap consumption will increase seven-to-eight-fold by 2050 in comparison to 2015. With the emphasis on the rapid implementation of scrap-based EAFs technology in the ELE scenarios, the cumulative scrap consumption will further increase about one-third more than in the NPS scenarios during the study period. The DRI scenarios, the scrap demand projection is the lowest of all the scenarios; the projection is around 40% lower in the DRI scenarios than in the NSP scenarios. Another interesting finding is that the cumulative scrap consumption is 20–24% lower in all the LSD scenarios in comparison to all the HSD scenarios, signaling that a lower steel demand is essential for reducing scrap consumption.

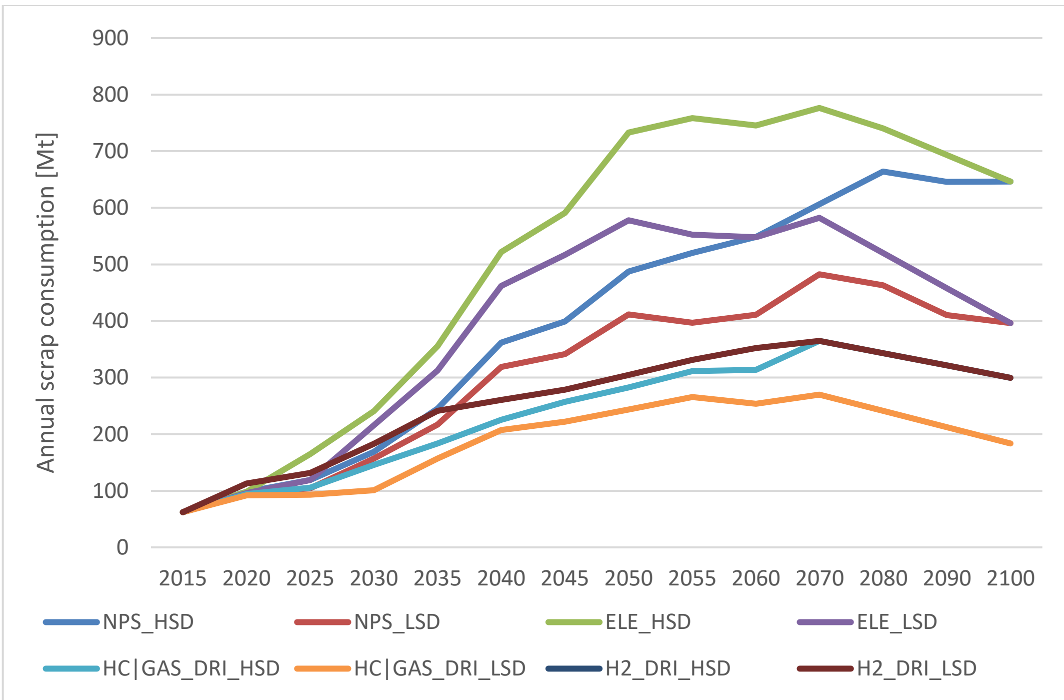


Figure 8: Scrap consumption in China's iron and steel industry

Pig iron, an intermediate material of steel products, is mainly produced from iron ore oxides using BFs or scrap recycling using EAFs. The BFs uses a heat and mass transfer process. During this process, materials, such as sinter, pellets, flux, and limestone, and energy sources (e.g., coke, coal, and electricity) are fed into a shaft furnace to produce a hot metal at around 1500°C; thus, large amounts of CO_2 are emitted. Scrap smelting for iron making is more efficient than using a BF because it only uses electricity. DRI technology is another advanced pig iron-making approach; however, it consumes more energy than the BF-BOF and scrap-based EAFs steel making routes, depending on its operation conditions (e.g., temperature, charging method, and sulfur and phosphorus content). The advantage of the DRI-based iron-making method is that the product has a low amount of metallic elements (e.g., copper and nickel) and nitrogen, which allows for the production of high-quality steel products with low metallic residuals (e.g., slag) (Battle et al., 2014). The pig iron consumption in China's iron and steel industry for all the scenarios is presented in Figure 9. Overall, the production of steel products has a considerable effect on pig iron consumption; the LSD scenarios consume 8–14% less pig iron than the HSD scenarios. In the NPS scenarios, pig iron consumption peaks in 2020 (916–934 Mt), then it declines drastically until 2070. It is not surprising that the DRI-based scenarios have the highest pig iron demand resulting in a high amount of iron ore requirements (see Figure 7). The high electrification assumptions of the 100% scrap EAFs steel-making routes in the ELE scenarios have the lowest demand for pig iron. In comparison to the NPS scenarios, the demand for pig iron is 16–27%

higher in the DRI scenarios and 20–33% lower in the ELE scenarios.

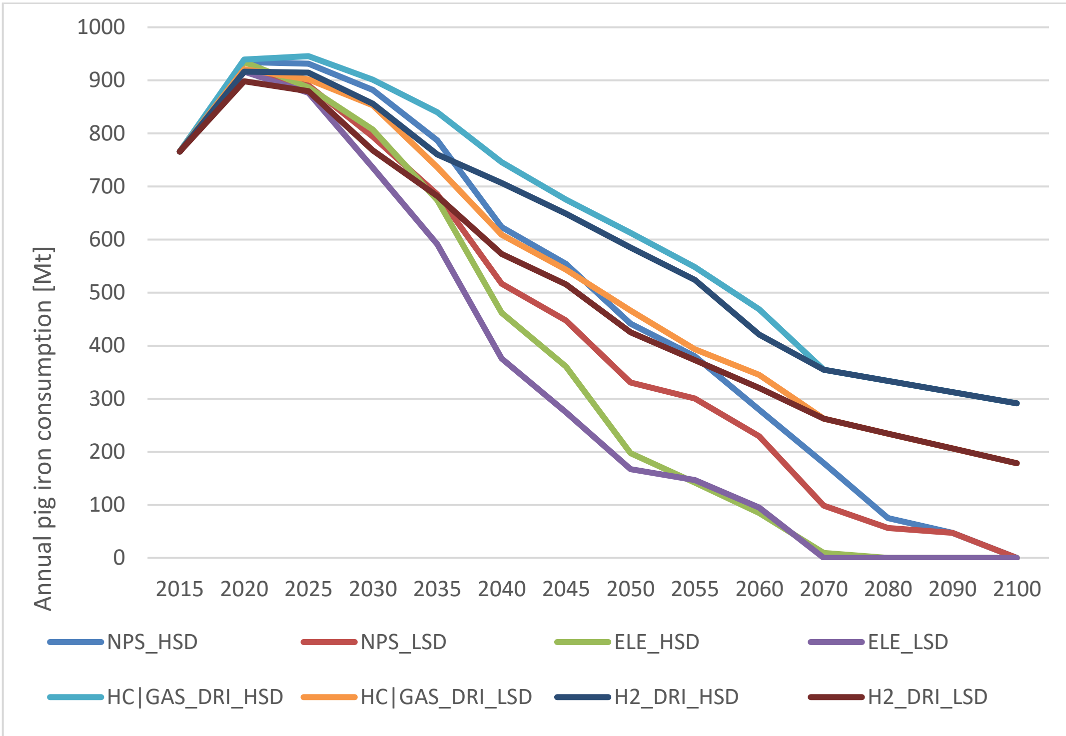
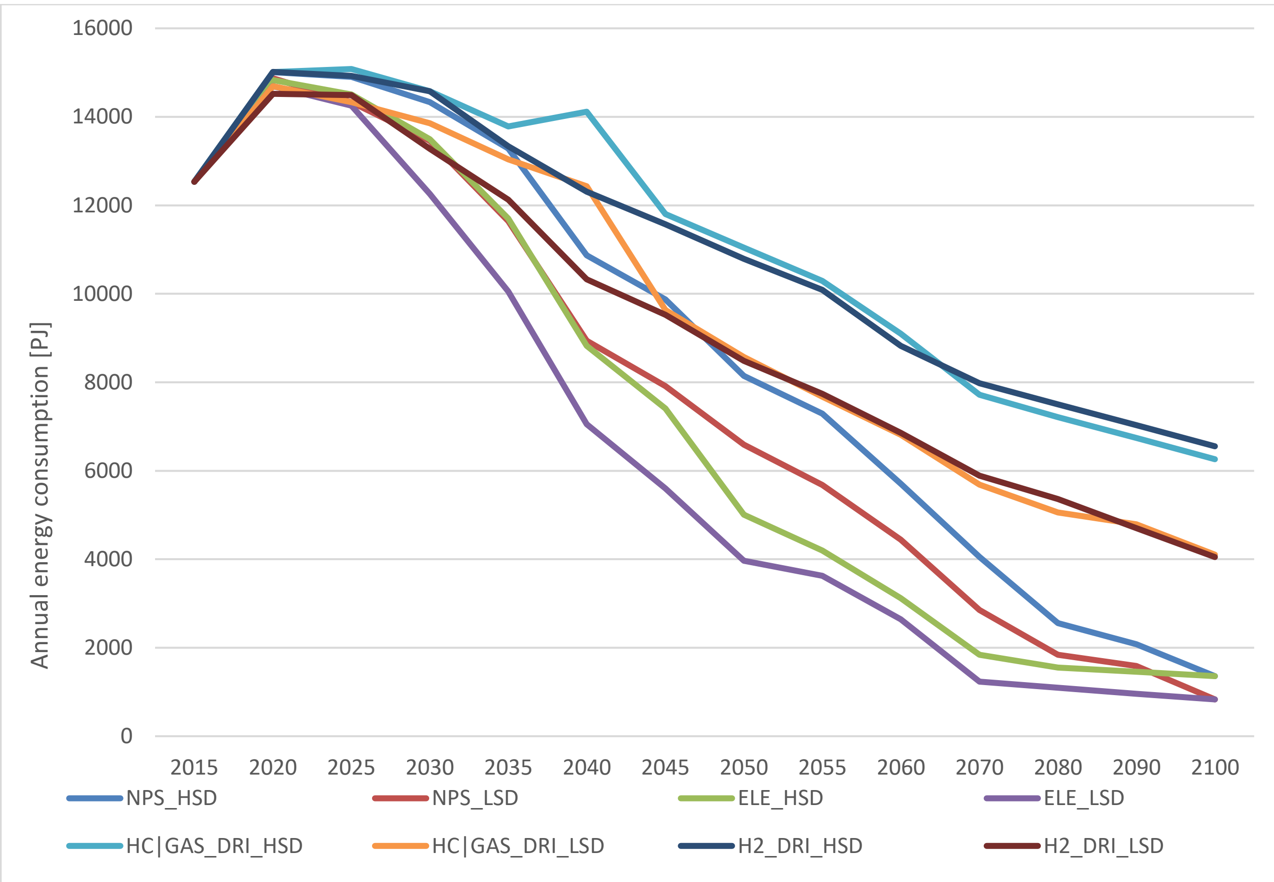


Figure 9: Pig iron consumption in China's iron and steel industry

4.3 Energy consumption and the proportions of different energy sources

The projected energy consumption and the proportions of different energy sources used in China's iron and steel industry are depicted in Figure 10. As seen in the top section of Figure 10, overall, all the scenarios project an increase in energy consumption until 2020, then that consumption rapidly declines at different rates through 2100. Overall, by 2100, the ELE scenarios have the lowest levels of energy consumption (89–93% lower than 2015), while the DRI-based scenarios have the highest levels (48–68% lower than 2015). The main reason for this are: 1) the energy intensity for pig iron by using 100% scrap-based EAFs technology is 5.8 GJ/t, while the energy intensity using DRI-based technology is around 11.8 GJ/t (Zhang et al., 2019b, 2014); 2) the low steel demand pattern would reduce the amount of energy required by 4–20%, depending on whether CCUS is installed. Based on different stages of the scenarios, energy consumption increases at an average annual rate of 3% from 2015 to 2020 to meet the growing steel demand, consistent with the projection from the China Energy Conservation Association (CECA) (CECA, 2020). Between 2020 and 2030, the energy consumption of the different scenarios differs widely. For example, the NPS_HSD, HC|GAS_DRI_HSD, and H2_DRI_HSD scenarios show a stable trend, while the other scenarios decline modestly due to the implementation of efficient technology (e.g., scrap-EAFs technology) and low steel demand, especially for the building sector where retrofitting of existing buildings is essential. In comparison to the NPS scenarios, the energy reductions in the ELE scenarios are 10% and 40% lower in the 2030–2045 period and 2050–2090 period, respectively. The main reason for this is that the installed capacity for 100% scrap-based EAFs technology in the ELE scenarios is 13–15% in comparison to the NPS scenarios during the same period. In contrast, to meet the demand for steel and the net zero emission reduction target, over three-times more energy is consumed in the DRI-based scenarios than the ELE-based scenarios due to the implementation of CCUS technology. In terms of the proportions of various energy sources, there is a clear shift toward the use of electricity and hydrogen in China’s iron and steel industry in the next two decades (see the bottom section of Figure 10). Coal consumption is expected to be extensive in the NPS scenarios and remain stable through 2070, accounting for over 70% of the total energy in China’s iron and steel industry. At the same time, the CO_2 emissions in the NPS scenarios will exceed 300 Mt by 2060; thus, China's carbon neutrality target cannot be achieved before 2060. The electricity consumption in the ELE and DRI scenarios will continue to increase from 10–18% in 2030 to 25–44% in 2070, due to the implementation of **primary-based EAF and secondary-based EAFs technologies.** It is important to note that while high steel production accelerates the implementation of advanced technology, which results in the use of clean energy sources, such as electricity and hydrogen, the impact is limited.



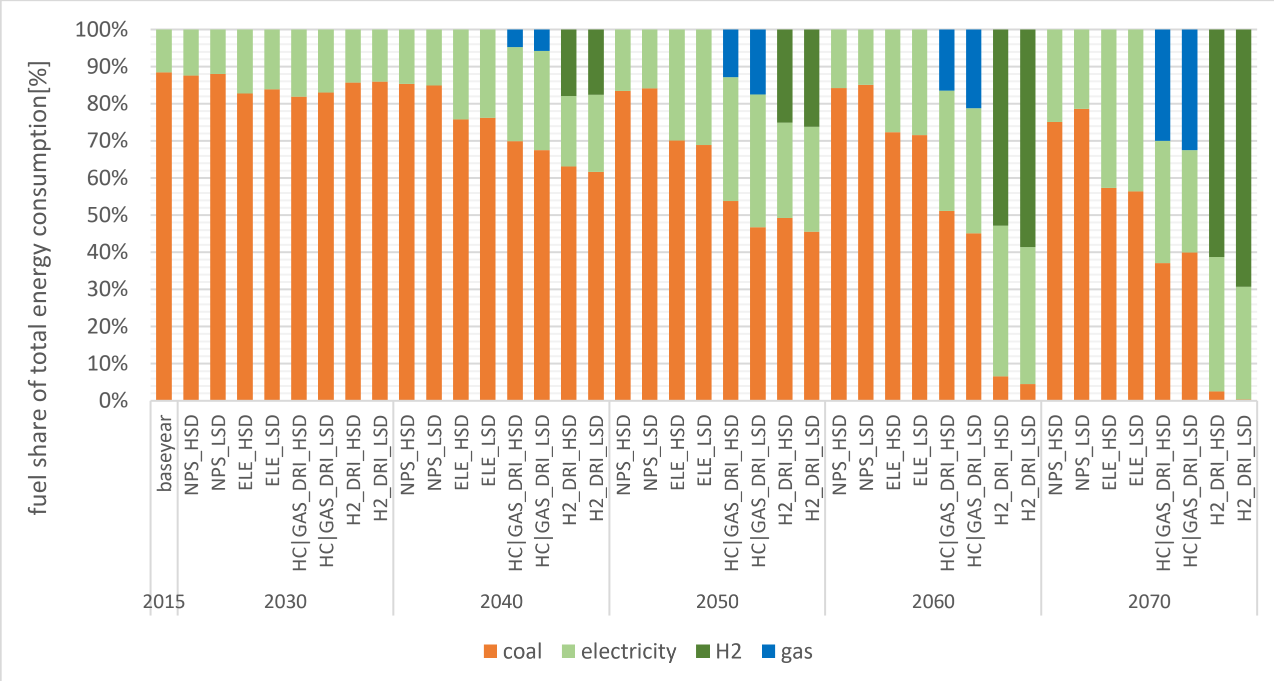


Figure 10: Total energy consumption (top) and the proportions of various energy sources used (bottom) in China's iron and steel industry

4.4 Water consumption and its sources

Water shortages are one of the most important challenges for sustainable development and for tackling climate change. Global water consumption will increase by 30% in 2050 due to increases in the world's population, industrial activity, and changing consumption patterns. Water consumption for industrial purposes will increase 2.5-times in Asia in the middle of the current century (Boretti and Rosa, 2019). The iron and steel industry uses large amounts of water; it ranks fifth in water consumption in China (Tong et al., 2019). Thus, in this study, we attempted to analyze how selected steel-making technologies in the near zero emission pathways would affect water consumption in China's iron and steel industry. Note that, to avoid the uncertainty, the intensity of each technology process (e.g., water consumption per activity of technology) remained the same during the study period.

The top section of Figure 11 presents the linear reducing trend of water consumption in China's iron and steel industry. Overall, the total water consumption peaks at 5300 MM^3 in 2020, then declines to 1600–2600 MM^3 in 2100. The main sources of the decline in water consumption are changes in activity (i.e., the decline in steel demand) and the use of different steel-making technologies that have limited effects on overall water consumption. Specifically, in the NPS_HSD scenario, the total water consumption in 2050 will be at the level it was in 2015; in the NPS_LSD scenario, the total water consumption in 2040 will be at the level as was in 2005, due to changes in steel output. Moreover, 43–65% of water consumption will be reduced in the NPS scenarios by the end of 21^{st} century. The water consumption seen in the DRI and ELE scenarios differs by 7% from the consumption seen in the NPS scenarios due to the implementation of different steel-making technologies. The water consumption in different scenarios varies widely (see the bottom section of Figure 11). As shown in the bottom section of Figure 10, in 2015, 35% of the water that is used is consumed in pigiron_prod_bf (iron making with a blast furnace), 19% is consumed in steel_finishing_prod, and 15% is consumed in iron ore beneficiation. According to the model used in this study, between 2050 and 2060, pigiron_prod_bf continues to be a major source of water consumption and accounts for 17–23% of the total consumption. Around 40% of the water that is used will be consumed by crudesteel_prod_eaf_prim technology in the ELE scenarios and crudesteel_prod_eaf_sec in the DRI scenarios. Together, steel_cold_rolling_prod and steel_finishing_prod account for another 40% of the water consumption.

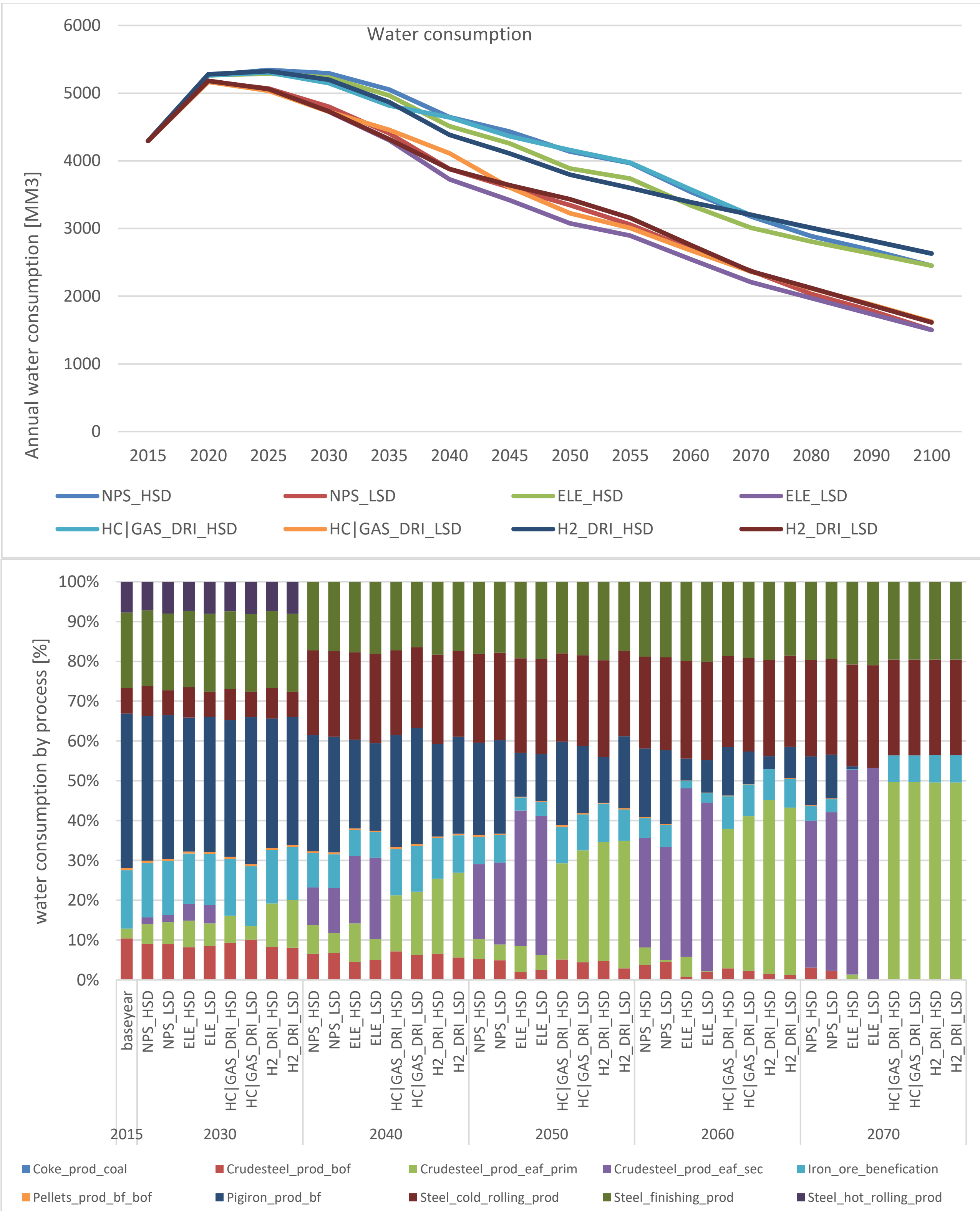


Figure 11: Water consumption (top) and the associated sources (bottom) in China's iron and steel industry

5. Uncertainties analysis

Modelling and understanding uncertainty is essential for modelers and policy makers to design relevant policies and implement actions to reach a specific target. Multiple approaches (e.g., robust optimization and stochastic programming, chance-constrained optimization) have been widely used to address uncertainties over the last 20 years (Apap and Grossmann, 2017). Robust optimization and chance-constrained optimization are used to better understand the uncertainty of multi-parameters and the associated effects; however, they cannot identify what technologies are most essential for any given solution (Giannakidis et al., 2015). In contrast, stochastic programming with endogenous uncertainty or decision-dependent uncertainty can be used to optimize a system with a given target. The key advantage of this approach is providing an optimal solution with an appropriate choice for long-term planning (Hellemo et al., 2018). Robust optimization and chance-constrained optimization are mostly used in short-term assessments; the stochastic optimization is preferred for long-term planning. Therefore, a scenario-based stochastic optimization with endogenous uncertainty is used in the MESSAGEix model to address the uncertainty challenges (Zhang et al., 2019a).

In this study, we assumed that the technology characteristics (e.g., intensities for fuel, materials, and water) remain constant over the study period, because we assume that these parameter uncertainties have limited impacts on CO_2 emission reductions at the national scale. For example, the full implementation of the best available energy efficiency technologies to improve energy and material efficiency in China's iron and steel industry can only reduce CO_2 emissions by 9% by 2050 in comparison to the baseline scenario where we assume the efficiency of each technology remains constant (Zhang et al., 2019a). Therefore, we set two different steel production patterns to assess the activity uncertainties in the definition of the zero emissions pathways (see Section 3.2.2). We found that 20–30% of CO_2 emissions would be avoided by 2050 due to the changes in steel demand. At the same time, 19–22% of energy, 18–26% of iron ore, and 10–22% of water consumption would be reduced. Note that, in the absence of resource and scrap availability and the technology spillover effects at the local level, a discussion of the parameter uncertainties related to these characteristics will not be considered here; further study is needed by extending the current MESSAGEix - China model to include the provincial/city level.

6. Conclusion and areas for further research

With China's announcement of its goal to reach carbon neutrality before 2060, it is important to explore pathways to achieving net zero emissions in energy-sensitive sectors, especially in manufacturing industries. China's iron and steel industry is the largest energy consumer and emitter of CO_2 in the global iron and steel industry, accounting for 50% of CO_2 emissions globally and 15% of the total CO_2 emissions in China. In this study, the process-based MESSAGEix-China iron and steel model was developed and used to present a comprehensive analysis to explore zero emission pathways in China's iron and steel industry, and to assess the associated impacts on the consumption of materials, energy, and water.

Overall, we found that there are multiple pathways to achieve zero emissions in China's iron and steel industry by the end of the 21st century; however, the energy, material, and water requirements of these pathways vary widely. In all the investigated scenarios, reductions in CO_2 emissions are limited before 2030, but they decline significantly between 2030 and 2060 due to the rapid application of 100% scrap-based EAFs and hydrogen-based DRI-EAFs steel-making technologies. However, there are still 70–360 Mt of CO_2 emissions by 2060; thus, other sectors and measures (e.g., forest and negative emissions technology) have to offset these emissions in order to achieve China's carbon neutrality goal. Furthermore, the presented efforts to achieve zero emission differ widely in terms of their impacts on the consumption of materials and energy. For example, the NPS and DRI scenarios have the largest iron ore demand, which is 25–40% higher than the demand seen in the ELE scenarios. The scrap consumption is 25–220% higher in the ELE scenarios than in the NPS and DRI scenarios. The ELE scenarios have the lowest levels of energy consumption, which is 20% and 150% lower than the NPS and DRI scenarios, respectively. The emission reduction efforts were found to have a limited effect on total water consumption in comparison to the production of steel products.

Although the Chinese government is committed to its carbon peak and carbon neutrality goals, China's iron and steel industry and the associated sectors face a lack of clarity regarding the actual policies and the advanced technologies they will need to implement. According to this study's key findings, to implement sector-based strategies/policies, it is necessary to involve many producers (e.g., between steel, scrap and electricity and hydrogen generation). Within the process of policy development, all key stakeholders (e.g., producers on the supply side, end-users on the demand side, and policy makers) are required to assess the competitiveness of the technological options (e.g., based on the availability of iron ore, water, and scrap, access to renewable-based electricity and hydrogen, and the potential for geological storage for CCUS), the investment, the infrastructure requirements, and the costs. Once the strategy/policy has been implemented, its progress must be monitored and the policy must be updated.

Future research should:

- Better represent the relationship between the supply and demand of energy, raw materials, and steel in the model with various scales, as these are dynamic processes across sectors and regions.
- Extend the MESSAGEix – China model at the regional scale, which will allow for more accurate projections for long-term planning.
- Include more parameters (e.g., air quality, water, and materials) to quantify what cross-cutting strategy would reach multiple targets with the least cost.
- Perform nesting with the IIASA's MESSAGEix global integrated assessment model to assess China's global contribution to reducing CO_2 emissions.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (71904007 and 72004006), the GEIGC Science and Technology Project on "Modelling Air Pollution Control and Environmental Health Perspectives under the Green and Low Carbon Transition of Global Energy System" (2900/2020-75001B), the Fine Particle Research Initiative in East Asia Considering National Differences (FRIEND) Project through the National Research Foundation of Korea (NRF) funded by the Ministry of Science and ICT (Project No. 2020M3G1A1114622), the Beihang Youth Hundred Program, and the Beihang Youth Talent Support Program. We extend our gratitude to the anonymous reviewers who provided valuable comments and suggestions for how to improve this manuscript. All remaining errors remain the sole responsibility of the authors.

Data accessibility

The key data used in the figures in this paper are provided in the electronic supplementary material. Further information and requests for original efficiency/cost/activity/capacity data should be directed to the lead author, Shaohui Zhang (s_zhang@buaa.edu.cn and shaohui.zhang@iiasa.ac.at).

References

Apap, R.M., Grossmann, I.E., 2017. Models and computational strategies for multistage stochastic programming under endogenous and exogenous uncertainties. Computers & Chemical Engineering 103, 233–274. https://doi.org/10.1016/j.compchemeng.2016.11.011

Battle, T., Srivastava, U., Kopfle, J., Hunter, R., McClelland, J., 2014. Chapter 1.2 - The Direct Reduction of Iron, in: Seetharaman, S. (Ed.), Treatise on Process Metallurgy. Elsevier, Boston, pp. 89–176. https://doi.org/10.1016/B978-0-08-096988-6.00016-X

Berner, R.A., 2003. The long-term carbon cycle, fossil fuels and atmospheric composition. Nature 426, 323–326. https://doi.org/10.1038/nature02131

Boretti, A., Rosa, L., 2019. Reassessing the projections of the World Water Development Report. npj Clean Water 2, 1–6. https://doi.org/10.1038/s41545-019-0039-9

Cai, W., Zhang, C., Suen, H.P., Ai, S., Bai, Y., Bao, J., Chen, B., Cheng, L., Cui, X., Dai, H., Di, Q., Dong, W., Dou, D., Fan, W., Fan, X., Gao, T., Geng, Y., Guan, D., Guo, Y., Hu, Y., Hua, J., Huang, C., Huang, H., Huang, J., Jiang, T., Jiao, K., Kiesewetter, G., Klimont, Z., Lampard, P., Li, C., Li, Q., Li, R., Li, T., Lin, B., Lin, H., Liu, H., Liu, Q., Liu, X., Liu, Y., Liu, Zhao, Liu, Zhidong, Liu, Zhu, Lou, S., Lu, C., Luo, Y., Ma, W., McGushin, A., Niu, Y., Ren, C., Ren, Z., Ruan, Z., Schöpp, W., Su, J., Tu, Y., Wang, J., Wang, Q., Wang, Yaqi, Wang, Yu, Watts, N., Xiao, C., Xie, Y., Xiong, H., Xu, M., Xu, B., Xu, L., Yang, J., Yang, L., Yu, L., Yue, Y., Zhang, S., Zhang, Z., Zhao, J., Zhao, L., Zhao, M., Zhao, Z., Zhou, J., Gong, P., 2020. The 2020 China report of the Lancet Countdown on health and climate change. The Lancet Public Health. https://doi.org/10.1016/S2468-2667(20)30256-5

China Electric Power Yearbook Editorial Committee, 2015. China Electric Power Yearbook. China Electric Power Press, Beijing.

China Energy Conservation Association, 2020. Energy saving and low carbon development of China's iron and steel industry [WWW Document]. URL http://www.cecaweb.org.cn/home/column.php?portal_id=1&column_id=21&column_group=&column_type=0&parent_id=20&content_id=2925 (accessed 1.7.21).

China Industry Information Network, 2015. Demand Analysis of China's Iron and Steel Industry in 2014 [WWW Document]. Demand Analysis of China's Iron and Steel Industry in 2014. URL http://www.chyxx.com/industry/201507/330432.html (accessed 2.15.18).

China Metallurgical Mining Enterprises Association, 2014. Analysis of future steel demand by end use sectors [WWW Document]. Analysis of future steel demand by end use sectors. URL http://www.mmac.org.cn/planning/Show.Asp?ID=2270 (accessed 2.15.18).

Chris, B., 2019. Low and zero emissions in the steel and cement industries.

Climate Action Tracker, 2020. China going carbon neutral before 2060 would lower warming projections by around 0.2 to 0.3 degrees C | Climate Action Tracker [WWW Document]. URL https://climateactiontracker.org/press/china-carbon-neutral-before-2060-would-lower-warming-projections-by-around-2-to-3-tenths-of-a-degree/ (accessed 1.20.21).

Creutzig, F., Fernandez, B., Haberl, H., Khosla, R., Mulugetta, Y., Seto, K.C., 2016. Beyond Technology: Demand-Side Solutions for Climate Change Mitigation. Annu. Rev. Environ. Resour. 41, 173–198. https://doi.org/10.1146/annurev-environ-110615-085428

Creutzig, F., Roy, J., Lamb, W.F., Azevedo, I.M.L., Bruin, W.B. de, Dalkmann, H., Edelenbosch, O.Y.,

Geels, F.W., Grubler, A., Hepburn, C., Hertwich, E.G., Khosla, R., Mattauch, L., Minx, J.C., Ramakrishnan, A., Rao, N.D., Steinberger, J.K., Tavoni, M., Ürge-Vorsatz, D., Weber, E.U., 2018. Towards demand-side solutions for mitigating climate change. Nature Climate Change 8, 268–271. https://doi.org/10.1038/s41558-018-0121-1
CSDRI, 2019. China Steel Yearbook 2019.
CSDRI, 2016. China Steel Yearbook 2015.
Dagnachew, A.G., Poblete-Cazenave, M., Pachauri, S., Hof, A.F., Ruijven, B. van, Vuuren, D.P. van, 2020. Integrating energy access, efficiency and renewable energy policies in Sub-Saharan Africa: a model-based analysis. Environ. Res. Lett. https://doi.org/10.1088/1748-9326/abcbb9
Doug, G., 2019. The Role of Steel Manufacturing in the Global Economy. Oxford Economics, UK.
Energy Transitions Commission, Rocky Mountain Institute, 2021. China 2050: zero carbon pathway of a modernized country. Beijing, China.
FocusEconomics, 2018. The Story of Steel. The Story of Steel. URL https://www.focus-economics.com/blog/steel-facts-commodity-explainer (accessed 8.26.21).
Fricko, O., Havlik, P., Rogelj, J., Klimont, Z., Gusti, M., Johnson, N., Kolp, P., Strubegger, M., Valin, H., Amann, M., Ermolieva, T., Forsell, N., Herrero, M., Heyes, C., Kindermann, G., Krey, V., McCollum, D.L., Obersteiner, M., Pachauri, S., Rao, S., Schmid, E., Schoepp, W., Riahi, K., 2017. The marker quantification of the Shared Socioeconomic Pathway 2: A middle-of-the-road scenario for the 21st century. Global Environmental Change 42, 251–267. https://doi.org/10.1016/j.gloenvcha.2016.06.004
Ghadaksaz, H., Saboohi, Y., 2020. Energy supply transformation pathways in Iran to reduce GHG emissions in line with the Paris Agreement. Energy Strategy Reviews 32, 100541. https://doi.org/10.1016/j.esr.2020.100541
Giannakidis, G., Labriet, M., Gallachóir, B.Ó., Tosato, G. (Eds.), 2015. Informing Energy and Climate Policies Using Energy Systems Models: Insights from Scenario Analysis Increasing the Evidence Base, Lecture Notes in Energy. Springer International Publishing. https://doi.org/10.1007/978-3-319-16540-0
Grubler, A., Wilson, C., Bento, N., Boza-Kiss, B., Krey, V., McCollum, D.L., Rao, N.D., Riahi, K., Rogelj, J., Stercke, S.D., Cullen, J., Frank, S., Fricko, O., Guo, F., Gidden, M., Havlík, P., Huppmann, D., Kiesewetter, G., Rafaj, P., Schoepp, W., Valin, H., 2018. A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. Nature Energy 3, 515–527. https://doi.org/10.1038/s41560-018-0172-6
Hana, M., Tiffany, V., Araceli Fernandez, P., Peter, L., Timur, G., 2020. The challenge of reaching zero emissions in heavy industry – Analysis [WWW Document]. IEA. URL https://www.iea.org/articles/the-challenge-of-reaching-zero-emissions-in-heavy-industry (accessed 12.4.20).
Hasanbeigi, A., Morrow, W., Sathaye, J., Masanet, E., Xu, T., 2013. A bottom-up model to estimate the energy efficiency improvement and CO2 emission reduction potentials in the Chinese iron and steel industry. Energy 50, 315–325. https://doi.org/10.1016/j.energy.2012.10.062
He, K., Wang, L., 2017. A review of energy use and energy-efficient technologies for the iron and steel industry. Renewable and Sustainable Energy Reviews 70, 1022–1039. https://doi.org/10.1016/j.rser.2016.12.007
Hector, P., 2020. Analysis: Going carbon neutral by 2060 'will make China richer' [WWW Document]. Carbon Brief. URL https://www.carbonbrief.org/analysis-going-carbon-neutral-by-2060-will-make-china-richer (accessed 12.2.20).
Hellemo, L., Barton, P.I., Tomasgard, A., 2018. Decision-dependent probabilities in stochastic programs with recourse. Comput Manag Sci 15, 369–395. https://doi.org/10.1007/s10287-

018-0330-0
Huppmann, D., Gidden, M., Fricko, O., Kolp, P., Orthofer, C., Pimmer, M., Kushin, N., Vinca, A., Mastrucci, A., Riahi, K., Krey, V., 2019. The MESSAGEix Integrated Assessment Model and the ix modeling platform (ixmp): An open framework for integrated and cross-cutting analysis of energy, climate, the environment, and sustainable development. Environmental Modelling & Software 112, 143–156. https://doi.org/10.1016/j.envsoft.2018.11.012
IEA, 2021. Net Zero by 2050 – A Roadmap for the Global Energy Sector.
IEA, 2020a. Iron and Steel Technology Roadmap – towards more sustainable steelmaking.
IEA, 2020b. World Energy Outlook 2020. International Energy Agency (IEA), Paris, France.
IEA, 2010. IEA-ETSAP | Energy Demand Technologies Data [WWW Document]. URL https://iea-etsap.org/index.php/energy-technology-data/energy-demand-technologies-data (accessed 2.15.18).
IRENA, 2020. Reaching Zero with Renewables (No. 978-92-9260-269–7).
Lauri, M., 2020. Influential academics reveal how China can achieve its 'carbon neutrality' goal [WWW Document]. Carbon Brief. URL https://www.carbonbrief.org/influential-academics-reveal-how-china-can-achieve-its-carbon-neutrality-goal (accessed 12.2.20).
Ma, D., Chen, W., Yin, X., Wang, L., 2016. Quantifying the co-benefits of decarbonisation in China's steel sector: An integrated assessment approach. Applied Energy 162, 1225–1237. https://doi.org/10.1016/j.apenergy.2015.08.005
Material Economics, 2019. Industrial Transformation 2050- Pathways to Net-Zero Emissions from EU Heavy Industry.
Megan, D., Isabelle, G., 2019. Which countries have a net zero carbon goal? [WWW Document]. URL https://www.climatechangenews.com/2019/06/14/countries-net-zero-climate-goal/ (accessed 12.2.20).
Messner, S., Strubegger, M., 1995. User's Guide for MESSAGE III [WWW Document]. URL http://pure.iiasa.ac.at/4527/ (accessed 6.20.17).
National Bureau of Statistics, 2019. China Statistical Yearbook 2019. China Statistics Press.
National Bureau of Statistics, 2016. China statistical year book 2002-2016.
Normile, D., 2020. Can China, the world's biggest coal consumer, become carbon neutral by 2060? Science | AAAS.
Rapier, R., 2020. Estimating The Carbon Footprint Of Hydrogen Production [WWW Document]. Forbes. URL https://www.forbes.com/sites/rrapier/2020/06/06/estimating-the-carbon-footprint-of-hydrogen-production/ (accessed 12.9.20).
Rogelj, J., Popp, A., Calvin, K.V., Luderer, G., Emmerling, J., Gernaat, D., Fujimori, S., Strefler, J., Hasegawa, T., Marangoni, G., Krey, V., Kriegler, E., Riahi, K., Vuuren, D.P. van, Doelman, J., Drouet, L., Edmonds, J., Fricko, O., Harmsen, M., Havlík, P., Humpenöder, F., Stehfest, E., Tavoni, M., 2018. Scenarios towards limiting global mean temperature increase below 1.5 °C. Nature Climate Change 1. https://doi.org/10.1038/s41558-018-0091-3
Song, Y., Huang, J.-B., Feng, C., 2018. Decomposition of energy-related CO2 emissions in China's iron and steel industry: A comprehensive decomposition framework. Resources Policy, Sustainable management and exploitation of extractive waste: towards a more efficient resource preservation and waste recycling 59, 103–116. https://doi.org/10.1016/j.resourpol.2018.06.004
Steven, V., Avetik, C., Oliver, R., Junjie, M., Charlie, T., 2017. The growing importance of steel scrap in China.
Sullivan, P., Krey, V., Riahi, K., 2013. Impacts of considering electric sector variability and reliability in the MESSAGE model. Energy Strategy Reviews, Future Energy Systems and Market Integration of Wind Power 1, 157–163. https://doi.org/10.1016/j.esr.2013.01.001

Sun, W., Wang, Q., Zheng, Z., Cai, J., 2020. Material–energy–emission nexus in the integrated iron and steel industry. Energy Conversion and Management 213, 112828. https://doi.org/10.1016/j.enconman.2020.112828

Tanzer, S.E., Blok, K., Ramírez, A., 2020. Can bioenergy with carbon capture and storage result in carbon negative steel? International Journal of Greenhouse Gas Control 100, 103104. https://doi.org/10.1016/j.ijggc.2020.103104

The Royal Society, 2021. The carbon cycle: Better understanding carbon-climate feedbacks and reducing future risks.

Tong, Y., Cai, J., Zhang, Q., Gao, C., Wang, L., Li, P., Hu, S., Liu, C., He, Z., Yang, J., 2019. Life cycle water use and wastewater discharge of steel production based on material-energy-water flows: A case study in China. Journal of Cleaner Production 241, 118410. https://doi.org/10.1016/j.jclepro.2019.118410

University of Groningen, 2020. Steel Industry: Production Processes (No. 9932590). University of Groningen.

van Sluisveld, M., de Boer, H.S., Daioglou, V., Hof, A., van Vuuren, D., 2021. A race to zero - assessing the position of heavy industry in a global net-zero CO2 emissions context. Energy and Climate Change 100051. https://doi.org/10.1016/j.egycc.2021.100051

Vuuren, D.P. van, Stehfest, E., Gernaat, D.E.H.J., Berg, M. van den, Bijl, D.L., Boer, H.S. de, Daioglou, V., Doelman, J.C., Edelenbosch, O.Y., Harmsen, M., Hof, A.F., Sluisveld, M.A.E. van, 2018. Alternative pathways to the 1.5 °C target reduce the need for negative emission technologies. Nature Climate Change 8, 391. https://doi.org/10.1038/s41558-018-0119-8

Wang, C., Wang, R., Hertwich, E., Liu, Y., 2017. A technology-based analysis of the water-energy-emission nexus of China's steel industry. Resources, Conservation and Recycling 124, 116–128. https://doi.org/10.1016/j.resconrec.2017.04.014

Wen, Z., Meng, F., Chen, M., 2014. Estimates of the potential for energy conservation and CO2 emissions mitigation based on Asian-Pacific Integrated Model (AIM): the case of the iron and steel industry in China. Journal of Cleaner Production 65, 120–130. https://doi.org/10.1016/j.jclepro.2013.09.008

Wen, Z., Wang, Y., Li, H., Tao, Y., De Clercq, D., 2019. Quantitative analysis of the precise energy conservation and emission reduction path in China's iron and steel industry. Journal of Environmental Management 246, 717–729. https://doi.org/10.1016/j.jenvman.2019.06.024

World Steel Association, 2017. Steel Statistical Yearbook 2017.

Yue, H., Worrell, E., Crijns-Graus, W., 2018. Modeling the multiple benefits of electricity savings for emissions reduction on power grid level: A case study of China's chemical industry. Applied Energy 230, 1603–1632. https://doi.org/10.1016/j.apenergy.2018.09.078

Zhang, S., 2016. Energy Efficiency for Clean Air : Capturing the multiple benefits for climate, air quality, and public health in China (Dissertation). Utrecht University, Utrecht.

Zhang, S., Worrell, E., Crijns-Graus, W., Wagner, F., Cofala, J., 2014. Co-benefits of energy efficiency improvement and air pollution abatement in the Chinese iron and steel industry. Energy 78, 333–345. https://doi.org/10.1016/j.energy.2014.10.018

Zhang, S., Yi, B.-W., Worrell, E., Wagner, F., Crijns-Graus, W., Purohit, P., Wada, Y., Varis, O., 2019a. Integrated assessment of resource-energy-environment nexus in China's iron and steel industry. Journal of Cleaner Production 232, 235–249. https://doi.org/10.1016/j.jclepro.2019.05.392

Zhang, S., Yi, B.-W., Worrell, E., Wagner, F., Crijns-Graus, W., Purohit, P., Wada, Y., Varis, O., 2019b. Integrated assessment of resource-energy-environment nexus in China's iron and steel industry. Journal of Cleaner Production 232, 235–249. https://doi.org/10.1016/j.jclepro.2019.05.392

Zhao, F., Fan, Y., Zhang, S., 2021. Assessment of efficiency improvement and emission mitigation potentials in China's petroleum refining industry. Journal of Cleaner Production 280, 124482. https://doi.org/10.1016/j.jclepro.2020.124482

Appendix Table 1

Technology list in MESSAGEix–China iron and steel model

Technology	Technology explanation
Sinter_prod_bf_bof	sinter production in BF-BOF process
Pellets_prod_bf_bof	pellets production in BF-BOF process
Iron_ore_extr_open_pit	iron ore extraction by open pit mining technology
Iron_ore_extr_underground	iron ore extraction by underground mining technology
Iron_ore_benefication	iron ore production by iron ore processing/benefication technology using primary iron ore to secondary iron ore-used in sinter/pellets plants
Crudesteel_prod_bof	crude steel production in basic oxygen furnace route
Crudesteel_prod_eaf_prim	crude steel production in pig iron based electric arc furnace with DRI process
Crudesteel_prod_eaf_sec	crude steel production in 100% scrap based electric arc furnace process
Steel_hot_rolling_prod	hot rolled steel production by hot rolling from cast steel
Steel_cold_rolling_prod	cold rolled steel production by cold rolling from cast steel
Steel_finishing_prod	steel production by finishing process (including coating, painting, etc.) from rolling steel
Steel_cast_prod	cast steel production in casting process from crude steel
Pigiron_prod_bf	pig iron production in blast furnace process and will be used in BOF route
Pigiron_prod_h2_dri	pig iron production by hydrogen-based DRI process and will be used in EAF route
Pigiron_prod_coal_dri	pig iron production by coal-based DRI process and will be used in EAF route
Pigiron_prod_coal_dri_ccus	pig iron production by coal-based DRI process with CCUS and will be used in EAF route
Pigiron_prod_gas_dri_ccus	pig iron production by natural gas-based DRI process with CCUS and will be used in EAF route
Pigiron_prod_gas_dri	pig iron production by natural gas-based DRI process and will be used in EAF route
Pigiron_prod_smelt	pig iron production in oxygen-rich smelting reduction process and will be used in BOF route
Pigiron_prod_smelt_ccus	pig iron production in oxygen-rich smelting reduction process with CCUS and will be used in BOF route
Coke_prod_coal	coke making by coal
lime_prod	lime production from limestone

Appendix Table 2

Projection of high steel demand and the associated steel end-user's activity

Item	Unit	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2070	2080	2090	2100
population	100 million	1267	1308	1341	1383	1412	1426	1450	1444	1430	1410	1395	1344	1294	1183	1072	966	874
GDP	million $	2995	4708	7922	11498	15072	20078	24862	29971	36365	42754	48074	55376	61304	56056	50790	45761	41424
total_building stock	100 million sq2	30418	39881	50129	57268	67900	75744	81654	85993	89152	91372	92494	91163	89679	83778	77517	71292	65849
residential building stock per person	m2/person	21	26	31	33	37	39	41	43	44	45	46	46	47	48	48	49	50
residential building stock	million sq2	26616	33997	41839	46084	52175	56307	59291	61374	62797	63687	63892	62429	60902	56436	51813	47294	43365
commercial building stock per person	m2/person	3	5	6	8	11	14	15	17	18	20	21	21	22	23	24	25	26
commercial building stock	million sq2	3802	5884	8290	11184	15725	19437	22363	24619	26355	27685	28602	28734	28778	27342	25704	23998	22483
newly built buildings	million sq2	-	9462	10248	7139	10632	7844	5910	4339	3159	5262	5110	3681	4244	889	1314	1940	3156
crude_steel consumprion per building stock	t/sq2	-	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
crude_steel_consumption_building	Mt	62	179	320	419	575	460	347	254	185	309	300	216	249	52	77	114	185
automotive_owner per 1000 persons	vehicles per 1000 person	13	24	58	118	194	241	289	337	384	432	480	500	500	500	500	500	500
automotive_owner_total	million vehicles	16	32	78	163	273	344	419	486	550	609	669	672	647	592	536	483	437
automotive_produced	million	2	5	15	23	25	32	39	45	51	56	62	62	60	55	49	45	40
crude_steel_consumption_automotive	Mt	7	12	43	55	60	75	91	106	120	133	146	147	141	129	117	105	95
appliances per household	number per household	1	2	2	3	3	4	4	5	6	6	7	7	8	9	9	10	10
total_ownership_appliance	million	387	648	913	1238	1700	2040	2403	2720	3018	3296	3577	3752	3905	3839	3721	3572	3371
household size	person per household	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
appliances produced per year	million	45	128	244	319	351	405	454	441	468	481	522	447	454	264	240	226	190
crude_steel_consumption_appliances	Mt	1	5	8	11	14	16	18	17	18	19	20	17	18	10	9	9	7
number of household	million	368	400	433	484	539	544	553	551	546	538	532	513	494	452	409	369	334
value_added_industry	Billion $	1034	1727	3104	4564	5789	7353	9224	11299	13357	14857	16239	17820	19072	20891	22523	23929	24985
crude_steel_consumption_industry	Mt	53	148	225	206	363	464	555	616	610	445	410	469	371	539	484	417	313

crude_steel_stocks	Mt	14	14	14	13	19	20	20	19	18	17	17	16	15	14	13	12	12
crude_steel_net_exports	Mt	-10	-5	26	100	33	63	63	62	58	56	54	53	48	45	43	40	37
crude_steel demand	Mt	124	345	597	690	1011	1015	1011	993	934	905	876	849	779	731	688	645	601
crude_steel production	Mt	128	353	637	803	1064	1097	1093	1074	1010	979	947	918	842	790	743	697	650
steel_products	Mt	96	277	583	753	933	949	951	937	910	879	850	825	756	710	668	626	583

Appendix Table 3

Projection of low steel demand and the associated steel end-user's activity

Item	Unit	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060	2070	2080	2090	2100
population	100 million	1267	1308	1341	1383	1412	1426	1450	1444	1430	1410	1395	1344	1294	1183	1072	966	874
GDP	million $	2995	4708	7922	11498	15072	20078	24862	29971	36365	42754	48074	55376	61304	56056	50790	45761	41424
total_building stock	100 million sq2	30418	39881	50129	57268	67900	75287	81324	85993	89252	91372	92494	91163	89679	83778	77517	71292	65849
residential building stock per person	m2/person	21	26	31	33	37	39	41	43	44	45	46	46	47	48	48	49	50
residential building stock	million sq2	26616	33997	41839	46084	52175	55850	58961	61374	62897	63687	63892	62429	60902	56436	51813	47294	43365
commercial building stock per person	m2/person	3	5	6	8	11	14	15	17	18	20	21	21	22	23	24	25	26
commercial building stock	million sq2	3802	5884	8290	11184	15725	19437	22363	24619	26355	27685	28602	28734	28778	27342	25704	23998	22483
newly built buildings	million sq2	-	9462	10248	7139	10632	7387	6037	4669	3259	5162	5110	3681	4244	889	1268	1907	3156
crude_steel consumprion per building stock	t/sq2	-	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
crude_steel_consumption_building	Mt	62	179	320	419	575	433	354	274	191	303	300	216	249	52	74	112	185
automotive_owner per 1000 persons	vehicles per 1000 person	13	24	58	118	194	241	289	337	384	432	480	500	500	500	500	500	500
automotive_owner_total	million vehicles	16	32	78	163	273	344	419	486	550	609	669	672	647	592	536	483	437
crude_steel_consumption_per_automotive	t/vehicle	4	2	3	2	2	2	2	2	2	2	2	2	2	2	2	2	2
automotive_produced	million	2	5	15	23	25	32	39	45	51	56	62	62	60	55	49	45	40
crude_steel_consumption_automotive	Mt	7	12	43	55	60	74	88	100	111	120	129	127	120	108	96	84	75
appliances per household	number per household	1	2	2	3	3	4	4	5	6	6	7	7	8	9	9	10	10
total_ownership_appliance	million	387	648	913	1238	1700	2040	2403	2720	3018	3296	3577	3752	3905	3839	3721	3572	3371
household size	person per household	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3

appliances produced per year	million	45	128	244	319	351	405	454	441	468	481	522	447	454	264	240	226	190
crude_steel_consumption_appliances	Mt	1	5	8	11	14	16	18	17	18	19	20	17	18	10	9	9	7
number of household	million	368	400	433	484	539	544	553	551	546	538	532	513	494	452	409	369	334
value_added_industry	Billion $	1034	1727	3104	4564	5789	7272	8816	10415	12008	13031	13869	14868	15583	16834	17859	18605	18944
crude_steel_consumption_industry	Mt	53	148	225	206	363	440	458	474	472	304	249	296	212	371	304	221	101
crude_steel_stocks	Mt	14	14	14	13	19	19	18	17	15	14	13	13	12	10	9	8	7
crude_steel_net_exports	Mt	-10	-5	26	100	33	60	57	54	49	46	43	41	37	34	30	26	23
crude_steel demand	Mt	124	345	597	690	1011	963	917	865	792	745	698	657	599	541	483	426	368
crude_steel production	Mt	128	353	637	803	1064	1041	992	936	857	806	755	710	647	585	522	461	398
steel_products	Mt	96	277	583	753	915	899	860	816	769	724	678	637	581	525	469	413	357