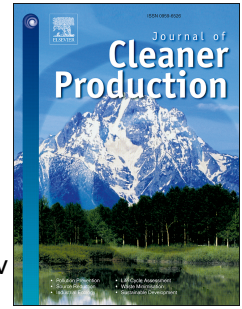


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Integrated assessment of resource-energy-environment nexus in China's iron and steel industry

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1 Integrated assessment of Resource-Energy-Environment Nexus in China's iron and steel industry

2
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14
15 **Abstract:** MESSAGEix model are widely used for forecasting long-term energy consumption
16 and emissions, as well as modelling the possible GHGs mitigations. However, because of the
17 complexity of manufacturing sectors, the MESSAGEix model aggregate detailed technology
18 options and thereby miss linkages across sub-sectors, which leads to energy saving
19 potentials are often not very realistic and cannot be used to design specific policies. Here,
20 we integrate Material/Energy/water Flow Analysis (MEWFA) and nexus approach into the
21 MESSAGEix to estimate resource-energy-environment nexus in China's iron and steel
22 industry. Results show that between 2010 and 2050 energy efficiency measures and route
23 shifting of China's steel industry will decrease raw material input by 14%, energy use by 7%,
24 water consumption by 8%, CO₂ emissions by 7%, NO_x emissions by 9%, and SO₂ emissions

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1 by 14%, respectively. However, water withdrawal and PM_{2.5} emissions will increase by 14%
2 and 20%, respectively. The main reason is that water withdrawal and PM_{2.5} emissions in the
3 process of BF-BOF are over 4 times lower than the process scrap-EAF. Therefore, policy
4 makers should consider nexus effects when design integrated policy to achieve multiple
5 targets. Finally, future directions on enhancing the representation of manufacturing sectors
6 in IAMs are given.

7
8 **Keywords:** IAMs; MESSAGEix; Iron and steel industry; Energy efficiency benefits; China;
9 Resource-Energy-Environment Nexus

10

11 1. Introduction

12

13 Energy system models are increasingly used to assess future climate change and its socio-
14 economic impacts. Scenarios, such as Representative Concentration Pathways (RCPs) and
15 Shared Socioeconomic Pathways (SSPs), developed by several Integrated Assessment
16 Models (IAMs) show a wide range of projections for assessing mitigation policies, depending
17 on the actions modelled to response of the climate change and other relevant
18 environmental issues, such as water scarcity and air pollution (Marangoni et al., 2017; Moss
19 et al., 2010; Riahi et al., 2017; Rogelj et al., 2016; Wada et al., 2014; Walsh et al., 2017). Key
20 feature of IAMs is that they integrated multiple knowledge into a single framework to
21 explore human actions interact with natural world, especially help us understand how
22 technologies, socioeconomic behaviour, and natural change can avoid greenhouse gas
23 emissions (Bruckner, 2016).

24

25 Recently, nexus approach have been widely employed to identify trade-offs and synergies
26 across space, and time (Albrecht et al., 2018; Kaddoura and El Khatib, 2017; Namany et al.,

1 2019; Zhang et al., 2018). Evaluating current literatures, many studies simply distinguish
2 three groups of nexus, namely system-wise approaches, holistic, and system think
3 approaches (Harwood, 2018). Mannan et al. summarized the development of integrated Life
4 Cycle Assessment (iLCA) and energy-water-food (EWF) nexus methodology and found that
5 iLCA and EWF nexus play a significant role in environmental burdens and would have large
6 effects on EWF resource sectors (Mannan et al., 2018). There is growing recognition that
7 integrating nexus approach into IAMs. For example, the Climate, Land, Energy and Water
8 (CLEW), developed by International Atomic Energy Agency (IAEA), is an integrated tool that
9 aims to assessing interactions between water, energy, climate, land, and material use at the
10 global scale (International Atomic Energy Agency, 2017). Tokimatsu used a bottom-up
11 energy model to assess potential for renewable energy technologies application and the
12 associated metal demand, under different climate target scenarios, and found that energy-
13 mineral nexus play an important role when underpin policy making (Tokimatsu et al., 2018,
14 2017). Fang et al. used a multiregional input-output model with an atmospheric chemical
15 transport model to estimate clean air policy and the associated environmental impacts in
16 China, and found that environmental policy not only can improve air quality in the target
17 region, but also can lower CO₂ emissions and decrease water consumption (Fang et al.,
18 2019).

19
20 To date, such model-based scenarios have not unambiguously examined the efficiency of
21 various possible policies, and how they will be financed in major emitting sectors (e.g.,
22 building and industry) (Rogelj et al., 2016). For example, the specific industry characteristics
23 and the complex interactions with and within sectors are not included in most of IAMs used
24 to evaluate policy strategies (Kermeli et al., 2016; Worrell and Kermeli, 2017). Over time,

1 narrowing scenario uncertainty is extremely difficult because it requires increased
2 confidence in future technology and society conditions (Brown and Caldeira, 2017).
3 Furthermore, it remains unclear how to best evaluate the synergies or co-benefits of
4 resource/energy/water efficiency, climate, and air quality across sub-sectors and distinct
5 features across regions (Pauliuk et al., 2017). Therefore, future IAMs need to provide more
6 accuracy and transparent projections when designing specific policies to achieve future
7 targets (e.g., Nationally Determined Contributions (NDCs), Sustainable Development Goals
8 (SDGs)). New knowledge applied in state-of-the-art IAMs to further improve the
9 representation of sub-sectors and the associated interactions is urgently required to support
10 the design and evaluation of policies at national, regional, and global scales. The aim of this
11 paper is to address this gap by integrate Material/Energy/water Flow Analysis (MEWFA) and
12 nexus approach into the Model for Energy Supply Strategy Alternatives and their General
13 Environmental Impacts (MESSAGEix) to estimate potential for energy and material efficiency
14 improvement, emission reductions of GHG and air pollutants, and resource-energy-
15 environment nexus. Specifically, resource-energy-environment nexus of China's iron and
16 steel industry, in this study, aims estimate decline trade-offs, improve synergies of resource,
17 energy, water, and emissions of GHGs and air pollutants, improve energy and resource or
18 material efficiency, and guide development of new decision- and policy-making. To integrate
19 industrial sub-sectors into system model (e.g., IAMs) and assess the associated potential
20 solutions for climate mitigation, we firstly integrate iron and steel industry into the
21 MESSAGEix model, because of its large contribution to CO₂ emissions (29% of industrial
22 direct emissions) and pollution, and its high level of resource and energy demand (20% of
23 industrial energy use) (Worrell and Carreon, 2017). This approach takes the advantages of
24 the model's high level of detail technology to estimate the energy & resource saving

1 potential, emission reductions, nexus with and within sectors, as well as the associated
2 investment. Also, the future dynamic use of raw/process material, energy, water, and
3 emissions of the system can be optimized in MESSAGEix. We first introduce the process
4 technologies to quantify the future activity of energy and water consumption, emissions of
5 greenhouse gases (GHGs) and air pollution and associated co-benefits and trade-offs in
6 China's iron and steel industry during the period 2010-2050. Then, we investigate the
7 potential resource requirements (including raw material and process material), energy and
8 water use, and emissions of the selected energy efficiency measures within the alternative
9 scenarios and compare these findings with those of the baseline scenario.

10

11 2. Overview of iron and steel industry in China

12

13 Iron and steel products, as key industrial materials, are widely used to meet requirements of
14 economic development, especially for infrastructure and other construction projects
15 (Cullen et al., 2012). Over the last 150 years, the world crude steel consumption increased
16 to over 1.6 billion tons in 2016 and is expected to continue to rise also in the long-term
17 future, partly because of the societal transition, via application of steel products in new
18 technologies (Milford et al., 2013; Worrell and Carreon, 2017). China has been the world's
19 largest steel consumer and producer since 1996. Crude steel production from China
20 increased from 100 million tons (Mt) in 1996 to 808 Mt in 2016, nearly 50% of global total
21 (World Steel Association, 2017). Studies in the Chinese iron and steel industry have
22 demonstrated steel consumption will peak by around 2030 and then decline gradually (Yin
23 and Chen, 2013; Zhang et al., 2014).

24

1 Steel can be produced via four main routes: blast furnace, basic oxygen furnace (BF-BOF),
2 scrap- Electric arc furnace (EAF), direct reduction (DRI)-EAF (also named Direct Reduced Iron
3 (DRI), and open-hearth furnace (OHFs). The process shares of steel production vary widely
4 across countries. In 2016 BF-BOF dominated, accounting for 74.3% of world steel production,
5 followed by scrap-EAF (25.2%) (World Steel Association, 2017). The other steel production
6 routes, such as DRI-EAF and OHF contributed only a minor portion, with a share of around 5%
7 of the total produced amount. However, China has the highest share of BF-BOF steel
8 production, accounting for 94%, followed by scrap-EAF (6%) (World Steel Association, 2017).
9 The BF-BOF route includes process technologies of coke making, sinter making, iron making
10 and steel making, while the EAF route includes scrap melting or DRI and steel making. The
11 key difference among the process technologies is the type/amount of raw material and
12 energy they need. For example, iron ore and less scrap (range: 10-30%) are typically used in
13 BF-BOF to produce steel. In contrast, almost 100% scrap is used in the scrap-EAF route
14 (Yellishetty et al., 2010), where the scrap-EAF route consumes less energy than the BF-BOF
15 route (Oda et al., 2013).

16

17 Regarding energy and environmental challenges, it is important to note that among
18 industrial sectors, iron and steel industry is the globally largest one in energy needs,
19 emissions of CO₂ and air pollution, and consumption of resource-based manufacturing
20 sectors, accounting for 20% of world industrial energy use and 29% of industrial direct CO₂
21 emissions (Worrell and Carreon, 2017). The Chinese iron and steel industry is responsible for
22 24% of industrial energy and 22% of water use, and releases 21% of CO₂, 10% of SO₂, 15%
23 NO_x, and 10% of PM_{2.5}, respectively (Wang et al., 2017; Zhang, 2016; Zhang et al., 2014).
24 Specifically, the blast furnace is the most energy-intensive part of the steel making in the BF-

1 BOF route, while sintering is the main source of air pollution in this route (Wu et al., 2015).
2 Inversely, the EAF was the largest electricity consumer (CSDRI, 2016).

3

4

5 **3. Methodology**

6 **3.1 MESSAGEix model**

7

8 MESSAGE, developed by the International Institute for Applied Systems Analysis (IIASA), is a
9 dynamic system optimization model that is widely used to investigate future development
10 of medium- to long-term energy planning and policy analysis (Keppo and Strubegger, 2010;
11 Sullivan et al., 2013). Further, MESSAGE links to the macro-economic model (MACRO) to
12 consistently assess the interaction between macroeconomic production, natural resources,
13 energy demand and supply, and emissions (Messner and Schratzenholzer, 2000). The
14 advantage of the MESSAGE-MACRO combination is that its two components can run
15 independently from each other.

16

17 Many different modelling frameworks and IAMs (including MESSAGE-V) have been
18 developed and used to assess various purposes with specific constraints and diverse scales
19 (Fattori et al., 2016). However, obstacles of interdisciplinary, transparency, scientific
20 standards and uncertainty in most of energy systems modelling remain unaddressed (Hilpert
21 et al., 2017). To closing the gaps, the MESSAGEix, based on MESSAGE-V, is developed and
22 implemented under IIASA's ix modelling platform (ixmp). The new feature of MESSAGEix has
23 allowed improved openness and transparency, compared to the existing MESSAGE-V model.
24 In addition, the ixmp provides an efficient work-flow for data processing and
25 implementation of models across disciplines and spatial scales. The key advantage of

1 MESSAGEix is that it allows modellers to easily exchange data input, integrate external data
2 source, and link with other models, such as the Greenhouse Gas - Air Pollution Interactions
3 and Synergies (GAINS) model. More detailed modelling information of MESSAGEix as
4 described by Huppmann et al., (Huppmann et al., 2018) and the tutorial of MESSAGEix
5 (IIASA's Energy group, 2018).

6

7 **3.2 MESSAGEix – iron and steel model**

8

9 MESSAGEix – iron and steel model, developed in this study, is a technology-based model in
10 the MESSAGEix family that depicts the system with a high level of details on natural
11 resource, energy, water, emissions, and the associated technologies. We integrate
12 material/energy/water Flow Analysis (MEWFA) and nexus approach into the MESSAGEix
13 model to assess the impacts of raw/process materials on long-term scenario perspectives in
14 the iron and steel industry. The work-flow of MESSAGEix – iron and steel model is given in
15 Fig. 1, this efficient workflow can be summarized as: 1) forecast the future steel demand via
16 sectorial intensity use curve (see section 3.2.1); 2) import database into IIASA's ix modelling
17 platform (ixmp), MESSAGEix framework, run the model, and export/report the results, via
18 Python standardized user interface; 3) assess the nexus of natural resources, energy, water
19 and environment pollution. To increase the transparency and accessibility of the model the
20 extensive information (e.g., database for iron and steel industry, specific technology
21 parameters and related Python script) can be provide upon request, based on the discussion
22 with the relevant policy makers and plant managers.

23

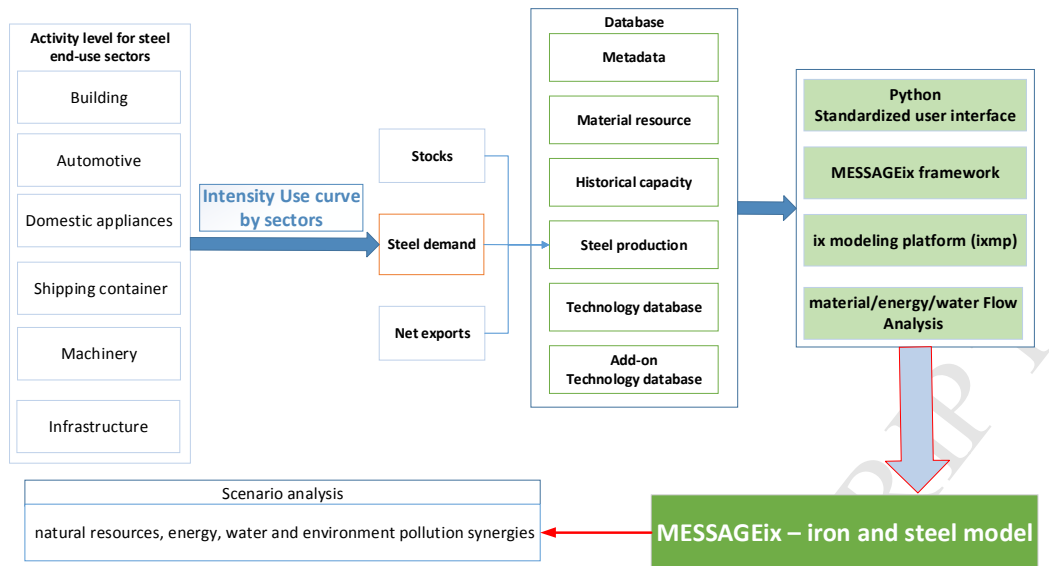


Fig. 1: Work-flow for MESSAGEix – iron and steel model

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The core of MESSAGEix - iron and steel model is a Reference System for Material, Energy, and Water (RSMEW) flow that represents the most important carriers of energy, material and water and associated technologies. The detailed information of for the Reference System for Material, Energy, and Water (RSMEW) flow can be found in Appendix Table A. Technologies (including process technologies and related energy efficiency measures) characterized by capital and operating costs, installed capacity and related activities, different input/out efficiencies, and emission factors. For steel industry, iron ore is agglomerated in sinter plants to produce sinter, while pellets are formed from pellet plants at high process temperature. These products are converted to pig iron in a blast furnace. Then, the pig iron is supplied to the basic oxygen furnace (BOF) or electric arc furnace (EAF) to produce crude steel. The model in this study allows for a more complete description of the process (i.e. iron ore extraction, limestone extraction, coke making, sinter making, pellets making, pig iron making, steel making with BOF, steel making with EAF, direct reduced iron ore, and casting, rolling, and finishing (steel_crf)) involved in the iron and steel

1 industry. Of overall 11 process technologies and 54 current best energy efficiency measures
2 are considered in the current MESSAGEix - iron and steel model (see Appendix S1 and S2).

3

4 We modelled the period from 2010 to 2050 with a 5-year interval. The current best available
5 energy efficiency measures are introduced to capture the changes in use energy, water, and
6 subsequent emissions, based on scenario analysis. An important feature of this phase is the
7 introduction of the functional parameters for process technology and energy efficiency
8 measures (see 3.2.2). Currently, the MESSAGEix – iron and steel model cannot automatically
9 generate the dynamic feedback with the steel consumption sectors. Therefore, an
10 exogenous assumption on the future activity of steel consumers is obtained from state-of-
11 the-art models. Intensity use curves are developed and adopted to quantify the interactions
12 between iron and steel industry and related key consumers of steel products (see 3.2.1).

13

14 *3.2.1 Projection of future steel products/steel-cast*

15

16 Currently, two approaches (e.g. demand curve, supply curve, and intensity use curve) are
17 widely used to project future demands of industrial products, such as cement and steel. The
18 first approach is based on the direct relationship with macro-economic variables (e.g. steel
19 intensity to GDP per capita combined with investment share as a socio-economic variable)
20 (M. Tanaka, 2010), which are often used in state-of-the-art energy models, like The Targets
21 IMage Energy Regional (TIMER) model (Neelis and Patel, 2006). The second approach is the
22 sector specific approach based on major steel consuming sectors, which depends heavily on
23 the quality of information available for the economy (S. Zhang et al., 2018).

24

1 In this study, the Intensity Use (IU)² Curve is developed to estimate interactions between
 2 steel industry and the associated end-use sectors. The historical steel consumption is shown
 3 in Appendix S3. Because of data constraints, the IU curves based on physical units are
 4 employed in the building, automotive, and domestic appliances, and shipping container
 5 sectors, while the IU curves, based on direct relationships with macro-economic variables,
 6 are developed and used in the machinery and infrastructure sectors (see Eq. (2)).

$$\begin{aligned}
 \text{Steel demand} &= \sum_i \text{steel demand} = \sum_i \frac{\text{product}}{\text{population}} * \frac{\text{steel demand}}{\text{product}} * \text{Population} \\
 &= \sum_i \text{product intensity} * \text{steel intensity} * \text{population} \quad \text{Eq. (1)}
 \end{aligned}$$

$$\begin{aligned}
 \text{Steel demand} &= \sum_i \text{steel demand} = \sum_i \frac{\text{value added}}{\text{population}} * \frac{\text{steel consumption}}{\text{value added}} * \text{Population} \\
 &= \sum_i \text{product intensity} * \text{steel intensity} * \text{population} \quad \text{Eq. (2)}
 \end{aligned}$$

9
 10 The net imports share of total steel product is assumed unchanged in the future, while
 11 transport losses and change of stocks of steel products are beyond the scope of this study.

$$\text{Steel production} = \text{steel demand} + \text{net imports} + \text{change of stocks} \quad \text{Eq. (3)}$$

15 3.2.2 Linkage between process technologies and energy efficiency measures

16
 17 Energy efficiency is marked as the “first fuel” because it is considered to be more
 18 competitive than any other fuel, in terms of cost effectiveness and availability (IEA, 2016;
 19 Yang and Yu, 2015). Increasing energy efficiency and reducing GHG emissions, especially in
 20 the demand sectors, has been an integral part of the national climate strategy worldwide.
 21 However, the economic and technical emission mitigation potential of demand sectors (e.g.,

² The ratio between the material demand and these socio-economic variables are named as the intensity of use (IU)

1 cement, steel, aluminium, chemical, and paper) based on specific retrofitting/new
 2 technology have not been systematically explored in state-of-the-art energy models, partly
 3 because there is limited data and few mature methodologies.

4
 5 In this study, we developed a new feature that allows seamless interaction with process
 6 technologies and best energy efficiency measures in MESSAGEix – iron and steel industry
 7 model. Specifically, the parameter of `addon_conversion` (Eq. 4), a conversion factor, was
 8 used to build linkages between add-on technologies and parent technology. Here, add-on
 9 technologies represent energy efficiency measures or retrofitting/mitigation technologies
 10 (e.g. coal moisture control, low temperature heat recovery, etc.), while parent technology
 11 represents the process technology (e.g. coke making, iron making). If the add-on technology
 12 is already implemented in the base year, the parameter of `addon_minimum` will be
 13 introduced to represent the minimum deployment fraction of add-on technology relative to
 14 parent technology. Further, the parameters of `addon_activity_up` and `addon_activity_low`
 15 will be used to model future diffusion of add-on technology. Note that these two
 16 parameters provide an upper/lower bound on the activity of an add-on technology that has
 17 to be operated jointly with a parent technology. The `addon_activity_up` is calculated by
 18 using Eq. (4), which provides an upper bound on the activity of an add-on technology.
 19 Similarly, the `addon_activity_low` is presented in Eq. (5), which provides a lower bound on
 20 the activity of an add-on technology.

$$\sum_{\substack{y^v \\ y^v \leq y}} \text{addon_conversion}_{n,t^a,y^v,y,m,h} * ACT_{n,t^a,y^v,y,m,h} \leq \sum_{\substack{t,y^v \\ t \sim t^a \\ y^v \leq y}} ACT_{n,t,y^v,y,m,h} \quad \text{Eq. (4)}$$

$$\sum_{\substack{y^v \\ y^v \leq y}} \text{addon_minimum}_{n,t^a,y^v,y,m,h} * \text{addon_conversion}_{n,t^a,y^v,y,m,h} * ACT_{n,t^a,y^v,y,m,h} \geq \sum_{\substack{t,y^v \\ t \sim t^a \\ y^v \leq y}} ACT_{n,t,y^v,y,m,h} \quad \text{Eq. (5)}$$

1
2 The advantage of this feature is that the MESSAGEix – iron and steel industry model not only
3 can assess the accurate estimation of actual potential per technology and associated costs,
4 but also allows to make accurate technology comparisons and figure out how to achieve
5 single/multiple targets (e.g., by building new production line to change production structure
6 or implementing retrofitting technology) and indicate what costs could be involved.

7 8 **3.4 Data sources and scenario assumptions**

9 **3.4.1 Data sources**

10
11 The historical, annual outputs of floor space, passenger vehicles, trucks, washing machines,
12 refrigerators, air conditioners, length of railways, highways, and petroleum and gas pipelines,
13 as well as value added of the machinery sector are obtained from of the China Statistical
14 Yearbook 2010-2016 (National Bureau of Statistics, 2016, pp. 2010–2016). The historic steel
15 consumption by end-use sector (e.g. building, machinery, automotive, domestic appliances,
16 shipping container, and infrastructure) is obtained from China Industrial Information
17 Network (China Industry Information Network, 2015), China Metallurgical Mining
18 Enterprises Association (China Metallurgical Mining Enterprises Association, 2014), and the
19 report released by the company of Founderfu (Han, 2017). The intensity use curve by sector
20 was developed on the basis of the above factors.

21
22 Exogenous scenario parameters of future activities of steel end-use sectors were taken from
23 the baseline scenario of Integrated Policy Model for China (IPMC) and the Integrated Model
24 of Economy, Energy and Environment for Sustainable Development/Computable General
25 Equilibrium model (IMED/CGE) and combined with sectorial intensity use curve to forecast
26 the steel demand by sectors until 2050 (Wang et al., 2017). All data on domestic iron ore

1 production, iron ore import and consumption of limestone were obtained from the China
2 Steel Yearbook 2016 (CSDRI, 2016).

3

4 Developing technology database is a core part of MESSAGEix – iron and steel model.
5 Parameters of energy use by fuel, material consumption, and water consumption, cost, by
6 each process technology are taken from China Energy Statistical Yearbook, China Steel
7 Yearbook, relevant literature surveys, and communication with Chinese experts (CSDRI,
8 2016; National Bureau of Statistics of China, 2013, 2011). Parameters of commodity prices
9 are from the China Steel Yearbook (CSDRI, 2016), while variable cost by each process is
10 taken from IEA-Clean Coal Centre and Metals Consulting International (MCI) (IEA, 2012;
11 Metals Consulting International, 2018). Because we could not obtain sufficient information
12 of China's Direct Reduced Iron (DRI) technology, the physical parameters related to DRI
13 technology are based on German steel plants and Energiron DRI plant (Otto et al., 2017;
14 Tenova, 2018). The cost of DRI technology is taken from the Energy Technology Systems
15 Analysis Program (ETSAP) of the International Energy Agency (IEA) (IEA, 2018.).

16

17 Several studies have demonstrated a substantial reduction of energy use and CO₂ emissions
18 in the different processes of iron and steel industry by implementing energy efficient
19 measures (Hasanbeigi et al., 2013; Hasanbeigi et al., 2013d; Zhou et al., 2011). However,
20 most IAMs hardly consider the representation of energy efficiency measures in their
21 industry modules (Kermeli et al., 2016). Therefore, it is important to integrate energy
22 efficiency measures in IAMs to analyse what specific policies to be implemented and what
23 are the cost-optimal strategies/measures for the mitigation of climate change.

24

1 In this study, we developed a mitigation technology database (including 54 energy efficiency
2 measures by the process) in MESSAGEix – iron and steel model (see Appendix S2 and S3). In
3 this database, the key parameters (e.g., fuel saving, electricity saving, water saving, cost,
4 and application rate for base year) of selected energy efficiency measures were obtained
5 from Energy Research Institute (ERI) of China, National Development and Reform
6 Commission (NDRC) of China, The Institute for Industrial Productivity (IIP), Environmental
7 Protection Agency (EPA) of USA, Lawrence Berkeley National Laboratory (LBNL), and related
8 studies (IIP, 2013; Hasanbeigi et al., 2013a; Hasanbeigi et al., 2012; US EPA, 2010; Wang et
9 al., 2017; Xu, 2011; Zhang et al., 2014).

10

11 The CO₂ emission factor for coal is taken from LBNL (Hasanbeigi et al., 2013b; Ke et al.,
12 2012). The CO₂ emission factor for electricity generation is taken from regional grid baseline
13 emission factors of China (National Center for Climate Change Strategy and International
14 Cooperation of China, 2010). The energy-related emission coefficients of SO₂, NO_x, PM_{2.5} are
15 taken from the Ministry of Environmental Protection (MEP) of China (Ministry of
16 Environmental Protection of China, 2013), and relevant literature (Hasanbeigi et al., 2017;
17 Wu et al., 2015). The process emission factors for PM_{2.5}, SO₂, NO_x, and CO₂ are taken from
18 the GAINS model available at < <http://gains.iiasa.ac.at/models/index.html>> and other
19 publically available literature (Wu et al., 2015; Zhang et al., 2016, 2015a).

20

21 *3.4.2 Scenario assumptions*

22

23 The emphasis of this paper is not only on the introduction of the methodology, but also on
24 modelling the synergies between raw/process material and energy use, water withdrawal
25 and consumption, and emissions of GHG and air pollutants in Chinese iron and steel industry.

1 Two scenarios are constructed: a baseline (BL) scenario and an energy efficiency (EE)
 2 scenario (see Table 1). The EE scenario is a mitigation scenario that requires stringent
 3 energy policies to accelerate the implementation of energy efficiency measures, whereas
 4 the BL scenario assume no additional policy adoptions. Specifically, we include 40 energy
 5 efficiency measures in EE scenario (see Appendix S4), which represents the cost-effective
 6 potential for energy efficiency improvement in China's iron and steel industry. The future
 7 technology diffusions of selected energy efficiency measures for energy efficiency scenario
 8 are projected through using linear deployment approach. The future steel production is
 9 assumed unchanged in both BL and EE scenarios during the study period. Note that the
 10 sulphur content of iron ore produced in China is higher than in other regions (e.g., Australia
 11 and Brazil) (China Pollution Source Census, 2011; MEP of China, 2017). To meet the demand
 12 for high-quality steel products, we therefore assumed that the imports share of total iron
 13 ore consumption remains unchanged in the future. One highlight of MESSAGEix is that it is
 14 easy to develop alternative scenarios. It means that the EE scenario can be simply
 15 constructed, via copying the BL scenario and introducing the function of add-on technology.

16
 17 Table 1 Key features of different scenarios

Scenarios	Scenario Description	
	Common features	Different features
Baseline (BL)	The future steel production is assumed unchanged Discount rate is 10%	The BOF share of total steel production will decrease by 2% per 5 year* No new policies are considered.
Energy efficiency (EE)	The imports share of total iron ore consumption remains unchanged in the future	40 cost effective energy efficiency measures (see appendix S4) will be introduced to MESSAGE-steel module

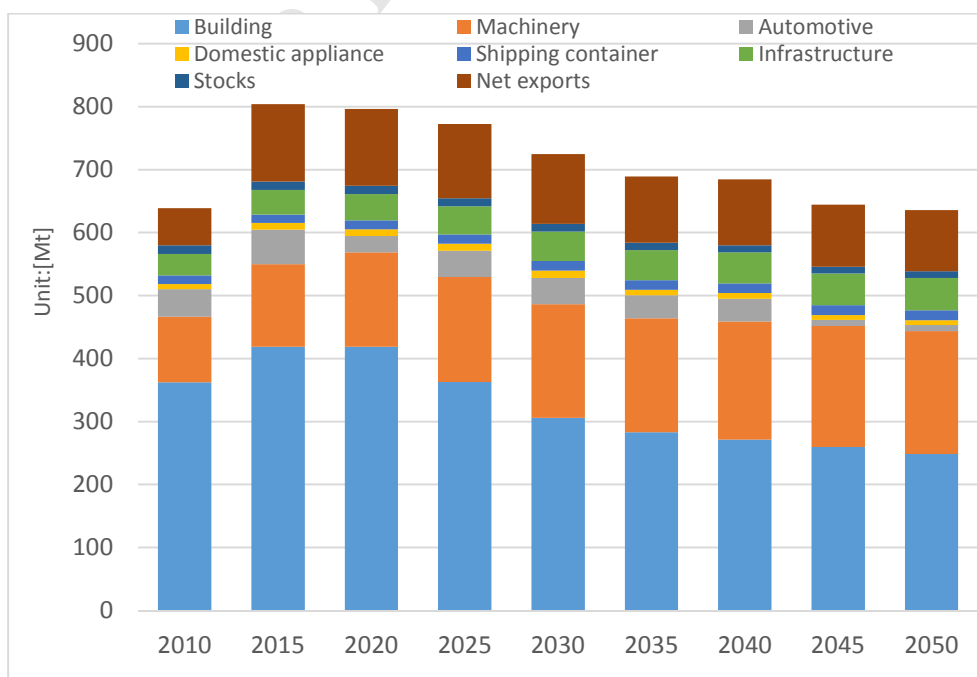
18
 19 **4. Results and Discussion**

20 **4.1 Steel demand and production from 2010 to 2050**

21

1 Fig. 2 presents the steel demand by end-use sectors and its production in China from 2010
 2 to 2050. Between 2010-2015, steel production shows an annual increase of 5%, rising from
 3 639 Mt to 804 Mt, and after that it decreases gradually to 636 Mt by 2050. These results are
 4 consistent with those of other studies, such as IEA (IEA, 2017) and Yin and Chen (Yin and
 5 Chen, 2013). On the demand side, the building sector will retain a dominant role in total
 6 steel consumption, although with a declining overall share. Compared to 2010, the building
 7 share of total steel consumption is reduced by 18% by 2050 due to saturation of the market.
 8 In contrast, the machinery sector shows a minor increase of steel consumption over the
 9 forecast period. The main reason is that implementation of retrofitting/new technology to
 10 improve energy efficiency and emission mitigation leads to demand growth for steel
 11 products. Similarly, increasing personal income and population growth have a large
 12 contribution to the growth of steel consumption in the automotive sector. Domestic
 13 appliances and shipping containers are projected to decline at much lower annual rates of
 14 0.3% and 0.4%, respectively.

15



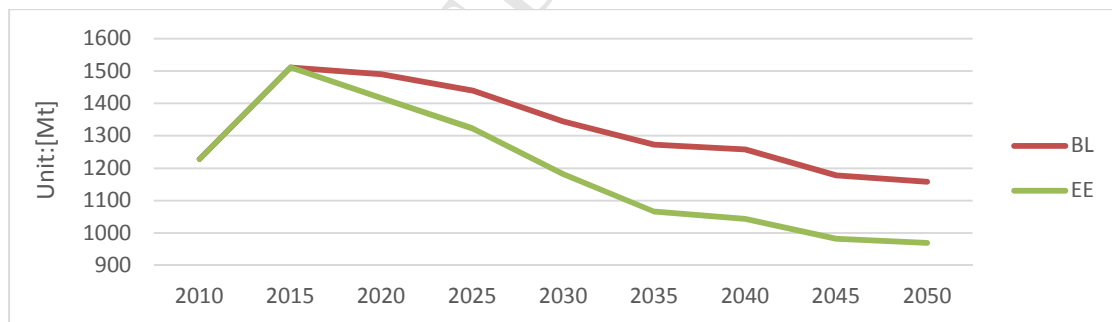
16

Fig. 2: Steel demand and production from 2010 to 2050

4.2 Material consumption from 2010 to 2050

4.2.1 Raw material consumption

Fig. 3a (top panel) presents the total raw material consumption (i.e. iron ore, limestone and scrap) in China's iron and steel industry, under BL and EE scenarios. For both scenarios (BL and EE), raw material consumption peaks in 2015 at levels almost 20% higher than 2010. After 2015, the consumption in BL scenario reduces to 1138 Mt by 2050, due to decreased steel production. The EE scenario shows that the consumption will decrease by up to 20% compared with BL primarily due to the shift of steel production from BOF to EAF. Regarding the raw material demand by type (Fig. 3b (bottom panel)), in BL, Chinese steel production relies heavily on iron ore (amounting to 87% of the total), followed by scrap (10%). Compared to BL, the scrap share of total raw material consumption will increase by 13%, due to increased EAF production.



3 (a): Top panel



3 (b): Bottom panel

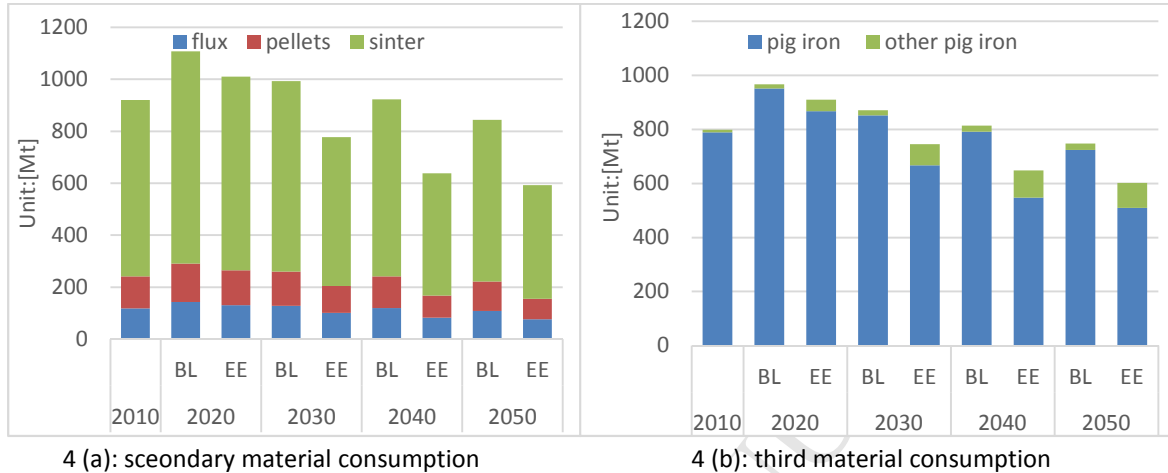
Fig. 3: Raw material consumptions in the baseline (BL) and energy efficiency (EE) scenarios

4.2.2 Process material consumption

Estimation of process material demand for steel industry is important because it does not only have large impact on energy/resource consumption and emissions, but also affects the accuracy of predictions for future economic growth. In the BL Scenario, the demand for process materials (i.e., sinter, pellets, flux, pig iron, and other pig iron) shows substantial increase before 2020, then gradually declines until by 2050 (Fig. 4 (upper left)). Specifically, the lowest demand of secondary materials (i.e., sinter, pellets, and flux) in EE is about 600 Mt in 2050, 26% lower than BL, due to reduction of pig iron demand. Compared to BL, the material efficiency (the ratio of useful product output to material input) has a large improvement, because crude steel production from the EAF route increases drastically. This projection is possible as EAF based steel production already accounts for 75% and 66% in USA and Europe, respectively (van Ruijven et al., 2016). Further, slag is a main waste material in the steel industry, which can occur at iron making and steel making processes. As shown in Fig. 4 (bottom right), slag production grows to 1800 Mt by 2020 in the BL scenario, then declines to 1400 Mt by 2050 and the share of iron making process in total slag production declines slightly from 52% in 2010 to 43% by 2050. In the EE scenario, slag

1 production is further reduced by 13% by 2050 compared with the BL. However, the share of
 2 EAF process is the largest contribution to slag production, 40% higher than in the BL
 3 scenario.

4

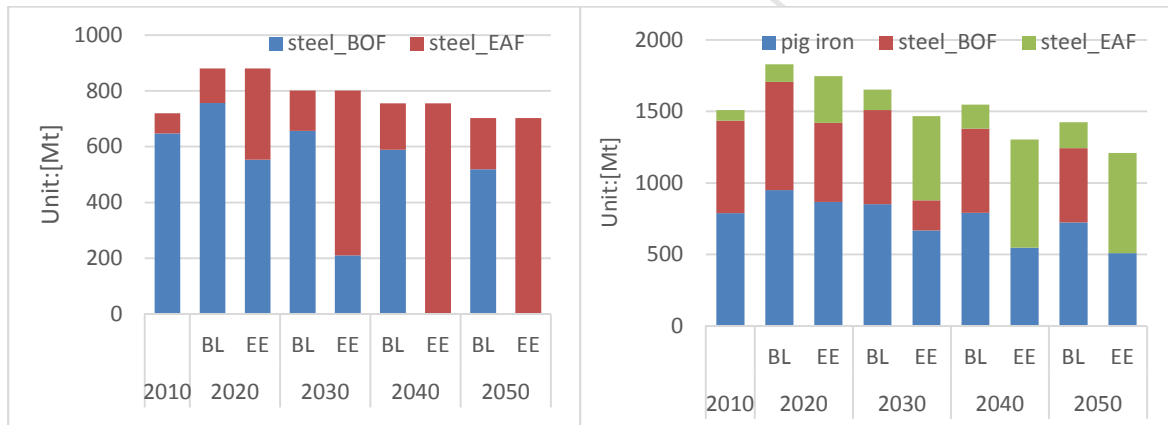


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6

4 (a): secondary material consumption

4 (b): third material consumption



7

8

4 (c): crude steel production by process

4 (c): slag production by process

9

Fig. 4: activities of process materials in baseline (BL) and energy efficiency (EE) scenarios

10

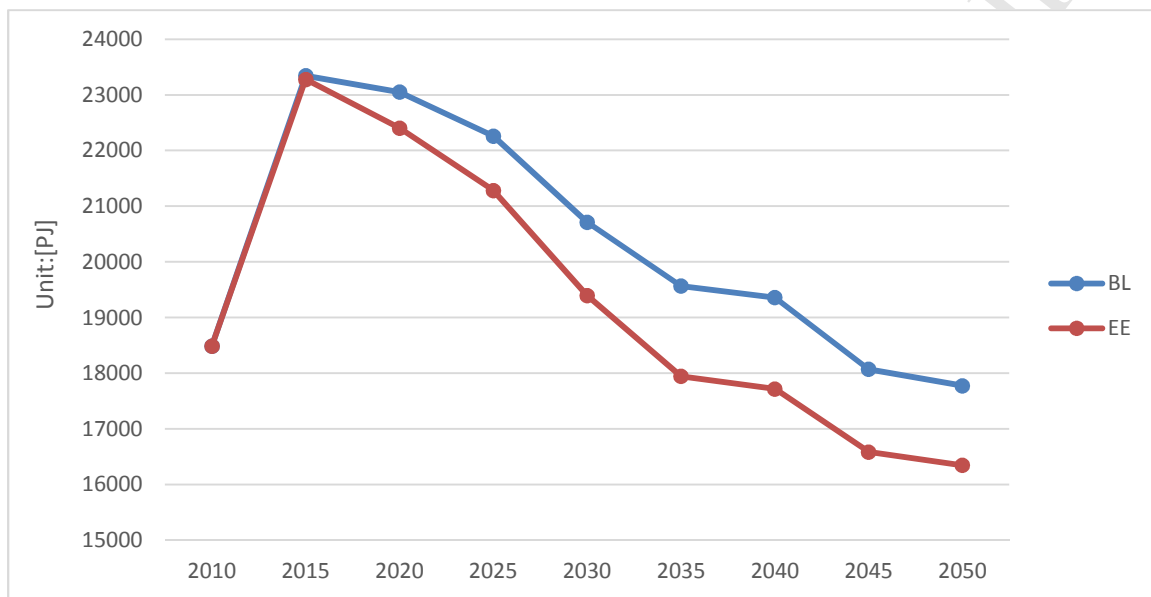
11 4.3 Energy consumption from 2010 to 2050

12 4.3.1 Total final energy consumption

13

14 Fig. 5 presents the historical and projected trends of total final energy consumption for the
 15 Chinese iron and steel industry. Energy consumption in 2010 of this study was 16% higher
 16 than our previous study (Zhang et al., 2014), due to different system boundaries used. Both
 17 scenarios show that energy consumption in the Chinese iron and steel industry reached a
 18 peak in 2015, at around 23 EJ, and then faces a decline as a result of a decrease in steel

1 production. Further, 8% of energy consumption could be saved via implementation of
 2 energy efficiency measures. Regarding to energy mix in the Chinese iron and steel industry,
 3 coal and coke together account for 89% of total energy consumption, followed by electricity
 4 (10%) (See Fig. 5-6 and Fig.8). In this study we assume that coal as raw materials and main
 5 energy will directly use to produce coke, via the coke making process.



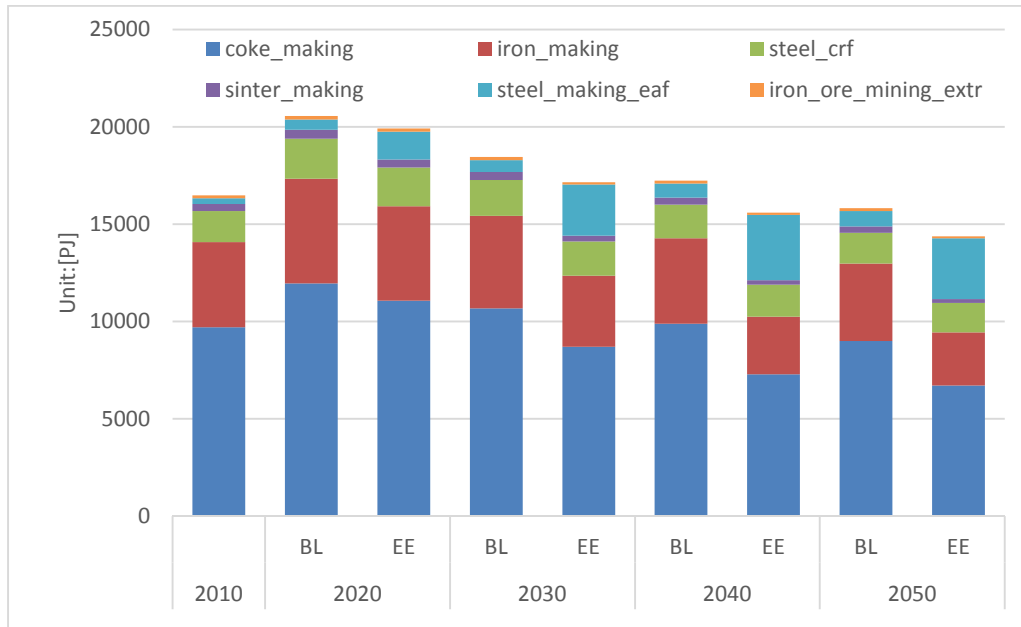
7
 8 Fig. 5: total final energy consumption in baseline (BL) and energy efficiency (EE) scenarios
 9

10 4.3.2 Coal consumption by process

11 Fig. 6 shows coal consumption by process for the two scenarios. In the BL scenario, coal
 12 consumption is projected to increase to 20227 PJ by 2020 and then decrease to 15572 PJ by
 13 2050, 23% higher and 13% lower than 2010, respectively. Implementing the selected energy
 14 efficiency measures in the EE scenario would further decrease the coal consumption by 5%
 15 in 2020 and 10% by 2050. The majority of coal consumption in the 2010-2050 period is for
 16 coke making, accounting for over 50%, followed by iron making (25%) and casting, rolling
 17 and finishing (7%). For coke making, adopting energy efficiency measures (i.e. coke dry
 18 quenching (CDQ), coal moisture control (CMC), variable speed drive on coke oven gas
 19

1 compressors, and programmed heating in coke oven) and reducing of coke demand would
 2 lead to 12-22% of coal saved, compared to BL.

3



4 Fig. 6: Coal consumption by process in baseline (BL) and energy efficiency (EE) scenarios

5

6 4.3.3 Coke consumption by process

7

8 Coke consumption in steel industry is mainly due to the processes of iron making and
 9 casting, rolling, and finishing. Fig. 7 shows coke consumption by process from 2010 to 2050,
 10 under different scenarios. As shown in the figure, the coke consumption in BL scenario is
 11 projected to peak around 2020, and then decrease gradually, in line with declining pig iron
 12 demand. Coke consumption in BL scenario is forecast to decrease by 8% between 2010 and
 13 2050, from 9020 PJ in 2010 and to 8281 PJ by 2050, while adopting energy efficiency
 14 measures in EE scenario will further decrease by 21% in 2050. Compared to BL, the EE
 15 scenario projects that the iron making process would decrease coke consumption from
 16 7400 PJ in 2020 to 4200 PJ by 2050, while other processes (sinter making and pellets making)
 17 shares of coke consumption change slightly.

18

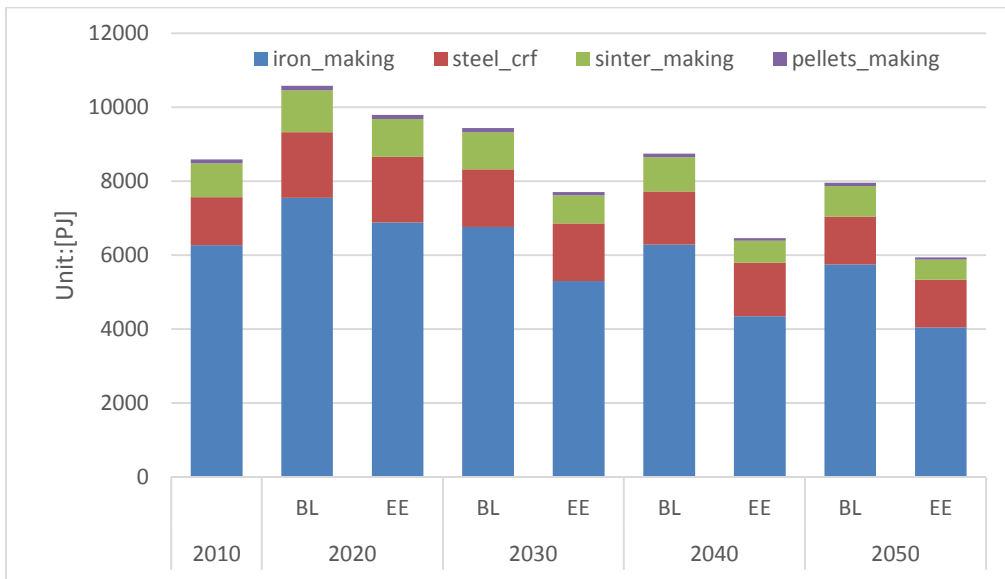


Fig. 7: Coke consumption by process in baseline (BL) and energy efficiency (EE) scenarios

4.3.4 Electricity consumption by Process

Fig. 8 presents process electricity consumption in the Chinese iron and steel industry from 2010 to 2050, under BL and EE scenarios. As compared to the consumption trends of coal and coke, the difference is that electricity consumption in both scenarios is projected to increase from 2000 PJ in 2010 to approximately 2500 PJ in 2020, and decline slightly thereafter. For the BL scenario, electricity consumption breakdown remains the same, with the majority of consumptions arising from the process of casting, rolling, and finishing (steel_crf), accounts for 37% of the total, followed by BF-BOF (20%) and iron making (16%). Electricity consumption of BF-BOF in the EE scenario will decrease drastically until 2040, while the EAF share of total electricity consumption will increase significantly (due to route switch from BF-BOF to EAF to produce steel). Energy efficiency measures would lead to a small decrease in electricity consumption for other processes (i.e., iron ore mining extraction, sinter making, pellets making, coke making, iron making, and casting, rolling, and finishing (steel_crf)) of Chinese iron and steel industry.

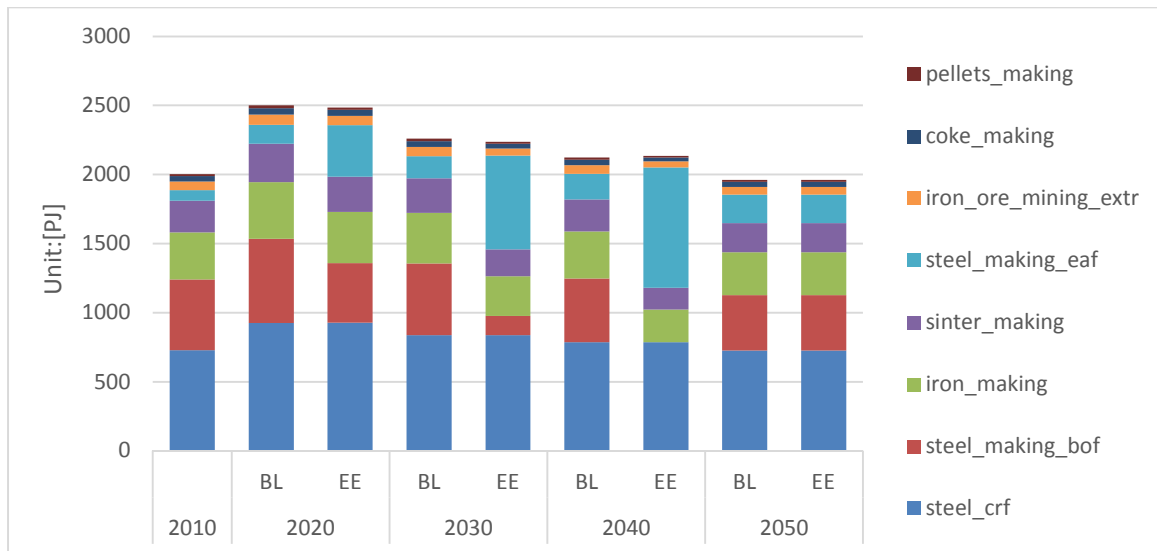


Fig. 8: Electricity consumption by process in baseline (BL) and energy efficiency (EE) scenarios

4.4 Water withdrawal and consumption

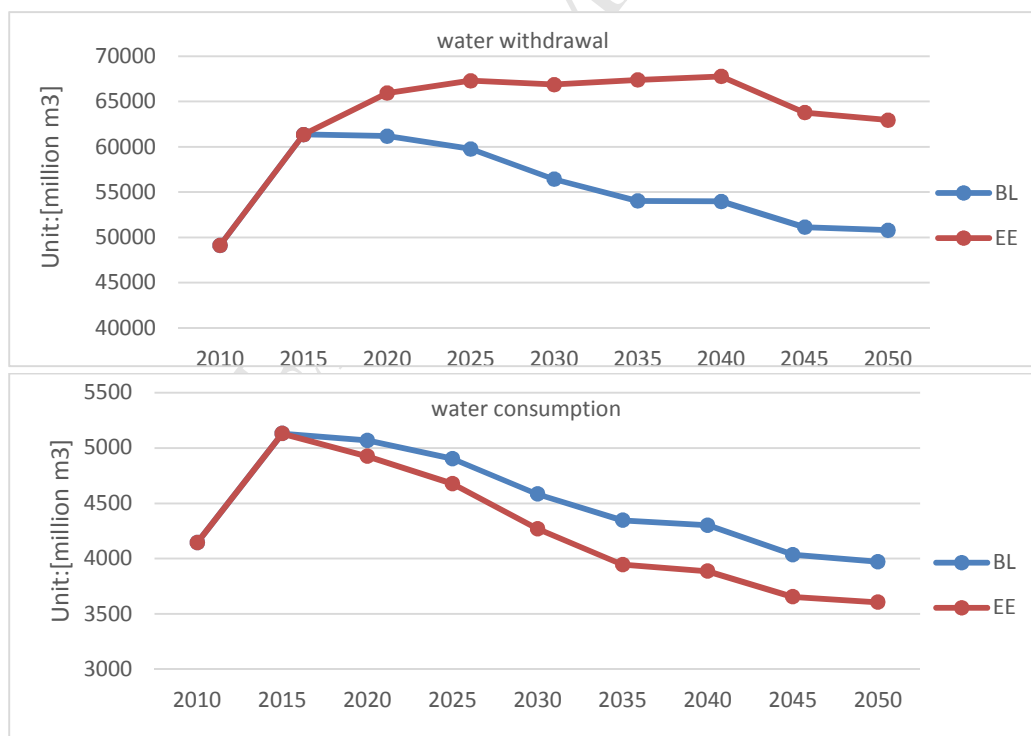
4.4.1 Total water withdrawal and consumption

Policy impacts on water resources management (e.g. water efficiency, and water scarcity) has become one of the most important parts of the Sustainable Development Goals (e.g., SDG-6 and SDG-12). As mentioned before (see section 2), over 50% of the global steel production belongs to China, while only 7% of world freshwater reserves are in China (China Water Risk, 2017). In 2010, water withdrawal for the Chinese iron and steel industry was 48,900 million m³ (representing 11% of all withdrawals in China), while 4,200 million m³ water was consumed (China Water Risk, 2017; National Development and Reform Commission of China, 2013). Therefore, disruptions in water supply and competition for water use rights would have large impacts on steel production.

Fig. 9 shows the recent historic total water withdrawal and consumption³ and the projection for these in steel industry between 2020 and 2050. Water withdrawal in the BL scenario

³ In this study, water withdrawal is defined as the total volume removed from a water source such as a lake or river. Often, a portion of this water is returned to the source and is available to be used again, while water consumption is defined as water removed for use and not returned to its source (Duke Energy, 2018).

1 peaks at 60,300 million m³ by 2015, then decreases to 49,900 million m³ by 2050 (Fig. 9
 2 upper). However, the EE scenario projects an increase in water withdrawal an additional 40%
 3 by 2030 and 23% by 2050, respectively, compared to 2010. The main reason is that the
 4 technology shift from BF-BOF to scrap-EAF would cause an additional 40 m³ of water
 5 withdrawal when producing 1 ton of crude steel (CSDRI, 2016). For BL scenario, route shift
 6 from BF-BOF to scrap-EAF and demand reduction leads to a larger drop in water
 7 consumption (the reduction potentials are 1% higher than water withdrawal). The trend of
 8 water consumption in the EE scenario differs greatly when compared to the trajectory of
 9 water withdrawal (Fig. 9 bottom panel). In the medium term, that is, up to 2035, the water
 10 consumption decreases from 5,100 million m³ in 2015 to 3,960 million m³ in 2035, at an
 11 annual average of 1.2%.



14 Fig. 9: Total water withdrawal and consumption in baseline (BL) and energy efficiency (EE) scenarios

15 4.4.2 Water withdrawal and consumption by process

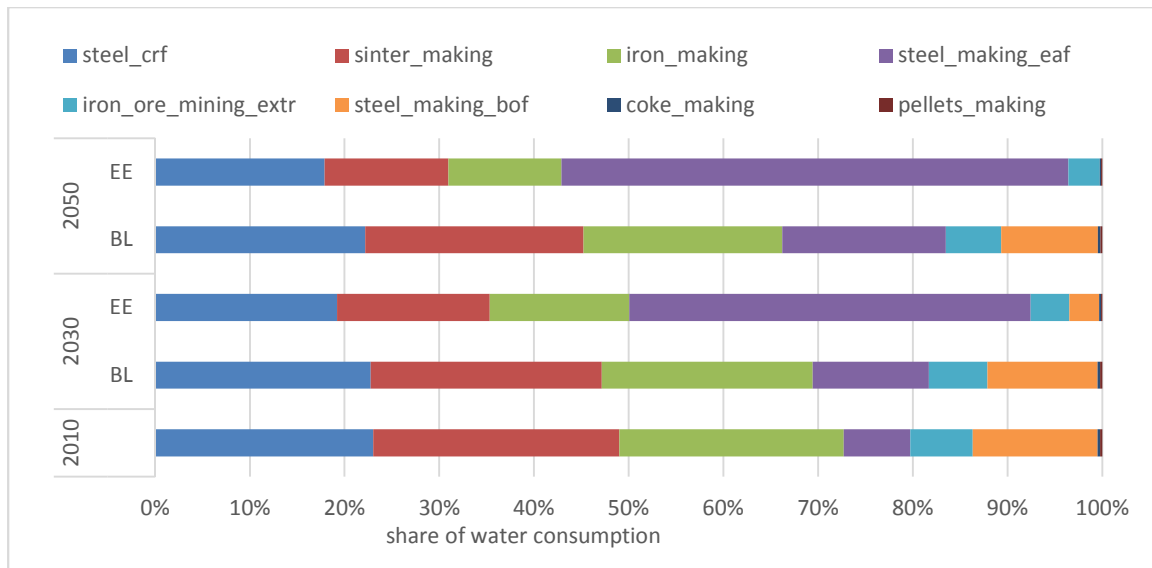
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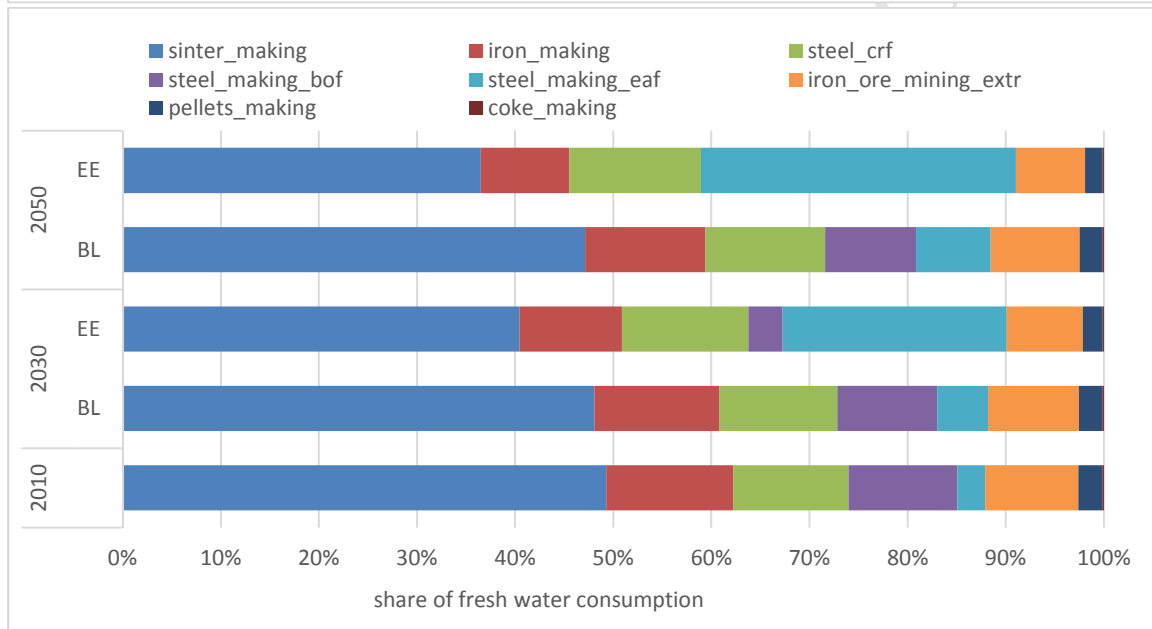
1 A detailed breakdown of the water withdrawal and consumption projected for 2010-2050 is
2 presented in Fig. 10. As shown in Fig. 10 upper, in 2010 water withdrawal of the Chinese
3 iron and steel industry was around 50000 million m³, 27% of which was consumed by sinter
4 making, followed by iron making, and steel_crf, which accounted for 27%, 24%, and 23%
5 respectively. For the BL scenario, the water withdrawal and consumption by the process will
6 change slightly over the study period. For example, EAF's share of total water withdrawal in
7 the BL scenario increases only by 10% from 2010 to 2050, while it is expected to further
8 grow to 40% by 2050, under EE scenario assumptions.

9
10 In terms of water consumption by process, as illustrated in Fig. 10 (bottom panel), in 2010
11 48% of freshwater was consumed for sinter making, followed by processes of iron making,
12 steel_crf, and BOF, which respective shares of 14%, 11%, and 11%, respectively. For the EE
13 scenario, the top largest share of fresh water withdrawal is projected in sinter making,
14 which accounts for 37%, followed by EAF (28%), due to route shift from BF-BOF to scrap-EAF.
15 Combined, coke making, BOF, and pellets making account for only 3%, partly caused by the
16 implementation of energy efficiency measures such as Top-pressure recovery turbines (TRT)
17 in iron making, and Coal moisture control (CMC) and Coke Dry Quenching (CDQ) in coke
18 making.

19



1



2

3

Fig. 10: Share of water withdrawal and consumptions in baseline (BL) and energy efficiency (EE) scenarios

4

5

6 4.5 Projected emissions of CO₂ and air pollutants

7 4.5.1 CO₂ emissions by types

8

9 We estimate the CO₂ emissions of China's iron and steel industry by 2050 under BL and EE

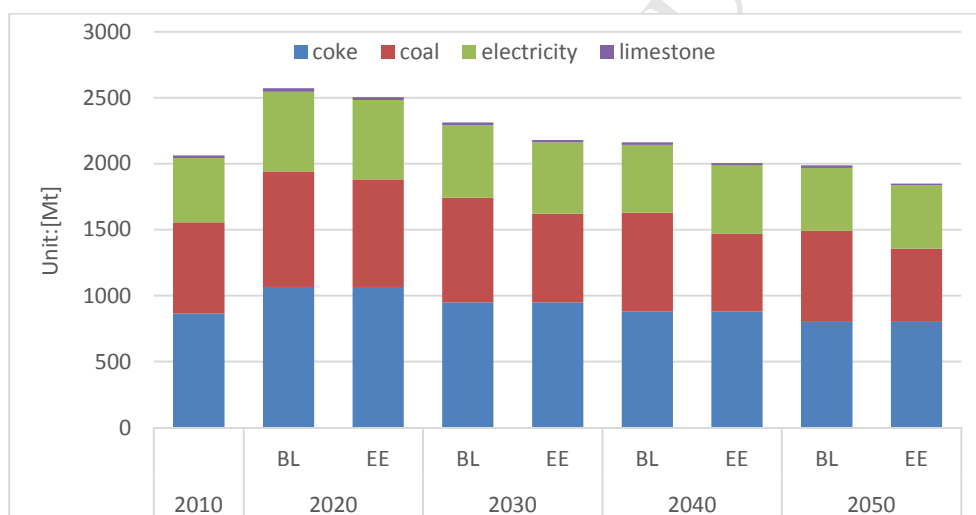
10 scenarios. Note that the total CO₂ emissions in this study is higher than previous studies

11 (Hasanbeigi et al., 2017; Zhang et al., 2014), due to different system boundaries used. For

12 example, most of previous studies have only calculated the direct energy related CO₂

13 emissions (Hasanbeigi et al., 2013c; Zhang et al., 2014), while we consider both the direct

1 and indirect emissions - the process emissions from limestone and energy related emissions
 2 from the processes of coke making, and iron ore mining. As shown in Fig. 11, in 2010 the
 3 largest source for Chinese iron and steel industry is coke that accounts for 44%, followed by
 4 coal (31%) and electricity (23%). We show that fossil fuel related CO₂ emissions in both
 5 scenarios are expected to remain at the present level. The total CO₂ emissions in BL scenario
 6 are projected to peak at around 2500 Mt in 2020, and then decrease to 1957 Mt by 2050.
 7 Adopting energy efficiency measures and shifting from BF-BOF to scrap-EAF in EE scenario
 8 leads to 5-8% of emissions avoided during the study period.



10 Fig. 11: CO₂ emissions by fuel types in baseline (BL) and energy efficiency (EE) scenarios
 11
 12

13 4.5.2 PM_{2.5} emissions by process

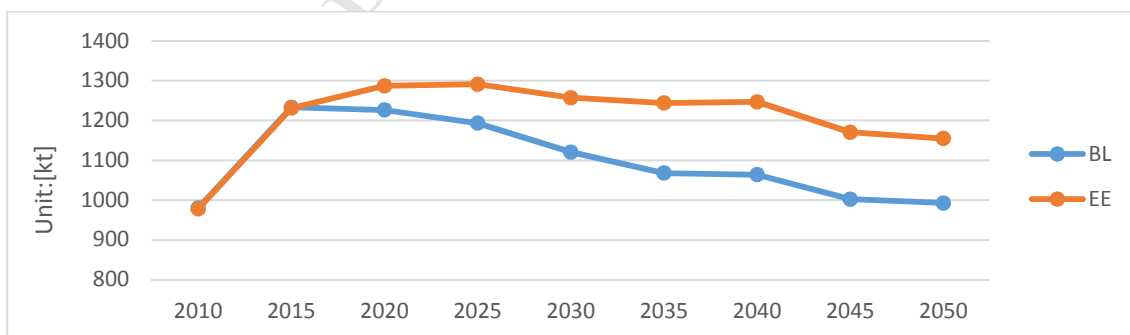
14 Major sources of PM_{2.5} emissions in steel production are from fuel combustion, process
 15 emissions (e.g., sinter making, iron making, steel making, and raw material extraction), and
 16 indirect emissions of electricity consumption. We present the levels of total PM_{2.5} emissions
 17 and its contributors in Chinese iron and steel industry (see Fig. 12). In future projections, the
 18 total PM_{2.5} emissions in the BL scenario increase drastically until they peak at around 1200
 19 kt in 2015 and decrease thereafter, due to the changes of outputs of steel products (see Fig.
 20

1 12 – top panel). However, the emissions in the EE scenario will increase until around 2025,
 2 and then start to go down slowly, due to the increasing share of EAF technology, which has
 3 the process emission factor of EAF 3 times higher than BOF in China (Wang et al., 2016; Wu
 4 et al., 2015).

5

6 Regarding $PM_{2.5}$ emissions by types for the China's iron and steel industry (see Fig. 12 –
 7 bottom panel), in 2010 around 50% of emissions come from coal combustion in Chinese iron
 8 and steel industry, followed by the process emissions of sinter making and BOF, which
 9 together account for 30%. The shares evolve along the same patterns as the year 2010 in BL
 10 scenario. For the EE scenario, with increasing application of EAF technology, EAF's share of
 11 total $PM_{2.5}$ emissions will increase by 35% in 2050, compared to 2010 (see Fig. 12 - bottom
 12 panel). If we only consider the emissions from fuel combustion and electricity consumption
 13 for steel production, the energy related $PM_{2.5}$ emissions in the EE scenario will decrease by
 14 20% as compared to the BL scenario, as result of the implementation of energy efficiency
 15 measures.

16



17

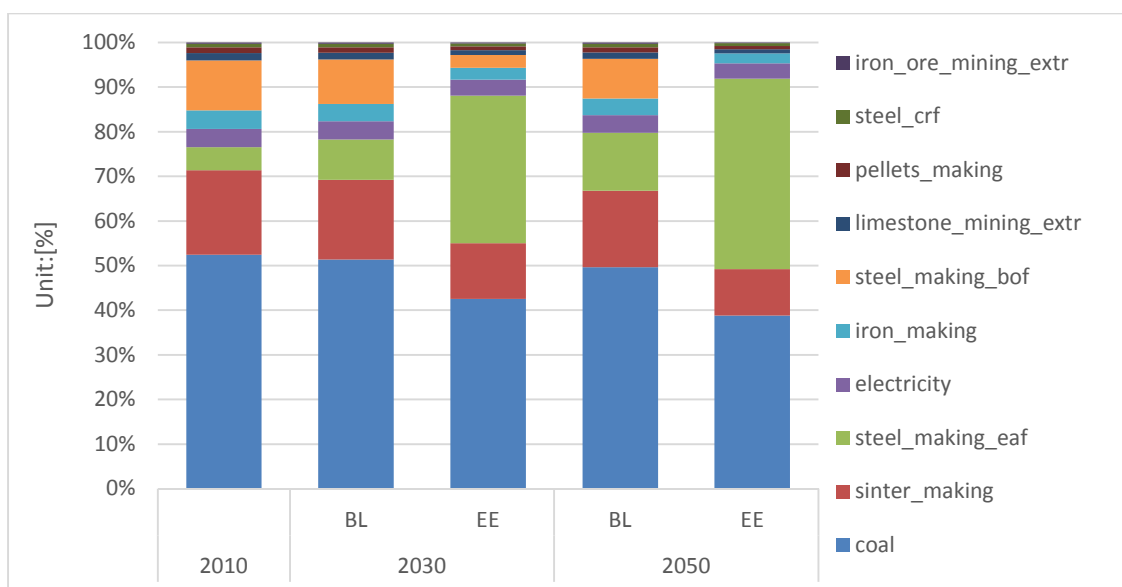


Fig. 12: PM_{2.5} emissions by fuel types and process in baseline (BL) and energy efficiency (EE) scenarios

4.5.3 NO_x emissions by process

NO_x emissions of China's iron and steel industry for the period 2010-2050 are shown in Fig. 13. Overall, the emissions in BL scenario will increase up to 5900 kt by 2020 and 4500 kt by 2050 - approximately 20% higher and 6% lower respectively, than the year 2010. For the EE scenario, the total NO_x emissions are expected to further decline by 5-10% through the implementation of energy efficiency measures. In comparison to the contributors of PM_{2.5} emissions, coal's share of total NO_x emissions in Chinese iron and steel industry is significantly higher, as the emissions are mostly formed under the high temperature conditions – meaning that the combustion of fossil fuels is usually involved. Both scenarios show that the energy related NO_x emissions (including coal and electricity) is projected to remain steady, over 90%, from 2010 through 2050.

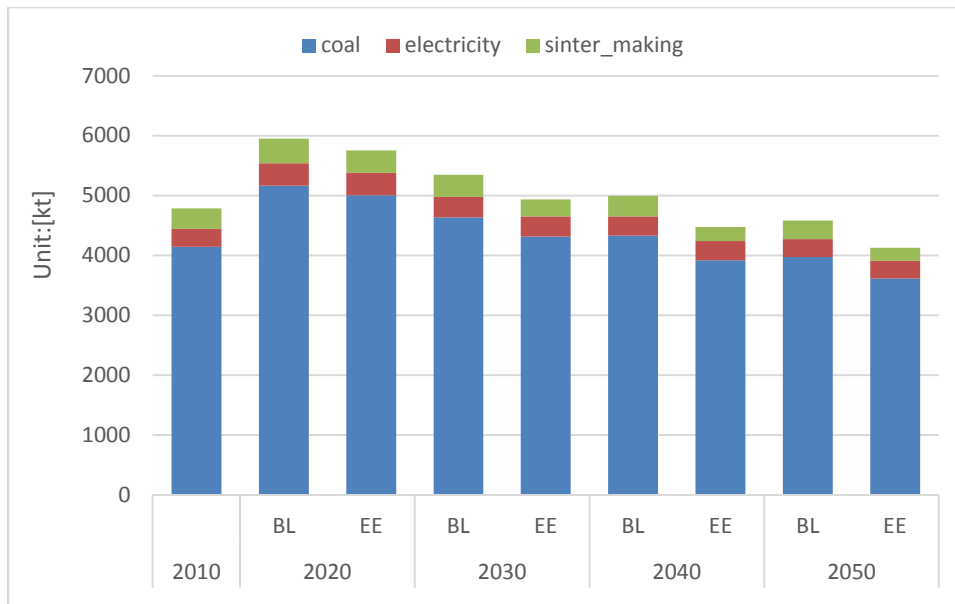


Fig. 13: NO_x emissions by fuel types and process in baseline (BL) and energy efficiency (EE) scenarios

4.5.4 SO₂ emissions by process

The iron and steel sector is China's largest industrial SO₂ source, and originates mostly direct emissions of coal combustion and sinter making, as well as indirect emissions of electricity consumption (Ma et al., 2012). Fig. 14 gives an overview of SO₂ emissions for the period 2010-2050, which after a rapid increase until 2015, shows a gradual decline up to 2050. In the BL scenario, SO₂ emissions peak at around 3000 kt in 2020 and fall to 2300 kt in 2050, due to reductions in steel products. With the implementation of energy efficiency measures and adoptions of EAF in EE scenario, the SO₂ emissions peak at 2770 kt in 2020 and fall to 2000 kt in 2050, at average 8 – 13% lower than BL level. Both scenarios also demonstrate that coal is expected to account for the major share (60%) of total the emissions, whereas coal's share remains consistent in BL and EE scenarios over the study period.

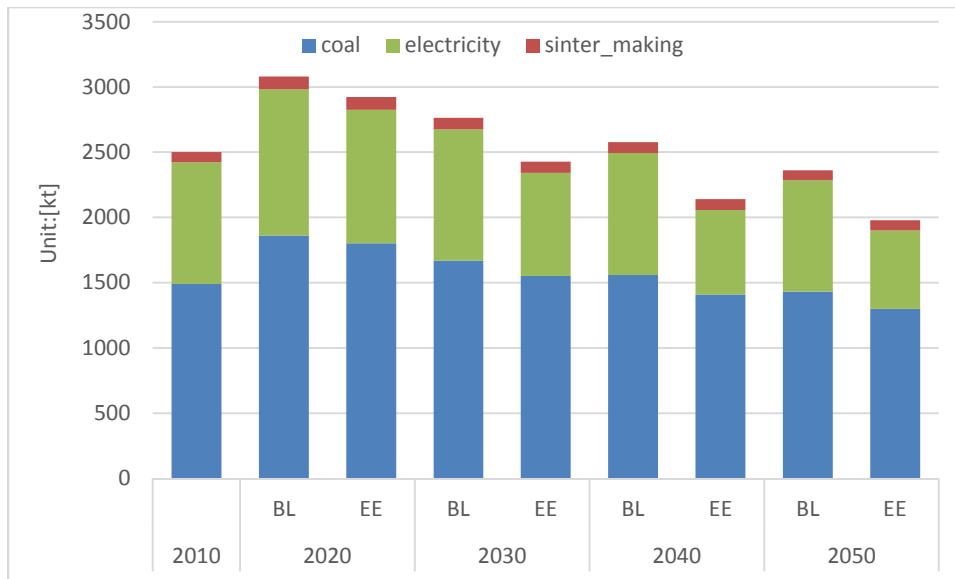


Fig. 14: SO₂ emissions by fuel types and process in baseline (BL) and energy efficiency (EE) scenarios

This study demonstrates that adopting energy efficiency measures combined with shifting route from BF-BOF to scrap-EAF have large potentials to reduce raw material consumption, improve energy and water use efficiencies, and decrease emissions of SO₂ and NO_x. At the same time, these efforts lead to higher scrap consumption and water withdrawal, and increased PM_{2.5} emissions. Further, air pollution control technologies (e.g. electrostatic precipitator, Selective Non Catalytic Reduction or Selective Catalytic Reduction, and Flue Gas Desulfurization) and Carbon Capture and Storage can further decrease emissions of GHG and air pollutants, but will need extra investment and consume additional energy.

5 Discussion for model uncertainty

Model uncertainty (i.e. model structure uncertainty, parameter uncertainty, and the uncertainty related to assumptions such as boundary conditions) is very important in the decision-support processes, because models cannot predict the future with precision (Nilsen and Aven, 2003; Zhang et al., 2015b). Development of the demand sector in integrated assessment models, like MESSAGEix – iron and steel model, is a key issue to provide a holistic understanding of the dynamics energy and resources systems. Like all integrated

1 assessment models, there are several considerable uncertainties in certain parts of the
2 MESSAGEix – iron and steel model, e.g. natural resource availability, material/energy
3 substitution and its trade off across regions, development of the markets of iron and steel
4 both nationally and internationally, as well as in robust technology strategies and related
5 investment portfolios. Several studies indicate that policy makers are more interested in
6 robust strategies rather than uncertainties, due to the robustness of policy actions have
7 lesser impacts via changes in the uncertain model elements (Amann et al., 2011). Therefore,
8 a MESSAGE robust decision-making framework with an endogenous representation of
9 uncertainties (e.g. errors of input parameters) has been developed (Krey and Riahi, 2009)
10 and used to quantify the uncertainties inherent in socioeconomic and technological
11 response strategies to energy and climate challenges. Specifically, stochastic optimization
12 with a fully endogenous representation of uncertain parameters (e.g., technology
13 parameters, and intensity use of materials) and policy robustness (e.g., changes in carbon
14 price) can be used to tackle multiple challenges with minimization cost or maximization
15 resource utilization. Note that the objective of this study is to introduce that how to develop
16 sub-sectors in the IAM MESSAGEix. Therefore, the model uncertainty of the case study was
17 intentionally left beyond the scope of this paper.

18

19 **6. Conclusion and implications for further research**

20

21 Improvement in the representation of the industry in MESSAGEix is necessary to reconcile
22 how behaviour and policy interacts with strategies to tackle multiple challenges, e.g. climate
23 targets and SDGs. To depict the individual characteristics and complex interactions within
24 and with industries, this paper describes how the iron and steel industry is modelled in
25 MESSAGEix. Specifically, we integrate Material/Energy/Water Flow Analysis (represents

1 carriers of energy, material and water and the associated technologies) and nexus approach
2 into the MESSAGEix framework to develop the MESSAGEix – iron and steel industry model.
3 This model can not only quantify synergies between raw material uses, consumptions of
4 scrap, energy and water, emissions of CO₂ and air pollution, and the potential costs and
5 benefits of different efforts, but can also yield valuable insights into the interactions across
6 sectors. For example, adopting energy efficiency measures and switching BF-BOF to scrap-
7 EAF in the EE scenario is projected to decrease raw material by 14%, energy by 7%, water by
8 8%, CO₂ by 7%, NO_x by 9%, and SO₂ by 14% respectively, compared to BL scenario. At the
9 same time, water withdrawal and PM_{2.5} emissions in the EE scenario will increase by 14%
10 and 20%, compared to the BL scenario. However, additional air pollution control
11 technologies can efficiently decrease PM_{2.5} (Zhang et al., 2014). It means that the energy
12 efficiency measures of Chinese iron and steel industry would leads to huge resource-energy-
13 environment nexus and have large impacts on economic saving potential. Therefore, policy
14 makers should consider nexus effects to overcome the barriers (e.g., capital constraint,
15 imperfect information, institution governance, et al.) of energy efficiency measures when
16 designing integrated policies to achieve multiple targets.

17

18 Moreover, for future works within the MESSAGEix - iron and steel model, we need to
19 consider what innovation technology/measures will be used to improve the efficiency of
20 steel production, e.g., how to introduce the hydrogen and renewables in the steel industry
21 in a cost-effective manner. We also need to evaluate that new steel products will be
22 required by the demand sectors (e.g., building and transportation industries). We
23 recommend that introducing manufacturing sub-sectors to IAMs would allow to study new
24 specific energy/water saving and emission mitigation options and develop more efficient

1 policies, including co-benefits of improvement options for IAMs to be modelled more
2 accurately. Therefore, future works that employ and expand the presented approach to
3 develop the manufacturing sectors (e.g., steel, cement, pulp and paper, chemical,
4 aluminium, etc.) in MESSAGEix at global and regional/country scales would be valuable, so
5 these efforts can accurately quantify the impacts of various strategies and response to
6 future challenges. For the purpose, the MESSAGEix model is already distributed on Github
7 with an open-source license (Huppmann et al., 2018).

8

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10

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21

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Appendix S1: List of process technology

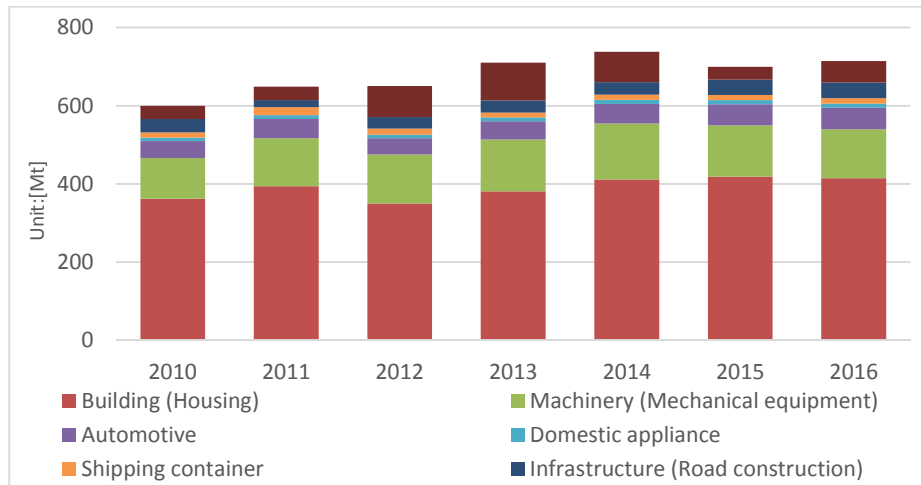
Process technology
coke_making
iron_making
steel_making_bof
steel_making_eaf
iron_ore_mining_extr
pellets_making
sinter_making
steel_crf
steel_making_dri
iron ore extraction
limestone extraction

Appendix S2: List of energy efficiency measures in MESSAGE – iron and steel technology database

Parent_technology	Energy efficiency measures
coke_making	Coke dry quenching (CDQ)
coke_making	Coal moisture control
coke_making	Programmed heating in coke oven
coke_making	Pressure Shift-Absorbing Technique in Hydrogen Making
coke_making	Variable speed drive on coke oven gas compressors
iron_making	Improved blast furnace control
iron_making	Cogeneration for the use of untapped coke oven gas, blast furnace gas, and basic oxygen furnace-gas in integrated steel mills
iron_making	Dry Bag Dedusting System of Blast Furnace Gas
iron_making	Improved hot blast stove control
iron_making	Injection of coke oven gas in BF
iron_making	Injection of pulverized coal in BF
iron_making	Injection of plastic waste in BF
iron_making	Moisture Removing Blowing Technique in Blast Furnace
iron_making	Recovery of blast furnace gas
iron_making	Top-pressure recovery turbines (TRT)
pellets_making	Small pellet sintering technology
sinter_making	Heat recovery from sinter cooler
sinter_making	Increasing bed depth
sinter_making	Improved charging method
sinter_making	Low temperature sintering
sinter_making	Reduction of air leakage
sinter_making	Ring cooler fluid sealing technology
sinter_making	Use of waste fuel in sinter plant
steel_crf	Integrated casting and rolling (Strip casting)
steel_crf	Automated monitoring and targeting systems
steel_crf	Continuous annealing

steel_crf	Controlling oxygen levels and variable speed drives on combustion air fans
steel_crf	Endless Hot Rolling of Steel Sheets
steel_crf	Flameless oxyfuel burners
steel_crf	Hot charging
steel_crf	Heat recovery on the annealing line
steel_crf	Insulation of reheat furnaces
steel_crf	Low temperature rolling technology
steel_crf	Multislit Rolling Technique on the Bar Rolling
steel_crf	Process control in hot rolling
steel_crf	Preventative maintenance in integrated steel mills
steel_crf	Recuperative or regenerative burner
steel_crf	Reduced steam use in the acid pickling line
steel_crf	Waste heat recovery from cooling water
steel_making_bof	Efficient Ladle preheating
steel_making_bof	Energy monitoring and management systems
steel_making_bof	Recovery of BOF and sensible heat
steel_making_bof	vacuum degassing from liquid iron
steel_making_bof	Variable speed drives for flue gas control, pumps, fans in integrated steel mills
steel_making_bof	Variable speed drive on ventilation fans
steel_making_eaf	Adjustable speed drives (ASDs) on flue gas fans
steel_making_eaf	Bottom stirring/gas injection
steel_making_eaf	Direct current (DC) arc furnace
steel_making_eaf	Improving process control in EAF
steel_making_eaf	Oxy-fuel burners/lancing
steel_making_eaf	Preventative maintenance in EAF plants
steel_making_eaf	Scrap preheating
steel_making_eaf	Converting the furnace operation to ultra-high power (UHP) (Increasing the size of transformers)
steel_making_eaf	wet and heat recovery of slag

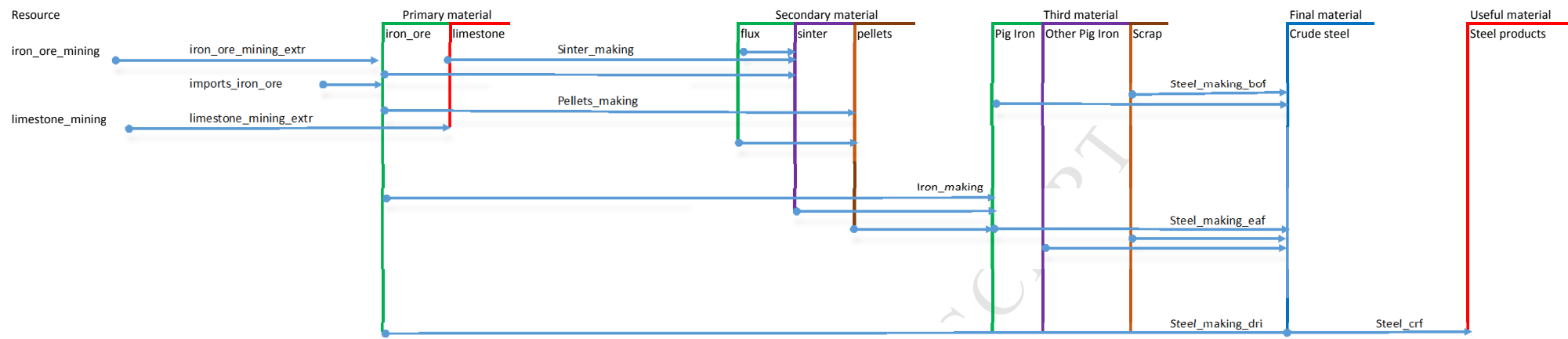
Appendix S3: Historic steel consumption by end-use sectors

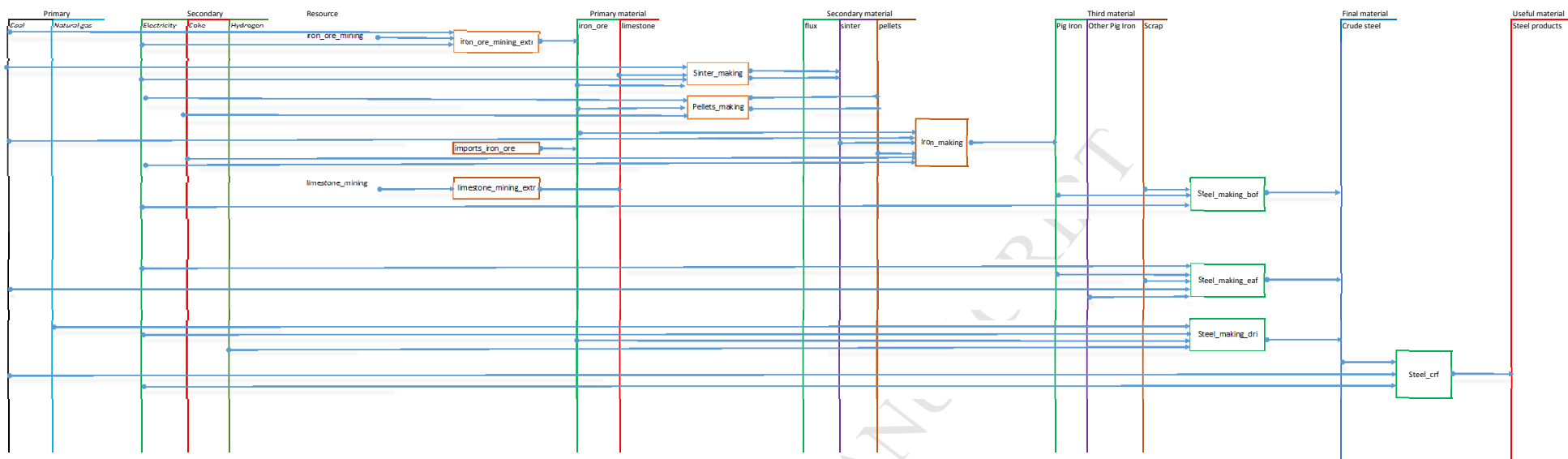


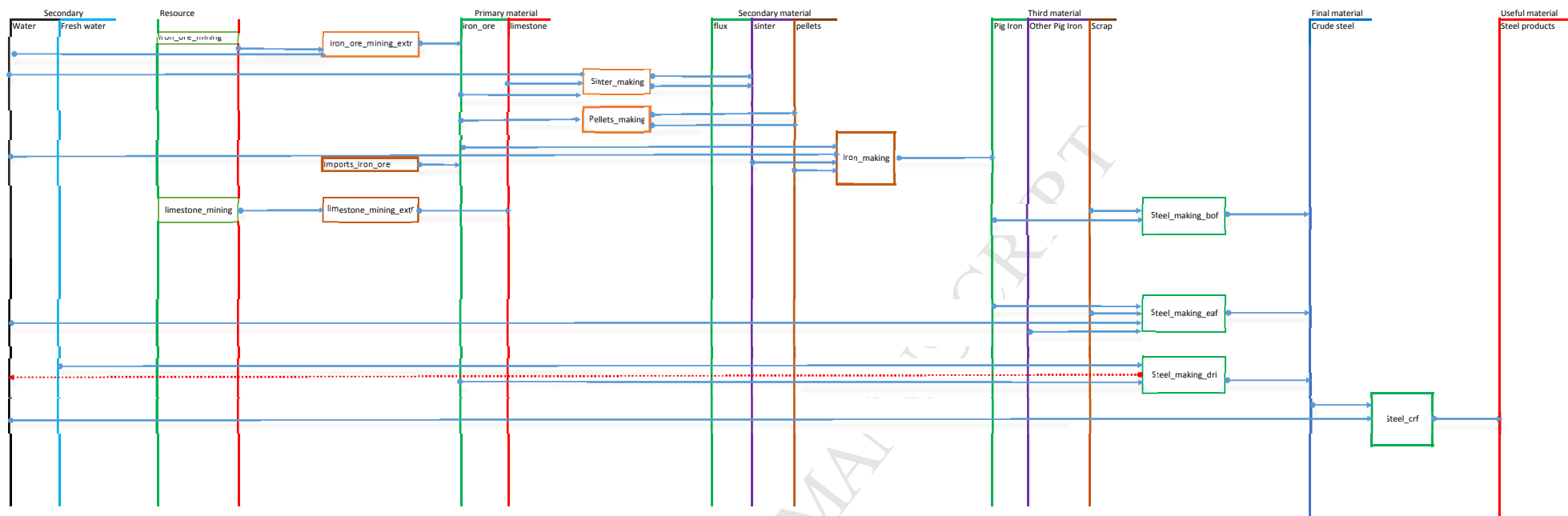
Appendix S4: List of energy efficiency measures that adopted in EE scenario

Parent_technology	Energy_efficiency_measures
coke_making	Coke dry quenching (CDQ)
	Coal moisture control
	Pressure Shift-Absorbing Technique in Hydrogen Making
Sinter_making	Heat recovery from sinter cooler
	Increasing bed depth
	Low temperature sintering
	Reduction of air leakage
	Ring cooler fluid sealing technology
	Use of waste fuel in sinter plant
Pellets_making	Small pellet sintering technology
Iron_making	Improved blast furnace control
	Cogeneration for the use of untapped coke oven gas, blast furnace gas, and basic oxygen furnace-gas in integrated steel mills
	Dry Bag Dedusting System of Blast Furnace Gas
	Improved hot blast stove control
	Injection of pulverized coal in BF
	Injection of plastic waste in BF
	Moisture Removing Blowing Technique in Blast Furnace
	Recovery of blast furnace gas
	Top-pressure recovery turbines (TRT)
Steel_making_bof	Energy monitoring and management systems
	Recovery of BOF and sensible heat
	vacuum degassing from liquid iron
	Variable speed drives for flue gas control, pumps, fans in integrated steel mills
Steel_making_eaf	Direct current (DC) arc furnace
	Improving process control in EAF

	Oxy-fuel burners/lancing
	Preventative maintenance in EAF plants
	Scrap preheating
	wet and heat recovery of slag
Steel_crf	Endless Hot Rolling of Steel Sheets
	Flameless oxyfuel burners
	Hot charging
	Heat recovery on the annealing line
	Integrated casting and rolling (Strip casting)
	Low temperature rolling technology
	Multislit Rolling Technique on the Bar Rolling
	Process control in hot rolling
	Preventative maintenance in integrated steel mills
	Recuperative or regenerative burner
	Reduced steam use in the acid pickling line







Process technology

coke_making

iron_making

steel_making_bof

steel_making_eaf

iron_ore_mining_extr

pellets_making

sinter_making

steel_crf

steel_making_dri

iron ore extraction

limestone extraction

ACCEPTED MANUSCRIPT

Parent technology	Energy efficiency measures
coke_making	Coke dry quenching (CDQ)
coke_making	Coal moisture control
coke_making	Programmed heating in coke oven
coke_making	Pressure Shift-Absorbing Technique in Hydrogen Making unit: Kg ce/Nm ³
coke_making	Variable speed drive on coke oven gas compressors
iron_making	Improved blast furnace control
iron_making	Cogeneration for the use of untapped coke oven gas, blast furnace gas, and basic oxygen furnace-gas in integrated st
iron_making	Dry Bag Dedusting System of Blast Furnace Gas
iron_making	Improved hot blast stove control
iron_making	Injection of coke oven gas in BF
iron_making	Injection of pulverized coal in BF
iron_making	Injection of plastic waste in BF
iron_making	Moisture Removing Blowing Technique in Blast Furnace
iron_making	Recovery of blast furnace gas
iron_making	Top-pressure recovery turbines (TRT)
pellets_making	Small pellet sintering technology
sinter_making	Heat recovery from sinter cooler
sinter_making	Increasing bed depth
sinter_making	Improved charging method
sinter_making	Low temperature sintering
sinter_making	Reduction of air leakage
sinter_making	Ring cooler fluid sealing technology
sinter_making	Use of waste fuel in sinter plant
steel_crf	Integrated casting and rolling (Strip casting)
steel_crf	Automated monitoring and targeting systems
steel_crf	Continuous annealing
steel_crf	Controlling oxygen levels and variable speed drives on combustion air fans
steel_crf	Endless Hot Rolling of Steel Sheets
steel_crf	Flameless oxyfuel burners
steel_crf	Hot charging
steel_crf	Heat recovery on the annealing line
steel_crf	Insulation of reheat furnaces
steel_crf	Low temperature rolling technology
steel_crf	Multislit Rolling Technique on the Bar Rolling
steel_crf	Process control in hot rolling
steel_crf	Preventative maintenance in integrated steel mills
steel_crf	Recuperative or regenerative burner
steel_crf	Reduced steam use in the acid pickling line
steel_crf	Waste heat recovery from cooling water
steel_making_bof	Efficient Ladle preheating
steel_making_bof	Energy monitoring and management systems
steel_making_bof	Recovery of BOF and sensible heat
steel_making_bof	vacuum degassing from liquid iron
steel_making_bof	Variable speed drives for flue gas control, pumps, fans in integrated steel mills
steel_making_bof	Variable speed drive on ventilation fans
steel_making_eaf	Adjustable speed drives (ASDs) on flue gas fans
steel_making_eaf	Bottom stirring/gas injection
steel_making_eaf	Direct current (DC) arc furnace
steel_making_eaf	Improving process control in EAF
steel_making_eaf	Oxy-fuel burners/lancing
steel_making_eaf	Preventative maintenance in EAF plants
steel_making_eaf	Scrap preheating
steel_making_eaf	Converting the furnace operation to ultra-high power (UHP) (Increasing the size of transformers)
steel_making_eaf	wet and heat recovery of slag

Highlights

- A new approach for manufacturing sectors in MESSAGEix model is developed
- Resource-Energy-Environment Nexus in China's iron and steel industry are quantified
- Energy efficiency would lead to large reductions of material, water, and emission
- Industrial characteristics should be modelled in long-term energy system models