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Original Articles

Environmental and economic sustainability of key sectors in China's steel industry chain: An application of the Emergy Accounting approach

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ABSTRACT

Increasing urbanization day–by–day requires new housing and transportation infrastructures. As a consequence, demand for steel – a basic material for buildings construction as well as for vehicles and railroads – would also increases. This study applies Emergy Accounting (EMA) to assess the Chinás steel industry environmental performance and to identify key application sectors. Subsequently, this study calculates emergy–based indicators capable to assess the present economic performance, environmental sustainability, and land resource appropriate utilization. Building on these indicators, changes of sustainability scenarios in key application sectors are also investigated, with special focus on increased use of recycled steel. The results show that the environmental impacts of steel use in downstream sectors, specially in the Housing and Vehicles Sectors, are significantly higher. Furthermore, the downstream sectors also have a very large requirement for embodied land. Additionally, the Emergy Benefit Ratio (EBR) shows non-negligible advantages to China derived from importing raw iron from abroad at international market prices. Finally, when the recycling rate of scrap steel increases, the performance of downstream sectors improves, with the Vehicle sector showing the most significant changes. Although the benefits of steel-based economy to society are clear, multidimensional sustainability concerns and international competition for primary resources necessitate a transition towards increased recycling and innovative materials within a strictly enforced "circular economy" policy.

1. Introduction

Driven by urbanization, China's steel industry has rapidly developed in recent years, especially the use of steel in the building and infrastructure, mechanical equipment, automotive, and metal products sectors. A report from the National Bureau of Statistics shows that China produced 1 billion tons of crude steel and consumed 950 million tons in 2019, representing an increase of 9.6% per year. This increase means that the use of steel plays an increasingly important role in societýs development. However, although steel use promotes economic development, it also has an impact on resources availability and environmental quality. Therefore, to understand the overall impact of China's steel industry from a sustainability perspective, it is necessary to evaluate the entire industrial chain of steel production, especially its use in key application sectors of the economy.

At present, sustainability research on the Chinese steel industry has mainly focused on the steel production step. Sun et al. (2019) used the Total Environmental Impact Score (TEIS) approach to assess multiple air emissions from China's steel production processes and found that the sintering step releases the largest amount of carbon dioxide. Ma et al. (2018b) employed an ISO 14046 standardized approach to analyze China's water footprint in crude steel making and found that improving the performance of iron ore mining helps reduce the gray water footprint. Qi et al. (2018) analyzed the carbon footprint of Chinese steel companies by using the life cycle assessment method and quantified the extent to which steel production and local forested areas may be

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important factors to determine if the carbon emissions by steel plants exceed the local carbon carrying capacity. Su and Zhang (2016) investigated the energy and material consumption of residential buildings in China and found that the energy and environmental costs of steel products used in construction increases with an increase in the number of floors of buildings. Malone et al. (2018) assessed the material structure of China's steel industry by means of ecological indicators and found that environmental and technological improvement of the production infrastructure has great potential to help reduce the waste generated during steel manufacturing. The above literature shows that most current research focuses on the production process of crude steel, but ignores the many applications of steel in various industrial processes. Therefore, to fully assess the sustainability of the Chinese steel industry, it is necessary to carry out our research on multiple processes and identify the key application sectors, where steel is used.

As a method for evaluating the environmental costs generated by a system, Emergy Accounting has been widely used in the sustainability research of the Chinese steel industry in recent years. Shen et al. (2019) investigated the trend toward environmental sustainability in China's steel industry from 2005 to 2015, using a comprehensive emergy-based framework and they observed that the sustainability of the system decreased by 31.49% over this time. Ma et al. (2018a) explored the sustainability of China's steel production system, focusing on the performance of four indicators, the input index, the output index, the input–output index, and the sustainability index and found that the environmental load of the pelletizing process was the highest over the entire manufacturing chain. Han et al. (2014) analyzed the ecological efficiency of a landmark building in Beijing using a series of emergy indicators. These researchers found that steel for construction relied less on local renewable resources and caused severe environmental stress. Pan et al. (2016) studied a steel production company in China, and their results indicated its unsustainability in the long run, due to the use of large amounts of nonrenewable inputs and a strong dependence on imports. The above literature shows that several scholars have only used the emergy accounting approach to investigate the steel production process from the perspective of environment and resources, or of environment and import. To systematically evaluate the sustainable development of the steel industry, it is necessary to look carefully at the broad interaction of resource use, trade, recycling and environment.

The present study aims to evaluate the impact of China's steel industrial chain on trade, resource utilization and environmental load as well as to optimize the sustainable development of key application sectors, where steel plays a major role. The novelty of this study can be summarized in three points: firstly, this work quantifies the multiple steps of the steel industry from a whole life cycle perspective; Secondly, the emergy accounting method is used to quantify the direct and indirect resources consumption in all processes of the Chinese steel industry chain, as well as to calculate emergy–based indicators capable to reflect the sustainability of China's steel industry under the three main dimensions, i.e. environmental performance, resource utilization and international trade. Finally, the recycling of scraps into secondary steel for use in the main downstream sectors is simulated, to design scenarios of potential improvements of the steel recycling rate in China. The contribution of this research moves beyond monetary value, and integrates it with environmental values, most often disregarded. And the results of this study provide a major reference for monitoring and orienting the production activities of relevant departments and enterprises in China.

Therefore, in this study we first built on previous emergy-based studies and then applied the emergy accounting approach to create a suitable set of indicators for the entire upstream and downstream chain of production and use. Then, we created scenarios based on different percentages of crude steel and recycled steel use, to discuss the environmental performances of selected downstream sectors. Finally, based on recycling scenarios and calculated environmental performances, we propose policies for increased sustainability of steel manufacturing and use in China.

2. Methods

2.1. Investigated systems and processes

Fig. 1 illustrates the diverse roles of the Chinese provinces (regions) within the steel industry. Considering that some provinces (regions) play several roles at the same time, this map indicates the most important role of each one in the supply–chain, as indicated by Tables A1–A4, which show the rate of the four roles in China in descending order per category. Colors in the map represent the main attribute of each province. The overview of China's steel industry chain and related information is therefore shown in Fig. A1 and Table A5.

2.2. Emergy Accounting analysis

Emergy Accounting (EMA) is a valuable method to evaluate the quantity and the quality of all direct and indirect inputs of resources required by production and recycling processes (Odum, 1996; Brown and Ulgiati, 2004a). It uses available energy (exergy) of one kind (in general solar) directly or indirectly required to generate a product or service, in units of solar emergy joule (sej). The amount of emergy to generate a unit of product or service is named UEV (Unit Emergy Value, sej/unit). Emergy of inflows and UEVs are calculated on the basis of the total annual renewable emergy driving the Biosphere, i.e. the latest Geobiosphere Emergy Baseline (GEB) estimate of 12.0 E + 24 seJ/yr (Brown et al., 2016). UEVs calculated with reference to previous emergy baselines have been updated or recalculated. This method evaluates the environmental impacts from the supply side (amount, efficiency, fraction renewable, imported resources, land demand, etc).

2.2.1. Accounting of indirect resource consumption in Chinese steel industry chain

During the processes of production, application, and recycling in the steel industry chain, focus is most often placed on consumption of direct use of material and energy resources, ignoring the importance and role of indirect use of resources, namely the free renewable resources supporting all processes in the biosphere. The main driving resources (solar insolation, geothermal heat, gravitational potential, named "global tripartite" by Brown and Ulgiati, 2016) in turn generate secondary and tertiary resource flows such as wind, rain, runoff, which have a huge role in environmental and economic processes providing a number of so–called ecosystem services (dilution of pollutants, CO_2 uptake and storage, temperature regulation, water purification, river water, topsoil formation and renewal, among others). Calculation procedures are described in Brown and Ulgiati (2016) while results related to the present study are shown in the Appendix.

Therefore, not only the free renewable resources contribute to material and energy resource generation, but they also converge to the development of economic processes, providing appropriate environmental conditions in each process step. As a consequence, upstream steps (starting from the global "tripartite") contribute to and are embodied into the next downstream steps, supporting the final product (s), depending on the interaction among upstream resource flows towards downstream processes. The detailed accounting processes and results are shown in Tables A6–A23.

2.2.2. Sustainability evaluation indicators in Chinese steel industry chain based on emergy

The emergy- based indicators according to processes is helpful to evaluate the development level of steel industry chain. Based on previous studies, we construct sustainability indicators, which are suitable for the steel industry chain, from the perspectives of trade, ecological environment and (land) resources. The detailed formulas, meaning and the perspectives are shown in Table 1.

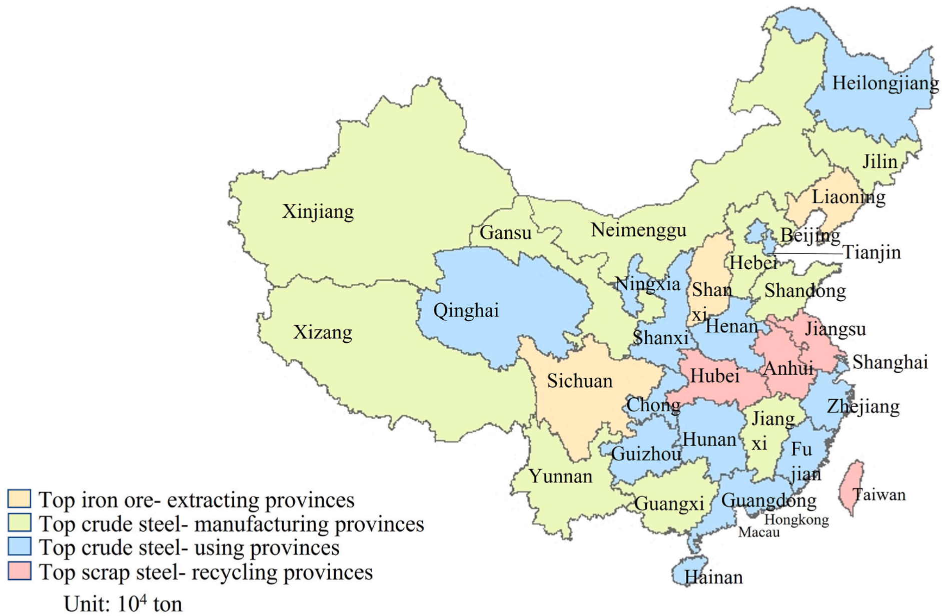

Fig. 1. Top iron and steel processing and using provinces (regions) in China.

Table 1
Description of different emergy indices involved in emergy analysis.

Indices	Calculation	Signification	Perspective	Reference
Emergy Benefit Ratio (EBR)	$\frac{Amount_{tradedresource}*UEV_{resource}}{Money_{paid}*EMR}$	Evaluates the relationship between imported resources in the environment and the economy	Trade	(Odum, 1996; Brown and Ulgiati, 2014b)
Emergy Yield Ratio (EYR)	$\frac{R+N+F+L\&S}{F+L\&S}$	Measures the ability of a larger system to exploit local resources	Self–reliance Equilibrium	(Odum, 1996; Brown and Ulgiati, 2004b; Santagata et al., 2020a; Santagata et al., 2020b)
Environmental Loading Ratio (ELR)	$\frac{N+F+L\&S}{R}$	Measures the potential environmental pressure pushing the system far from its natural equilibrium	Sustainability Renewability	
Emergy Sustainability Index (ESI)	$\frac{EYR}{ELR}$	Indicates the global performance of the system in using local resources compared to the environmental pressure exerted	Investment into economic system	
Renewable fraction of emergy used (%R)	$\frac{R}{R+N+F+L\&S}$	Indicates the proportion of emergy from renewable resources		
Product emergy money ratio (EMR_p)	$\frac{R+N+F+L\&S}{econvalueofproduct}$	Measures the total emergy investment needed to generate an economic unit value associated with the product (sej/$)		
Empower Density (ED)	$\frac{R+N+F+L\&S}{Area*t}$	Define the relation of emergy, land and time	Land constraints	(Brown and Ulgiati, 2001; Viglia et al., 2018)
Renewable Empower Density (RED)	$\frac{R}{Area*t}$		Renewable land Constraints	
Embodied land (EL)	$\frac{R+N+F+L\&S}{RED}$	Calculates the land virtually needed to support the intermediate or final product if the process were only based on renewables	Virtual land Associated to products	

2.3. Scenarios for a sustainable iron and steel future

To understand the environmental impact of steel production methods on the downstream steel sectors, we first assess the environmental performances of the different steps of steel production; then, we simulate the different production ratios of primary and recycled steel and assess the emergy performance of two downstream sectors, building construction and vehicle manufacturing, which are the largest steel consumption activities in China. Considering that the output of recycled steel in China currently accounts for only 11% of the total, we discuss the extent to which the emergy indicators of the two sectors change when the fraction of recycled steel moves from 11% to higher percentages. The assumptions and related information are shown in the section 3.3.

2.4. Data sources

The system boundary of the study is China's mainland, and its scope is shown in Table 2.

Considering that there are many steel-using sectors, we selected as downstream research objects the Housing and Vehicle sectors which,

Table 2
Processes and references for the steel industry in China.

Processes	References
Iron ore extracting and refining	Ma et al. (2018a), Norgate and Haque (2010) and Ecoinvent v3.1 database (Ecoinvent, 2014)
Pelletizing	Ma et al. (2018a)
Sintering	
Puddling	
Crude steel making	
Using steel in a main downstream sector (housing)	Tulevech et al. (2018)
Using steel in a main downstream sector (vehicle)	Ribeiro et al. (2007)
Recycling scrap to make steel	Zygomalas et al. (2020)

together, account for more than 70% of steel use. Data on product outputs for each stage of the entire production chain are from the Steel Yearbook 2018. In all these studies and data sources, the key inflows to steel processing and use are considered, including renewable sources, iron and steel products and labor and services. Most of the UEVs used in this study are from the UEV database 2018 by Brown and Ulgiati (2020) and from the National Environmental Accounting Database v2.0 (http://www.emergy-nead.com/home). UEVs of steel products at different stages are calculated in this study. Detailed data on the materials and energy used, and their corresponding UEVs are shown in Tables A6–A23.

2.5. Sensitivity analysis

Considering that the data for some steps have been taken from literature dealing with other countries, we conducted a sensitivity analysis of the key processes in this study. This paper uses one-step at-a-time method (Cho et al., 2016; Pan et al., 2020) to analyze the influence of different inputs on the emergy values of steel products.

The sensitivity analysis includes two parts. The first part discusses the influence of electricity on the steel industry. We increase or decrease the UEV of electricity in three processes (BOF, buildings and vehicles) by 3%, 5%, 10% and 20% respectively, in order to see the changes of Unit Emergy Values of primary steel (BOF), of steel for housing and of steel for vehicles. The results are shown in the Table A24. Comparing with the emergy value of the products, it is easy to see the changes are not significant, around 0.1%. The second part simulates the impact of using different fractions of recycled scrap steel on Chinese steel industry, especially the downstream key sectors. The contents of this part are shown in Section 3.3.

3. Results

3.1. Environmental assessment of the steel industry chain in China

An Energy Systems Language diagram of China's steel industry within the largest world system is shown in Fig. 2. The green-shaded diagram represents the extraction and production processes of China's steel industry, and the yellow-shaded diagram represents countries that export raw minerals to China. The diagrams show the storage of underground iron ore created by the environmental work of the biosphere powered over geological time by solar insolation, deep heat, and gravitational potential (marine and earth tides). The underground mineral is mined and lifted to the surface, where it undergoes a number of refining processes to yield intermediate products and primary steel (Basic Oxygen Furnace, BOF steel), given input flows of water, energy, machinery, and chemicals, as well as labor and services. China imports iron powder, pellets and sintered iron to supply its sintering and puddling processes (https://oec.world). The largest fractions of these raw iron materials are from Australia (61%), Brazil (24%), South Africa (4%) and a few other iron exporting countries. Upstream steps in the process transfer their intermediate products to the downstream ones. The BOF primary steel is then used as an input to several manufacturing processes and use sectors, crucial to the economy of the country. After use, steel scraps are returned back to recycling processes (Electric Arc Furnace, EAF) to yield secondary steel. The diagrams also show waste production and emissions, which are released back to the atmosphere and affect the global environmental network. The systemic picture provided by the diagrams helps create inventories for each production step, understand the environmental aspects of the process and calculate performance indicators for the entire production chain.

The detailed emergy inputs and outputs of mining and primary steelmaking sectors are reported in Tables A6, A8, and A13. Additionally, the emergy evaluation of "scrap recycling" with respect to

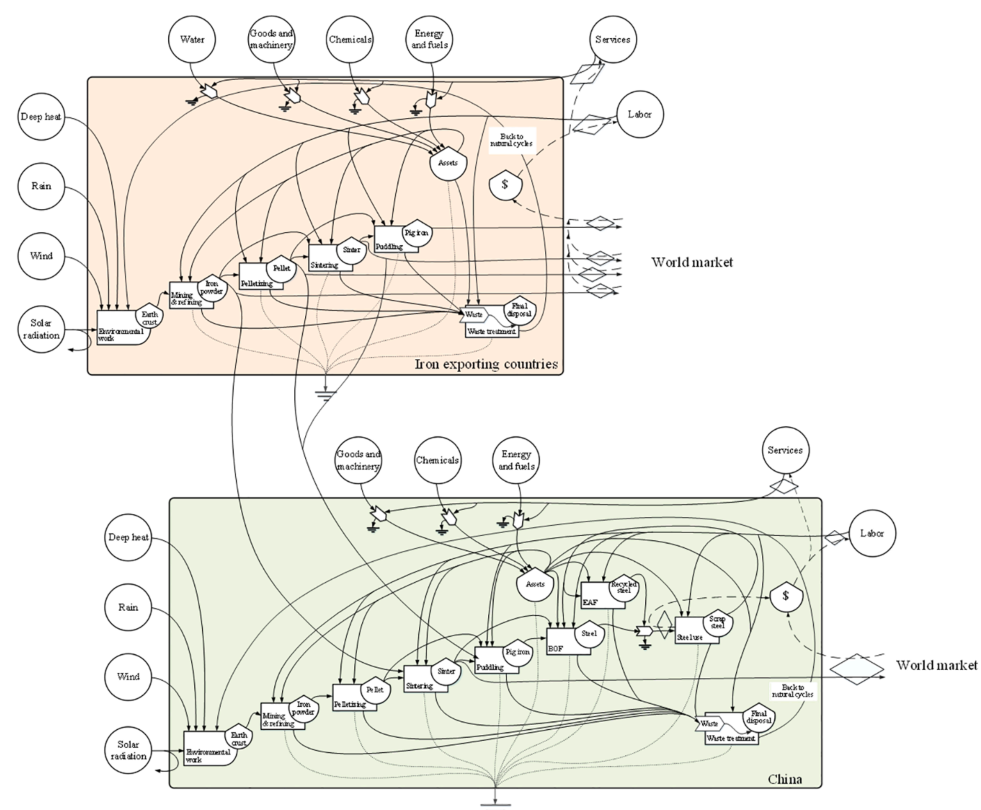

Fig. 2. Emergy system diagram of China's steel industry.

secondary steel making (EAF process) is shown in Table A15. Other process steps (e.g., sintering and pelletizing) and related footnotes are analyzed in Tables A9–A20. Each Table calculates the total emergy U supporting the process step under study and its associated UEV, which is a measure of process efficiency. UEVs are calculated with and without including the emergy associated with Labor and Services (L&S) to easily separate the emergy of raw resources from the additional emergy associated with direct and indirect labor, translating into infrastructure, countrýs global economy and know-how.

Fig. 3 compares the UEVs of the different process steps in China's steel industry. Values in Fig. 3 are based on calculation results with and without including the cumulative emergy of labor and services associated with all inflows (in the investigated step and cumulative from all previous steps). What is quantified as the emergy of labor in the *i-th* step is accounted for in the next step as the emergy of services associated with the intermediate product transferred from step i to step $i+1$.

During the process, the UEV of iron ore steadily increases over the production of intermediate products (Fig. 3), from a low 1.56 E + 15 sej t^{-1} of iron ore (with L&S) to a four times higher value of 5.75E + 15 sej t^{-1} of primary steel (BOF), also including labor and services. After that step, the UEV decreases in the production process of secondary steel (EAF) to a value of 4.00 E + 15 sej t^{-1}, lower than for primary steel, due to the assumption that the primary mineral circulates through two life cycles after mining, which halves the initial treatment costs allocated to each cycle. Further assumptions are made that input scraps for secondary steel have the technical quality of sinter product (i.e. the same UEV) and that recycling occurs more than once within the same technology time framework (e.g., 5 times for Vehicles (Held, 2021) and 2 times for Housing technology (Dara et al., 2019). More detailed information is shown in the Appendix). Of course, manufacturing requires additional emergy flows for specific purposes and characteristics, as well as L&S, which explains the increase of the UEVs in each step. Finally, a mix of primary and secondary steel is refined and manufactured and becomes the structural component of buildings and infrastructures, as well as of vehicles and other products. In these use processes, the UEV values are affected by the weighted average of primary and secondary steel components as well as by additional material flows to meet the technical requirements.

3.2. Assessment of trade, land resources and environment based on emergy

3.2.1. Steel trade assessment

According to Table 1, the EBR of iron powder import is:

EBR = 2.12 E24 sej/(1.87 E11 $/yr * 3.55 E12 sej/$) = 3.19

The result means that for each emergy unit (sej) sent out by China associated to payment for imported iron powder, approximately 3.19 sej are received by China as emergy of the iron powder. Even considering the uncertainty of this estimate at the country level (in this study, due to the use of 2014 data, the most recent available values) compared with iron imports in 2018, it is clear that the emergy benefit to China as a purchaser of iron is very high, very similar to other benefits gained by several countries that import primary resources such as food or fossil fuels (see Argentina vs worldwide trade of maize, Rotolo et al. 2018; Ecuador vs USA shrimp trade, Odum, 1996; and USA vs worldwide trade of fossil oil, Odum, 1996). This finding confirms previous results from Tian et al. (2018) about losses and gains in China's foreign trade.

3.2.2. Land resource assessment in the China steel industry

Table 3 reports indicators concerning emergy concentration and virtual allocation of land to process steps investigated. The ED indicator, calculated according to Table 1, expresses the emergy per unit direct and indirect land related to each step. Moving from a step to another the total emergy increases, but the total land occupied also increases at different rates, so that ED most often decreases, indicating a decrease of the emergy concentration, except for both downstream use sectors. The Embodied Land EL_i indicator is calculated as the ratio of total emergy use at the i–th step and the average Renewable Empower Density of China, also according to Table 1, as if the entire emergy demand should be covered only by means of renewable emergy. Of course, the more emergy is used for the process, the more direct and indirect land would be needed to run the process if based on renewables, except when recycled steel is produced. In the latter case, land is virtually used more than once, and in particular no additional land for extraction is needed. Understanding how environmental resources concentrate step-by-step allows identification of the most resource-intensive steps and helps design innovative patterns within the process chain. Moreover, by identifying embodied land EL_i demand based on land-related, the emergy assessment allows land use planning and appropriate constraints on economic activities to move towards sustainable land use. For the sake of clarity, if a BOF steel plant imports raw materials from previous steps together with other needed resources (electricity, water, and fuel)

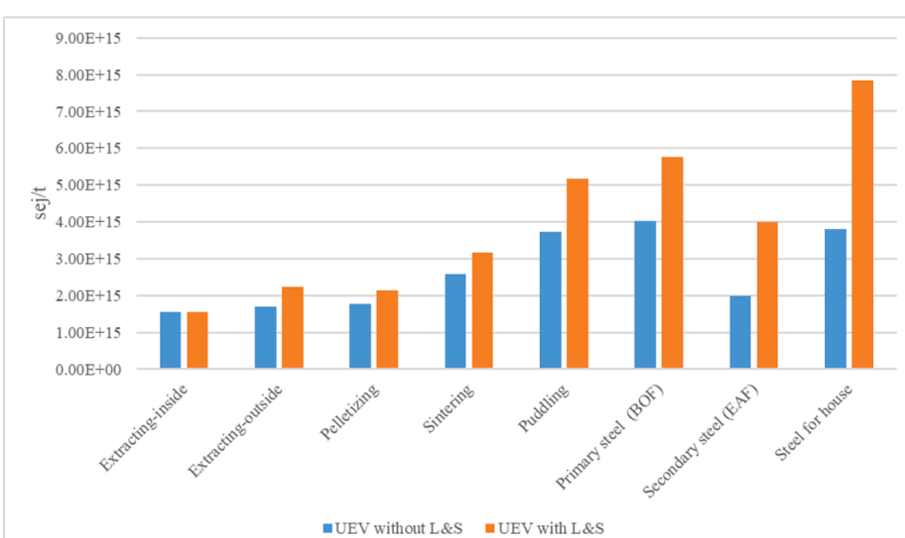

Fig. 3. UEVs of iron and steel making processes, with and without L&S.

Table 3
Empower density and embodied land indicators in China's steel industry.

	Extracting	Pelletizing	Sintering	Puddling	Primary steel making (BOF)	Scrap recycling (EAF)	Steel for housing sector	Steel for vehicle sector
ED (sej/yr* m^2)	4.46E + 15	2.06E + 15	1.29E + 15	5.49E + 14	5.31E + 14	4.93E + 14	9.86E + 14	7.18E + 14
EL_i (m^2)	3.59E + 13	6.17E + 12	5.12E + 13	5.77E + 13	6.22E + 13	4.28E + 12	6.49E + 13	1.97E + 13

from the rest of the economy, its final product (BOF steel) embodies labor, land, renewable and nonrenewable emergies, which affect the emergy density and embodied land demand.

3.2.3. *Environmental performances of steelmaking steps*

The calculated emergy indicators of the investigated process is always related to the upstream industrial processes (always including the emergy associated with Labor and Services, to also account for the environmental support from large scale infrastructure and associated know-how) (Fig. 4). All indicators are referred to the nationwide area involved in the investigated and upstream process steps to allow an appropriate comparison among the steps, as well as among other industrial processes.

Fig. 4a relates to the reliance of each process step on local resources. As always in raw material extraction activities (minerals and fossil energy), the process makes a large amount of emergy available in the form of iron minerals at relatively low extraction cost. Instead, the steps after extraction may require much more investment for refining and processing. As a consequence, the extraction step shows high benefits (high EYR) because a small investment from human technology allows the exploitation of the huge work of nature over millions years to generate the underground stored resource. After the raw resource is extracted, at least a comparable amount is needed in the form of electricity and machinery to process it to a form that is usable in the rest of the economy. This lowers the EYR step-by-step, as it can be generally expected for a transformation process. Acquiring raw resources with high EYR is beneficial for an economy because it is the starting point of manufacturing activities and added value. Instead, purchasing manufactured goods very likely requires a huge monetary compensation for the additional resources required in the processing, especially L&S, which decreases the benefit to the purchaser.

Fig. 4b shows the ELR (Environmental Loading Ratio) in each step of the manufacturing chain. ELR indicates how far a process is pushed from the environmental equilibrium of nature. In fact, fully natural processes only use locally renewable resources and their ELR is equal to 0, according to Table 1 formula. The higher the ELR, the higher the distance of the investigated process from environmental equilibrium. The use of locally nonrenewable and imported emergy flows compared with the renewable emergy available locally causes a large displacement from environmental equilibrium. In Fig. 4b, as expected for a heavy industrial process, the ELR is always very high (a logarithmic scale is used to allow comparison of the extraction step with the following ones). Calculations refer to the renewable emergy available over the entire area involved in the process: step by step, N + F + L&S emergy increase, and the involved area also increases, which dilutes the pressure and lowers the calculated ELR. Fig. 4c shows the environmental sustainability (ESI, the environmental benefit per unit of environmental cost) to be very low, as expected, being that iron and steel are nonrenewable products processed by investing nonrenewable resources. The low percentage of renewable emergy involved in the processing steps is shown in Fig. 4d. The larger the involved area, the larger the renewable emergy (sun, wind, deep heat) supporting the process. However, this advantage is offset by the nonrenewable investments needed for the process to occur. Therefore, the percentage of renewable resources associated with the area where the process develops is always very small compared with other flows. It appears slightly higher in EAF because when dealing with recycled materials the nonrenewable emergy of extraction and premanufacturing decreases and is smaller for every new recycling cycle.

Fig. 4e and f show, respectively, the Empower Density (decreasing in the downstream steps, due to the larger area involved) and the EMR_p, the emergy investment associated with one unit of economic value generated in the process, which also decreases in downstream steps indicates improved economic performance for the same investment. Both values can be compared with the country's ED and EMR to understand the environmental position of investigated iron and steel processes within the national economy (most recent 2014 values are available at NEAD, 2020, http://www.emergy-nead.com/country/data).

3.3. *Scenarios for the downstream steel sectors*

In this study, we first calculated the UEV and performance indicators of the EAF process, assuming a 100% inflow of iron and steel scraps as raw material to be converted to secondary steel. However, the calculated UEV value depends on how many times the same material undergoes the conversion from scrap to secondary steel, which, in turn, affects the allocation of mining and refining costs. This process depends on the nationwide effort to implement the collection and conversion of scraps. In the calculation of the UEV of EAF steel, we assumed that secondary steel is made by recycling scraps only once, which is a very conservative estimate. Mining and refining emergy costs are thus allocated to two output flows, steel production from sinter first and then the steel production from scraps. At the present rate of recycling steel in China, only 11% of total annual steel production is recycled, which means that most of the BOF steel produced annually is dispersed, landfilled, or stored without undergoing any recycling. Our conservative estimate of the UEV of EAF steel is thus only applicable to a small fraction of steel in China. The amount of secondary steel produced poses a constraint to the fraction of secondary steel that can be used in the main steel-using sectors, namely, in vehicle and building production. Simulating increasing use of secondary steel in these sectors entails also advocating increased efforts for scrap collection and processing and generates lower primary emergy demand and UEV estimates. Since the rate of nationwide recycling depends on regulatory and market dynamics and since steel-using sectors may not be characterized by the same use rate of secondary steel, some uncertainty must be considered in the generation and interpretation of scenarios related to the use of recycled steel in vehicle and building production.

Fig. 5 shows to what extent the UEV values (i.e. the environmental efficiency) of steel used in the two selected downstream sectors (Vehicle and Housing) may change when the percentages of secondary steel use increase. As noted above as well as in the Methods Section, this depends on the number of turnover cycles occurring in the nationwide steel industry which, in turn, is affected by the general recycling policy of the country, as well as on the fraction of secondary steel use within the specific sector investigated, which is affected by technological choices. When the proportion of scrap steel reuse increases, the UEVs of the steel used in the two investigated sectors decrease, with different rates depending on whether L&S are included. According to Fig. 5, when the emergy of L&S is not included, the UEVs are approximately 50% smaller (as expected with L&S) and the values related to the Housing sector are smaller than for the Vehicle sector, except for EAF use rates higher than 80%. At such rates, the Vehicle sector shows lower UEV values (i.e., lower demand for resources per unit of steel used) than the building sector. When L&S emergy is included, its importance becomes

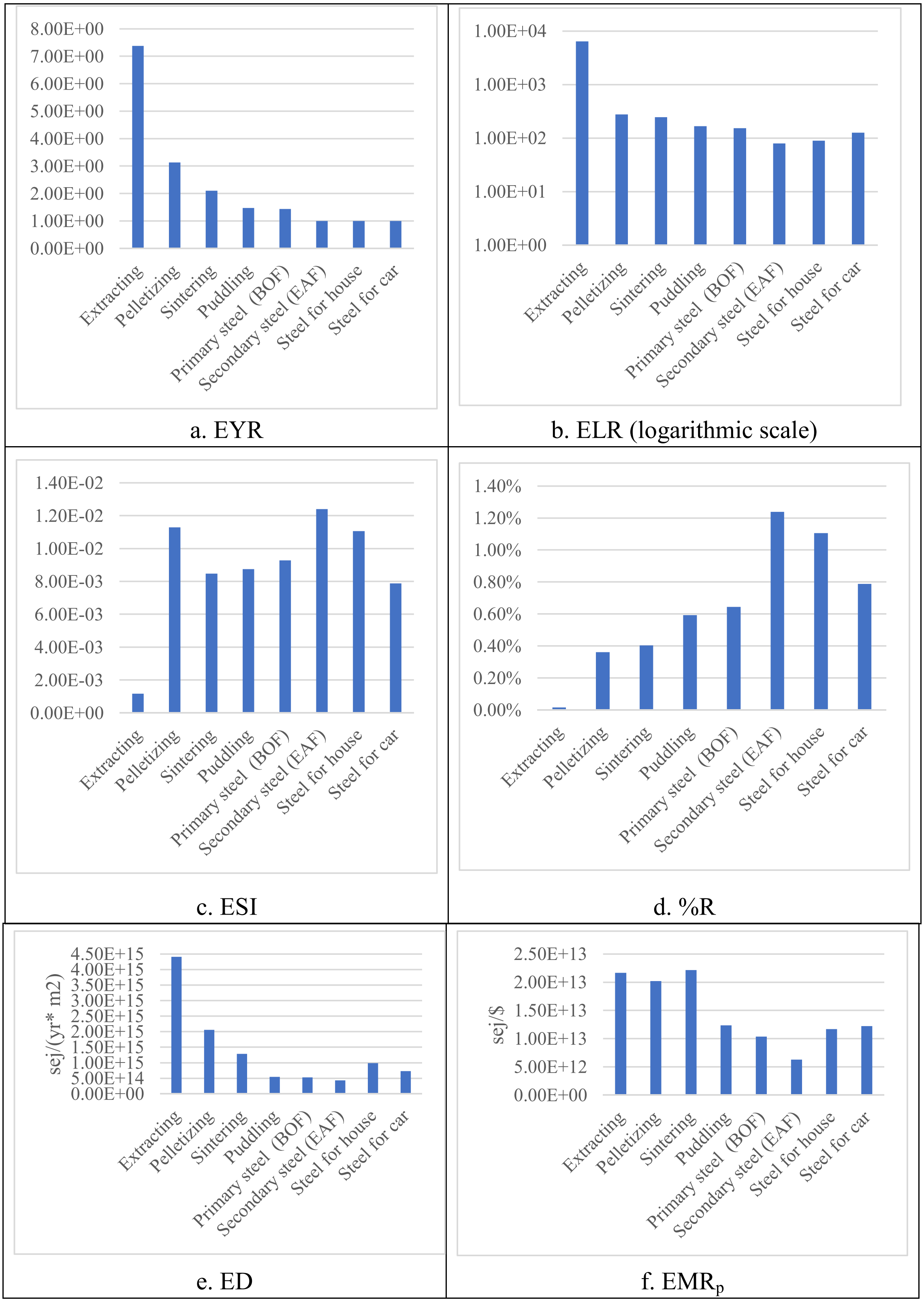

Fig. 4. Emergy indicators with L&S for processes of China's steel industry.

overwhelming compared with UEVs without L&S, which indicates a large contribution of the resource cost of infrastructure and know-how associated with the global functioning of these sectors. Moreover, considering that L&S is calculated from direct and indirect labor, it appears that these flows are considerably higher for the Housing sector than for the Vehicle sector.

Fig. 6 shows the trends of other emergy performance indices when the proportion of scrap steel recycling increases. Appropriate understanding of these trends requires a look at the numerical values, the relation to trends in other sectors, the relation to the nationwide values

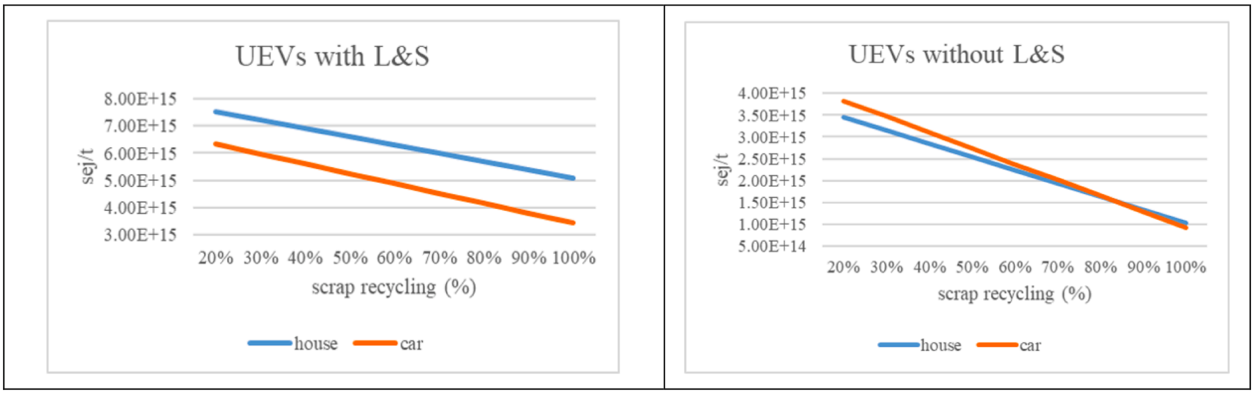

Fig. 5. UEV of total steel used in the Vehicle and Housing sectors (with and without L&S).

for the country's economy (most recent 2014 values are available at NEAD, 2020, http://www.emergy-nead.com/country/data), and consideration of the factors that affect each sector such as efforts for nationwide collection and recycling of scrap steel; the number of turnover cycles in each sector and the acceptance of secondary steel by different sectors depending on their quality requirements). The EYR is not reported in Fig. 6, since it́s always equal to 1 for both sectors as expected for technological conversion processes, whereas it is always approximately 2.0 for the Chinese economy as a whole. As observed in Fig. 6a, the ELR is always higher for the Vehicle sector than for the Housing sector, although both sectors decrease following the increased rate of secondary steel use and reach approximately the same value when the use rate approaches 100%. The higher ELR (between 60 and 120) associated with the Vehicle sector is due to the additional inflows needed for vehicle manufacture and includes higher L&S appropriate for such a highly-technological sector (for reference China's 2014 ELR is 45). As a consequence, the sustainability indicator (ESI, Fig. 6b) increases in proportion to the increased use of recycled steel, but remains in a very low range (0.009 to 0.017). However, it shows a better performance for the Housing sector which is still lower than the China's average ESI of 0.044. No hope exists to detect a high renewability for these sectors (Fig. 6c); both are heavily reliant on fossil fuels and minerals with renewable fractions that range between 0.008% and 0.017%, which is lower than the average %R of 0.022% for China. The emergy intensity of the product (i.e. emergy use per unit of monetary value associated to the product), EMR_p, is very high at low recycling rates and decreases with increasing rates of secondary steel use (from approximately 11 E + 12 to 5.5 E12 sej/$, Fig. 6d), although it never approaches the country's value of 3.55 E + 12 sej/$. Embodied Land, EL, associated with total steel use in the two sectors (Fig. 6e), ranges from 1.0 E13-2.0E13 m^2 for the Vehicle sector to a high 4.0–6.0 E13 m^2 for the Housing sector, which translates into a potential range of 1.0–6.4 times the total land area of China, which would be required if the process were powered by renewable resources only. For this result, it should be noted that the lower EL value is equivalent to use of the entire surface of China to collect renewable resources in support of fully recycled steel production in the Vehicle sector only. Although this estimate is equivalent to a virtual land demand, such a result is alarming, especially if coupled to similar estimates about other economic activities, and raises questions about the long-term sustainability of the Chinese (and World) economy. Finally, the Empower Density declines (in the range 9.5 E14-3.0E14 sej m^{-2} s^{-1}), although its value is considerably higher than the country's 3.17 E12 sej m^{-2} s^{-1} (Fig. 6f). In other words, the value of Empower Density (ED) remains higher than the average of ED value of Chinese economy. It means that the steel industry uses much more concentrated emergy over a small land than the entire economy of China.

4. Discussion

4.1. Sustainability of the Chinese steel industry chain

4.1.1. Extraction, refining and beneficiation of iron ore

A resource input to the economy depends on the investment needed to extract it and to make it available to the next economýs steps for further processing. Resources are available in limited quantity (some are more abundant than others) and concentration, which may require large-scale efforts for extraction and processing. The generation time of iron ore via geological processes affects the turnover time of the resource and consequently its availability and renewability. The emergy approach expresses these characteristics very clearly. In terms of emergy indicators, this translates into two main indices: UEV and %R. For iron ore, in Fig. 3 the UEV at the extraction site is approximately 1.5–1.7 E15 sej/t, with very little contribution from L&S, whereas the %R is, of course, negligible (0.0002%). For comparison, fossil oil at the extraction site has a UEV of approximately 5.79 E15 sej/t (Brown and Ulgiati, 2001) and similarly negligible renewability. Instead, the UEV of industrial paper production ranges between 2.95 E15 and 4.48 E15 sej/t depending on the wood used and shows a %R of approximately 35% (Corcelli et al., 2018), while the UEV of mais has different estimates in different places, but it is approximately 0.5–0.7 E15 sej/t dry matter and has a %R range of approximately 15%-30% (after Rótolo et al., 2015). All the above UEVs are reported without L&S. Of course, the addition of L&S increases the UEV value and captures and incorporates further societal costs of the global and of the country's economy. UEVs clearly express the environmental production cost of a raw resource and/or manufactured good and thus suggest the supply-side quality of products and a renewability based on environmental production patterns over the entire supply-chain. The emergy of production costs and renewability of production carry a quantification of value beyond, although not fully replacing, monetary market value.

4.1.2. Step-by-step assessment of the production of intermediate and final iron products and primary steel

We have investigated the entire supply chain of iron and steel products, including sinter, pig-iron, primary and secondary steel, as well as steel adjusted to specific uses (vehicles and buildings). Not only results help quantify the most resource-demanding steps and specific inflows, but improvement options and potential resource recovery or recycling could also be identified step by step. Fig. 3 clearly shows an increase of the UEVs and proportional changes of the related performance indicators in each step from mining to BOF (primary steel, Blast Oxygen Furnace), a decrease of UEV when secondary steel is produced from scraps, and a new increasing trend for the transformation of steel used in specific applications (i.e., Vehicle and Housing sectors), primarily due to additional materials that are added to complement the properties of steel for these uses.

Fig. 6. Trends of the main emergy-based performance indicators of Housing and Vehicle sectors according to increased recycling.

4.1.3. Steel recycling and increased use of secondary steel and replacement materials in the economy

Fig. 6 points out the effects on the emergy indices of increasing rates of scrap recycling. Although increasing recycling provides better performance indicators, the latter keep showing results that cannot be identified as “sustainable”, being almost fully based on the use of nonrenewable energy and materials. As a consequence, being aware that it is very difficult to even think of a future without steel in several important sectors (such as vehicles and mobility infrastructure), supply-chain and scenario indicators suggest efforts aimed at increasing collection and recycling and, at the same time, limiting iron and steel use to unavoidable options. Research for replacement alternatives is in progress (e.g., mass timber buildings, Yale University, 2020; increased use of graphene, Nature 2020; bamboo reinforced concrete, Bamboo-TECH, 2020; Vogl et al., 2021).

4.1.4. Upstream and downstream environmental aspects of the steel supply and use chain; the added value of the emergy approach

Most often assessments of environmental aspects are limited to CO_2 or emissions of toxic chemicals, as well as water use. These are important assessment results that should not be disregarded and indeed provide a valuable understanding of the environmental impacts of iron and steel production and use in several impact categories (Global warming Potential, Human and Eco-toxicity, and Freshwater Eutrophication, among others) (Liu et al., 2019; Liu et al., 2020). However, the added value of the emergy evaluation performed in the present study relies on the awareness that any economic activity is supported at larger scales by the biosphere’s work to generate resources (and replace the ones depleted), as well as by the global country’s efforts to allow the economic activities in each sector (infrastructure, research and education, health services, mobility, administration, environmental care), measured by the emergy value of direct and indirect labor. Lack of awareness of this large-scale support and related environmental evaluation is equivalent to thinking that any specific economic activity can be developed independently of interaction with external societal structures and organizations, as well as global environmental integrity, which is not true and cannot be disregarded. This study adds a quantification of the past and present, upstream and downstream ecosystem work to replace resources, provide clean air and fresh water, and support food production and labor, among other environmental services. This kind of assessment is expressed in emergy performance indicators, which include the large-scale picture surrounding the specific process under study. Awareness of this reliance on the much-needed biosphere work for resource turnover as well as environmental functioning and integrity in support of economic dynamics and human life is crucial and pushes business, policy, and society to select sustainable production and consumption patterns and technologies. EMA results, similar to those summarized in Fig. 3 to Fig. 6 regarding the iron and steel supply chain, place an environmental value on resources and commercial goods that calls for and promotes responsible choices.

4.1.5. Direct and indirect labor and associated social and economic costs

Direct and indirect labor is, of course, an important factor in any economic and production process. This factor is important not only because of the monetary cost of work force, which can be low or high depending on international and national market factors, but also because of other factors affecting the environmental cost of direct and indirect labor. In fact, other factors behind direct and indirect labor play important roles. Workers must be able to eat, purchase goods for their life, support their families, and move from living to working places; educated labor requires investments over the entire school and university system to develop skills, technological know-how and scientific information; and labor is required in any sector of the economy and resources supporting labor thus cannot be disregarded (Da Niel and Lu, 2014; Ulgiati and Brown, 2014a). In other terms, it takes emergy to support labor and labor to support society and the economy. Fig. 3 clearly shows much higher UEVs when L&S are added to the evaluation as crucial input flows of emergy resources. Moreover, the difference between UEVs with L&S and UEVs without L&S becomes increasingly larger when approaching the final steps (BOF and EAF) or the important steel-using sectors. The emergy assessment of labor and services provides a more comprehensive measure of the role of infrastructure, lifestyles, know-how and information in economic processes, compared with more process-specific input flows of fuels, materials, goods and machinery. Countries that promote high-quality education levels, and thus economic processes based on highly educated labor, are more likely to develop wealth and well-being. Production processes are based on fractions of highly educated, expensive labor and fractions of less educated, cheaper labor: economies that disregard the value of labor and the needed investments for it are less likely to be stable and sustainable.

4.1.6. Aspects of trade for raw resource acquisition and manufactured goods marketing

China imports iron powder with an Emergy Benefit to the Purchaser of approximately 3.2 to 1, which is an important factor for China's economic growth coupled to other beneficial imports. In contrast, China is increasingly using its rare minerals internally to develop its own economy, instead of selling them abroad and thus losing economic development opportunities. For the iron and steel trade, due to its relatively high EBR, imported iron has the potential to drive the economic processes of China without returning large amounts of emergy to the countries where the iron comes from. Exporting countries most often sell primary resources at low cost because of the low cost of the extraction process and because they do not need to invest for primary resource production. In so doing, governments of exporting countries have the impression, under market pressure, that they are benefiting from primary resource export, which disregards the most important imperative to process resources at home to develop jobs and sell manufactured goods to generate higher income. This is why some countries become richer and richer and other countries remain poor or face a very slow development. It is evident that the emergy balance in trade makes a very crucial contribution to stability and well-being. Tian et al. (2018), after assessing the emergy benefits and costs in China's trade worldwide, suggest that a more balanced trade can be achieved through compensating primary resource-exporting countries by returning to them know-how, education, information, and services for increased well-being, instead of looking for the hard-to- achieve monetary balance of market prices.

4.1.7. Assessment of the contribution and environmental/economic sustainability of the iron and steel sector within the entire country's economy

While China benefits from iron imports (EBR = 3.19) and steel use in support of its technology and economic processes, there is no doubt that steel processing requires huge investments that might instead be allocated to other economic sectors and perhaps provide more profitable alternatives. This is suggested by Fig. 4a, with EYR quickly declining from a relatively high of 7 to values slightly higher than 1 for the BOF and EAF sectors and equal to 1 in the Housing and Vehicle production sectors. In general, the consumption of a large number of nonrenewable resources requires China to invest more money for imports or to degrade domestic resource-rich areas through extraction, which is not conducive to the sustainable development of the national economy in the long-term. In addition, the use of large amounts of coke, limestone, metal powders (such as high magnesium powder), electricity and fuels makes the emergy cost of steel production significantly increase, especially for sintering and puddling, which lowers the EYR and other performance indicators. All in all, while it is undeniable that iron and steel have played and still play an important role in the development of the Chinese economy, this occurs at the expense of other sectors that could provide similar or even better alternatives for the use of resources. It may be time to gradually move out of the steel-based economy and move to innovative materials (such as the above-cited graphene and high quality wood) and processes less reliant on nonrenewable resources. The strong commitment of China to develop a circular economy is an important starting point for this change.

4.2. Scenario analysis of downstream steel sectors

Figs. 5 and 6 focus on important aspects of two main steel using sectors of the Chinese economy, Housing construction and Vehicle manufacture, with scenarios that depend on an increased rate of steel recycling. When the proportion of steel scrap recycling changes, the environmental and economic sustainability indicators of the housing construction industry and the automobile manufacturing industry significantly improve. Tables A17 and A19 show in detail that the performances of the Automobile manufacturing sector and Building construction sector are very dependent on a variety of factors (labor, other input materials, land demand) that do not always generate the same relative ranking of the two sectors. A careful evaluation of each indicator for both sectors is thus needed for a deeper understanding. Unfortunately, most of the calculated and compared indicators of these two sectors, although showing undeniable improvements according to increased recycling, cannot hide the fact that iron and steel are nonrenewable materials that affect the economy similarly to fossil fuels. Just for the sake of clarity, Fig. 4 shows that the average EMRp (the emergy cost per unit of value generated) of primary steel (BOF), approximately 1.0E13 sej/$, is much higher than the countrywide value of 3.55 E + 12 sej/$, and the same occurs for the Housing and Vehicle sectors, with approximately 1.2–1.3E13 sej/$. A better result is achieved if the fraction of secondary steel increases up to 100%, which results in an EMRp of 6–7 E12 sej/$ (Fig. 6d), although this is still higher than for the country's level. 100% recycling may appear a dream and unlikely to fully occur. Before reaching a full recycling, steel may more likely be replaced by new materials or new technologies or new lifestyles.

Compared with the same indicators calculated for the Chinese economy as a whole, most of the results have shown that the iron- and steel-based sectors perform worse than the large scale economy, which calls for much needed improvements. Once again, the issue is not to deny the benefits achieved but to identify alternatives that gradually lead China towards increased use of less emergy-intensive materials, increased circularity and more renewable resource use.

4.3. Policy implications

To improve the sustainability of the Chinese steel industry and ecosystem integrity, some important strategies are suggested:

1) In order to decrease the environmental cost and promote long-term economic development in China's steel industry chain, iron and steel enterprises must be encouraged and supported to use more scraps to produce secondary steel. Considering that the cost of iron ore is most often lower than that of scraps (Omura et al., 2016), the Government could decrease the tax burden on scrap steel and goods manufactured with recycled iron and steel. Promoting an interactive and mature scrap steel recycling system may also play an important role in increasing scrap collection and use. In addition, the Government, the administrative regional authorities and departments could increase investment in favor of research and adoption by iron companies and towards less resource demand and less polluting technologies in iron ore extraction and processing. They could also implement policies to increase the awareness of populations and operators of "Green Mine" opportunities such as developing new sustainable technologies.

2) In order to decrease the embodied land demand by the steel sector, as well as other industrial activities, it is necessary to increase the resource efficiency in each step as well as to increase the fraction of renewable resources in intermediate processes, especially in the steel production phase. Limiting the demand of fossil fuels and encouraging the use of renewable electricity sources, as well as the use of heat to address the energy needs of steel processing would help decrease land demand and improve other performance indices. This change might be achieved by decreasing the cost of renewable energy and by providing support to production sectors to go beyond traditional fossil fuels, especially coal.

3) To improve the environmental performance of the downstream sectors (Housing, Vehicles, Infrastructure), it might be a good choice to decrease the use of steel in these sectors. Research on alternative materials for Housing, Vehicles and other downstream sectors may improve the environmental and economic performance of the Chinese Industrial and Household sectors.

4.4. Innovative aspects

It is nothing new to underline the environmental impacts of economic activities. What is needed is generating an increasing awareness of the extent economic activities are supported by the work of biosphere, in generating resources and providing environmental services, thanks to which activities develop and grow. If this large–scale support is ignored, the environmental integrity will also be disregarded. The emergy method used in this study to evaluate the steel industrial supply chain is appropriate for the task of identifying and quantifying the biosphere support across time and spatial scales. Emergy indicators are very telling in this regard and promote wise and informed policy choices. Within such comprehensive assessment, direct and indirect labor (services) play a crucial role. It takes emergy to support labor (education, information, know–how, societal infrastructures, food, housing and so on). Most approaches such as LCA and Material Flow Accounting, although very useful for environmental assessment, disregard labor and assign to the economic disciplines the task to quantify labor, in monetary terms. Emergy quantifies labor and services depending on their resource demand for all the aspects of human life of which labor is a co–product and which monetary assessments do not capture properly.

Trade is another very important factor in evaluating the relation of resources and economic growth. Some countries are rich with resources that play an important role in industrial development (rare earths, iron and steel, copper, among others), while other countries are not. Economies use monetary values determined by market oscillations to regulate "fair" exchange of resources (terms of trade, willingness to pay), in so contributing to worldwide wealth disparity. The emergy approach quantifies value according to the biosphere work needed for resource generation, processing and supply, in order to put resource exchange on an equitable basis. In this paper we show the emergy benefits (i.e. the support to the importing economy) associated to primary resources, in order to overcome and integrate the monetary evaluation. This is a fundamental contribution to environmentally and socially concerned policy–making as well as to global trade stability. When resources are valued in environmental terms, their forthcoming scarcity appears more evident and options of circular economy (i.e., designing processes in order to extend resource life and decrease impacts from extraction) can be better understood and promoted.

5. Conclusions

To comprehensively evaluate the Chinese steel industry and identify the sustainable development of its key application sectors, it is necessary to study the production and application processes from the perspectives of environmental performance, international trade, and land resource utilization. This research first used Emergy Accounting to calculate the environmental performance of the steel industry chain. Then, we created Emergy-related indicators based on previous studies to assess the sustainability of the environment, trade, and land resources from the perspective of life cycles. Finally, scenarios were designed for sustainability improvement in selected downstream sectors when considering different proportions of primary and secondary steel.

The results show that the steel industry places a huge load on the environmental performance of the Chinese economy as a whole, due to high resource demand in all steps of the supply chain. Steel scraps recycling improves sustainability, although this effort might not be sufficient, considering other nonrenewable and high emergy intensive resources involved in the process. Second, the Chinese economy is largely dependent on iron powder imports from abroad, which places a limit on China's self-reliance to supply this crucial industrial material. However, the emergy evaluation of Chinese trade highlights that emergy imports are much higher than the emergy exports associated with the iron trade. Larger scale unsustainability of iron markets worldwide may produce unexpected international changes due to the development necessities of primary-resource exporting countries and the consequent decrease of the present profitability to China, which potentially affects other sectors of trade and the economy. Third, the steel making sector has a large demand for land, because a large amount of land is indirectly and directly needed in resource acquisition and processing, which thus decreases the available land for other economic activities. The huge land demand mainly comes from downstream use phases, especially the Housing and Vehicle sectors. Finally, for downstream application sectors, improving the recycling and reuse of scrap steel will significantly improve their environmental and economic performance, especially in the Vehicle sector. The sustainability problems linked to raw resource availability, environmental performance of the steel industry and overwhelming virtual land demand highlighted in this study suggest urgent efforts towards scrap recycling in a circular economy as a transition solution and gradual replacement via innovative materials as at least partial solutions towards a "beyond steel" economy. In conclusion, the use of the emergy evaluation method offered a valuable way to go beyond monetary evaluations over the entire steel supply chain. We do not claim that monetary evaluations are useless, but point out the need for integrating them through environmental aspects that help prevent misuse of important resources and redirect trade and technological research towards fair and innovative solutions.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2021.108011.

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