A Review on Embodied Carbon Reduction Strategies of Iron and Steel Building Products

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Abstract
Whilst the operational carbon emission of building continues to attract significant attention, the embodied carbon emission of building materials receives increasing attention in both industrial and academic fields. Iron and steel are very popular building materials in modern construction and they are among the most carbon-intensive building materials. In recent years, numbers of studies have been conducted to disclose the embodied carbon emission of iron and steel building products and explore the possible carbon reduction strategies. This study aims for discovering the status quo and features of the available carbon reduction strategies of iron and steel building products through an review on existing literatures. Numbers of reduction strategies have been identified through a broad review of research articles and subsequently been systematically analyzed. Results of this study reveal that alternative fuel & renewable energy, alternative ironmaking processes, alternative reducing agents, carbon capture and storage, waste gas recovering, are key measures to achieve low-embodied-carbon iron and steel building products. In many cases, the carbon reduction strategies work cooperatively to achieve maximum performance. Alarmingly, the impacts of policy drivers, and management measures such as a thorough life cycle analysis of manufacturing process and use of local raw materials have been overlooked in most researches. The challenges and barriers of implementing the reduction strategies have also been discussed in this research.

Keywords
Carbon emission reduction strategies, embodied carbon of building, iron and steel building products

1 Introduction

The building sector puts the most environmental pressure on the earth. It is among the sectors that consume most energy and generate most carbon emissions (Praseeda *et al.*, 2016). In the European Union (EU), buildings are responsible for 42% of the energy consumption and 35% of greenhouse gases (GHGs) predominantly carbon dioxide (EC, 2011). Early researches in the field of building carbon footprint have put their emphasis on the operational emission reduction, as the operational emission accounts for the largest part throughout building lifecycle. With the growing application of energy efficiency measures, the proportion of operational energy has been considerable reduced in recent years. As a result, the research focus has been gradually shifted to the reduction strategies of embodied carbon of building. The biggest proportion of building embodied carbon is the building material embodied carbon, i.e., the carbon emissions related to production of building materials (also called "cradle-to-site" carbon emission). In some European countries, the manufacturing of building material generated around 10% of the nations' total carbon emissions (Gielen, 1997). Among the numerous of building materials, iron and steel products are ones of the most commonly used and ones with the largest carbon intensity. Researches have proved that, structural materials i.e., concrete and steel, have the largest carbon emission shares in modern construction (Oma, 2018; Wen *et al.*, 2015; Kua and Wang, 2012).

The demand of global crude steel is predicted to be increased by 122% by 2050 (IEA, 2009). Being one of the industry sectors that have the most energy and carbon saving potential, iron and steel industry has the obligation on carbon reduction. Therefore, in recent decades, increasing number of researches have been conducted aiming for mitigating the embodied carbon of iron and steel products. In spite of the increasing researches on this topic, very limited studies have been conducted to systematically review the available results of them. Quader *et al.* (2015) comprehensively reviewed the breakthrough technologies for improving the energy efficiency and carbon emission of iron and steel manufacturing. Ren *et al.* (2021) reviewed numbers of carbon reduction technologies and estimated their reduction potential through integrating the results of the reviewed studies. Quader *et al.* (2015), Quader *et al.* (2016) and Ren *et al.* (2021) have also provided cost analysis of the carbon reduction strategies. These review articles focused on the emerging technologies applied during the manufacturing of iron and steel products. Unfortunately, very few of them mentions the importance of management and political measures. Besides, these review articles did not provide a holistic review of the carbon reduction strategies throughout a cradle-to-site boundary.

Therefore, this paper holistically reviews the relevant existing researches with an aim to identify the carbon reduction strategies of the production routes of iron and steel building products within the cradle-to-site boundary. Through a systematic analysis of the reviewed research results, this paper summarizes the status quo and features of the existing carbon reduction strategies applied in the manufacturing of iron and steel building products. The limitations and barriers of implementing the reduction strategies have also been discussed. The findings of this study will form part of the contribution to the body of knowledge and also help the industrial practitioners in the relative fields to improve their environmental strategies.

2 Methodology

This study begins with a search of peer-reviewed journal articles in the relevant field. The search results only consider the articles published in the latest 10 years because it is a rapidly developing research topic. This reviewing study focus on the low-carbon (energy efficient) strategies applied in production of the iron and steel building products within the cradle-to-site boundary. Keywords are proposed to be searched across a commonly recognized literature database i.e., Science Direct. The following keywords and combination of keywords were searched in the literature database:

- Iron and steel building products
- Embodied carbon/CO_2/GHG/energy
- Carbon/CO_2/GHG mitigation/reduction
- Energy efficiency
- Ironmaking and steelmaking

The titles of more than 400 peer-reviewed journal article were identified falling within the keywords area. After an initial scrutiny of abstracts, 46 representative articles were selected for this reviewing study as they provided detailed analysis of carbon reduction (energy efficiency) strategies.

3 Findings and Discussions

After a detailed scrutiny of the selected research articles, 10 (groups of) carbon reduction strategies within the cradle-to-site boundary of iron and steel building products were identified (Table 1).

Table 1. Carbon Reduction Strategies (CRS) Identified in the Reviewed Articles

Carbon Reduction Strategy (CRS)	
CRS1	Improving equipment efficiency/productivity for raw material preparation
CRS2	Dry quenching of coke
CRS3	Alternative ironmaking technologies
CRS4	Alternative reducing agents
CRS5	Scrap recycling
CRS6	Waste gases recovery
CRS7	Alternative fuel & renewable energy
CRS8	Carbon capture and storage
CRS9	Management measures
CRS10	Policy drivers

3.1 Carbon Reduction Strategies

3.1.1 Improving Equipment Efficiency/Productivity for Raw Material Preparation

Ferreira and Leite (2015) carried out a lifecycle assessment of iron ore mining. Their study found the consumption of electricity leading the carbon emission of entire mining process. Thus, they have identified the electricity from renewable sources e.g., hydroelectric plants as an efficient carbon reduction strategy. Gan and Griffin (2018) conducted research on carbon assessment for up-stream processes such as iron ore mining, ore processing, sintering, pelletizing, and associated transportation. In their research two carbon reduction possibility were identified: i) open pit mining rather than underground mining and, ii) increasing the proportion of pelletized iron ore over sintered iron ore.

3.1.2 Dry Quenching of Coke

Coke is an essential feedstock of blast furnace ironmaking. The extremely hot coke (approx. 1,200°C) made in coke oven must be cooled down to proper temperature in order to be used for the following ironmaking process. The traditional way of cooling is realized by spraying cooling water. This method leads to high carbon emissions and heat loss. The coke dry quenching process was consequently proposed. In this method, the hot coke is cooled by blown in circulated gas in a coke cooling tower. The coke is cooled down meanwhile the gas is heated to a high temperature and readily to be reused in waste heat boiler. The coke dry quenching has numbers of advantages including less carbon emission, waste heat recovery, less moisture content of coke, less cost and etc.

3.1.3 Alternative Ironmaking Technologies

The commonly alternative ironmaking technologies include direct reduction of iron ore, and electrolysis of iron ore. The principal reaction of direct reduction of iron ore is to reduce iron ore to iron into the solid-state i.e., in the form of pellets. Coal, CH_4 and H_2 can be used as reduced agents. Instead of blast furnace, the direct reduction process takes place in shaft furnace. A number of chemical reactions happen in the shaft furnace. The final direct reduced iron (DRI) can be used in subsequent handling i.e., electrical arc furnace (EAF) steelmaking. The most commonly mentioned DRI making is that with hydrogen (H_2), also called hydrogen direct reduction (H-DR).

Electrolysis has been used for decades to extract metal ion from ore in many metallurgical industries such as aluminium and copper. The principle of direct electrolysis of iron ore is similar as other metal electrolysis. It takes place in the electrolyte with required temperature and with cathode and anode presented. The ferric ion gathered in the cathode and the oxygen is collected in the anode side. Thus, it is deemed as zero-carbon emission technology in many researches (Quader *et al.*, 2016).

3.1.4 Alternative Reducing Agents

Many materials can be used as substitution of coal and coke as reducing agent in ironmaking such as oil, CH_4, H_2, plastics, pulverized coal, coke oven gas, biomass and etc. Among them, the coke oven gases (containing rich CH_4 and H_2) and biomass are recognized as top options for low-carbon ironmaking. As by-products of coke-making, the coke oven gases, if reused as reducing agent, results in zero environmental burden in the ironmaking process. H_2 based ironmaking, i.e. DRI making, has been regarded as one of the most effective carbon emission reduction strategies (Ren *et al*., 2021). In the other hand, biomass is also an ideal substitution of coal and coke as reducing agent both in blast furnace and DRI route ironmaking. Study has proved that employing biomass reducing agent decrease the overall cost and reduce carbon emissions by 20 million tons (Fu *et al*., 2012).

3.1.5 Scrap Recycling

The EAF steelmaking route can substantially reduce the carbon footprint of steel product as it eliminates the most carbon intensive processes i.e., coke-making, sintering, ironmaking, and BOF steelmaking. Research has proved that if the electricity used for EAF is generated by clean energy such as hydropower, wind power and nuclear power, ultra-low carbon production can be achieved (Quader *et al.*, 2015). EAF route steelmaking consumed half of the energy of BF-BOF route (Hernandez *et al.*, 2018). That means the growth of shares of EAF can be an effective way of carbon reduction. Unfortunately, in the developing countries such as China, the relatively high price of electricity and cost of steel scrap hinder the widespread of EAF route steelmaking (Ren *et al*., 2021).

3.1.6 Waste Gas Recovering

The exhaust gases of coke oven, blast furnace and basic oxygen furnace contain CO_2, CO, H_2, N_2, CH_4 and etc., among which the CO, H_2, CH_4 can be utilized as fuel in the iron and steel making plants. Besides, the hot exhaust gases of coke oven contain massive heat which can be used for pre-heating processes in coke making plant; the waste gases of blast furnace and basic oxygen furnace can be used as heating gases in iron and steel plants, as well as reheating gases in rolling mill. Moreover, owning to its chemical properties, the blast furnace top gases, containing rich H_2 and CH_4, which can be use as reducing agent in ironmaking. In additional to these, the exhaust gases are proposed to be used beyond iron and steel production, such as to provide heat and energy in power plants and as feedstock for methanol production plant (Lundgren *et al.*, 2013).

3.1.7 Alternative Fuels & Renewable Energy

Biofuels such as charcoal made from biomass can be used in sintering and ironmaking process (Wai *et al.*, 2017). Previous studies proved that the net carbon emission released from blast furnace can be reduced by 90% (Nogami *et al.*, 2004) and 96% (Ng *et al.*, 2011) if biomass charcoal is used as substitute of fossil fuels. Besides, biomass fuels can also be adopted as alternative fuel in the EAF. Oliveira *et al.* (2015) demonstrated a biomass integrated gasification combined cycle for generation of electricity and thermal energy for EAF steelmaking. The results shown that adopting biomass fuel yields much lower net CO_2 emission than that of fossil fuel. However, this novel approach is in theoretical stage and further study is required.

3.1.8 Carbon Capture and Storage

Carbon capture and storage is the umbrella term for the technologies of capturing carbon emissions from major emission sources, then transporting, sequestrating or storing for further industrial usage. The commonly available carbon capture technologies include pressure swing adsorption, membrane adsorption, chemical absorption, physisorption and etc. The captured CO_2 is usually liquefied for the ease of transported. Captured carbon can be used as feedstock for methanol production, fuel production, syngas (CO and H_2) production, and gas and bio fertilizer. The most common way of carbon sequestration is geological sequestration including land sequestration, seabed saline aquifer sequestration, depleted oil or gas reservoir sequestration and etc. (Ras *et al.*, 2019).

3.1.9 Management Measures

During the scrutiny of the abstracts of articles in the initial screening, it was found that very few researches explored the carbon reduction potential of carbon management measures. Ren *et al.* (2021) mentioned about several management measures to improve the energy consumption and carbon emissions in the iron and steel industry in China. They included mitigating the iron and steel products consumption i.e., increasing the service life of iron and steel products, and production management technologies i.e., information technology empowered management. Other management measures include energy monitoring and management, lifecycle energy/carbon assessment, use of local raw materials and etc. However, these measures were barely mentioned in the examined articles let alone an analysis of their carbon reduction potential.

3.1.10 Policy Drivers

The situation of policy drivers is similar to that of management measures. Few researches mentioned about or recommended policies that improve energy efficiency and carbon mitigation. In developed countries, the development towards low-carbon iron and steel industry has gained considerable supports from governments or NGOs. There are spotted initiatives emerging in China in recent years, mainly initiated by private iron and steel manufactures. Yu *et al.* (2015) studied the impact of economics and policy intervention in Chinese iron and steel industry with regards to carbon emission. The results shown that investment in technologies would significantly reduce carbon emission, but the investment expansion had a negative impact on carbon mitigation (Yu *et al.*, 2015).

3.2 Synergy of Carbon Reduction Measures

Table 2 summarizes the reviewed literatures on the embodied carbon reduction strategies of iron and steel building products. It can be observed that about half of previous researches analysed the feasible or performance of multiple carbon reduction strategies as an integrated system. It further proves that carbon reduction strategies work cooperatively to achieve maximum performance as deemed in many researches (Quader *et al.*, 2015; Zeng *et al.*, 2009). For example, the H-DR ironmaking followed by EAF steelmaking coupled with furnace gas recovery and cabon capture and storage technology could achieve completely fossil fuel free iron and steel production and ultimate carbon reduction (Otto *et al.*, 2017).

Table 2. Carbon Reduction Strategies (CRS) Identified in the Reviewed Articles

Literature	**Country/ Region**	**Carbon Reduction Strategies (CRS)**									
		CRS1	**CRS2**	**CRS3**	**CRS4**	**CRS5**	**CRS6**	**CRS7**	**CRS8**	**CRS9**	**CRS10**
Awuah-Offei and Adekpedjou, 2011	NA									√	
Kirschen et al., 2011	Germany			√							
Fu et al., 2012	Taiwan				√						
Ghanbari et al., 2012	Finland				√			√			
Ansari and Seifi, 2012	Iran										√
Giannetti et al., 2013	Brazil									√	
de Castro et al., 2013	Brazil				√						
Ho et al., 2013	Australia								√		
Hui et al., 2013	China						√				
Johansson, 2013	Sweden							√			
Germeshuizen and Blom, 2013	South Africa			√				√			
Arens and Worrell, 2014	German		√		√		√				
Arasto et al., 2014	Finland			√					√		
Han et al., 2014	Korea						√		√		
Tsupari et al., 2015	Finland			√					√		
Li and Zhu, 2015	China	√	√		√	√	√			√	
Yu et al., 2015	China										√
Quader *et al.*, 2015	EU						√		√		
Ghanbari et al., 2015	Finland				√		√	√	√		
Ferreira and Leite, 2015	Brazil							√			
Oliveira et al., 2015	Brazil							√			
Weigel et al., 2016	Germany			√					√		
Quader et al., 2016	EU			√	√		√		√		
Pal et al., 2016	Indian			√					√		
Guo et al., 2016	China				√						
Pohlmann et al., 2016	Brazil							√			
Cheng et al., 2016	China							√			
Yilmaz et al., 2017	Germany			√							
Otto et al., 2017	Germany			√		√		√	√		
Zhang et al., 2017	China						√				
Wei et al., 2017	NA							√			
Vogl et al., 2018	Sweden			√				√			
Gan and Griffin, 2018	China	√									
Shen et al., 2018	China									√	
An et al., 2018	China										√
Mandova et al., 2018	EU							√			
Suopajärvi et al., 2018	Sweden & Finland				√			√			
Ras et al., 2019	NA								√		
Long et al., 2020	China				√	√		√			
Lin and Wu, 2020	China										√
Ren et al., 2021	China			√			√		√	√	
Müller et al., 2021	German			√		√		√			
Pimm et al., 2021	UK			√				√			
Yu et al., 2021	China				√						
Liu et al., 2021	China			√	√			√			
Purhamadani et al., 2021	Iran	√									
	Total:	**3**	**2**	**14**	**12**	**4**	**9**	**17**	**12**	**5**	**4**
	% (out of 46):	**7%**	**4%**	**30%**	**26%**	**9%**	**20%**	**37%**	**26%**	**11%**	**9%**

3.3 Lack of Management Measures and Policy Drivers

It is observed that the CRS7 alternative fuel & renewable energy (37% of researches mentioned), CRS3 alternative ironmaking processes (30% of researches mentioned), CRS4 alternative reducing agents (26% of researches mentioned), CRS8 carbon capture and storage (26% of researches mentioned), and CRS6 waste gases recovery (20% of researches mentioned) rank top 5 most mentioned carbon reduction strategies in the reviewed 46 researches. Which is in line with the facts that the fossil fuel basis blast furnace ironmaking generates the largest proportion of the cradle-to-site carbon emissions of iron and steel products.

On the other hand, management measures and policy drivers have been severely overlooked. Adopting local raw materials should be regarded as an important carbon management measure. Take China as an example, more than half of the iron ore were imported from overseas including Australia (22.5%), Brazil (7.7%), South Africa (1.5%), India (0.8%) (GACPRC, 2019). If the same transportation mode i.e. shipping applied, the increase of import proportions from Asia or near Asia areas can substantially reduce the transportation associated carbon emissions. However, none of the reviewed study mentioned such management improvements. Besides, a thorough a lifecycle energy/carbon assessment of manufacturing process is an also effective way to perform better energy/carbon management, which is unfotunately barely mentioned in the reviewed articles.

3.4 Challenges and Technology Barriers of Implementing the Carbon Reduction Strategies

3.4.1 Direct Reduction of Iron Ore with Hydrogen

The main challenge of direct reduction of iron ore with H_2 is the availability and cost (Chevrier, 2020). The costly distribution infrastructure, purify system and associate safety issues are major challenges of its large-scale application. It's worth noting that majority of the global H_2 are produced from fossil fuels (mostly natural gas) by steam methane reformer using natural gas as the feed-stock. The final outputs contain H_2 and CO which can be easily converted to CO_2. Therefore, the popular mode of H_2 production today is not a low-carbon process. In other words, although the DRI route is a low-carbon process, the H_2 which used as feed stock is embodied with considerable carbon emission. Thus, DRI can be regarded as the most efficient way to reduce the embodied carbon of ironmaking only if paired with sustainably produced H_2.

3.4.2 Electrolysis of Iron Ore

Compared to the blast furnace and DRI route, direct electrolysis of iron ore generates nearly zero carbon emissions and costs less. But this is a relatively new ironmaking method and has not been applied in commercial scale. This is because of its low productivity due to reaction rate i.e., 5 kg iron per day (Quader *et al.*, 2016). Recent research in EU has been experimenting rising the reaction temperature in order to boost the reaction speed (Müller *et al.*, 2021). This method was predicted could be applied in industry in 2030s (Quader *et al.*, 2016).

3.4.3 Waste Gas Recovering

The exhausted gases of an integrated steel mill are usually a mixture of various gases with massive residual heat. The waste gas recovering has great potential in terms of carbon emission reduction. However, the efficiency of gas separation/utilization/scheduling systems in steel mill is the biggest challenge posed in front of the industry and researchers.

3.4.4 Carbon Capture and Storage

As the fossil fuels are irreplaceable in the near future in the iron and steel industry, it is foreseeable that the carbon capture and storage would play an important role in the embodied carbon reduction strategy. However, there are still numbers of difficulties to be solved before this method being maturely adopted. The efficiency of carbon capture depends on the concentration and purity of CO_2. The technical issues of concentrating the CO_2 and eliminating the impurities are yet to be improved. Besides, transportation and storage of CO_2 requires infrastructures such as land, infrastructures, storage technologies, logistical facilities, which give rise to challenges including high capital cost and long project development times, investment risk, lack of financial incentives, concerns of operational safety and etc. (IPCC, 2014a, b).

4 Conclusions and Further Research

Concerning the intensive embodied carbon emissions of iron and steel building products, abundant researches have been carried out to propose and evaluate the carbon reduction strategies. This reviewing study has identified the available embodied carbon reduction strategies of iron and steel building products in recently published literatures. 46 relevent peer-reviewed articles have been reviewed and 10 carbon reduction strategies have been identified. It is observed that alternative fuel & renewable energy, alternative ironmaking processes, alternative reducing agents, carbon capture and storage, waste gas recovering, are the most frequentely studied technology improvements to achieve low-carbon iron and steel building products. The carbon reduction strategies ususally work cooperatively to achieve maximum performance. Although been most analysied in the existing literatures, the abovementioned technology measures have their limitations and barriers during implementation. One important finding of this study is that the relevent policy drivers and management measures have been largely igored in existing literaures. The findings of this study are expected to contribute to the body of knowledge and also help the industrial practitioners to improve their environmental strategies.

Due to the word limit of the conference paper, only 46 peer-reviewed articles have been reviewed in this study. Therefore, more articles should be covered in the future reviewing study. Besides, quantitative evaluation of carbon reduction potential should be further reviewed in order to disclose the effectiveness of the emerging carbon reduction strategies of iron and steel building products.

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