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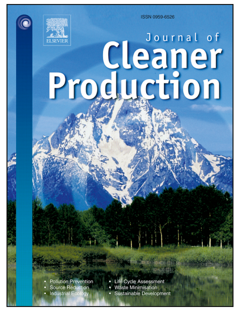

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Hasan Muslemani: Writing as part of PhD thesis: Conceptualization, Development of Methodology, Data Collection, Data Curation, Formal Analysis, Writing – Original Draft, Funding Acquisition; **Xi Liang:** Conceptualization, Supervision, Writing – Review & Editing, Funding Acquisition; **Katharina Kaesehage:** Supervision, Development of Methodology, Writing – Review & Editing, Funding Acquisition. **Francisco Ascui:** Conceptualization, Supervision, Validation, Writing – Review & Editing, Funding Acquisition. **Jeffrey Wilson:** Writing – Review & Editing, Funding Acquisition.

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Abstract

The creation of a market for steel produced by less carbon-intensive production processes, here called 'green steel', has been identified as a means of supporting the introduction of breakthrough emission reduction technologies into steel production. However, numerous details remain under-explored, including exactly what 'green' entails in the context of steelmaking, the likely competitiveness of green steel products in domestic and international markets, and potential policy mechanisms to support their successful market penetration. This paper addresses this gap through qualitative research with international sustainability experts and commercial managers from leading steel trade associations, research institutes and steelmakers. We find that there is a need to establish a common understanding of what 'greenness' means in the steelmaking context, and to resolve various carbon accounting and assurance issues, which otherwise have the potential to lead to perverse outcomes and opportunities for greenwashing. We identify a set of potential demand-side and supply-side policy mechanisms to support green steel production, and highlight a need for a combination of policies to ensure successful market development and avoid unintended consequences for competition at three different levels: 1) between products manufactured through a primary vs secondary steelmaking route, 2) between 'green' and traditional, 'brown' steel, and 3) with other substitutable materials. The study further shows that the automotive industry is a likely candidate for green steel demand, where a market could be supported by price premiums paid by willing consumers, such as those of high-end luxury vehicles.

Key Words: Iron and steel industry, green steel, decarbonization, climate policy, market analysis

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1. Introduction

The global steel sector is the second largest industrial sector by share of greenhouse gas (GHG) emissions (after cement) due to its heavy reliance on fossil fuel consumption (Quader et al., 2015). The steel industry generates between 7% and 9% of total carbon dioxide (CO_2) emissions from the global use of fossil fuel, and on average, 1.85 tonnes of CO_2 (tCO_2) were emitted for every tonne of steel produced in 2018 (Worldsteel, 2020a). As demand for steel is forecasted to increase over the next decades (Xuan and Yue, 2016), decarbonizing the industry in line with the Paris Agreement's target of reducing global net emissions to zero by 2050 (UNFCCC, 2015) is a major challenge.

Studies exploring emission reduction potential in the steel sector, however, show that the capacity to reduce emissions using traditional energy-efficiency measures is limited to collectively abating around 25–40% of average CO_2 emissions per tonne of crude steel produced (Li and Zhu, 2014; Morrow et al., 2014; He and Wang, 2017; An et al., 2018; Liang et al., 2020). To achieve further reductions, breakthrough technologies are required, such as carbon capture, utilization and storage (CCUS) (Al Reyadah, 2017), using hydrogen (HYBRIT, 2017; Ahman et al., 2018) or biomass (CSIRO, 2013) as reducing agents, or electrolysis (i.e. using electricity to reduce iron ore) (Worldsteel, 2019a).[1] However, these technologies are not readily available, with some in early research stages and others only at the pilot/demonstration phase (Leeson et al., 2017; Karakaya et al., 2018; Kushnir et al., 2020).

Deploying such technologies has the potential to fundamentally impact emission trajectories and reshape the technological landscape within the steel sector (Iyer et al., 2015). Furthermore, if deployed early, these technologies could help mitigate higher long-term costs of climate action (Bassi et al., 2012; Bibas et al., 2015; Riahi et al., 2015).

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[1] Other routes to decarbonizing the steel industry include reducing overall steel demand (Chen et al., 2014) and/or increasing global steel recycling trends (Johnson et al., 2008). However, with projected increases in future steel demand and hence in production (Pauliuk et al., 2013a), and with limited availability of steel scrap for recycling (i.e less than 30% of new steel is produced using steel scrap) (Pauliuk et al., 2013b; Napp et al., 2014), the need for the aforementioned breakthrough clean technologies becomes all the more evident (Morfeldt et al., 2015).

However, despite their potential, practical experience with these technologies is limited, and the lack of established business models to support them further hinders their commercial viability (e.g. Kapetaki & Scrowcroft, 2017; Element Energy, 2018; Muslemani et al., 2020). One potential long-term solution to commercializing these technologies is to establish a market for 'green' steel produced by less GHG-intensive production processes (Element Energy, 2018, p. 27), which could underpin a cleaner production roadmap for the industry and incentivize its decarbonization over time (Saritas and Aylen, 2010).

Here, it is imperative to make a definitional distinction between 1) steel products which have lower GHG or carbon *footprints* (due to different production processes), and 2) 'low-carbon steel' products which are an existing type of product with minimal *carbon content* (0.04-0.30%) in the final products themselves.[2] As such, the term 'green steel' will hereinafter be used to refer to steel products manufactured using less GHG-intensive production processes, and not to refer to products with lesser amounts of physical carbon content. Green steel is also differentiated from 'sustainable steel' in that its scope is limited to lower GHG emissions while sustainable steel - and materials in general – also encompasses other issues such as energy and resource efficiency, circularity and reduction of other pollutants (Ding, 2014).

Although a number of industry-focused studies (e.g. Element Energy, 2018; Muslemani et al., 2020) have suggested that the creation of a green steel product market may be a viable means of creating a revenue stream to support greener steel production, key questions remain, including: 1) what would a 'green' steel product actually be? 2) how could governments support the creation of markets for such products? and 3) is there likely to be any voluntary demand for such products? To address these questions, this paper investigates the key challenges, prospects and opportunities of creating a market for green steel products, as perceived by steel industry stakeholders. The paper is structured as

[2] 'Low-carbon steels' are rich in ferrite – a solid solution phase of carbon dissolved in alpha-iron – which is the softest phase of steel. Low-carbon steels are versatile, low-cost and are widely used in industries from agriculture to heavy machinery industry.

follows: section 2 provides a review of the concept of green steel, and section 3 outlines the qualitative research methods employed. Section 4 presents key findings and discussion, while section 5 provides recommendations and concludes.

2. Background: Green steel concept

Steel is a key structural input material into major industries, such as construction/buildings and auto manufacturing. As part of a supply chain feeding into the production of finished consumer products, steel is analogous in its role to other intermediate products such as energy resources and other construction materials. Similarly, producing 'green' steel is akin to producing green energy or environmentally-certified wood, where the functionality or utility of the product and the end-user's experience are not necessarily affected (Roe et al., 2001; Yoo & Kwak, 2009; Sardianou & Genoudi, 2013), as no additional direct benefits accrue to the end-user apart from the reputational value associated with purchasing products manufactured via cleaner production routes (Bhoi et al., 2015). This can be compared with other types of green products which are functionally different to their 'brown' alternatives, and which provide direct benefits to the end-user, such as energy savings from more fuel-efficient vehicles.

There is a lack of research, or indeed consensus, on the concept of green steel. The term 'green steel'[3] has been very rarely used in the academic literature and, when adopted, its definition has been broad. As examples, Bhoi et al. (2015) described green steel as 'eco-friendly and free of environmental pollution' (p. 25) and Singh and Rout (2018) as steel which has 'lower greenhouse gas emissions, cuts costs and improves the quality of steel' (p. 8).[4] A number of initiatives promoting the application of breakthrough technologies in steelmaking (Table 1) have led to various terms being coined for steel manufactured using

[3] The term 'Greensteel' also refers to a strategic plan adopted by the UK steel manufacturer Liberty Steel (n.d.) which aims at lowering proportions of exported scrap and instead promoting efforts for national scrap recycling.

[4] In contrast to the noted range of terms, the term *'clean steel'* is used to exclusively refer to high-purity steel products (e.g. Mazumdar, 2013; Campbell, 2017).

these technologies, including *'fossil-free'* (HYBRIT, 2017), '*carbon-lean'* (OECD, 2010; LowCarbonFuture, n.d.), and *'CO_2-lean' or 'CO_2-neutral'* steel (Eurofer, 2019a,b). More recently, the term *'responsible steel'* has been adopted to describe responsibly-sourced and produced steel products, although the term encompasses a multitude of elements – or twelve 'principles' – of which GHG emissions is only one (see Principle no. 8 in ResponsibleSteel, 2019: 7).

Table 1. Recent green steelmaking initiatives.

Company	Project/Technology	Location	Target
ArcelorMittal	Hydrogen reduction with grey hydrogen derived from natural gas	Hamburg, Germany	Fossil free by 2050
	Blast furnace + electrolysis for hydrogen production	Bremen, Germany	
	Hybrid blast furnace with direct reduced iron (DRI) gas injection	Dunkirk, Germany	
	Coke oven gas with grey hydrogen; hydrogen in DRI-EAF	Asturias, Spain	
HYBRIT (SSAB, LKAB and Vatenfall)	Replacing coking coal with hydrogen and fossil-free electricity	Sweden	Fossil free by 2045
Boston Metal, BHP & Vale	Molten oxide electrolysis (MOE) technology	Massachusetts, USA	n/a
China Baowu & BHP	Memorandum of Understanding to share technical expertise in reducing emissions from steel, including using CCUS	Multiple steelmaking bases in China	n/a
Ovako	Hydrogen use to heat steel before rolling	Hofors, Sweden	n/a
Liberty Ostrava	Building hybrid furnaces	Czech Republic	Hybrid furnaces built by 2022
Rogesa	Hydrogen in coke gas as reducing agent	Dillingen, Germany	Started operations in 2020
Tata Steel	Carbon capture and storage under North Sea; water electrolysis to produce hydrogen and oxygen	Ijmuiden, Netherlands	Carbon-neutral in Europe by 2050
Thyssenkrupp	Hydrogen as reducing agent; use of renewable hydrogen from RWE & feasibility study for water electrolysis plant	Duisburg, Germany	First phase testing in 2021, second phase in 2022.
Voelstalpine Primetals Tech.	Hydrogen as reducing agent to process iron ore concentrates	Linz, Austria	80% carbon emissions reduction by 2050
Tenaris, Edison and Snam	Electrolysis/hydrogen-based steelmaking	Bergamo, Italy	
Salzgitter AG (Salcos project)	Electrolysis/hydrogen-based steelmaking	Wilhelmshaven, Germany	2 million tonnes per year of DRI (by the end of first implementation stage, expected for 2025)
Duferco	Using hydrogen in beam furnace with green PPA.	Brescia, Italy	
Celsa, Statkraft & Mo industrial park AS	Electrolysis/hydrogen-based steelmaking	Norway	50% emissions reduction by 2030, decarbonization by 2050.
H2 Green Steel Initiative	Hydrogen-based steelmaking	Northern Sweden	Planned production to start in 2024. Annual production target of 5 million tons of green steel by 2030.

The lack of consensus on what defines greenness for steel is further complicated by the fact that steel is currently produced using two routes: a primary (integrated) route which is highly emissions-intensive, and a secondary route which uses recycled steel and is much less emissions-intensive (global averages of 1.85 tCO_2/t steel vs. 0.4 tCO_2/t steel, respectively) (Worldsteel, 2019b). This raises issues of comparability between emission reductions across the two routes, as reducing carbon emissions from the primary route to zero would actually achieve around 4.5 times the emission reductions of the same outcome from the secondary route. Primary steelmakers may feel that they are at a disadvantage in the race towards meeting green steel standards: such concerns may already be evident in the fact that all steelmakers who are part of the Science Based Targets initiative[5] are secondary steelmakers (Science Based Targets, n.d.). Due to the high rate of recycling which is possible for steel as a material (Yellishetty et al., 2011; Broadbent, 2016), steel production needs to be considered as a global system, rather than a one-way supply chain, if the creation of a market for green steel products is not to lead to perverse outcomes.

A number of existing initiatives address issues relevant to the development of a green steel market, such as standardization of product environmental footprint calculations (e.g. Ernst and Young, 2017; ResponsibleSteel, 2019), regulatory framework development (Eurofer, 2019b) and business model development for cleaner technologies in steelmaking (Muslemani et al., 2020). However, with the exception of a few studies (e.g. Arens & Vogl, 2019; Vogl et al., 2020), research on the opportunities and challenges of developing a market for green steel products is virtually non-existent.

One key challenge is that green steel will, at least initially, be more expensive than conventionally-produced steel, due to the higher costs of alternative production technologies: Swedish green steel producer, SSAB, estimates that green steel would be 20-30% more expensive to produce than traditional steel (SSAB, 2019). This may limit green steel consumption to smaller segments of environmentally-conscious consumers (Yuhanis,

[5] An initiative which aims at setting emission reduction targets for different industries in line with the Paris Agreement.

2004; Kavilanz, 2008; Deif, 2011; Olson, 2013; Ritter et al., 2015). Understanding the willingness to pay of those consumers for green steel products, however, is challenging, due to the complexity of the steel industry's supply chain and the number of industries which rely on steel as an input to a myriad of final end-user products, and thus is beyond the scope of this study. Instead, we investigate the challenges and opportunities for creating a market for green steel products from an industry stakeholders' perspective, to set the groundwork for future research on consumer willingness to pay for green steel.

3. Methodology

3.1. Design and setting

To understand the challenges and opportunities associated with creating a market for green steel products, we employed a qualitative methodology involving in-depth semi-structured interviews with key industry stakeholders. Interviews offered us the desired combination of breadth and depth (Tashakkori and Teddlie, 2003), and we were able to easily adapt them to the background expertise of the respondent. Dealing with our interviewees on an individual and more personalized basis also enabled a high response rate (Fox et al., 1988; Coughlan et al., 2009). Moreover, interviews offered an 'intensive method' of primary data collection which provided valuable insight into the beliefs and actions of those being interviewed (Smith, 1975; Davies et al., 2014).

A semi-structured interview approach offered us the flexibility to cover a number of questions or specific subject areas, which ensured that certain key topics were covered, but also allowed the interviewees to provide knowledge on aspects that were of interest to them. The topics covered through the interviews included: 1) their views on the definition of green steel, 2) implications of developing a green steel market on the wider steel industry, and 3) potential support mechanisms for green steel production. Additional questions specific to the expertise of each interviewee were further prepared to enhance the quality of responses. All interviews were held online between March and October 2020, were typically of one hour in length, and were recorded for transcription. Prior to the interviews, interviewees were sent the interview guide (see supplementary material), outlining the purpose of the study, and asked whether they opted to make their feedback publicly available.

3.2. Sampling

As steel is a globally-traded commodity involving producers operating within different regions with different policy contexts, our research targeted stakeholders from leading global steel-producing countries and regions (e.g. UK, US, China, Japan, Australia, South Korea, India, South America and the EU). Industry stakeholders were selected through a number of steel trade associations which represent a wide range of steel-related organizations. This identification process followed a three-stage, top-down approach (Figure 1), with the World Steel Association (Worldsteel) as a starting point. Worldsteel is the world's largest steel industry association and operates on a global scale; its members include regional and national steel industry associations and research institutes (i.e. 'affiliated' members) and steel producers ('regular' members) from every major steel-producing country (Worldsteel, n.d.).

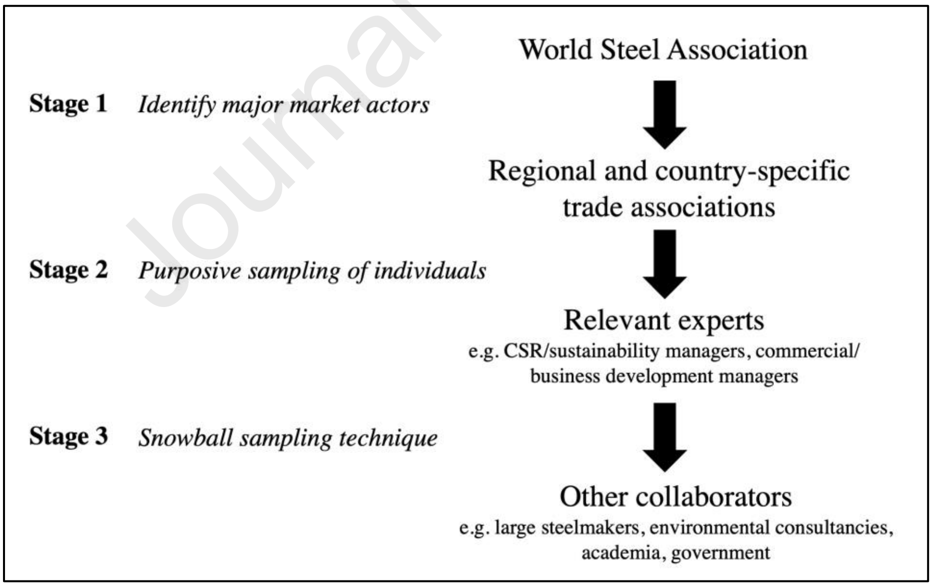

Figure 1. Top-down research approach.

In the first stage, a set of 15 of Worldsteel's affiliated region- and country-specific members (i.e. trade associations) were collated, including ones which cover the top 25 largest countries by volumes of steel production (Worldsteel, 2019c). Another 11 trade associations and membership organizations which are non-affiliates of Worldsteel were also identified using online searches. The total of 26 membership organizations is presented in Table 2.

Table 2. Steel trade and membership associations.

Region/country	Corresponding trade/membership association(s)
Global	World Steel Association (Worldsteel)
	International Iron Metallics Association (IIMA)
	ResponsibleSteel*
Europe	The European Steel Association (Eurofer)
United Kingdom	British Stainless-Steel Association (BSSA)
	UK Steel Association
	British Constructional Steelwork Association (BCSA)
	Mineral Products Association (MPA)
	Materials Processing Institute (MPI)
	National Association of Steel Service Centres (NASS)
	The Institute of Materials, Minerals and Mining (IOM3)
	International Steel Trade Association (ISTA)
United States	American Iron and Steel Institute (AISI)
	The Association for Iron & Steel Technology (AIST)
China	China Iron and Steel Association (CISA)
	The Chinese Society for Metals (CSM)
	China Metallurgical Industry Planning and Research Institute
Japan	Iron and Steel Institute of Japan (ISIJ)
	Japan Iron and Steel Federation (JISF)
Australia	Australian Steel Institute (ASI)
	Australian Steel Association (ASA)
South Korea	Korea Iron and Steel Association (KOSA)
India	Indian Steel Association
	Steel Authority of India
South America	Latin American Steel Association (Alacero)
	Brazil Steel Institute
	Argentine Chamber of Steel (Acero Argentino)

*ResponsibleSteel includes members from different parts of the steel supply chain but is not a trade association.

In the second stage, a purposive sampling technique was adopted to identify experts within these associations, and within member companies of these associations, who suited the sampling criteria set by the researchers (i.e. knowledge of low-carbon technology options, product marketing, and/or low-carbon policy options for steelmaking). An expert is here defined as one who is well-acquainted with the subject being investigated and who demonstrates a willingness to provide relevant, well-reflected and honest views on the subject matter (Crano et al., 2014; Bryman, 2016). The resulting set of individuals included experts in environmental compliance/reporting and commercial strategies, such as CSR/sustainability managers, commercial/business development managers, and where applicable, top management personnel, including chairpersons and CEOs. In the third stage, a snowball sampling technique was adopted, where participants were asked for suggestions about other potential internal or external collaborators. Individuals identified using this method included experts within large steelmaking companies, environmental consultancies, academic institutions and government. Before approaching them, these individuals were screened to verify that they met the same criteria outlined above. Overall, this technique facilitated easy access to influential stakeholders in the industry.

All participants were approached by email, and of the 184 individuals who were contacted, 39 initially agreed to take part in this research. Of these, 21 eventually participated in the study (Table 3, ID 1–21). After the initial set of interviews, and as the automotive industry was identified by respondents as a likely candidate for green steel use, more targeted interview questions were later sent to automotive market experts who were identified using a similar purposive sampling technique as described above, including sustainability experts within leading automotive associations and automakers (ID 22–27). This brought the total participants in this study to 27 individuals and enhanced the reliability and validity of our initial results through data triangulation (Guion et al., 2011).

Complete anonymity as to the identity and organizational affiliation of the interviewees was offered, except where interviewees explicitly opted to publicize their views. A list of all participants, by position and type of organization, is presented in Table 3.

Table 3. Study interviewees.

ID	Position	Type of organization
1	Director, Energy and Climate Change	Steel trade association (UK)
2	Director	Steel trade association (UK)
3	Scientific Officer	Industrial legislative authority (Europe)
4	State Manager & Manufacturing Advisor	Steel trade association (Australia)
5	Vice President, Environment	Steel trade association (United States)
6	Vice President, Sustainability	Steel trade association (United States)

ID	Position	Type of organization
7	Senior Director of Technology	Steel trade association (United States)
8	Director, Government Affairs	Steel trade association (United States)
9	General Manager, Corporate Sustainability	Top 3 largest steel producers (Global)
10	Director, Safety Health and Environment	Steel trade association (Global)
11	Head of Environment and Climate Change	Steel trade association (Global)
12	Director, Technical	Top 3 largest steel producers (Global)
13	Chief Executive Officer (Chris McDonald)	Materials Processing Institute (MPI) (UK)
14	Doctoral Researcher	Academic Institution (Europe)
15	Chairman & Chief Engineer	Industry planning institute (China)
16	Policy Officer	Legislative authority (Europe)
17	Senior Consultant	Low-carbon technology consultancy (UK)
18	Energy Analyst	Intergovernmental energy agency (Global)
19	Technology Analyst	Intergovernmental energy agency (Global)
20	Project Leader	Co-founder of CCS project in the industrial sector (UK)
21	Technical Manager	Major construction company (UK)
22	Researcher, Sustainability	Major car manufacturer (Global)
23	President and CEO	National automaker industry association (Canada)
24	Climate Protection Policy Manager	National automaker industry association (Germany)
25	CSR and Supply Chain Director	National automaker industry association (US)
26	Sustainability Manager	Major car manufacturer (Sweden/Global)
27	Sustainable Materials Specialist	Major car manufacturer (US/Global)

3.3. Data collection and analysis

A thematic qualitative text analysis (QTA) method was used to analyze the data collected during the interviews (Schulz, 2012; Kuckartz, 2014). The transcripts of all interviews were systematically evaluated, structuring the content into categories and subcategories. This included assigning 'codes' or 'labels' to sections of the data, i.e. sentences or phrases providing relevant information on one or more key research question(s). This coding was performed on each transcript following a two-step iterative process. First, holistic coding was performed on the full text, assigning a code to each sentence or section of the transcript. These codes were then grouped into five categories and corresponding sub-categories to form a category tree, or 'code system'. Second, the code system and its content were continuously refined, grouping related codes together under the same theme and eliminating unnecessary, irrelevant or overlapping ones: a method referred to as axial coding by Saldaña (2015). The final code system, including the codes' hit count (one per interviewee), is provided in Table 4, where interview findings were categorized into four overarching categories: 1) elements considered in defining steel 'greenness', 2) barriers to creating green steel products and implications on product competitiveness, 3) preference and choice of incentive/disincentive mechanism(s) to support a corresponding market, and 4) financing of green steel premiums. Count hits per each chosen sub-category are first arranged per type of the interviewee's affiliation, followed by a total count hit per subcategory.

Table 4. Code frame and interview hit counts (includes responses from initial set of interviewees ID 1-21).

Code structure, with categories numbered by Roman numbers, sub-categories as letters and codes as numbers.				
Categories, Sub-categories and Codes	**Sectors represented by interviewees**			**Sum of hits counted**
	Manufacturers	**Trade associations**	**Research institutes**	
I. Definition of green steel				
1. Embodied carbon content	3	8	10	**21**
2. Carbon savings during operational phase	3	5	3	**11**
3. Lifecycle approach	2	3	4	**9**
4. Wastewater management	2	2	3	**7**
II. Barriers to green steel product market creation				
1. Competition with lesser green steel	3	8	10	**21**
2. Increased costs	3	7	10	**20**
3. Carbon leakage	3	8	5	**16**
4. Comp. between primary and secondary routes	3	6	7	**16**
5. Right choice of technology	3	4	8	**15**
6. Demand concerns	2	5	4	**11**
7. First mover disadvantage	1	6	4	**11**
8. Comp. with other substitutable materials	2	3	4	**9**
9. Indirect relationship with consumers	-	5	4	**9**
10. Multiple emission sites during production	1	3	2	**6**
11. Knock-on effects on suppliers of steel industry	-	2	1	**3**
12. Market volatility	-	2	-	**2**
IV. Incentives vs disincentive mechanisms				
*A) Incentives**				
1. Government procurement	3	8	10	**21**
2. Setting standards for green products	3	9	9	**21**
3. Carbon border adjustment	3	4	4	**11**
4. EU-ETS	2	1	3	**6**
5. Contracts for Difference (CfD)	2	2	-	**4**
6. High carbon price	-	3	-	**3**
B) Disincentive	2	-	-	**2**
C) No specific preference	1	1	-	**2**
V. Financing of green steel premium				
1. Specific segment of steel consumers	2	6	7	**15**

Code structure, with categories numbered by Roman numbers, sub-categories as letters and codes as numbers.

Categories, Sub-categories and Codes	Sectors represented by interviewees			Sum of hits
2. General steel consumers	3	3	3	**8**
3. Taxpayer	1	1	-	**2**

*Interviewee allowed to choose more than one incentive mechanism.

A narrative was ultimately constructed from the processed data, where the content included in the identified codes was systematically described and common themes identified, with select interviewee quotes populating this narrative. It is worth mentioning that this method only allowed for qualitative conclusions to be made, as specific views of a number of experts could not be generalized to the sample group or recorded under common themes. Instead, only prevailing opinions within the sample group were provided. Furthermore, this approach allowed for examining similarities and differences within each category in an inductive manner. This helped derive generalizations within the sample group, albeit these could not be generalized to the wider steel sector as that would require a much larger sample size and more elaborate industry participation, which remains beyond the scope of this study.

4. Results & discussion

4.1. Conceptual understanding of 'greenness' in steelmaking

Our data revealed that participants had a converging, yet imprecise, overall concept of what 'green' means for steel as a product. All interviewees considered the carbon footprint, or the 'embodied carbon content', as a primary – and at times sole – factor for how green (or non-green) a steel product is. However, some interviewees argued that 'greenness' implies more than just lower GHG emissions, with the term ideally encompassing other aspects such as material use efficiency, water management, biodiversity impacts and other air emissions:

'The term 'green', in addition to involving a certain carbon profile, should include water usage, biodiversity or even human and labour rights which are factors that admittedly vary according to

where in the world you are… but for the sake of simplicity, if nothing else, carbon profiling has gotten a lot of attention' (interviewee 4).

A focus on greenhouse gas emissions makes sense for two main reasons: 1) the relative ease of measurability and the existence of carbon accounting methodologies applicable to steelmaking, and 2) the prominence of greenhouse gas emissions reduction as a primary policy focus in the steel sector globally: for example, Worldsteel's sustainable development policy states 'GHG emissions' as the first of 8 indicators of 'sustainable' steel (Worldsteel, 2020b), while the main objective of the EU's Low Carbon Roadmap is achieving 80–95% emissions reduction by 2050, compared to 1990 levels, in the European steel industry (Eurofer, 2019a). For these reasons, notwithstanding the importance of other environmental factors, we henceforth focus on GHG emissions as the primary factor determining the 'greenness' of 'green steel' in the remainder of this paper.

Even this narrow focus, however, raises numerous conceptual questions and associated challenges. For example, green steel could be defined in terms of absolute emissions (e.g. below a threshold of 0.2 tCO_2/t steel), or emission reductions relative to a baseline (e.g. 80–90% reduction compared with historical emissions or a sector average). In either case, a question is raised about where to draw the line. An alternative approach could be to pursue emissions labelling of steel products (again, in absolute and/or relative terms), so that consumers can make their own minds up about what level they consider to be 'green'.

There are also choices to be made between distinct carbon accounting methodologies, and between accounting options within methodologies, which can have significant bearing on measured GHG emissions or emission reductions. For example, an 'attributional' accounting methodology such as PAS 2050, ISO14067 or the GHG Protocol: Product Life Cycle Accounting and Reporting Standard (Greenhouse Gas Protocol, 2011) is commonly used to allocate life-cycle emissions to a product, but only measures GHG emissions within certain boundaries, to do with physical inputs and outputs. A consequential accounting methodology such as consequential life cycle assessment (European Commission, 2010) or the GHG Protocol for Project Accounting (Greenhouse Gas Protocol, 2005), on the other hand, is appropriate for estimating the overall system-wide changes in emissions which occur as a result of implementing an action, such as producing a green steel product

(Brander & Ascui, 2015). A consequential approach recognizes that the effects of an action go beyond its immediate physical inputs and outputs, so for example, if availability of a green steel product caused consumers to switch from timber to green steel in construction, the emissions resulting from this change would also need to be considered.

An example of the impact of different accounting options within methodologies can be seen in the case of attributional methodologies such as PAS 2050 (BSI, 2011) and ISO14067 (ISO, 2018), which, under certain circumstances, could allow a steelmaker to apply a zero 'contractual' emission factor to their electricity use or 'scope 2' emissions, if they have purchased instruments such as Guarantees of Origin (GOs) from renewable electricity generation, as opposed to using the 'location-based' emission factor corresponding to their physical supply. As most of the GHG emissions from secondary steelmaking are due to the use of electricity, this could effectively allow the steelmaker to claim that their products are 'zero-carbon', despite the fact that their purchase of GOs may not have made any difference to the total amount of renewable energy generated and thus not have made any real contribution to global climate change mitigation (Brander et al., 2018).

The infinitely-recyclable nature of steel also raises a challenge for attributional accounting, to do with the allocation of GHG emissions associated with recycled inputs and outputs, which in turn depends on how the relevant system boundary is defined (Broadbent, 2016). For example, scrap inputs may be considered as 'free' from environmental burden, or as embodying the burden associated with their original production, depending on whether the system is narrowly or more broadly defined. On this, interviewee 11 observed that:

> *'This [i.e. emissions allocation] has everything to do with boundaries: if you are just looking at direct emissions, then steel recycling is burden-free, and this becomes even more complicated when you consider how many times steel scrap can be recycled'.*

Interviewee 2 further added:

> *'There is plenty of evidence that if you take a partial decision based on embodied carbon alone, you risk making environmentally-perverse decisions, as you look at things in an embodied rather than a whole-life sense, which eventually sends you in the wrong direction'.*

Worldsteel addresses this by adopting a 'net-scrap' approach in its life cycle inventory methodology (Worldsteel, 2017), where steel scrap is allocated a 'debit' (or environmental burden) when used in the steelmaking process as an input, and a ‘credit’ (or environmental benefit) when recovered at end-of-life. As such, secondary producers may bear part of the primary production emissions burden, based on the extent to which secondary production depletes or enhances the pool of scrap available in the market (Broadbent, 2016).

How these carbon accounting issues are resolved may affect the relative competitiveness of primary versus secondary ‘green steel’ production. A number of interviewees (11) believed that the definition and methodology for calculating what counts as green can be highly political, as it may favour one production route over another:

> *‘Whichever way you produce green steel, it will always be easier to prove the greenness of the product if it is produced using the electricity (EAF) route, and so that route will take precedence as steel produced using this (secondary) route can be as green as the electricity used to produce it’ (interviewee 6).*

On the impacts of greening steel production on the competition between production routes, interviewee 10 further noted:

> *‘We [i.e. industry stakeholders] have always been of a view that there is a synergistic relationship between primary and secondary steelmakers because whatever is used in secondary steelmaking is made in primary steelmaking. Therefore, we do not feel that differentiating between one type of steel produced using a certain route and another is helpful because we end up driving scrap or moving a limited pot of scrap around, which may not be effective from a global perspective’.*

Even if a consistent definition and accounting methodology is adopted across the steel industry, there remains a question about whether green steel could be subject to fraudulent claims or ‘greenwashing’, given that there will be no observable differences in the final product (Feinstein, 2013). In this, green steel would be similar to other products, such as organic food or sustainably produced timber, which are differentiated primarily on the basis of their production processes, rather than any intrinsic qualities. The challenge of fraudulent claims for organic food led to the development of the first process-based product certification standards in the 1970s, and today a vast array of sustainability certification standards cover many global commodity products (Willer and Lernoud, 2019). A certification scheme could serve to assure consumers that green steel products which are not observably distinct from other less-green steel products were sourced, processed and delivered using lower carbon routes (Janssen and Hamm, 2012). It also serves to improve market efficiency by reducing information asymmetry along the marketing channel between producers and consumers (Lohr, 1998).

Indeed, a number of interviewees (8) expressed concerns over the possibility of greenwashing which may arise:

> *'A certification mechanism would ensure that a product cannot be passed off as green or faked; as history shows us that, if the incentive is great enough, people may go to all sorts of lengths... Absent such a 'policing' mechanism, 'green' in green steel may well remain a bit of PR greenwash' (interviewee 12).*

The potential for greenwashing, and the discrepancy which may arise between steelmakers using different production routes, could be reduced by 1) agreeing on a clear definition and carbon accounting methodology to support green steel product claims, preferably based on a consequential approach to quantifying system-wide emission reductions, rather than an attributional approach to quantifying embodied emissions within a defined boundary; 2) ensuring that any claims based on 'contractual' reduced emissions from purchased renewable electricity are restricted to renewable generation that is genuinely additional (i.e. that would not have been generated anyway) and therefore makes a contribution to climate change mitigation; 3) if an attributional approach must be taken, having recycled steel acknowledge the carbon footprint of the primary steel, and/or 4) setting different emission requirements for products made using each of the two production routes. Further research and policy debate is required in all of these areas, while Figure 2 summarizes all relevant factors impacting the greenness of steel as discussed in this section.

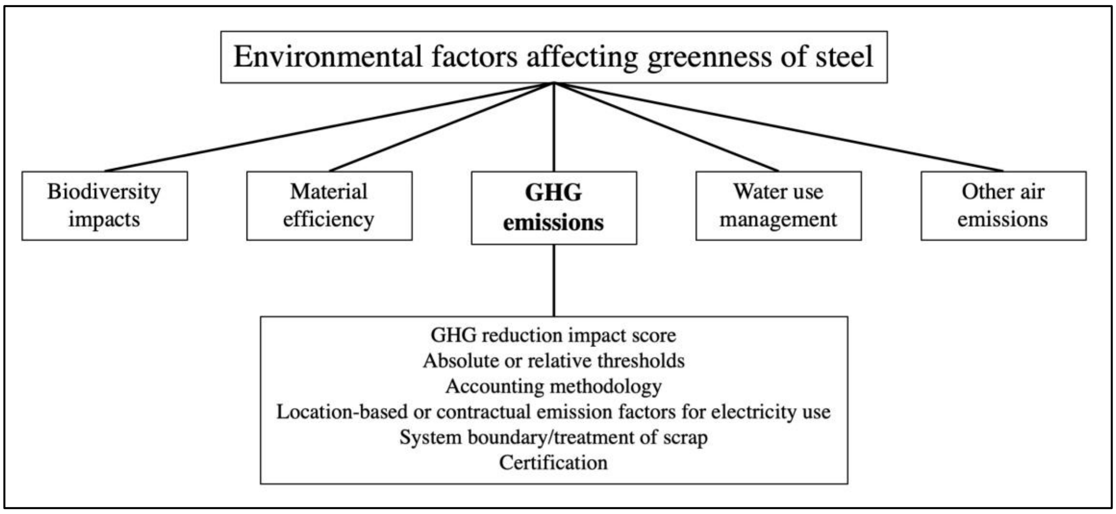

Figure 2. Factors affecting greenness of steel.

4.2. Policy support mechanisms

The competitiveness of a green steel product in the market was the most frequently discussed theme during the interviews. Due to the internationally-traded and highly competitive nature of steel as a commodity, where less-green steelmakers – whether national or international – sell emission-intensive products at lower prices, green steel products will have to compete on the basis of product differentiation (Conrad, 2005; Dangelico and Pontrandolfo, 2015) rather than cost. Interviewees also argued that green steel production may be appreciated in a domestic market, but not on a global scale, given the heterogeneity of policy support mechanisms which may apply in different regions and policy contexts. Here, we discuss a range of possible policy support mechanisms, which we divide into 'push' mechanisms which target green steel supply and 'pull' mechanisms which increase demand, and their corresponding impacts on product competitiveness.

Broadly, interviewees commented on the roles which different market participants – producers, consumers and government – could play in supporting a market for green steel: there was a general consensus that a transitional approach was needed, with governments initially sending strong investment signals to de-risk investments for producers. Subsequently, as producers grow confident that their competitiveness will not be compromised, standards on end-use products can help attract environmentally-conscious consumers into the market. A notable number of interviewees (15) believed that producers will not take the first initiative unless there is a certain and existing demand, and as such demand-side mechanisms are discussed first.

4.2.1. Demand-side 'pull' mechanisms

Most interviewees identified 1) government intervention through public procurement, 2) regulatory requirements on large steel consumers, and/or 3) setting a certifiable standard for 'green' steel as potential mechanisms which can promote demand for green steel. On the first two points, interviewees argued that governments could specify minimum green steel requirements in the awarding of public contracts, or mandate the use of a given amount of green steel by industries – either as a whole or by individual private companies operating within those industries, such as construction companies or automakers:

> *'Governments are indirectly large purchasers of large quantities of steel via the construction industry, for government buildings and infrastructure for example, and specifying [in contracts] that a certain content of the steel used in a project has to be from a specific green supplier or green route – based on a given definition of green steel – could be one way of supporting this [i.e. green steel demand] much more rapidly than incorporating green steel into only a few cars, which typically only target richer consumers' (interviewee 18).*

Admittedly, however, green public procurement may be impeded by a number of factors, including the lack of focus of public tenders on life-cycle performance in terms of GHG emissions, prioritization of the most economically advantageous offers, and a lack of the necessary skillsets within procuring authorities to design tenders with low-carbon priorities (Chiappinelli and Zipperer, 2017). Also, in the short term, this approach may limit green steel production to certain 'green suppliers' and its consumption predominantly to government-backed projects. Still, some participants argued that green steel production would, in time, become a mainstream practice due to three reasons: 1) steelmakers, and the supply chain as a whole, would seek to avoid production inefficiencies arising from having two distinct production lines for observably similar products, 2) large private steel consumers will become aware of the environmental virtues embedded in greener steel and shift purchasing behavior over time, and consequently 3) steelmakers would be hesitant to lose customers to competitors who are actually greening their production lines.

Some interviewees (10) noted that, once a green steel product begins to compete on the basis of differentiation from conventional, non-green steel, it will also face competition with other lower-carbon alternatives in the broader materials market, especially materials which can substitute for steel in certain applications, such as cement (in construction), aluminium (in car manufacturing), plastic (in packaging), or ceramics (in vehicle engine manufacturing). Moreover, greening the production of those substitutes themselves may serve to further displace the use of steel in finished products, such as using 'low-carbon' aluminium (e.g. produced largely with renewable energy) in passenger vehicles (Tjøtta, 2020). This was seen as both a threat and a possible driver of innovation in steelmaking:

'If any of the significant competing materials moved towards, or actually developed, a process with significantly-improved carbon profile, it would act as an incentive for steel producers to attempt to keep up in a way' (interviewee 5).

One option would be for green steel to target only those consumers who cannot substitute the usage of steel with other materials (an example here is the production of motors for electric vehicles, as motors rely on the principle of magnetism and thus, unlike a vehicle's outer body, cannot be substituted with aluminium).

In the absence of government procurement or other regulatory-driven demand, the market for green steel products is likely to be limited to certain niches of existing environmentally-driven consumers who are willing to pay a premium for greener steel. This may present an opportunity especially for companies already producing highly-differentiated steel products (such as SSAB in the Swedish market), where consumers are more likely to remain loyal to their supplier (Chang and Fong, 2010). A similar approach is already observable in the aluminium sector, where 'low-carbon aluminium' is set to be marketed as a niche product on the London Metals Exchange from 2021 (Sanderson, 2020). However, the disadvantage of developing a niche market for green steel is that it may not be particularly helpful in terms of decarbonizing the industry in the short term, unless sufficient policy support is provided to promote the practice from niche to mainstream over time (Foxon et al., 2005; Foxon, 2010).

Regardless of the approach used to promote demand for green steel, most interviewees (20) stressed the importance of setting certified standards for what 'green' means in order to enhance consumer trust in green product labelling and traceability. This resonates with Element Energy's (2018) emphasis on creating a standardized certification scheme for low-carbon products while simultaneously raising awareness of the carbon intensity of goods amongst consumers.

Further interviews with automotive industry experts revealed that demand for green steel in end-products can be enhanced if a circular economy thinking was adopted, one which also accounts for the greenness of input materials. For example, in the case of the automotive industry, the EU End-of-Life Vehicle (ELV) Directive (2000/53/EC) (European Commission, 2000) could be revised in line with the EU Green Deal to add resource efficiency and minimal climate impacts to the set of requirements of materials used in, and recycled from, vehicles, effectively creating a case for 'green steel vehicles'. Respondents also noted that while demand for greener material has been coming from original equipment manufacturers (OEMs) rather than end-users themselves, end-users could be made aware of the energy and carbon footprint of their vehicles, through marketing initiatives for instance, after which they may become more inclined to change their purchasing behavior, and in turn encourage companies to adapt their manufacturing strategies.

4.2.2. Supply-side 'push' mechanisms

In terms of green steel supply, some interviewees argued that steelmakers may be more receptive to reward-based mechanisms than legal enforcement or disincentives (e.g. carbon taxation). Despite this claim, there is strong evidence that adopting a combination of incentive and disincentive mechanisms has been successful in driving similar emerging markets elsewhere, such as the UK Renewables Obligation mechanism, which required energy suppliers to purchase a certain percentage of electricity from renewables or pay a penalty, which was recycled back as incentives for renewable energy developers; or the Rota 2030 automotive industry policy in Brazil, which enforces emission efficiency requirements on vehicles produced by an OEM, which can be offset by producing a larger share of electric and hybrid vehicles (Marx et al., 2018). Similar to demand-side regulatory requirements on major steel consumers, supply-side regulatory mandates could be placed on steelmakers to produce a given proportion of their steel as green, or to meet a certain 'green threshold' for all steel produced on average. This could be implemented in various ways, including via a tradeable certificate scheme for green steel, similar to the UK Renewables Obligation, where steel end-users or final suppliers in a supply chain would be required to purchase a certain proportion of green certificates per unit of steel, while producers of green steel would be awarded certificates which they could sell to offset their increased production costs.

Regardless of the implementation method, and unless the costs of mandated green steel production are fully subsidized by government (for example through a contract for difference (CfD) mechanism (Richstein, 2017)) or fully recovered from niche green steel consumers, affected domestic producers would tend to lose market share to overseas competition from countries without equivalent green mandates. One way to hedge against this would be to apply a carbon border adjustment (CBA), i.e. taxation on the carbon content of imported steel (Eurofer, 2019b), which would ensure that all final consumers face the same internalized cost of carbon. However, it is noteworthy that only those governments that already have high carbon prices in place may be willing to introduce such adjustments. The EU, which imports around 10 million tonnes of steel more than it exports (Eurofer, 2019b: 3) and has a carbon price of €53/tCO_2 as of June 14, 2021, is one of the more likely candidate regions for implementing carbon border adjustments, which is currently being developed.

If carbon border adjustments were to be adopted, numerous questions remain about how they could be implemented in practice. There is potential for unintended consequences, such as displacement of steel consumption by alternatives, which might have higher or lower life cycle emissions. In the EU for example, a CBA may expose EU steel producers, and in turn their related value chains, to carbon costs on their entire production, putting them at a disadvantage against importers who would only be liable for carbon costs on steels they import to the EU. Around 20% of EU steel consumption comes from imports (from China, Russia, India, Turkey, Ukraine, etc.) which are not subject to the same carbon costs as EU steel. A CBA should be designed in a way that importers face carbon costs which are comparable to the EU steel industry to provide an incentive great enough to invest in green steelmaking while also avoiding carbon leakage and resource shuffling (e.g. switching between production routes which have very distinct carbon footprints).

A number of interviewees (8) linked any potential success of a CBA with addressing the shortcomings of free allocations provided under the EU ETS, while also acknowledging that a well-designed CBA would incentivize other jurisdictions with high steel trade with the EU to follow suit in greening their own steel production. Here, the definition of the carbon content, or 'greenness', of traded steel products is key to enabling a robust and meaningful CBA: as part of the European Commission's 2020 public consultation on a possible CBA mechanism, Eurofer (2020) suggests that a CBA should cover Scope 1 and 2 emissions, which, unless measured consistently amongst domestic and international suppliers, could risk circumventing the primary objective of the mechanism. Here, the EU's Product Environmental Footprint approach (Ernst & Young, 2017) may serve as a starting point to develop a transparent and robust methodology on which both product labelling and taxation could be based.

Even if successful, a carbon border adjustment only serves to protect a domestic market from being undercut by *imported* products but does not ensure that exports can compete on a level playing field in overseas markets (for instance, the UK lime sector, as a major supplier to the steel sector, is a significant exporter whose overseas markets cannot be protected by UK Government intervention). Exports could be protected by exempting them from domestic green steel production mandates, but this would undermine the goal of decarbonizing the steel industry. It is therefore evident that implementing green production mandates in combination with carbon border adjustments will have significant implications on international trade and climate diplomacy, with close cooperation needed between major trading partners.

To avoid some of the complexities associated with implementing such adjustments on an EU or global scale, Neuhoff et al. (2016) propose applying a consumption-based charge on carbon-intensive materials, calculated as the product of the weight of the material, a product-specific benchmark for primary production using best available technologies, and the prevailing carbon price, creating what EURACTIV (2021) referred to as a 'notional ETS'. A liability for the charge would be created at the point of production or import, passed down the supply chain and paid by the end consumer, with collected funds being used by governments for climate action. The advantage of such a mechanism from the perspective of green steel production is that it would impose a cost of carbon on all emissions-intensive materials, thus addressing substitution concerns as well as reducing the cost differential between green and non-green steel, while simultaneously raising funds which could, in part, support green steel research, development and demonstration.

Some interviewees argued that regulatory measures should focus on increasing the rate of steel recycling; however, it is noteworthy that while recycling more scrap may be possible in some countries, developing countries are normally short of scrap resources and primary steelmaking will remain an integral part of their economic welfare (Döhrn and Krätschell, 2014). Another option raised by an interviewee was to consider lowering steel consumption altogether:

> *'however there is a moral and ethical dilemma with this especially for developing countries where increases in GDP are closely correlated with steel consumption per capita, and which only levels out once a country reaches a certain level of development' (interviewee 18).*

As steel manufacturing from iron ore will still be needed in some regions, efforts should be made to switch to electric arc furnaces where possible, especially in areas where blast furnaces are coming to their end of life. Interviewee 13 maintained that the only reason this trend has not been witnessed in regions such as the UK is their high national energy prices, which represents a potential area where policy intervention can reduce energy prices and encourage investments in EAF steelmaking.

As outlined above, a range of policy mechanisms thus exist on the demand and supply side of a potential green steel market (Figure 3). However, the choice of specific policies, and combinations of those policies, hinges on the policy landscape in different regions, including government attitudes towards market intervention. Ad-hoc mechanisms may also be needed for major steel-producing countries which produce greener steel than they import (e.g. United States), which further emphasizes the need for highly context-dependent support policies. Major steelmakers and their largest customers (e.g. construction companies and automakers) may also voluntarily set emissions targets, for instance as part of the Science Based Targets Initiative. In fact, a few steelmakers including SSAB and Vale have already set such science-based targets (SBTi, 2020). Further research is needed to appraise the effectiveness of these different policy combinations.

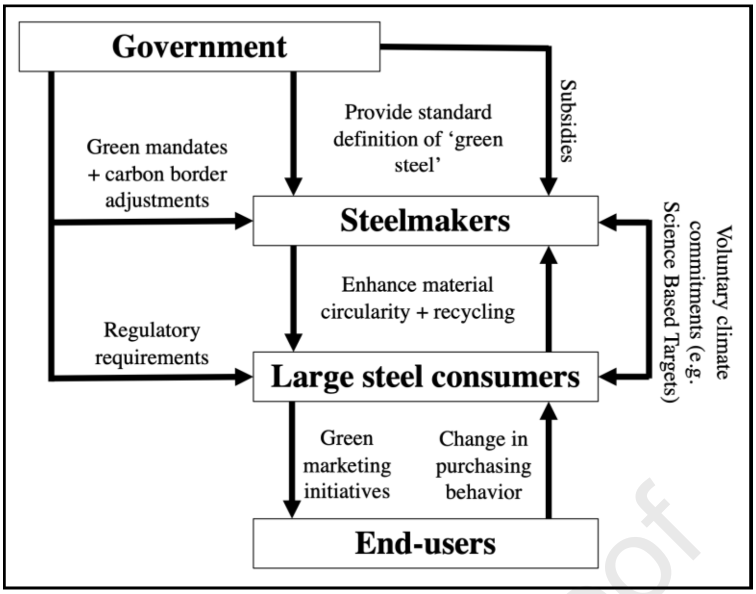

Figure 3. Mechanisms to support a green steel market.

4.3. Potential markets for green steel products

We investigated the potential for green steel uptake in different sectors, if we assume that the additional costs of green steel production will not be 100% subsidized by governments. Interviewees representing steel producers pointed out that substantial additional costs could not be borne by steel producers, as they operate on increasingly miniscule margins in a globally competitive market. At the other end of the supply chain, evidence suggests that individual consumers generally do not have a high willingness to pay for products which do not exhibit improved performance or quality compared to their less environmentally-friendly counterparts (see, for instance, Roe et al. [2001] and Saphores et al. [2007] where individuals were not willing to pay more than 1% more on average for green electricity and green electronics, respectively). However, certain niche consumers may be willing to pay higher prices for greener steel in specific end products. The sectors mentioned most often by the initial set of interviewees (ID 1-21) as having potentially higher willingness to pay were the construction and automotive sectors, which represent two of the largest sectors by steel consumption (Figure 4). Follow-up, targeted interviews with sustainability experts from both sectors (ID 22-27) provided further insight on this, as outlined next.

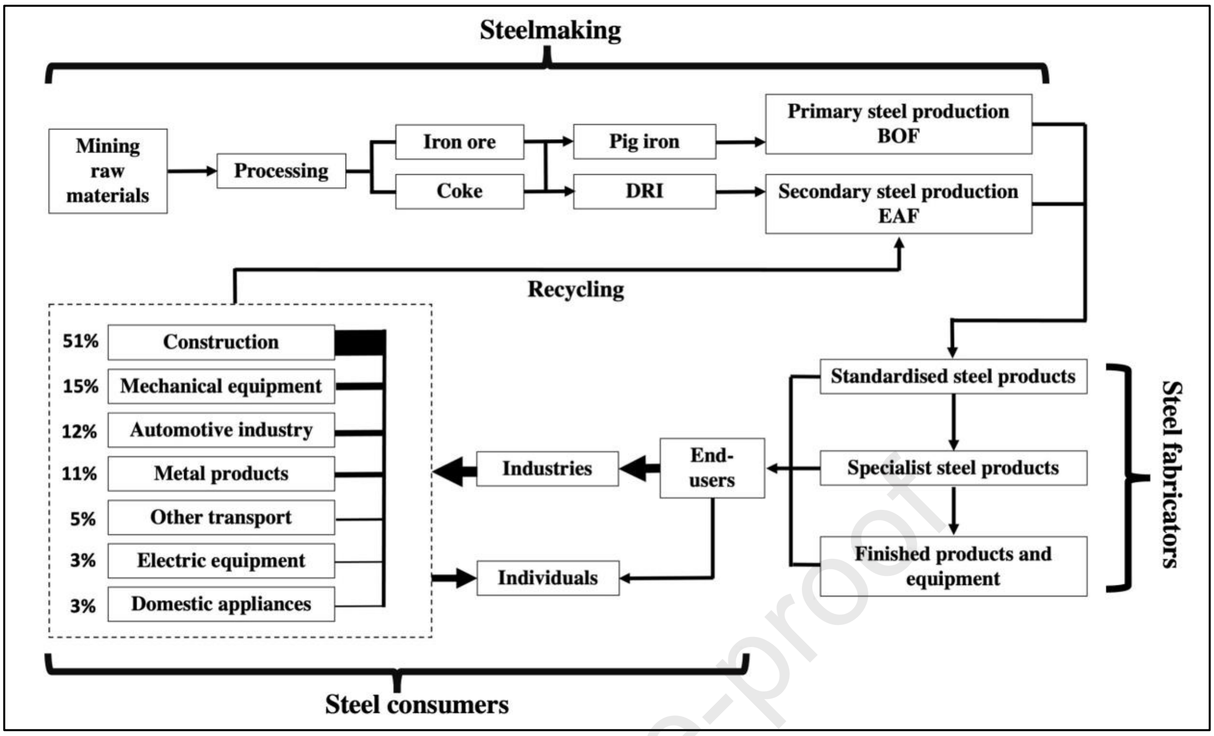

Figure 4. Schematic diagram of the steel industry supply chain. Percentages of global steel consumption by sector are representative of steel usage in 2018, as reported by Worldsteel (2018).

4.3.1. Construction sector

The construction sector is responsible for around half of steel consumption worldwide (51%) (Worldsteel, 2018). However, there are two main challenges which may hinder any voluntary uptake of green steel by the sector. Firstly, the sector's supply chain is risk-averse, highly decentralized and intensely fragmented (Arora et al., 2014), involving many actors such as architects, fabricators, constructors, building commissioners, owners and renters of finished buildings. It would be exceptionally difficult to coordinate efforts between these actors, and in addition, most of these actors operate on small profit margins (McAdam & Brown, 2001):

> *'The construction industry is really contractual and has a fragmented supply chain. In a construction project, you have multiple layers of contractors and subcontractors and every one of them tries to balance out their margins and shave costs down. Unless the entity at the top of the chain specifically specifies a need for green steel and is prepared to pay a premium for it, it is not going to happen' (interviewee 13).*

In the US, while there have been calls for improvement in embodied emissions in construction material, the resulting initiatives have typically been driven by the architect or designer of the building and not implemented at a federal level (interviewee 5). Notable examples of such initiatives are the Embodied Carbon in Construction Calculator (EC3) tool which aims at selecting lower-carbon options for construction (Building Transparency, n.d.), and the California-based Buy Clean programme which has a similar objective (Buy Clean, n.d.). Nonetheless, it is worth noting that these initiatives were not designed to directly incentivize major production technology changes but are instead set up to identify and adopt existing lower carbon options.

Secondly, steel is only one of many components in the make-up of finished buildings, and consumers do not necessarily perceive greenness of buildings in terms of GHG emissions during construction, but more in terms of energy usage and hence of emissions intensity during the operational phase. This suggests that any demand for green steel products from the construction sector is likely to be associated with green buildings which are already operating at higher operational emission efficiency levels, as embodied emissions from their construction will account for a relatively larger part of whole lifecycle emissions. However, it is imperative to note here that the green buildings market currently constitutes a very small part of the overall construction industry: by 2024, it is forecast that the global green building market will be valued at around 328 million USD (Market Research Future, 2018) while the total construction market is estimated at 11 trillion USD by the same year (Business Wire, 2020), rendering any potential role for green steel to decarbonize the global construction sector relatively insignificant.

4.3.1.1. Automotive sector

In contrast to the construction sector, green steel is more likely to be adopted by the automotive sector due to: 1) the higher proportion of primary steel used in cars than in buildings[6], 2) a much less complex supply chain with fewer market participants than the construction sector (interviewee 10), and, as underlined by many interviewees, 3) a relatively insignificant increase in the incremental cost of a vehicle if made with green steel.

Indeed, on the latter point, considering that on average there is 0.9 tonnes of steel per manufactured car (Worldsteel, 2020c), and assuming a trading price of €600–750 per tonne of steel based on 2019 trends (World Steel Prices, 2020) and that the introduction of breakthrough emission reduction technologies into steelmaking might increase the cost of steel production by 20–40% (based on upper-end ranges as reported in the literature, e.g. Element Energy [2018]), the cost per car manufactured would increase by only €108–270. Given that the range of retail prices of average gasoline and diesel cars is between €20,000–27,500 (International Council on Clean Transportation, 2019), the overall increase in the incremental cost of finished vehicles would be between 0.5–1%. More specifically, with CCS as the deployed technology, Element Energy (2018) reports that up to 75% of carbon emissions can be captured from integrated steelworks, leading to an increase of 19% in the cost of steel production: this translates to an increase of around €103–129, or 0.5%, in incremental costs of a vehicle. Rootzén and Johnsson (2016) showed that CO_2 trading and investments in CO_2 abatement at integrated steelworks (assuming the purchase of emission allowances at a carbon price of €100/tCO_2 abated) would have a similar impact: an increase of around 0.5% in the final retail price of cars using steel from those steelworks.

Interestingly, while most interviewees maintained that this makes an obvious case for green steel usage by the auto industry, interviewee 22, a sustainability expert at a global auto manufacturing company, warned that cost increases – even if small – may not necessarily be absorbed by auto manufacturers:

> *'For mid-sized passenger cars, profit margins can actually be as low as €200 per car, rendering manufacturers increasingly hesitant to absorb costs associated with the implementation of lower*

[6] Steel used in construction is not subject to the strict grading requirements which are typical of steel used in vehicles: where recycled steel may suffice for a construction project, vehicular steel requires additional input of pure, primary steel, especially for forming complex shapes on automobile bodies (interviewee 14).

carbon production options. It may be that auto manufacturers could instead pass costs down to consumers, as evidence from the increasing demand for electric vehicles shows that there is a high willingness to pay for greener vehicles' (interviewee 22).

A case could especially be made for incorporating green steel into high-end, highly fuel-efficient luxury and heavy-duty vehicles, as 1) in the case of fuel-efficient vehicles, emissions embedded in the vehicle's makeup will typically contribute a larger proportion of its lifecycle GHG emissions, and 2) in both cases of fuel-efficient and heavy-duty vehicles, costs could potentially be passed on to consumers who may be willing to pay an additional, relatively-insignificant premium compared to the total cost of the vehicle; additionally 3) manufacturers of both types of vehicles may themselves be willing to absorb some additional incremental costs as they are likely to be operating at higher profit margins than mass-market producers (interviewee 23). OEMs may be relatively risk-tolerant in entering an uncertain market if they perceive an opportunity to establish a first-mover advantage in a new supply chain that may be more lucrative in the future. An example of this is Toyota's 2012 joint venturing with Tesla to produce the RAV4 EV model: only a few thousand units were produced and circulated in the US in order to test the market (Chen and Perez, 2018). Today, in the US, interviewee 8 noted that:

'It seems that auto makers are moving away from focusing solely on so-called tailpipe emissions versus the actual embodied carbon that enters into the vehicles. So, I think in the automotive industry the incentive or the direction toward greener products, including steel, probably needs to come from the OEMs themselves, rather than from the consumer, at least at this point'.

Despite cost and energy-efficiency commonalities with luxury vehicles, electric vehicles are unlikely to provide significant demand for green steel adoption, at least at present, as heavy subsidies channelled at the EV market are still aiming to increase their global market penetration rather than greening their manufacturing.

5. Conclusions

Establishing a market for low-carbon products such as 'green steel' has emerged as an innovative solution to drive a clean technology transition in steelmaking. Fortunately, a green steel market can benefit from many precedents such as the creation of markets for organic foods or the rise in renewable energy generation, where lessons can be learnt from early market failures and the mechanisms that drove the products' eventual roll-out to the market. One of the main takeaway messages from this work has been the need to avoid greenwashing and unintended consequences which could arise from having different routes to green steelmaking and different methodologies to account for that greenness. This could be achieved by agreeing on a clear definition and accounting methodology, preferably based on a consequential approach to quantifying emission reductions, ensuring that any claims based on 'contractual' emission factors are restricted to renewable generation that is genuinely additional, and having recycled steel acknowledge the carbon footprint of primary steel, and/or setting different standards for each production route.

Another common problem with any market intervention is that it can distort competition, including between domestic and overseas producers, between primary and secondary production routes, and between steel and substitute materials. A general conclusion is that a mix of policy instruments which promote consistency between sectors and across countries is highly desirable. In the absence of government procurement or other regulatory-driven demand, the market for green steel products is likely to be limited to niches of highly-differentiated products for environmentally-conscious consumers. Growing from these niches to the mainstream, which is necessary to achieve the decarbonization goals of the Paris Agreement, is likely to require more active government intervention on the supply and/or demand side.

This paper made evident a case for green steel use in the auto industry, especially in high-end luxury and heavy-duty vehicles. This comes at a time when major automakers worldwide are becoming more attentive to their operational carbon footprint and the indispensability of undertaking full life-cycle assessments in their endeavour to achieve transparent climate action. However, this work leaves many areas of research to be desired, specifically the need to:

- Establish an accounting methodology that fairly accounts for consequential lifecycle emissions produced from primary and secondary steel production routes;
- Investigate a combination of complementary region- and country-specific policy mechanisms which may economically and politically support a case for green steel production and consumption; and

- Evaluate the likelihood of incorporating green steel in auto manufacturing through wider market consultations and studies appraising the consumer's willingness to pay for 'green steel vehicles'.

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Author contributions

Hasan Muslemani: Writing as part of PhD thesis: Conceptualization, Development of Methodology, Data Collection, Data Curation, Formal Analysis, Writing – Original Draft, Funding Acquisition; **Xi Liang:** Conceptualization, Supervision, Writing – Review & Editing, Funding Acquisition; **Katharina Kaesehage:** Supervision, Development of Methodology, Writing – Review & Editing, Funding Acquisition. **Francisco Ascui:** Conceptualization, Supervision, Validation, Writing – Review & Editing, Funding Acquisition. **Jeffrey Wilson:** Writing – Review & Editing, Funding Acquisition.

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Declaration of interests

☒ 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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