



Original research article

Towards a CO₂-neutral steel industry: Justice aspects of CO₂ capture and storage, biomass- and green hydrogen-based emission reductions

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ABSTRACT

A rapid transition towards a CO₂-neutral steel industry is required to limit climate change. Such a transition raises questions of justice, as it entails positive and negative impacts unevenly distributed across societal stakeholders. To enable stakeholders to address such concerns, this paper assesses the justice implications of three options that reduce emissions: CO₂ capture and storage (CCS) on steel (up to 70%), bio-based steelmaking (up to 50%), and green hydrogen-based steel production (up to 100%). We select justice indicators from the energy, climate, labour and environmental justice literature and assess these indicators qualitatively for each of the technological routes based on literature and desk research. We find context-dependent differences in justness between the different technological routes. The impact on stakeholders varies across regions. There are justice concerns for local communities because of economic dependence on, and environmental impact of the industry. Communities elsewhere are impacted through the siting of infrastructure and feedstock production. CCS and bio-based steelmaking routes can help retain industry and associated economic benefits on location, while hydrogen-based steelmaking may deal better with environmental concerns. We conclude that, besides techno-economic and environmental information, transparency on sector-specific justice implications of transforming steel industries is essential for decision-making on technological routes.

1. Introduction

The global economy is currently heavily dependent on the exploitation of fossil fuels. In 2019, 80% of the global energy system was based on fossil fuels [1]. The fossil fuel industry and industries directly dependent on fossil fuels have become ingrained in our society and economy, accounting for about 30% of global GDP and providing 23% of total employment globally in 2020 [2]. The extraction, transport and use of fossil fuel are accompanied by a significant environmental impact [3], including through CO₂ emissions, which needs to be reduced to net zero by 2050 or 2070 to limit global warming to levels in accordance with the Paris Agreement [4]. Despite the urgent need to reduce greenhouse gas (GHG) emissions, decarbonisation progress of most high emitting

industries is not aligned with the Paris Agreement goals [5]. Further growth and industrialization are taking place in developing regions [6,7], while developed regions struggle to decarbonise existing facilities, citing increased production costs in a globally competitive industry as reasons for the lack of progress [8,9].

One of the fossil-dependent, hard-to-decarbonise industries is the steel industry (including primary iron production). The steel industry produced a gross value added of US\$500 billion in 2017, 0.7% of global GDP, or US\$2.9 trillion and 4.1% if the up-and downstream supply chain is included [10]. It employs 6.1 million people directly and an additional 89.9 million indirectly [10]. Direct CO₂ emissions of the steel industry account for about 7% of global energy-related CO₂ emissions¹ as a result of the consumption of about 8% of global final energy [11]. The

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¹ Energy-related CO₂ emissions include both those from the combustion of fossil fuels and industrial process emissions, totaling 36 Gt CO₂/yr in 2019. When including indirect emissions from the power sector and the combustion of steel off-gases (a further 1.1 Gt CO₂/yr), the share of energy system CO₂ emissions attributable to the iron and steel sector rises to 10% [11].

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projections of steel demand by 2050 indicate ranges between current demand [12] and growth of over a third [11,13]. These demand projections account for effects that could reduce steel demand, such as an increasingly circular economy and material substitution. In order to achieve CO₂-neutral steel production in three to four decades from now, technological transformations are needed as efficiency improvements in traditional steelmaking have nearly been exhausted. The average energy and GHG intensity of steel hardly changed over the past two decades, as moderate improvements in energy efficiency in some parts of the world have been offset by the construction of less efficient plants elsewhere [11,14]. If steel cannot be substituted with lower-impact materials, deep emission reduction of steel production will require technologies that have not yet been widely implemented on an industrial scale.

Three technological routes that can reduce emissions are currently considered as promising by the steel industry: direct reduction of iron with green hydrogen, CO₂ capture and storage (CCS), and bio-based steelmaking [11,15]. Hydrogen-based steelmaking could lead to a near CO₂-neutral steel industry as an individual technology. CCS can reduce emissions by up to 70% and bio-based steelmaking can reduce emissions up to 50%, but need to be combined in order to reach a CO₂-neutral industry. Differences in these technologies mean that they may not be cross-compatible with different steelmaking processes or innovations and have different infrastructure and resource requirements. This is in addition to differences in costs and the timescales at which they can realistically be implemented. Techno-economic assessments have been conducted, which have shown that under existing policies and regulations, there is often no business case for implementing these technologies [11,15–18]. However, in addition to techno-economic impacts, such transformations are unavoidably accompanied by justice aspects. The different technological routes towards a CO₂-neutral steel industry come with very different implications in terms of the burdens and benefits for various stakeholders.

So far, justness aspects of the transition towards a CO₂-neutral steel industry have not been widely addressed in the literature [19,20]. Societal aspects have received scarce attention, despite their clear relevance [21]. A mismanaged transition risks undue closure of industries, loss of jobs, high costs, and missed opportunities to reduce emissions [22]. Still, even under adequate management, the transition will know winners and losers. For example, those currently working in fossil fuel-based industries are potentially adversely affected through loss of employment [23] or low-income groups may not be able to afford sustainable products [24]. Thus, ensuring a fair distribution of burdens and benefits within the transition is recognised as an increasingly critical aspect of the transition, both in the academic literature [19,20,25,26] and in energy and climate policy such as the proposed just transition mechanism in the European Green Deal [27] or the US executive order on tackling the climate crisis [28].

Ensuring a so-called ‘just transition’ is not only an ethical or moral ambition but may ease and accelerate system transitions more generally [29,30]. By enabling a just transition, the industry can maintain its ‘social license to operate’ when resistance to the industry is rising [31,32]. Climate change mitigation and the associated transition to sustainability does not only impact society, society also shapes sustainability transitions. Academic discourse on sustainability transitions has broadened beyond the study of technological innovation to view transitions through a wider scope of socio-technological systems [33–38]. Socio-political elements such as legitimisation [39] and policy [40] are part of a set of enabling conditions for the systems transitions needed to limit global warming to 1.5C [41]. It is argued that a level distribution of burdens and benefits may increase public support for funding the energy transition [42,43], and transitions without public acceptability are unlikely to succeed [44]. If concerns of citizens, communities and NGOs are taken seriously, resistance to the inevitable change accompanying the transition may be mitigated [45], allowing trust to grow and conversations to focus on solutions.

This paper aims to fill the literature gap by presenting a broader,

literature review-based assessment of just transitions of the three technological routes towards climate neutrality in the steel industry. With some exceptions [46], most studies on just transitions focus on coal mining [47–50] rather than on fossil fuel-using sectors. To date, the only study looking into the societal impact and just transitions in specifically the steel industry, focusses on labour-related just transitions aspects [50]. We develop a holistic yet practical perspective of what deep emission reductions in the steel industry entail for society. The research question of this assessment is: How do technological routes for deep emission reduction in the steel industry differ in terms of justice?

The remainder of this paper is structured as follows. In Section 2, we provide contextual information on the steel industry and its relevance to just transitions. We develop our assessment methodology in Section 3. Section 4 features the qualitative assessment of justice in potential routes towards a climate-neutral steel industry. Finally, Section 5 contains the conclusion, and in Section 6, we discuss the implications of our results.

2. The steel industry and just transitions

Long lifetimes of steelmaking assets result in inertia in the steel industry. Even when new technologies are available, implementation can be slow, and accompanying GHG emission reductions are not realized quickly. The average lifetime of a blast furnace and basic oxygen furnace steelmaking plant is 40 years, but there are significant variations [11]. Every 17 years on average, a plant needs major servicing as the internal refractory lining of the blast furnace needs to be replaced [51]. The cost of relining is about half of the investment cost of a new blast furnace. These assets’ age and maintenance profiles are generally a good indicator for the decommissioning rate of steelmaking plants [11,51]. About 80% of the main assets globally in iron and steelmaking are younger than 20 years [14,51]. This is mainly due to investments in China, which doubled global steel production capacity between 2002 and 2013 [52] and put pressure on profitability of steel-making. Steel production has grown sharply in the last century, from 189 Mt. in 1950 to 1808 Mt. of crude steel production in 2018 [53]. Over the last decade, steel production has shifted towards China, growing from 38% to 51% of global crude steel production, while the shares of the European Union (15% to 9%), members of the North American Free Trade Agreement (9% to 7%), Japan (9% to 6%) and the Commonwealth of Independent States (9% to 6%) have declined. The relative share of steel consumption follows similar trends in these regions [53]. The combination of global growth in steel production, trade tariffs in the US, the EU Emissions Trading Scheme, and reduced steel consumption has resulted in global overcapacity, and increased imports and subsequent closure of steel industries in the EU and US [54–56].

The climate transition will likely change the production and consumption patterns of steel, as location advantages may relate more to the availability of green hydrogen [57] or CO₂ storage reservoirs than to, for instance, access to coal supply. This may lead to questions around the justness of transitions in areas that rely on a steel plant for employment and economic prosperity. The literature on just transitions in the declining coal industry and communities is extensive [47–49,58,59] and holds lessons for the steel industry. There are similarities and differences. Both the coal and the steel industry employ many people, are of economic significance at a regional level, and of strategic importance to countries, and are deeply intertwined with the local industrial ecosystem [10,11]. What makes steel production different from coal mining is that the global steel demand is expected to be stable or growing for the foreseeable future, whereas coal consumption is expected to decline rapidly [11,12]. Another difference is that in steel production, technological options that reduce GHG emissions from steelmaking are promising [11,15], while those for coal, including CCS, are less viable.

Whereas the discussion on justice for displaced coal miners is focused on dealing with the consequences of the transition away from coal

[48,60,61], the question of the consequences of the climate transition for steel-dependent regions is not as clear. Closing down the steel industry on a global scale is not an option due to continued demand for steel, but global overcapacity in steel production means that delocalisation of industry and carbon leakage are substantial risks [62]. Carbon leakage occurs when businesses transfer production to other countries with lower production costs due to less strict climate policies, moving, and potentially increasing global GHG emissions. Current policy frameworks are tailored to mitigate carbon leakage risk by effectively providing discounts for susceptible industries [63], while innovation policy focuses on green new technologies rather than decarbonizing the basic materials industry [64]. The just transition debate around the coal industry is about a fair termination of activities. In contrast, a just transition debate around the steel industry would focus more on finding satisfactory solutions for continuing operations in a strongly modified way. The choice of technologies to bring about deep emission reductions in the steel industry has far-reaching impacts on the industry itself [15] and the stakeholders that affect or are affected by the steel industry.

3. Conceptual framework and methodology

We conduct an assessment of justice aspects of technological routes towards climate neutrality of the steel industry. We use existing peer-reviewed and grey literature as the data source. Because of the explorative nature of this study, we do not conduct a systematic review. We first describe the technological routes and technological scope of the assessment in Section 3.1. Subsequently we build an assessment framework in Section 3.2. The indicators for the assessment are derived from the just transitions literature discussed in Appendix A. In Section 4, we will qualitatively assess each of the relevant indicators for each of the technological routes based on the available academic and grey literature.

3.1. Technological routes towards a climate-neutral steel industry

We evaluate three technological routes that could significantly reduce GHG emissions: CCS, bio-based steelmaking, and hydrogen-based steelmaking. The technological routes were selected on the basis of existing techno-economic assessments of steel emission reduction technologies [11,15,17,18,65]. These assessments consider CCS and bio-based steelmaking capable of significant emission reductions individually, and capable of deep emission reductions when combined, or even in some cases CO₂removal [66]. Green hydrogen-based steelmaking is capable of deep emission reductions in itself. We differentiate between green and blue hydrogen-based steelmaking. Green hydrogen is generated by electrolyzers powered with green electricity, blue hydrogen is generated by traditional steam-methane reforming with CCS. Our discussion focusses on green hydrogen-based steelmaking as emission reductions are higher compared to blue hydrogen-based steelmaking. However, we will mention reinforcing or cancelling effects of using blue hydrogen instead of green hydrogen. These assessments also consider CCS, bio-based and green hydrogen-based steelmaking technologically feasible by 2050, while direct electrification of primary steel production still has too many technological uncertainties to make an assessment [11,15,17,18,65]. Our assessment will discuss CCS and bio-based steelmaking separately, because each technology has its own implications for justice. However, as they need to be combined to reach CO₂-neutrality, we will explicitly note if there are effects that reinforce or cancel out each other, and treat them as cumulative for the purpose of discussion in comparison to hydrogen-based steelmaking. Efficiency improvements, CO₂ capture and utilization (CCU), and integration such as top gas recycling blast furnace (TGR-BF) or Hisarna in traditional steelmaking processes cannot achieve deep emission reductions, with most options reducing emissions up to 20% [11,15,17,18,65]. CO₂ capture and utilization (CCU) is not considered for two reasons: because the mitigation potential of CO₂capture is higher when CO₂ is stored

permanently instead of utilized in most cases [67], and because the scale at which CO₂ could be utilized in products is far smaller than the amount of CO₂ that is produced [68,69].

The scope of analysis for the assessment is effectively cradle-to-gate with the exclusion of the sourcing of iron or scrap metal. We make the assumption that the amount of scrap metal resources is far from sufficient to satisfy demand for crude steel [70] and the impact of iron ore mining does not differ between the different technological routes. We include upstream energy generation and resource extraction for the purpose of fuel in our scope of analysis because these strongly differ between the technological routes and can have major societal repercussions.

3.2. Indicators for justice

The potential contribution to a just transition of the different technological routes is assessed on the basis of indicators derived from literature on justice in sustainability transitions. Studies on justice related to sustainability transitions can be broadly categorized across two dimensions based on their approach: 1) by the earlier motives of justice: The labour perspective [71,72], environmental justice [71,73], climate justice [74,75] and energy justice [76,77], 2) type of justice: Distributional, procedural, recognitional and restorative justice [19,20,26,78–80].

Below we explain the core concepts in each of these approaches to justice in sustainability transitions and discuss how they could apply to the steel industry. From a review of different approaches to justice in sustainability transitions literature, we develop a set of indicators to assess the just transition potential of a technological route. In categorization of the indicators, there is overlap between the types and motives of justice; Indicators can generally be argued to fit under both a type and motive of justice. In order to avoid repetition in text and improve clarity, we structure the results along the earlier motives of justice (labour, environmental, climate and energy). The relevant types of justice (distributional, procedural, recognitional and restorative are included, but discussed under the relevant motive of justice. The results are summarized in Table 1. More detailed discussion on the different types and motives of justice, and how they relate to the indicators can be found in Appendix A. In the results section, we discuss how each indicator, denoted by codes in parentheses, relates to the individual emission reduction technologies in the steel industry.

4. Results

At the outset, the status quo of steel production is not neutral in terms of justice. Steel is essential in infrastructure, buildings and more. Demand is expected to remain stable or grow [11,12] despite advances in material substitution and an increasingly circular economy. The steel industry negatively impacts the local environment through particulate matter pollution (E10) [87–89]. Despite this, the jobs and secondary economic activity benefit local communities (L1,L2) [10], even though work in the steel industry is tough and comes with health and safety risks (L3) [90]. In terms of climate, GHG emission reduction efforts of the steel industry so far are not aligned with the Paris Agreement goal of limiting global warming to 2 °C or less (C12,C13,C14) [5]. Certain justice implications of transition routes are therefore not dependent on what new technology is implemented but on what happens with the existing industry. This goes for both burdens and benefits. For example, in terms of employment or economic benefits, continued economic activity may be more important than what that activity is, as is argued in earlier debates between labour and environmental justice [71,91]. In this section, we will discuss the themes in the just transition as relative to the existing industry.

Table 1

Overview of core concepts in different motives of justice (labour, environment, climate or energy), relevance to the steel industry and associated indicators.

Core concepts	Relevance to steel industry	Indicators
<p>Labour justice</p> <p>The 'just transition' was originally about sustained employment for workers in industries threatened by environmental policies [81]. The concept of labour justice was then expanded in scale and scope. In addition to job security, the discussion also included safety and worker rights for the labourers, and included people and communities dependent on the workers and regional economies, along with associated culture and identity. [71,82]. Additionally, the rights of workers to fair participation in decision-making is also considered under labour justice [19,20]</p>	<p>A transition of the steel industry could mean any number of changes for the employee, ranging from the type of work and working conditions, to a change in the number of jobs or potential relocation of the industry, which would not only impact the workers directly, but also their communities. From the perspective of labour justice, workers should be able to participate fairly in decision-making regarding the future of the industry.</p>	<p>Employment (L1) Community impact (L2) Worker's safety (L3) Fair employee participation(L4) Preservation of culture and identity (L5)</p>
<p>Environmental justice</p> <p>Environmental pollution, that disproportionately affected people of colour and lower socio-economic status, first spurred the environmental justice movement [73]. It has since developed to include different types of environmental burdens and risks, but also fair community participation in industrial development procedures and recognition and repair of previous injustice [71].</p>	<p>The choice of technology to reduce emissions in the steel industry largely determines the environmental burdens and risk as well as how pollution and risk are addressed. Procedural aspects may be relevant in the siting of infrastructure, for example, the siting of wind turbines or gas pipelines [83–85]</p>	<p>Non-GHG pollution (E6) Environmental risk (E7) Safety risk (E8) Fair community participation (E9) Addressing pollution and risk (E10)</p>
<p>Climate justice</p> <p>Climate justice builds on the idea that historic responsibility for, and adverse impacts of climate change are not distributed equitably among people [74]. It is often discussed through an intergenerational lens, as climate change impacts worsen in the future, while responsibility lies with past and current generations [86].</p>	<p>The steel industry shares in historic responsibility for emissions. The speed of implementation and emission reduction potential is dependent on the technology. Likewise, will this choice impact the future development of the industry.</p>	<p>Climate change impact (C11) Alignment with Paris goals (C12) Responsibility for emissions (C13) Carbon lock-in (C14) Distribution other costs and benefits (OD15)</p>
<p>Energy justice</p> <p>Reliable and affordable access to energy has become an essential human need. Energy justice is concerned with alleviating fuel poverty on an individual level and providing underdeveloped regions a chance to develop and reduce energy dependence [77].</p>	<p>Energy demand for steel production depends on the technology and could compete with energy demand by private consumers.</p>	<p>Affordability of energy (E16)</p>

4.1. Justice aspects steelmaking with CO₂ capture and storage

CCS can reduce GHG emissions in steel production by capturing up to 70% of the CO₂ from the plant's flue gases and permanently storing it away from the atmosphere in a geological formation (C12) [11,15,17,92], implying that additional actions are needed to reduce emissions to CO₂-neutrality. The implementation of CCS happens downstream from the steel production process. Significant parts of existing steelmaking facilities can continue to be used for CCS. However, parts will have to be adapted, for example, top gas recycling requires a rebuilding of the blast furnace [11,15,17]. In order to make these changes, the blast furnace needs to be offline, and this ideally coincides with the relining of the furnace (C14). From the perspective of labour, that would mean that existing employment in the industry is retained on location if CCS infrastructure is available. Temporary additional employment may be created through building the CCS infrastructure, and additional long-term employment in the maintenance and operation of the CCS facilities, using skillsets that are typically found in the oil and gas industry [93–95]. This would benefit both existing steelworkers and may provide opportunities to those at risk of unemployment due to a decline in fossil fuel extraction (L1,L2) [93–95].

CCS could help retain the identity and local culture by sustaining local communities that affiliate themselves with steel production and fossil industries [46]. Communities around steel plants may not always rely on that steel plant for economic prosperity and identity [50]. In those cases where steel plants are part of a larger industrial cluster, the loss of identity may be less pronounced. For example, if a steel plant becomes obsolete in a cluster because it is substituted by a hydrogen or bio-based steel plant elsewhere, this does not necessarily impact the region's identity if the rest of the industrial cluster remains unaffected [46] (L5). This is different from regions with closed coal mines that lost their identities, or where the steel mill is the core industry [96,97]. In such situations, communities could be dominated by families that moved to that region because of the mining or industry jobs. Those jobs becoming obsolete have a potentially devastating effect on those families (L2) [58,98].

A lack of changes in the underlying steel production process means that non-GHG pollution, such as particulate matter pollution, is not reduced [99]. It can even be argued that air pollution increases due to the additional power generation needed for the capture process (E6) [99], although it is unlikely that this power generation will be fossil-based given that we are assuming deep emission reductions also in the power sector. The negative impact of a steel plant on the local air quality has been ignored in the past [87,89,100,101] and using CCS for deep emission reductions could imply that these concerns remain unacknowledged and unaddressed (E10). Note that the application of CCS also perpetuates the need for coal in the steelmaking process. This avoids just transition issues associated with the closure of coal mines as previously discussed, but maintains the status quo on environmental impact from coal mines (E6) and jobs associated with health risks (L3). The CO₂ transport and storage operations inherently introduce additional environmental risks in the form of leakage, albeit primarily at the location of shipping, pipelines, and storage sites (E7,E8) [102]. Although the literature considers these risks to be small [103,104], the risk perceived by local inhabitants can be significant, with an enormous disparity between engineering-estimated and perceived risk in storage [105]. Fair community participation in CCS infrastructure development has been lacking in the past [106,107], and due to unfavourable views of the general public towards CCS [108], there may be a risk in future CCS projects (E9).

CCS on steel production has mixed implications for climate justice. Between CCS, bio-based and hydrogen-based steelmaking, the former has the most significant potential for short term, sizeable GHG emission reductions. While currently only one CCS plant is operational in the iron and steel sector [109] operators have plans in place to operate multiple industrial scale steel-based CCS projects before or around 2030 [109].

CCS in itself cannot make steel production fully CO₂-neutral but would contribute to short- and medium-term climate targets and preserve the carbon budget by reducing GHG sooner rather than later (C12) [110]. In the long term, combining CCS with bio-based steelmaking does allow for deep emission reductions [66,111]. While large scale BioCCS is controversial, mainly because of land-use implications of biomass cultivation and related emissions [112], the CCS infrastructure would enable combining biomass with CCS for deeper emission reductions (C11).

Finally, if CCS remains associated with fossil fuel-based industries, the development of CCS in steel-making could cause carbon lock-in, perpetuating the extraction and use of fossil fuels, preventing or slowing down efforts to reduce GHG emissions to near- or net-zero (C14) [38,113,114]. Carbon lock-in also reinforces the position of corporate entities, benefitting those that are already powerful and in part responsible for pollution and GHG emissions in the past (C13) [115].

We did not find evidence for impacts of CCS on indicators for fair employee participation (L4), distribution of other burdens and benefits (C15) and energy affordability (E16) in peer reviewed literature.

4.2. Justice aspects of biomass-based steelmaking

Biomass can be used in the steel industry to substitute fossil fuels in different parts of the steelmaking process, replacing coal breeze in sinter or pellet plants, coal or coke in the blast furnaces [15] or even in replacing coal or natural gas in the direct iron reduction production and electric arc furnaces [17]. The largest carbon input of biomass-based steelmaking are the cokes in the blast furnace. In the coking process, only a small portion (2–10%) of fossil materials can be substituted by biomass. As a result, the potential to reduce GHG emissions across the entire biomass-based steelmaking process is limited. Estimates of GHG emission reductions vary across the literature, with estimates of up to 50% GHG emission reduction if the maximum amount of fossil feedstock is substituted by biomass [116–118]. This means that biomass-based steel production does not qualify as a deep emission reduction technology. Technological progress is not expected to yield significantly larger amounts of fossil fuel substitution (C11).

Partial biomass substitution already occurs in very low amounts [119], but its global GHG reduction potential is limited by sustainable biomass supply (D11) [15,112,119]. Bio-based steelmaking can be phased in partially and implemented relatively quickly and therefore contribute to short- to medium-term GHG reduction targets (C12) [11,15,65], perhaps up to or shortly after 2030. Co-implemented with CCS, bio-based steelmaking does have potential for deep emission reductions [66,111] if the biomass is grown sustainably (C11). However, this could also contribute to carbon lock-in, as significant amounts of fossil fuels remain in use (C14).

Several of the justice implications of bio-based steelmaking run parallel to those of CCS. Existing plants can be adapted or retrofitted to utilise biomass [111] and therefore likely require little change in the workflow and workforce within local industries (L1). As a result, the impact on local communities is assumed to be minimal, allowing for the preservation of culture and identity (L2,L5). There is potential for additional employment throughout the biomass supply chain [120,121] where it can act as a stimulus to local economies (L2) [122,123]. Even though these jobs are upstream, and it is unclear if there will be a net increase in jobs by switching from fossil fuels to biomass, studies indicate jobs in the cultivation and processing of biomass are of higher quality compared to jobs in fossil fuel extraction (L1) [124].

The local environmental impact of steel plants decreases as bio-based steelmaking can lead to a slight reduction in particulate matter air pollution compared to burning coal [125]. However, other forms of pollution, such as graphite dust created by iron slag processing, would remain unacknowledged and unaddressed (E6). Bio-based steelmaking has significant upstream consequences due to the large amounts of required feedstock [112]. European BF-BOF steel plants would require

22% of the theoretical domestic woody biomass potential in Europe [126]. Biofuel production is land use intensive, causes direct and indirect land-use change, reducing biodiversity and causing additional GHG emissions (C12) [127]. Competition for land also leads to dispossession of land owned by locals, exclusion of locals, and diversion of water resources [122,123]. Biofuel production also potentially leads to an unequal distribution of burdens as it competes with food production, potentially causing food scarcity (C15) [128]. Furthermore, bio-based steelmaking also competes with the use of biomass for other GHG emission reduction efforts ranging from low-value energy generation to high-value pharmaceutical production (C11, E16) [129].

We did not find evidence for impacts of biomass-based steelmaking on indicators for workers safety (L3), (fair) employee participation (L4), environmental risk (E7), safety risk (E8), fair community participation (E9) and responsibility for emissions (E13) in peer reviewed literature.

4.3. Justice aspects of hydrogen-based direct reduction steelmaking

Primary employment for hydrogen-based steel production is likely similar to current DRI-EAF production sites and may have minor benefits in local secondary employment [50]. Considering the majority of existing primary steelmaking facilities is based on BF-BOF technology [14], switching to DRI-EAF often requires constructing new facilities, avoiding carbon lock-in (C14). Regions with favourable conditions for renewable energy and iron ore deposits (e.g. Australia and Brazil) may become a more attractive site for steelmaking [130], potentially relocating facilities along with jobs and communities (L2,L4,L5). The main benefit of hydrogen-based steel production in terms of employment is related to the fact that hydrogen is seen as the long-term option and therefore provides the most long-term job security (L1) [50]. Hydrogen-based steel production utilises the DRI-EAF process, causing significantly less environmental pollution than technologies that utilise the BF-BOF route (E6,E10) [131,132].

Sustainable hydrogen-based steel production with on-site electrolyzers requires large amounts of green electricity [133]. In regions without large scale geothermal or hydropower, there is increased need for solar panels and wind turbines, potentially causing injustices in community participation and distribution with regards to siting [83,85]. Development of wind and solar energy infrastructure can lead to the capture of resources or authority from the local public, marginalization of stakeholders, damaging the environment, and worsening existing inequalities (E9) [123]. The electricity requirements may also impact the market, driving up electricity prices for consumers, affecting low-income households to a larger degree (E16) [134]. Additionally, competition for a limited supply of green electricity [135] may impede other sectors reducing their GHG emissions through electrification (C11). Alternatively, hydrogen could be generated off-site in areas with easier access to green electricity at the cost of additional hydrogen transport infrastructure and associated costs – but also employment.

Given sufficient availability of green electricity, hydrogen substitution can make steel production fully CO₂-neutral in itself, in contrast to CCS or bio-based steelmaking (C11) [11,15,17,18,65]. While there are many projects looking to implement hydrogen-based direct reduction steel making, including a few already that are already online [136], affordable green electricity can currently only be generated on the required scale in regions with access to hydropower [137]; however, the expectation is that electricity generation elsewhere will reduce in GHG intensity over time globally. Allowing hydrogen-based steel production to become climate-neutral as availability and affordability of green electricity increases [138]. Therefore, hydrogen substitution is

considered a long-term option (C12) [11]. Alternatively, grey² and blue hydrogen-based steel production could act as stepping stone towards green hydrogen. This allows the development of hydrogen-based steel-making facilities while shortages of green hydrogen can be supplemented from other sources, but at the cost of lower emission reductions, and requires CCS infrastructure for blue hydrogen, which has other impacts on justice in itself.

We did not find evidence for impacts of hydrogen-based steelmaking on indicators for workers safety (L3), environmental risk (E7), safety risk (E8) and responsibility for emissions (C13).

5. Conclusion

This paper assessed the just transition aspects of different technological routes towards a CO₂-neutral steel industry. In order to reach deep emission reductions, only green hydrogen-based steelmaking or CCS combined with bio-based steelmaking suffice. We find that differences in justness between the different technological routes towards a CO₂-neutral steel industry can be expected. Still, we cannot conclude that one route is most just overall.

CCS and bio-based steelmaking do well on indicators tied to the labour perspective of justice by retaining employment at the existing steel plant site, along with other benefits for local communities tied to steel industry activities. However, in terms of recognitional and restorative justice, retaining the industry may mean that existing injustices such as particulate matter pollution remain completely or largely unaddressed by implementing CCS and bio-based steelmaking. CCS may also reinforce carbon lock-in, potentially delaying GHG emission reduction by crowding out alternative technologies and perpetuating injustices derived from the fossil fuel industry. Contrary to CCS and biomass-based steelmaking, green hydrogen-based steelmaking implies large shifts in employment and may thus lead to injustices from a labour perspective. Depending on the circumstances, industry might even relocate with consequences for employment and identity. On the other hand, the DRI-EAF production process would address environmental pollution and would escape current carbon lock-ins as the steel industry ties to the fossil-fuel industry are severed.

In terms of alignment with the Paris agreement, CCS and bio-based steelmaking could be implemented quickly but will not reach CO₂-neutrality by themselves. Combining CCS and bio-based steelmaking, however, would allow for deep emission reductions. Furthermore, the biomass-based steel production and CCS routes offer flexibility in terms implementation. It is possible to start with either, and implement the other at a later time, but in any case well before 2050. This does mean that GHG emission reductions are limited at first. It also creates a path dependence in that a supplementary technology would need to be implemented in the near future, especially for biomass only, which reduces emissions by less than CCS. Green hydrogen-based steelmaking could nearly reach CO₂-neutrality, but is projected to be implemented at large scale only in the medium term. Several companies have announced activity in hydrogen-based steelmaking, but in the short term, limited availability and affordability of green electricity hampers the speed of large-scale implementation.

Many differences in justness between the technological routes depend on context. For example, there are significant justice impacts upstream of the steel industry, and those differ between the technological routes. A detailed comparison of the impacts of coal mining, biomass cultivation, and increased demand for green electricity falls outside of the scope of this study, but can be significant. Implementation of the technological routes also depends on the availability of specific

² Grey hydrogen is currently the most common form of hydrogen and is generated from natural gas through steam methane reforming without capturing CO₂. Over time, steel plants that rely on grey hydrogen could switch to green hydrogen as its availability increases and costs decrease.

resources or infrastructure: CCS needs access to transport and geological storage, bio-based steelmaking requires sustainable biomass feedstock, and green hydrogen substitution requires vast amounts of affordable, low-CO₂ electricity. Although CO₂ can be exported, and biomass and hydrogen can be imported, this comes at additional costs and emissions, and competes with local demand for these resources. Each of these routes comes with potential justice issues regarding the siting of infrastructure and competition for resources, as well as potential leakage of environmental impacts to external stakeholders. Local availability creates soft limits, for example by increasing infrastructure or transport costs, to where these technologies are viable, and global resource availability creates hard limits to the scale at which these technologies can be implemented.

6. Discussion and future research

We acknowledge several limitations to our study. Firstly, we assume that large scale industry will continue to play an important role in the foreseeable future. Therefore, reducing emissions in industry is an essential part of moving towards a sustainable future. Secondly, in order to provide a comprehensive overview of relevant societal aspects of the sustainability transition of the steel industry we chose not to conduct a systematic review. This allows for more flexibility, but introduces bias in the selection and interpretation of papers despite the best efforts of the authors to remain neutral and consistent. Third, not all technologies have similar mitigation potentials. CCS and biomass-based steelmaking need to be combined in order to reach a CO₂-neutral steel industry, whereas green hydrogen-based steelmaking can reach deep emission reductions by itself. In the assessment we discuss these technologies separately, but it is important to be aware that the justice implications and other restrictions of CCS and biomass-based steelmaking may be cumulative in order to reach CO₂-neutrality. Fourth, while the categorization of indicators in just transition literature attempts to be comprehensive, indicators may have been missed, and overlap between the different indicators may occur, and some indicators could fit under multiple categories. Finally, the available literature on different indicators and technologies varied in number and was limited for some indicators and technological routes. For these reasons, the findings in this paper are indicative and future research will need to supplement our analysis.

We find that differences in justice between technological routes towards a climate-neutral steel industry are relevant and context-dependent. Although we did not conduct a systematic analysis of different contexts, we did find contextual factors that affect the justice implications of technological routes. Based on this analysis, we cannot distil an exact list of the aspects one should assess to minimise negative impacts and ensure a just transition, our findings imply that such an assessment should at least look at the role and state of the existing industry and access to resources for the industry, as many justice indicators propagate from both of these factors.

Employment and economic issues are very important in regions dependent on only the steel industry but matter less in diverse industrial ecosystems [46]. Environmental impacts and associated risks are relevant for existing industry that is currently polluting; however, these aspects are not highlighted or addressed everywhere currently [87–89]. Vulnerabilities related to the fair participation of communities and workers are more pronounced in developing regions or autocratic regimes than in regions where citizens already have a greater voice [85,139,140].

Access to resources and infrastructure is included in techno-economic assessments but has justice implications throughout the supply chain as well. There is limited regional capacity for the development of infrastructure or resource production in sustainable and fair ways. Exceeding those capacity limits may result in injustice but also in challenges to climate effectiveness. For example, greater demand for biomass could lead to land seizure for cultivation without regard for

social justice and biodiversity, resulting in less effective CO₂ emission reductions through land-use change [122,123,128,129]. Increased pressure on single resources may lead to increased injustice. A just transition of industry would need to use a mix of mitigation options adapted to the specific local circumstances around the plant.

Our study adds to the growing literature that shows that the justness implications of different deep emission reductions options are relevant and differ substantially between options [21–24]. Our findings in the steel industry have implications for other hard to abate sectors, like the petrochemical, aluminium, and cement industry. Comparisons of different ways to achieve deep emission reductions in those industries are currently based on assessments that focus on technological and economic potential [19,25,26,78]. The just transition findings have implications for the strategic decisions that industries have to make and the policies that different governmental bodies develop to shape those strategic decisions. Focusing on technological and economic potential often means that justness implications of these decisions and policies are overlooked, which is likely to result in unequal distributions of positive and negative consequences of those decisions and policies. This is an ethical concern because a fair distribution of costs and benefits is an end in itself. Still, it is also a practical concern because fairness is also a means to an end: unfairness nurtures resistance to implementing the decisions and policies, which hampers a smooth transition towards a more sustainable industry [29,30]. Too often, analyses of deep emission reduction options are based on a worldview where the industry has agency. At the same time, society is primarily considered as the subject undergoing the consequences of industry decisions. Our study stresses the importance of considering the industry as one of many elements in a broader socio-technical system [33–36,38,142]. Considering justness implications in sustainability investments can then be understood as an effort to align the goals of the different actors, which helps the system to evolve in the desired direction because all elements are pushing in the same direction [114]. In line with Dietz et al. [5], we argue that acknowledging the mutual interdependencies between industry and society, considering the justness implications of deep emission reduction options, is necessary for bringing about the required change.

The transitions that other hard to abate industries need to undergo to meet climate goals are both similar and different. They are similar in that they also rely on solutions like green hydrogen, CCS and biomass substitution. Our study has stressed the justness implications of such options regarding the unequally distributed costs and benefits. Future research could explore further how these other industries are different. We encourage researchers to repeat and improve on an analysis like ours on other industries and with other methodologies such as interviews, also taking a broad conceptualization of justness in terms of energy, climate, labour and environmental justice.

We also find that the impacts of a sustainability transition differ between communities. For example, each route burdens distinct communities due to infrastructure and feedstock requirements; CO₂ transport and storage, biomass cultivation, or electricity generation infrastructure are all developed in different locations. While there are options to minimise negative impacts on communities, such as developing infrastructure off-shore, we cannot completely avoid these impacts in a sustainability transition. Effectively, all options boil down to choosing who will bear which costs, which is a justice dilemma in itself. This means we should not only minimise the negative impacts of the transition, but also look into where those are minimized, and where not. This fits into a broader ethical discussion of distributive and climate justice [19,26,74,86]. The impacts of climate change are not distributed equitably, and nor are the impacts of the transition towards a sustainable future.

While we cannot answer the question of who should bear the burdens specifically, we reference the two main lines of thinking. First, the burdens should not fall on those that are already marginalised or overburdened. Research shows that typically the opposite occurs in many situations [19,73]. Additionally, the industry's transition might be

especially prone to impacts throughout the supply chain as decision-makers may prioritise the interests of local stakeholders over those that may be impacted throughout the supply chain across borders. Such supply-chain justice effects are currently not governed and would require enhanced international cooperation of a kind currently barely on the policy agenda. The second line of thinking is the principle that the polluter pays [143,144]. In this study, we compared the justness implications of different deep emission reduction options. But industries' decisions and government policies also have justness implications that are not tied to individual options to reduce greenhouse gas emissions. For example, regardless of which technology is implemented, the justness of investments is affected by the extent to which different parties bear the investments. If private industries attract private funds to finance the required investments, this may be seen as fair because it fits the principle that polluters pay for their negative externalities. If large amounts of public funds are used to invest in privately-held industries through subsidies however, this can be seen as an exacerbation of an unjust distribution between costs and benefits of the sustainability transition. Future research could broaden the scope of our analysis to also include justness implications of sustainability transitions that are not directly related to deep emission reduction options.

Finally, we did not consider the factors that encourage including justness implications in industry investments and governmental policies. Many industries compete in global markets, and maintaining a level playing field is a main concern. If justness implications are considered in one location but not others, this may lead to carbon leakage [145]. Future research could build on our analysis by studying the requirements that foster decisions and policies that consider the justness implications that we have revealed.

Declaration of competing interest

The authors declare that there are no conflicts of interest.

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Appendix A. Just transitions

The concept of justice in transitions has developed into four different fields: environmental justice, labour justice, and, more recently, energy justice and climate justice.

Environmental justice drew widespread attention in 1978, after in the United States dangerous chemicals were illegally dumped in landfills located near communities that disproportionately represented people of colour and people below the poverty line. This event spurred the creation of a grassroots justice movement and was followed up with academic work on the correlation between pollution, race, and poverty [73]. Environmental justice has developed to include not only the distribution of environmental burdens and benefits but also procedural aspects [71]. At times, the environmental justice movement has clashed with labour unions that advocated for loosened environmental regulation to sustain industries that provide employment [71,91].

Labour justice is associated with the idea that technological progress causes loss of jobs, as demonstrated by industrialization in previous centuries, the recent transition away from coal, and fear of job loss due to artificial intelligence in the future [146]. Even though technological innovation has not led to long-term unemployment above regional scales, individuals might become unemployed or experience feelings of loss, for instance, of personal or regional identity. For example, the closure of coal mines in the past displaced workers, often without

providing an alternative or compensation for individual employees and communities [96,97], while society as a whole benefitted from progress. Additionally, coal workers identify with this industry through providing for their families, despite hard and risky work, resulting in proud workers and tightly knit communities spanning generations. These communities were reluctant to relocate themselves and their families to find work they consider 'lesser' elsewhere and disrupting this community [58,98]. The term 'just transition' was coined by unions, focusing on sustained employment for workers for industries threatened by environmental policies [81]. The concept of a just transition was then expanded in scale and scope, including retraining, work safety, green jobs, culture and identity, people dependent on the workers and regional economies. [71,82]. This interpretation of a just transition has become ingrained in labour unions [147] and is included in national and international politics and policies such as the Paris agreement [148] and the European Green Deal [27].

Parallel to the labour-centric view, energy justice emerged as another essential element of justness throughout the energy transition [77,149]. Next to employment and other economic benefits, reliable and affordable access to energy is an essential human need. In developing regions, burning biomass for heating and cooking causes indoor air pollution, and a lack of access to electricity reduces quality of life and limits access to economic opportunities [150]. In developed regions, fuel poverty means people face financial barriers to access basic services, such as heating their houses, cooking their meals or driving their cars for essential trips [151]. On a larger scale, energy use is closely linked to economic growth [153]. Additionally, policies to promote access to sustainable energy often end up subsidizing the wealthy, for example, subsidies for electric vehicles or solar panel subsidies for home-owners rather than tenants [154]. A transition to renewables that does not take energy justice into account might deprive underdeveloped regions of an opportunity to develop and industrialise faster and reduce energy dependence and affordability in rural regions and more indigent poorer individuals [155].

Climate justice builds on the idea that adverse impacts of climate change are not distributed equitably among people [74]. For example, communities may be displaced from their homes due to sea level rise or droughts [156,157], potential water and food scarcity may make healthy food unaffordable to poorer populations [158]. These inequities are further exacerbated through an intergenerational lens. The next generation will experience increased climate change impacts, while bearing the greater part of the costs for the sustainability transition [26]. This has occasionally caused friction between environmental NGOs and labour unions that advocated for loosened environment regulation, in order to sustain industries that provide employment [159].

These initial four discourses are brought together in recent literature on justice in the energy transition by taking an approach analogous to that of system transitions literature, in which technology, economics, policy, culture and societal aspects are considered part of the same system. Transitions are structural, systemic changes that involve complex and long-term changes across multiple landscapes in that system [77,79,149,160,173]. A just transition, according to Newell and Mulvaney [80], requires attention for equity and justice, exploring challenges in combining energy and climate justice. Jasanoff [26] and Swilling [79] investigate the relation between sustainability and prosperity, linking the employment-focused just transition with climate justice. Notwithstanding these historical origins, the way just transitions are currently described does not distinguish labour, environmental, energy and climate-based justice but rather distributive, procedural and recognitional manifestations of justice [78,149].

Distributive or distributional justice concerns a fair and equitable distribution of burdens and benefits. While many distributive effects of the energy transition have the potential to increase injustice, it is not inherently regressive. For example, a transition to cleaner energy and industry could reduce negative impacts such as air pollution from industry or burning biomass indoors for heating and cooking [161].

Distributive effects can result from policies rather than physical effects such as proximity-based air pollution [162]. Carbon pricing or taxes make the polluter pay and reduce GHG emissions. However, low-income households spend larger shares of their income on essential products with a high carbon intensity, such as gas for heating, or rural communities spend more on fuel for their vehicles while not being able to afford the investments required for electrification [163].

Procedural justice calls for equitable involvement of all stakeholders in the transition process. This means that all groups can participate in the decision-making process fairly, requiring impartiality from policy-makers and full information disclosure [19,20]. Through procedural justice, calls for justice materialise [164,165]. Negative impacts are often located in areas with low socio-economic status [166,167] and have resulted in protest movements due to a lack of procedural justice [149]. Within the energy transition, fairness of the process is most often discussed in developing new infrastructure, for example, the siting of wind turbines or gas pipelines [83–85]. In recent papers, the concept of procedural justice has grown beyond conflict avoidance and towards community engagement [45].

Recognitional justice asks the questions 'Who is ignored?' and 'How should we recognise?' [14]. Groups can be neglected based on considerations of relationships, context, power, vulnerability, narrative and affect [168]. A lack of recognition can occur as various forms of cultural and political domination, insults, degradation and devaluation, and misrecognition [19,149]. An example would be fuel poverty, where governments in the UK mischaracterised certain social groups, the elderly and infirm, which rely on higher room temperatures. According to the government, their fuel poverty was caused by their inefficient use of scarce energy and treating them as suffering from a 'knowledge deficit', devaluing these groups instead of recognizing and engaging with these groups [149]. McCauley and Heffron [78] argue for a change in the triumvirate of justice aspects, replacing recognitional justice with restorative justice. Similar to recognitional justice, restorative justice looks at injustices that have already occurred (i.e. injustice first needs to be recognised) but then focuses on how harm that has been done can be repaired. This is not limited to individuals or communities [169] but can also be applicable to the environment [170] or climate [171] as a whole.

The transition of the steel industry has not been analysed from a broader just transition perspective, and therefore it is too early to try to converge on what could be the most important justness aspects. We therefore consider both the earlier motives for justice: labour [71,72], environment [71,73], climate [74,75] and energy [75,172], as well as the more recent types of justice: distributional, procedural, recognitional and restorative [19,20,26,78–80] in order to explore justice in routes towards a climate-neutral steel industry as exhaustively as possible.

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