Peer Review File

Manuscript Title: Global iron and steel plant CO2 emissions and carbon neutrality pathways

Reviewer Comments & Author Rebuttals

Reviewer Reports on the Initial Version:

Referees' comments:

Referee #1 (Remarks to the Author):

Review of "Assessment of CO2 emissions from global iron and steel plants and their carbon neutrality pathways"

The authors have clearly done a great deal of work to get to this stage, but the article and the work it reports suffers a number of shortcomings.

I'm very surprised that the authors have basically ignored hydrogen in this study. The word 'hydrogen' appears only once, on line 287 with the idea that DRI units are good in India because they could be transitioned to hydrogen inputs. Given that the steel industry in the developed world sees hydrogen as one of the most important options for mitigating emissions, this omission is very odd indeed.

One of the key mitigation options in the modelling work here is carbon capture, which is still extremely expensive because it is such an energy-demanding process. Throughout the paper the authors simply "assume that CCUS technology will be implemented". I can find no mention of the very high cost of CCUS. It appears that the authors simply decide that it will be available and it's just a matter of choosing to install it. (One way to reduce the cost of CCUS is to use an oxygen-rich environment, meaning less nitrogen, and therefore a higher concentration of CO2 in the offtake flow.)

The authors claim that shifting "from regional and industry-wide mitigation goals to strategies at the plant level" is "essential to effectively reduce emissions", but do not provide any support for this argument. How does having facility-level data improve this analysis over others done at more aggregated level? The work is presented as if disaggregated modelling is necessary but then make assumptions because not all data are available at the level of the analysis they desire.

The literature review of previous studies of steel emissions mitigation scenarios fits neatly into a mere four lines (lines 53-56), and this body of work is summarily dismissed as providing "insufficient evidence" because they did not use a dataset of individual plants. The authors' lack of discussion of why such studies are not useful is rather striking.

The assumption that the annual-average operating hours of every production unit in a country is identical is used to bridge the data gap, with no discussion of how reasonable this might be. If, for example, all the high-efficiency plants in a country run near capacity while all the old, inefficient plants are only brought online when demand is high, then the assumption would lead to very wayward results about mitigation paths.

The authors state that they "developed the most up-to-date global CO2 emission inventory for Global Iron and Steel Plants", which strongly implies that there already exist such datasets. If that's the case (and I believe it is), then these must be discussed as part of the literature review. That this dataset is the 'most up-to-date' is not a sufficient selling point. In fact, the dataset appears to only have data through 2018.

The abstract includes the following sentence: "Based on our results we suggest early retrofitting of current plants using deep decarbonization technology (including scrap-based EAF transformation, carbon capture, use and storage retrofit, and combinations of these decarbonization approaches), and ready-fit decarbonization technology for future plants." This suggestion appears to be wholy unreliant on the results of the analysis presented in the paper. It is clear a priori that applying decarbonisation technologies to steel plants would reduce emissions. The authors should reword either to make the statement not "based on our results" or they should make it something that is actually based on their results.

Lines 25-26: The authors suggest that China and India should work together, which is a nice statement, but how likely is this? To my reading it is very unlikely that India would accept help from China in the near future, and therefore the statement reads as wishing thinking rather than a useful policy contribution. Given real geopolitics, if the authors wish to retain this idea, can they propose (however loosely) an alternative to direct collaboration, such as a UN-directed or global industry body (World Steel) directed effort to share best practice?

Lines 98-99: The sentence concludes that the Middle East and North America have "sufficient local shale oil resources". Firstly, I don't believe there has been any shale oil development in the Middle East. Secondly, since the discussion is about natural gas, it would be more sensible to refer to "shale gas resources".

Section starting line 107: It is difficult in this section to understand how 'operating lifetime' has been defined. It appears to be used before it is defined. The statement that the average age (clearly defined) is much higher than the average operating years suggests that operating years comes to a close at some point, and potentially at the point of retrofitting. But on line 116 the idea of 'extending' the operating lifetime by retrofitting suggests that the point of retrofitting cannot be the end of one operating lifetime and the beginning of another. Please rewrite this section to make the definition clearer so that the meaning of the discussion comes through.

Lines 122-124: "We find a range of global average operation-years ... across regions." This would be clearer if the authors were to say that the operating lifetimes vary across regions.

Sentence starting line 155: I have read this several times, but cannot say I understand it. The fact that within the distribution of crude steel plants' operational years, most fall in the 0-24 year range allows the authors to conclude that "such plants had operated for less than 25 years"? Obviously if one is discussing plants that have operated for less than 25 years, then they have operated for less than 25 years. So I cannot follow the logic here (it seems entirely redundant).

Line 166: Add a citation for carbon lock-in.

Line 168: "could help to mitigate". It's very hard for me to imagine circumstances under which this would not help mitigation, so why use 'could' instead of 'would'?

Line 174: Are the average retrofitting cycles determined regionally? Presumably they vary considerably between countries.

Line 186: "due to sufficient scrap accumulation in Luxembourg". In the supplementary material the authors say that this is an assumption, but give no information on what basis this assumption is made. How can the reader have any idea of whether this assumption is reasonable?

Line 219: How have the authors determined when sufficient scrap would be available? Do they take into account export of steel which reduces this? Eg Korea exports a lot of steel in ships and other things; reduces its domestic availability of scrap.

Lines 272-3: "increasing scarp accumulation": I cannot see any indication that any forecasts are made of scrap availability. Rather than modelling improved scrap collection rates and improved scrap availability from a building-stock model, the authors seem to make vague assumptions that scrap will simply be available at some point. Since the transition to EAF plants is one of the greatest sources of mitigation, and these rely substantially on scrap, this leaves the modelling appearing to be rather ad hoc and arbitrary.

Lines 231-234: I'm not sure I've understood here. 85% of global emissions reduction in emerging countries, so I presume 15% in developed countries, but the authors appear to then mis-word the text with "advanced regions will likely reduce cumulative emissions by only 15%", which has an entirely different meaning. Please re-word.

In the same discussion it appears the authors suggest that developed countries will have very small reductions of emissions after 2030, with the reason remaining a unclear to me. If they're suggesting that all the decarbonisation methods that the authors have allowed for will have been implemented by that stage, then they're ignoring the methods they haven't allowed for, hydrogen being the obvious one.

Line 272: "using methane to substitute coal for heat": The authors say "methane", rather than "natural gas", so if methane is what they mean then I believe most of this in China is made from coal, with consequent higher emissions and therefore is not an example of a route that leads to decarbonisation.

Line 285: "India should promote fuel switching from coal to natural gas". Perhaps the authors are not aware, but India has extremely poor access to natural gas. In the Indian context this suggestion would be received with "Yes, wouldn't that be nice?"

Referee #2 (Remarks to the Author):

Dear authors,

Thank you for this very valuable contribution to the transformation of the steel industry worldwide towards CO2-neutrality. For the first time, all known steel plants worldwide are subjected to a careful analysis, taking into account the age of the plants, standard industrial modernization cycles and country-specific features.

You have carried out a very extensive study and, in a careful analysis of the available databases, have shown the current technological status of the steel industry on all continents. In doing so, you considered the retrofitting plans of the respective plants, the data available at the various locations on modernization intervals, the availability of raw materials, the energy mix and the political plans, and concluded various scenarios. Their impact on the respective CO2-savings potential is shown and proves the importance of the transformation in steel production for the global climate goals.

The methodology used is explained in a comprehensible manner and - with a number of necessary and documented simplifications - is appropriate for the purpose of the investigation. This work can be used in the future as a reference for country- or continent-related considerations.

The examples given in the supplement and the conclusions for a faster retrofitting process are helpful for decision-making processes. Of course, these decision-making processes are also subject to economic and socio-political constraints, which are not dealt with in this work.

Referee #3 (Remarks to the Author):

Summary: This paper creates a global database steel production at the plant-level, with key plant-level characteristics, such as age, technology type, and year(s) of retro-fitting. Steel demand is projected through 2050, and different scenarios are assumed about how these plants evolve through the period with different retro-fitting options that impact emission profiles. The resulting cumulative emissions can vary from a low of 49.9Gt to a high of 105.3Gt, with a range of 49.9-59.9Gt depending on various retrofitting options. The level of 105.3Gt refers to a scenario with no retro-fitting. The iron and steel sectors are critical components in achieving net zero emissions given the difficulty in reducing carbon emissions in these sectors. This paper provides insightful possibilities of future decarbonization of these very important sectors.

Evaluation: The authors have put together a very detailed and informative database on global steel production, which provides a snapshot of production spatially crossed with the various production technologies and their ensuing emissions. The various scenarios provide plausible pathways for future steel-based emissions with the same level of detail on the spatial and technological characteristics. The authors need to provide more details on the projections of steel demand and its allocation across the plants across the globe. Details to follow.

The following comments will focus on the projections of steel demand:

1. The authors could have considered alternatives to SSP2, notably SSP1 that has a narrative focused on deploying greener technologies—albeit in the context of higher income growth combined with

lower population growth. This could also be contrasted with SSP5, with much higher income growth and with the deployment of conventional technologies, i.e., with relatively high carbon emissions.

2. The authors do not describe in any detail the narrative they use in deploying SSP2—in particular the role and shape of investment. For example, as China matures as an economy (including a rapidly aging population), the infrastructure needs will presumably diminish considerably and we could see a rotation away from investment in traditional infrastructure, towards more investment in technology, R & D and knowledge—as well as perhaps a diminished role overall for investment and more consumption. Some of the latter is likely to include steel-intensive goods such as vehicles, but also more consumption of services. India is probably in a different situation on the development pathway with still significant infrastructure needs. Another factor that will influence steel demand and related emissions is the role of trade and trade policies. As demonstrated by the Trump Administration, this is traditionally a sensitive sector where security concerns often trump economic efficiency. In the future, moreover, this sector is likely to be one of the key targets of Carbon Border Adjustment Measures (CBAM), which are currently under discussion in a number of countries that are planning significant mitigation efforts that will drastically impact competitiveness. How are these various factors shaping development of the SSP2 projection using the G-RDEM model?

3. It is unclear in the discussion of the projections how new plants are being introduced. In the life-cycle of plants, in each year a number of older plants cease to exist and new ones start production. It appears that the number of plants in each country is static (see equation 10) and that the structure of plants is static (at base year levels). If this is not the case, the authors should describe in greater detail the allocation of production within country. There are several (non-competing) alternatives. First, one could use dynamic shares, i.e., update the shares each year depending on the other assumptions—such as retro-fitting, technology switching, etc. Second, one could assume that new plants use production technologies different from the average—depending on the policy environment. If policies are pushing cleaner technologies, why wouldn't new plants be cleaner than the average plant. In addition, even if there are no formal forward-looking expectations in their framework, one would assume that if policies are providing incentives for cleaner technologies, why would investors continue to invest in conventional, emission intensive technologies.

4. It would be good to clarify that retro-fitting only involves current technologies, i.e., there is no assumption of deployment of currently unused technologies such as carbon capture with storage, or alternative fuels such as hydrogen.

Minor points:
It is possible that 'processing routes' is commonly used in the production of steel and technology, but economists would probably use the term 'technologies' or 'production technologies'.
Line 119 two-third should read as 'two-thirds'
Line 147 forward, replace all instances of 'outputs' with 'output'
Line 157 replace 'indicated' with 'indicate'
Line 157 replace 'had' with 'have'
Line 273 replace 'scarp' with 'scrap'
In general, the paper should be re-read with a focus on improving the readability and grammar.

Author Rebuttals to Initial Comments:

Responses to reviewers' comments

Referee #1 (Remarks to the Author):

Review of "Assessment of CO2 emissions from global iron and steel plants and their carbon neutrality pathways"

The authors have clearly done a great deal of work to get to this stage, but the article and the work it reports suffers a number of shortcomings.

We appreciate the reviewer's positive tone and very constructive comments.

I'm very surprised that the authors have basically ignored hydrogen in this study. The word 'hydrogen' appears only once, on line 287 with the idea that DRI units are good in India because they could be transitioned to hydrogen inputs. Given that the steel industry in the developed world sees hydrogen as one of the most important options for mitigating emissions, this omission is very odd indeed.

We appreciate the constructive comment. As suggested, we have now added Hydrogen-based steelmaking as an option in the parameter set 4 about the potential low-carbon technology of the iron and steel plants **(*T5, T6*)**. (*Lines 631-641*).

We selected the CCUS technology with more maturity and potentially less cost as the representative of deep decarbonization technologies to discuss the importance of adopting deep decarbonization technology for the global iron and steel industry emission reduction and the realization of net-zero climate targets. CCUS technology will play an important role in the major emitting countries in the iron and steel industry, such as China with early experience with CCUS in the other sectors.

Two other reasons justify our choice to focus on CCUS in steel and iron plants:

(1) CCUS technology can retrofit many existing infrastructures, whereas Hydrogen-based steelmaking requires new equipment for the direct reduction of iron ore to replace the blast furnace and would depend more on renewable electricity (production of low-carbon Hydrogen), resulting in larger uncertainties at plant level;
(2) Many studies have shown that CCUS is a mature technology likely to be commercialized by the late

2020s, whereas the low-carbon Hydrogen-based steelmaking technology (100% electrolytic hydrogen) is still under development and likely to be ready by 2050. According to the IEA's analysis report, by 2050, only about 10 commercial-scale plants will deploy the 100% Hydrogen-based steelmaking route in the European Union, less than 5% of the total number of steelmaking plants. Moreover, previous studies have shown that, in most regions, retrofitting existing iron and steel plants with CCUS costs less than any of the proposed pre-commercial net-zero emission technologies. We have provided a more detailed explanation of why we selected CCUS as the representative technology for deep decarbonizing when we discuss the low-carbon development roadmap for global iron and steel production in the text. *(Lines 364-369)*.

We also considered the combination of adopting CCUS and H_2-based technology in the decarbonization scenarios (*Lines 300-301, Lines 337-341).* Our study shows that if CCUS and H_2-based technology are used together, the cumulative emissions of global iron and steel industry will be compressed to 36.7Gt (Figure 4d), 23% emission space saving comparing to default scenario.

References:

1. Flores-Granobles, Marian, & Saeys, Mark. (2020). Minimizing CO2 emissions with renewable energy: a comparative study of emerging technologies in the steel industry. *Energy & Environmental Science, 13*(7), 1923-1932. doi:10.1039/d0ee00787k
2. IEA. (2020). Iron and Steel Technology Roadmap Towards more sustainable steelmaking. Retrieved from https://www.iea.org/reports/iron-and-steel-technology-roadmap
3. Ren, Ming, Lu, Pantao, Liu, Xiaorui, Hossain, M. S., Fang, Yanru, Hanaoka, Tatsuya, . . . Dai, Hancheng. (2021). Decarbonizing China's iron and steel industry from the supply and demand sides for carbon neutrality. *Applied Energy*, *298*. doi:10.1016/j.apenergy.2021.117209
4. Yu, Xiang, & Tan, Chang. (2022). China's pathway to carbon neutrality for the iron and steel industry. *Global Environmental Change*, *76*. doi:10.1016/j.gloenvcha.2022.102574
5. Fan, Zhiyuan, & Friedmann, S. Julio. (2021). Low-carbon production of iron and steel: Technology options, economic assessment, and policy. Joule, 5(4), 829-862. doi:10.1016/j.joule.2021.02.018

One of the key mitigation options in the modelling work here is carbon capture, which is still extremely expensive because it is such an energy-demanding process. Throughout the paper the authors simply "assume that CCUS technology will be implemented". I can find no mention of the very high cost of CCUS. It appears that the authors simply decide that it will be available and it's just a matter of choosing to install it. (One way to reduce the cost of CCUS is to use an oxygen-rich environment, meaning less nitrogen, and therefore a higher concentration of CO2 in the offtake flow.)

We appreciate the constructive comment. As suggested, we have now discussed the cost of the low carbon technologies covered in this study, both in the text *(Lines 329-333) and Supplementary Information (Lines 301-310 in SI)*.

The adoption of innovative deep decarbonization technologies is necessary to achieve net-zero carbon production of steel, but it means higher costs for steel producers nowadays. However, the cost of CCUS has already declining with technology development. For example, the cost of CO_2 capture in the power sector has come down by 35% from the first to the second large-scale CCUS facility. Research found that this declining trend will continue as the market expands to make CCUS economically attractive in iron and steel production.

References:

1. Flores-Granobles, Marian, & Saeys, Mark. (2020). Minimizing CO2 emissions with renewable energy: a comparative study of emerging technologies in the steel industry. Energy & Environmental Science, 13(7), 1923-1932. doi:10.1039/d0ee00787k
2. Fan, Zhiyuan, & Friedmann, S. Julio. (2021). Low-carbon production of iron and steel: Technology options, economic assessment, and policy. Joule, 5(4), 829-862. doi:10.1016/j.joule.2021.02.018
3. IEA. (2020). *Iron and Steel Technology Roadmap Towards more sustainable steelmaking*., IEA, Paris https://www.iea.org/reports/iron-and-steel-technology-roadmap
4. IEA. (2020). *CCUS in Clean Energy Transitions*., IEA, Paris https://www.iea.org/reports/ccus-in-clean-energy-transitions
5. IEA (2021), *Is carbon capture too expensive?*, IEA, Paris https://www.iea.org/commentaries/is-carbon-capture-too-expensive

The authors claim that shifting "from regional and industry-wide mitigation goals to strategies at the plant level" is "essential to effectively reduce emissions", but do not provide any support for this argument. How does having facility-level data improve this analysis over others done at more aggregated level? The work is presented as if disaggregated modelling is necessary but then make assumptions because not all data are available at the level of the analysis they desire.

We appreciate the constructive comment. As suggested, we have revised the sentence to better illustrate the benefits of our analysis compared with those carried out at more aggregated levels (*Lines 16*). It is worth noting that all mitigation efforts, including technology retrofitting, will have to take place at facility level, with each processing unit should set individually according to its techs specification and they're after un-unified, with the decarbonization of the entire iron and steel industry depending on the efforts undertaken by every single plant (*Lines 55-62*).

We have also tried to better explain the benefits of our analysis at plant-level in terms of policy implications for emissions reduction of the global iron and steel industry. Compared with overall emissions reduction at the country, or the industry level globally, targeted retiring or timely retrofitting with low-carbon technology according to the plant-specific characteristics would better fit with the operation of iron and steel plants (operating lifetime, potential CO_2 mitigation options, etc.) and would allow the efficient realization of emissions reduction while minimizing the lock-in cost brought by the remaining operation lifetime. (*Lines 357-362*)

The literature review of previous studies of steel emissions mitigation scenarios fits neatly into a mere four Lines (Lines 53-56), and this body of work is summarily dismissed as providing "insufficient evidence" because they did not use a dataset of individual plants. The authors' lack of discussion of why such studies are not useful is rather striking.

We take the point and have included in the text a more detailed explanation of why previous studies are not sufficient to inform the decarbonization efforts of the iron and steel industry worldwide. In the case of studies at the country level, only some countries are covered, which isn't comprehensive enough to inform the decarbonization of the global iron and steel industry. In the case of studies at plant-level, they tend to discuss decarbonization of hypothetical plants, lacking consideration of actual operating details and the different development strategies of the countries where the plants are supposedly located. (*Lines 55-68*) We also added a detailed description of related literature review in the Supplementary Information (*Lines 6-21 in SI*).

The assumption that the annual-average operating hours of every production unit in a country is identical is used to bridge the data gap, with no discussion of how reasonable this might be. If, for example, all the high-efficiency plants in a country run near capacity while all the old, inefficient plants are only brought online when demand is high, then the assumption would lead to very wayward results about mitigation paths.

Many thanks for your point. We have re-run our uncertainty analysis to include operating hours as a key parameter and presented in our discussion of the uncertainties and limitations of this study We provide the description as below *(Lines 377-388)*.

In general, the average uncertainties of global CO_2 emissions are estimated to be 20% to 24% for plants with less than 25 years of operation, 22% to 28% for older plants (with more than 25 years of operation). Plant-level uncertainties vary among operation-year groups and regions, with larger uncertainties for older plants and developing regions due to incomplete information. CEADs-GSEI now estimates the annual actual output of each operating unit based on the country, type of processing unit, and capacity, but collecting actual operation-time data at plant level is challenging nowadays. Developing more accurate data reporting systems at the plant level for the global iron and steel industry under international cooperation could help deliver more comprehensive, granular, precise, and reliable data. CEADs-GSEI will be updated and improved as more and better data become available.

Further, a detailed description of uncertainties is also presented in the Supplementary Information.

The authors state that they "developed the most up-to-date global CO2 emission inventory for Global Iron and Steel Plants", which strongly implies that there already exist such datasets. If that's the case (and I believe it is), then these must be discussed as part of the literature review. That this dataset is the 'most up-to-date' is not a sufficient selling point. In fact, the dataset appears to only have data through 2018.

We appreciate the suggestion. We further collected about 100,000 data on the capacity, age, operating company, owner company, country of operation and owner company of 2019 iron and steel processing units globally. This effort has allowed us to update our emission inventories to 2019 and revise all related analysis in the manuscript. To the best of our knowledge, we have pioneered in developing global CO_2 emission inventory for global iron and steel plants with detailed operating information. We have included a brief discussion of other CO_2 emission inventory for iron and steel plants in the Introduction section (*Lines 71-73*). We have also revised the text to 'a comprehensive, publicly available, and up to date'. (*Lines 73-74*)

The abstract includes the following sentence: "Based on our results we suggest early retrofitting of current plants using deep decarbonization technology (including scrap-based EAF transformation, carbon capture, use and storage retrofit, and combinations of these decarbonization approaches), and ready-fit decarbonization technology for future plants." This suggestion appears to be wholy unreliant on the results of the analysis presented in the paper. It is clear a priori that applying decarbonisation technologies to steel plants would reduce emissions. The authors should reword either to make the statement not "based on our results" or they should make it something that is actually based on their results.

Thank you for your comment, and we have deleted this sentence.

Lines 25-26: The authors suggest that China and India should work together, which is a nice statement, but how likely is this? To my reading it is very unlikely that India would accept help from China in the near future, and therefore the statement reads as wishing thinking rather than a useful policy contribution. Given real geopolitics, if the authors wish to retain this idea, can they propose (however loosely) an alternative to direct collaboration, such as a UN-directed or global industry body (World Steel) directed effort to share best practice?

We appreciate the constructive comment on our analysis and the concern regarding the real geopolitics and the reliability of our policy implications. We believe climate mitigation should avoid any geopolitical influence. In the Conference of the Parties of the UNFCCC, China and India have appeared in many negotiating groups (BASIC, G-77 and China) together and committed to climate action. We have included the suggestion about building 'UN or other international cooperation-directed cooperation plans' for emissions reduction in the global iron and steel industry, to provide a more realistic policy implication particularly for the case of China and India. (*Lines 24-27*)
International alliances and cooperation are needed to promote financing efforts to reduce emissions in developing countries. (*Lines 344-351*)

Lines 98-99: The sentence concludes that the Middle East and North America have "sufficient local shale oil resources". Firstly, I don't believe there has been any shale oil development in the Middle East. Secondly, since the discussion is about natural gas, it would be more sensible to refer to "shale gas resources".

We thank the reviewer for pointing this out. We take this point and have replaced 'shale oil resources' with 'natural gas and shale gas resources'. We also added two citations to support the statement. *(Lines 114-115)*

Section starting line 107: It is difficult in this section to understand how 'operating lifetime' has been defined. It appears to be used before it is defined. The statement that the average age (clearly defined) is much higher than the average operating years suggests that operating years comes to a close at some point, and potentially at the point of retrofitting. But on line 116 the idea of 'extending' the operating lifetime by retrofitting suggests that the point of retrofitting cannot be the end of one operating lifetime and the beginning of another. Please rewrite this section to make the definition clearer so that the meaning of the discussion comes through.

We thank the reviewer for pointing out this ambiguous description. We have revised the text in this section to clarify the description of 'operation-years'. We have adopted 'operation-years' throughout the manuscript. In this study, the 'operation-years' of the iron and steel plant are defined as 'the total number of years from the commissioning year to 2019' for the original plants, or 'the total number of years from the last refurbishment year up to 2019' for the retrofitted plants. We have revised the text and have provided a definition right when the term was used for the first time. *(Lines 126-128)*
We have also included in the text a detailed explanation of what we mean by 'extend operating lifetime'. The expression 'extend the units operating lifetime' at Line 116 in the last version was intended to explain the point that many iron and steel plants through retrofitting could continue producing beyond the normal operating life (for example, 25 years for blast furnaces). *(Lines 135-137)*

Lines 122-124: "We find a range of global average operation-years ... across regions." This would be clearer if the authors were to say that the operating lifetimes vary across regions.

We take the point and have revised the text to 'We find that the average operation-years varies across regions' *(Lines 143-144)*. Given that we have now provided a clear definition of operation-years and used it consistently throughout the revised manuscript, we think it would help readers to keep the same wording also in the case of this sentence.

Sentence starting line 155: I have read this several times, but cannot say I understand it. The fact that within the distribution of crude steel plants' operational years, most fall in the 0-24 year range allows the authors to conclude that "such plants had operated for less than 25 years"? Obviously if one is discussing plants that have operated for less than 25 years, then they have operated for less than 25 years. So I cannot follow the logic here (it seems entirely redundant).

We appreciate the reviewer for pointing out this ambiguous description. We have revised the text to clarify. Our results show that 99% of the crude steel output, and the associated emissions, came from coal/charcoal-fired plants that had operated for less than 25 years. Thus, we inferred that 'the likely operating lifetime of global coal/charcoal-fired plants is less than 25 years'. *(Lines 178-179)*

Line 166: Add a citation for carbon lock-in.

We take the point and have added a reference related to carbon lock-in, that explains the concept of carbon lock-in. *(Lines 188)*

Line 168: "could help to mitigate". It's very hard for me to imagine circumstances under which this would not help mitigation, so why use 'could' instead of 'would'?

We thank the reviewer for pointing out this. We take the point and have replaced 'could' with 'would'. (*Lines 190*)

Line 174: Are the average retrofitting cycles determined regionally? Presumably they vary considerably between countries.

We appreciate the question, and have included a more detailed description of retrofitting-cycle in the text. We have added the definition of retrofitting-cycle adopted in this study, that is 'the number of years that go from one retrofitting to the next of plants', the first time it was used *(Lines 184-185)*.

In this study, the average retrofitting cycle was determined by processing routes. We also added a table showing the average value of the retrofitting cycle by processing routes in the Supplementary materials *(Table S3).*

Line 186: "due to sufficient scrap accumulation in Luxembourg". In the supplementary material the authors say that this is an assumption, but give no information on what basis this assumption is made. How can the reader have any idea of whether this assumption is reasonable?

We take the point and have added in the supplementary material two references related to scrap accumulation in Europe to provide a more compelling rationale for our assumptions. The scrap accumulation is tightly related to the development history of the iron and steel industry, with a longer operating history indicating that more steel products have reached end-of-life and are likely leading to more scrap accumulation. Previous studies have shown that in European Union countries the scrap share of total metallic inputs is 50% in 2019 and will likely reach saturation before 2030. Since the project of availability of scrap steel is out of scope of our study, we have to follow findings in exiting literature that the scrap accumulation might be sufficient in the EU and the US. *(Lines 190 in SI)*.

References:

1. Pauliuk, S., Milford, R. L., Muller, D. B., & Allwood, J. M. (2013). The steel scrap age. *Environ Sci Technol*, *47*(7), 3448-3454. doi:10.1021/es303149z
2. Dworak, Sabine, & Fellner, Johann. (2021). Steel scrap generation in the EU-28 since 1946 – Sources and composition. *Resources, Conservation and Recycling*, *173*. doi:10.1016/j.resconrec.2021.105692

Line 219: How have the authors determined when sufficient scrap would be available? Do they take into account export of steel which reduces this? Eg Korea exports a lot of steel in ships and other things; reduces its domestic availability of scrap.

Thank you for the questions. In this study we determine the availability of scrap resources according to the literature, especially from the IEA reports (see reply in your next question). Korea is also a key producing country with a mature stock of steel nowadays; although this country exports a lot of steel, previous studies found it tend to increase the scrap used rates in the near future. Thus, we think that developed regions will be equipped with sufficient scrap by 2030 and are expected to use more scrap in steel production.

References:

1. https://ieefa.org/articles/ieefa-china-japan-and-south-korea-stand-gain-most-increased-scrap-steel-recycling
2. IEA. (2020). Iron and Steel Technology Roadmap Towards more sustainable steelmaking. Retrieved from https://www.iea.org/reports/iron-and-steel-technology-roadmap

Lines 272-3: "increasing scarp accumulation": I cannot see any indication that any forecasts are made of scrap availability. Rather than modelling improved scrap collection rates and improved scrap availability from a building-stock model, the authors seem to make vague assumptions that scrap will simply be available at some point. Since the transition to EAF plants is one of the greatest sources of mitigation, and these rely substantially on scrap, this leaves the modelling appearing to be rather ad hoc and arbitrary.

We acknowledge the reviewer’s concern regarding the scrap availability. The projection of scrap steel is beyond the scope of the paper, we have adopted projections from IEA. We also have included a more detailed description of scrap availability considered in the Supplementary Materials text. *(Supplementary Information section 1.7)*

Scrap availability in the global iron and steel industry was about 800 million tons in 2019, 40% (320 million tons) coming from developed regions. According to World Steel Association's projections, global scrap availability will reach about 1 billion tonnes in 2030 and 1.3 billion tonnes in 2050. For the developed regions (European Union, North America, Japan and South Korea) with long-established steel infrastructures, scrap availability is sufficient nowadays and is likely to reach saturation before 2030.

China will become the leading driver of the growth of scrap availability over the next few years, owing to the aging of the substantial steel stocks built during the past two decades. China's scrap availability could reach roughly 300 Mt by 2030. India has currently a younger stock of steel infrastructure, and will see scrap availability soar over the next 15 years.

The scrap availability, because of the aging steel stock, across the rest of the developing regions will grow considerably by 2050 (the projection horizon for this study). We suggest that developing countries set policies to support scrap collection rates and so improve the share of scrap-based steel production.

Moreover, considering the monetary value of scrap and the need to reduce steelmaking CO_2 emissions nowadays, we believe that a higher scrap availability globally will allow regions with scrap in excess to trade it with those regions in need of it.

References:

1. https://worldsteel.org/media-centre/blog/2018/future-of-global-scrap-availability/
2. Fan, Zhiyuan, & Friedmann, S. Julio. (2021). Low-carbon production of iron and steel: Technology options, economic assessment, and policy. *Joule*, *5*(4), 829-862. doi:10.1016/j.joule.2021.02.018
3. Dworak, Sabine, & Fellner, Johann. (2021). Steel scrap generation in the EU-28 since 1946 – Sources and composition. *Resources, Conservation and Recycling*, *173*. doi:10.1016/j.resconrec.2021.105692
4. IEA. (2020). *Iron and Steel Technology Roadmap Towards more sustainable steelmaking*. Retrieved from https://www.iea.org/reports/iron-and-steel-technology-roadmap

Lines 231-234: I'm not sure I've understood here. 85% of global emissions reduction in emerging countries, so I presume 15% in developed countries, but the authors appear to then mis-word the text with "advanced regions will likely reduce cumulative emissions by only 15%", which has an entirely different meaning. Please re-word.

We thank the reviewer for pointing out this mis-word. We have revised the text to make it clearer.

In contrast, and along with stagnating production, cumulative emissions reductions in advanced regions over 2031-2050 only account for 16% of the global emissions reductions. *(Lines 254-256)*

In the same discussion it appears the authors suggest that developed countries will have very small reductions of emissions after 2030, with the reason remaining a unclear to me. If they're suggesting that all the decarbonisation methods that the authors have allowed for will have been implemented by that stage, then they're ignoring the methods they haven't allowed for, hydrogen being the obvious one.

We appreciate the question. We have revised the text to better explain the change in emissions reduction from 2020 to 2050 across advanced regions. *(Lines 252-258)* In the '5-year-ahead retrofitting' scenario, 29% of the total cumulative emissions reductions in advanced regions will be achieved over the short-term (2020-2030), whereas only 8% of the total cumulative emissions reductions will be achieved in the '5-year-late retrofitting' scenario over the same period as less plants can be retrofitted due to the delayed retrofitting. Correspondingly, over the long-term (2031-2050), the total cumulative emissions reductions will be 71% in the '5-year-ahead retrofitting' scenario and 92% in the '5-year-late-retrofitting' scenario thanks to the development of innovative deep decarbonization technologies. These last results show that the deployment of deep decarbonization technologies in the long-term will play a more important role in the 'late-retrofitting' scenario.

We have also included the analysis of a new scenario, '5-year-ahead retrofitting with CCUS technology and Hydrogen-based steelmaking technology' for the advanced regions and revised the text accordingly. *(Lines 337-341)* In this scenario, 71% of the total cumulative reductions in advanced regions will be achieved after 2030.

Line 272: "using methane to substitute coal for heat": The authors say "methane", rather than "natural gas", so if methane is what they mean then I believe most of this in China is made from coal, with consequent higher emissions and therefore is not an example of a route that leads to decarbonisation.

We appreciate the suggestion. We take the point and have replaced 'methane' with 'natural-gas' (*Lines 310*)

Line 285: "India should promote fuel switching from coal to natural gas". Perhaps the authors are not aware, but India has extremely poor access to natural gas. In the Indian context this suggestion would be received with "Yes, wouldn't that be nice?"

We thank you for the question. We have deleted this sentence.

Referee #2 (Remarks to the Author):

Dear authors,

Thank you for this very valuable contribution to the transformation of the steel industry worldwide towards CO2-neutrality. For the first time, all known steel plants worldwide are subjected to a careful analysis, taking into account the age of the plants, standard industrial modernization cycles and country-specific features.

You have carried out a very extensive study and, in a careful analysis of the available databases, have shown the current technological status of the steel industry on all continents. In doing so, you considered the retrofitting plans of the respective plants, the data available at the various locations on modernization intervals, the availability of raw materials, the energy mix and the political plans, and concluded various scenarios. Their impact on the respective CO2-savings potential is shown and proves the importance of the transformation in steel production for the global climate goals.

The methodology used is explained in a comprehensible manner and - with a number of necessary and documented simplifications - is appropriate for the purpose of the investigation. This work can be used in the future as a reference for country- or continent-related considerations.

The examples given in the supplement and the conclusions for a faster retrofitting process are helpful for decision-making processes. Of course, these decision-making processes are also subject to economic and socio-political constraints, which are not dealt with in this work.

We appreciate the reviewer's positive tone and very constructive comments. We have included the suggestion of building 'UN or other international cooperation-directed cooperation plans' to achieve emissions reduction in the global iron and steel industry, in order to provide a more realistic policy implication , particularly for the case of China and India. *(Lines 24-27)* We have also included a brief discussion about energy availability, we believe that energy should not be regarded exclusively as a national good but should instead be shared. International alliance and cooperation are needed to promote financing efforts to reduce emissions in developing countries. *(Lines 344-351)*

Referee #3 (Remarks to the Author):

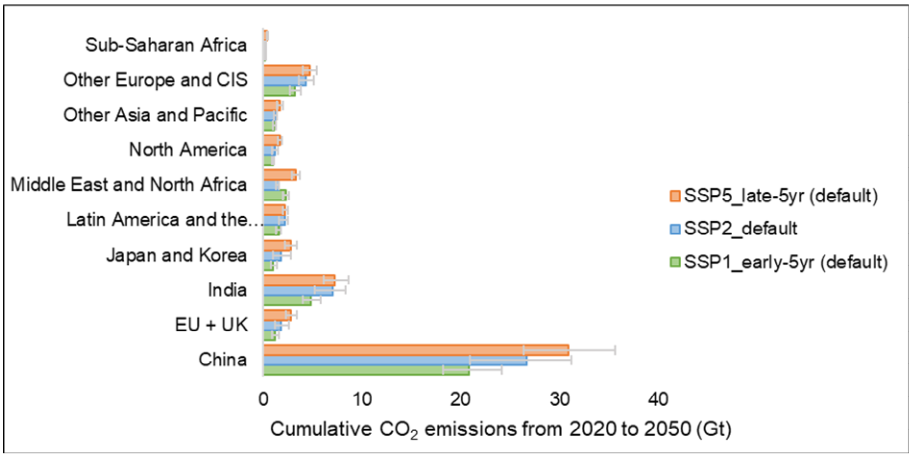
Summary: This paper creates a global database steel production at the plant-level, with key plant-level characteristics, such as age, technology type, and year(s) of retro-fitting. Steel demand is projected through 2050, and different scenarios are assumed about how these plants evolve through the period with different retro-fitting options that impact emission profiles. The resulting cumulative emissions can vary from a low of 49.9Gt to a high of 105.3Gt, with a range of 49.9-59.9Gt depending on various retrofitting options. The level of 105.3Gt refers to a scenario with no retro-fitting. The iron and steel sectors are critical components in achieving net zero emissions given the difficulty in reducing carbon emissions in these sectors. This paper provides insightful possibilities of future decarbonization of these very important sectors.

Evaluation: The authors have put together a very detailed and informative database on global steel production, which provides a snapshot of production spatially crossed with the various production technologies and their ensuing emissions. The various scenarios provide plausible pathways for future steel-based emissions with the same level of detail on the spatial and technological characteristics. The authors need to provide more details on the projections of steel demand and its allocation across the plants across the globe. Details to follow.

The following comments will focus on the projections of steel demand:

1. The authors could have considered alternatives to SSP2, notably SSP1 that has a narrative focused on deploying greener technologies—albeit in the context of higher income growth combined with lower population growth. This could also be contrasted with SSP5, with much higher income growth and with the deployment of conventional technologies, i.e., with relatively high carbon emissions.

We appreciate the constructive comment and have now included the newly added analysis on the decarbonization roadmap of the global iron and steel industry under SSP1 and SSP5 *(Lines 274-286, Supplementary Figure S5)*. Annual CO_2 emissions from iron and steel plants change with the production level and the deployment of low-carbon technologies (according to their reduction potential). Crude steel production was estimated with the CGE model, considering the socioeconomic transformation and the sectoral linkage. We analyzed the possible CO_2 emissions mitigation pathways at the plant level by optimizing when to retrofit each plant and how – this analysis is based on three key parameters: the type of processing routes, the latest retrofitting year, and operating lifetime. For SSP1, we have assumed that the deployment of deep decarbonization technologies in the iron and steel industry worldwide will be quite advanced (the default scenario under SSP1 is that the iron and steel plants will be retrofitted 5 years earlier than the planned retrofitting date), with cumulative CO_2 emissions ranging from 31.7Gt~43.5Gt (from 8-years-ahead retrofitting scenario to 2-years-ahead retrofitting scenario respectively). Considering that the SSP5 describes a future with high challenges to mitigation and low challenges to adaptation, we have assumed that under SSP5 the deep decarbonization technologies will be deployed later (the default scenario under SSP5 is that the iron and steel plants will be retrofitted 5 years later than the planned retrofitting date), with the related cumulative CO_2 emissions ranging from 48.8Gt~67.1Gt (from 2-years-late retrofitting scenario to 8-years-late retrofitting scenario respectively).



2. The authors do not describe in any detail the narrative they use in deploying SSP2—in particular the role and shape of investment. For example, as China matures as an economy (including a rapidly aging population), the infrastructure needs will presumably diminish considerably and we could see a rotation away from investment in traditional infrastructure, towards more investment in technology, R & D and knowledge—as well as perhaps a diminished role overall for investment and more consumption. Some of the latter is likely to include steel-intensive goods such as vehicles, but also more consumption of services. India is probably in a different situation on the development pathway with still significant infrastructure needs. Another factor that will influence steel demand and related emissions is the role of trade and trade policies. As demonstrated by the Trump Administration, this is traditionally a sensitive sector where security concerns often trump economic efficiency. In the future, moreover, this sector is likely to be one of the key targets of Carbon Border Adjustment Measures (CBAM), which are currently under discussion in a number of countries that are planning significant mitigation efforts that will drastically impact competitiveness. How are these various factors shaping development of the SSP2 projection using the G-RDEM model?

   Thank you. We use G-RDEM to generate the SSP2 projections from now to 2050. The G-RDEM is a computable general equilibrium tool for long-term counterfactual analysis and baseline generation from given gross domestic product (GDP) and population projections. It encompasses an implicitly directly additive demand system (AIDADS) with non-linear Engel curves, and debt accumulation from foreign saving; it introduces sector specific productivity changes, endogenous aggregate saving rates, as well as time-varying cost shares for value added and individual intermediates. Based on the general equilibrium principle and the above assumed/estimated mechanism, the dynamics of investment, consumption, and consumption structure is calculated **endogenously**, driven by changes in GDP and population. For example, as population in China is expected to decrease in the future, the need for infrastructure will decrease and the labor cost will increase. In this case, in G-RDEM, investment in the infrastructure sector will also decrease, whereas investment in high-tech sectors will increase. This endogenous mechanism can help us effectively avoid the model misspecification issue. In other words, we cannot confirm which exogenous investment path is a "correct" or "more realistic" one. Instead, given the general principle, we use the model to generate the counterfactual baseline. We have now included a concise description of the G-RDEM model and have referred readers to the documentation of the G-RDEM model. *(Lines 531-538)*

   Trade policy is not considered in this study; it represents our next research target, in particular we will try to understand how the global economic maximum CBM can facilitate the decarbonization of the global iron and steel industry.

3. It is unclear in the discussion of the projections how new plants are being introduced. In the life-cycle of plants, in each year a number of older plants cease to exist and new ones start production. It appears that the number of plants in each country is static (see equation 10) and that the structure of plants is static (at base year levels). If this is not the case, the authors should describe in greater detail the allocation of production within country. There are several (non-competing) alternatives. First, one could

use dynamic shares, i.e., update the shares each year depending on the other assumptions—such as retro-fitting, technology switching, etc. Second, one could assume that new plants use production technologies different from the average—depending on the policy environment. If policies are pushing cleaner technologies, why wouldn't new plants be cleaner than the average plant. In addition, even if there are no formal forward-looking expectations in their framework, one would assume that if policies are providing incentives for cleaner technologies, why would investors continue to invest in conventional, emission intensive technologies.

We appreciate the points raised and have now included in the text a more detailed description of our methods related to the crude steel production plant. *(Lines 555-560)*. We have used the transformation of processing units within the plant to represent the transformation of the iron and steel production structure (inner-plant retrofitting: the outdated units will be replaced by new processing units with lower carbon technology). The decision to eliminate old processing units and install new ones within a plant, is determined by the plant's operating characteristics (e.g., the life cycle of processing units) and market demand (e.g., socio-economic scenario).
We have comprehensively analyzed the possible CO_2 emissions mitigation pathways of the global iron and steel industry, considering the influence of policy, technology development, and the processing characteristics at country-, industry- and plant-levels, by using eight parameters: the type of processing routes of the iron and steel plants, the year of the latest retrofitting, the average operating lifetime, the potential low-carbon technology of the iron and steel plants, the time window of the low-carbon technology adoption, the number of times the iron and steel plants have been retrofitted, the order of countries adopting low-carbon technology, and the retrofitting schedule of the iron and steel plants.

4. It would be good to clarify that retro-fitting only involves current technologies, i.e., there is no assumption of deployment of currently unused technologies such as carbon capture with storage, or alternative fuels such as hydrogen.

Thank you for the comment. We analyze possible CO_2 emissions mitigation pathways at the plant level, over the short term and long term, by proposing the deployment roadmap of the currently used technologies (fuel switch, transformation of the iron and steel processing route) and the innovative deep decarbonization technologies (implementation of the Carbon capture, use and storage (CCUS) technology, and the Hydrogen-based steelmaking technology). *(Lines 622-641)* Global cumulative emission reductions will be 49.1Gt~69.7Gt from 2020 to 2050 with the implementation of both current and deep decarbonization technologies. The detailed results were presented in Figure 3, Figure4 and detailed descriptions were shown in the relevant section.

Minor points:

It is possible that 'processing routes' is commonly used in the production of steel and technology, but economists would probably use the term 'technologies' or 'production technologies'.

We thank the reviewer for pointing out the different descriptions of 'processing routes' in different fields. As suggested, we have now included a detailed description of 'processing routes' the first time it was used in the main text to provide a more flexible description suitable for diverse readers. *(Lines 85-86)*

Line 119 two-third should read as 'two-thirds'

Thank you. This is a typo and we have revised it. *(Lines 139)*

Line 147 forward, replace all instances of ‘outputs’ with ‘output’

Many thanks. We have revised all these errors in the manuscript carefully. *(Lines 168, 171, 176)*

Line 157 replace ‘indicated’ with ‘indicate’

Thank you. This is a typo and we have revised it. *(Lines 178)*

Line 157 replace ‘had’ with ‘have’

Thank you. This is a typo and we have revised it. *(Lines 178)*

Line 273 replace ‘scarp’ with ‘scrap’

Thank you. This is a typo and we have revised it. *(Lines 311)*

In general, the paper should be re-read with a focus on improving the readability and grammar.

Many thanks. We’ve taken the opportunity to thoroughly revise the text for clarity and flow, and believe it is now free of errors.

Reviewer Reports on the First Revision:

Referees' comments:

Referee #1 (Remarks to the Author):

I thank the authors for their careful responses and modifications to the manuscript, which have led to an improved work.

A few minor comments:

Page 1 "will reduce 69.6 Gt emissions globally" might be better written as "would lead to cumulative global emissions reductions of 69.6 Gt CO2", which helps the reader distinguish between cumulative reductions and the emissions in the single year 2021 later in the sentence.

Page 1 "should work together": this idea might be better phrased as "Technology cooperation between the two largest producers (China and India) would likely lead to more rapid mitigation" or similar, to avoid the use of normative "should" and be more direct about the reason.

Page 2 "net-zero CO2 emissions systems in every sector of the economy": In fact the net-zero target is global, and does not need to be achieved by every sector, nor every region, as long as globally emissions are net-zero. So you could rephrase as "net-zero CO2 emissions across all sectors globally"

Page 2 "with each processing unit should set individually according to its techs specification and they're after un-unified": Something went wrong in this new text, which doesn't make sense. Please correct.

Figure 1 has a scale on it (1:140 900 000), but such a scale only makes sense on printed materials, and the scale by definition changes when viewed on a screen at different levels of zoom, so remove the scale it that's easy.

Page 5 "sufficient local natural gas and shale gas" would be better as simply "sufficient local natural gas", since shale gas is also natural gas. "Shale" specifies its origin, not any difference in quality.

Page 5 "units were regularly retrofitted": I'm not sure what's regular here. Perhaps the word "regularly" should be dropped.

Page 5 "production will be fit" doesn't make sense to me. Please correct.

Referee #2 : no further comments to authors

Referee #3 (Remarks to the Author):

The authors have obviously put a lot of new effort in this revision, but I am not sure it is a huge improvement, and in my mind, there are still some unanswered questions.

1. I'm not sure how to interpret the sensitivity analysis with respect to the SSPs. Are the numbers cited the full range of potential emissions, with and without mitigation, or only the reduction range. Back of the envelope calculations suggest that a no-mitigation scenario under SSP1 could possibly see a reduction in total cumulative emissions compared with SSP2, depending on the speed of the roll-out of emission saving technologies, but could just as well see an increase given the higher GDP growth. SSP5 is more problematic. The same type of the back of the envelope calculations shows that cumulative emissions could rise by up to 2.5 times under SSP5, compared to SSP2 (i.e., 250 gt) given the very high GDP growth. The authors need to clarify better the discussion of the SSPs and make it clear when they are referring to cumulative emissions that it is actual cumulative emissions or reductions in cumulative emissions.

2. I am not convinced by the argument regarding savings/investment in their implementation of the G-RDEM model. It seems that they are largely relying on simulating G-RDEM using default parameterization and there is no discussion of the results—how do domestic/foreign savings and domestic investment as a share of GDP evolve over time? And are the trends plausible? I am not convinced that the drivers in the savings equation are good explanatory variables for savings (they certainly haven't been for Japan), nor convinced of the out-of-sample estimates for the coefficients. Moreover, aggregate savings/investment is only part of the story. The conversion of savings into investment goods also should change over time—away from construction materials towards investment in R & D, information technologies, etc.
3. I thank the authors for the discussion on 'new' plants, but probably still don't understand exactly what is being done. If I understand correctly, the number of plants is static (in each country), but the number of units within each plant, and its technology can change. What determines the technology of a new unit? The traditional characteristics of the existing plant? Are there any caps on how many units a plant can have?
4. There are still many spots in the paper where the English is rough. Notably, I would suggest re-phrasing the new sentences related to the role of global institutions—some of which is also editorializing. See for examples lines 60-64. See also lines 106-108, which on one reading suggests that India is producing 67% of global steel output. On lines 240-243, this is a trite observation since you say earlier that 8 countries represent the vast majority of emissions.

Author Rebuttals to First Revision:

Response to Referees' comments:

Referee #1 (Remarks to the Author):

I thank the authors for their careful responses and modifications to the manuscript, which have led to an improved work.

We appreciate the reviewer's positive tone and constructive comments.

A few minor comments:

Page 1 "will reduce 69.6 Gt emissions globally" might be better written as "would lead to cumulative global emissions reductions of 69.6 Gt CO2", which helps the reader distinguish between cumulative reductions and the emissions in the single year 2021 later in the sentence.

We appreciate the suggestion. We take the point and have revised the text 'will reduce 69.6 Gt emissions globally' to 'would lead to cumulative global emissions reductions of 69.6 Gt CO_2'. (*Lines 24-25, in Page 2*)

Page 1 "should work together": this idea might be better phrased as "Technology cooperation between the two largest producers (China and India) would likely lead to more rapid mitigation" or similar, to avoid the use of normative "should" and be more direct about the reason.

We acknowledge the reviewer's concern regarding the word 'should'. We have deleted the related policy recommendations from the manuscript, following the editor requirement.

Page 2 "net-zero CO2 emissions systems in every sector of the economy": In fact the net-zero target is global, and does not need to be achieved by every sector, nor every region, as long as globally emissions are net-zero. So you could rephrase as "net-zero CO2 emissions across all sectors globally"

We appreciate the suggestion. We take the point and have revised the text to 'net-zero CO_2 emissions across all sectors globally'. (*Lines 32, in Page 2*)

Page 2 "with each processing unit should set individually according to its techs specification and they're after un-unified": Something went wrong in this new text, which doesn't make sense. Please correct.

We thank the reviewer for pointing out this mis-sentence. We have revised the text to ‘with each processing unit should set individually according to its techs specification’ to make it clearer. (*Lines 41-42, in Page 2*)

Figure 1 has a scale on it (1:140 900 000), but such a scale only makes sense on printed materials, and the scale by definition changes when viewed on a screen at different levels of zoom, so remove the scale it that's easy.

We appreciate the suggestion. We take the point and have deleted the scale on Figure 1.

Page 5 "sufficient local natural gas and shale gas" would be better as simply "sufficient local natural gas", since shale gas is also natural gas. "Shale" specifies its origin, not any difference in quality.

We thank the reviewer for pointing out this. We take the point and have simplified the text to ‘sufficient local natural gas’. (*Lines 88-89, in Page 3*)

Page 5 "units were regularly retrofitted": I'm not sure what's regular here. Perhaps the word "regularly" should be dropped.

We thank the reviewer for pointing out this. We have deleted this word.

Page 5 "production will be fit" doesn't make sense to me. Please correct.

We appreciate the suggestion. We have revised the text to ‘all low-carbon upgrade of existing plants will be fit during the retrofitting window’ to make it clearer. (*Lines 114-115, in Page 4)*

Referee #2: no further comments to authors

Referee #3 (Remarks to the Author):

The authors have obviously put a lot of new effort in this revision, but I am not sure it is a huge improvement, and in my mind, there are still some unanswered questions.

1. I'm not sure how to interpret the sensitivity analysis with respect to the SSPs. Are the numbers cited the full range of potential emissions, with and without mitigation, or only the reduction range. Back of the envelope calculations suggest that a no-mitigation scenario under SSP1 could possibly see a reduction in total cumulative emissions compared with SSP2, depending on the speed of the roll-out of emission saving technologies, but could just as well see an increase given the higher GDP growth. SSP5 is more problematic. The same type of the back of the envelope calculations shows that cumulative emissions could rise by up to 2.5 times under SSP5, compared to SSP2 (i.e., 250 gt) given the very high GDP growth.

Please let us clarify that we are not aiming to provide any validation of different SSPs, which is not a concern in this paper. Based on the SSPs simulations from IIASA SSP database (https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=about#v2) and G-RDEM, we projected and compared the steel production, and associated emissions, under SSP1, 2, & 5, as the reviewer suggested in previous round of comments.

There is some significant difference in terms of default technology retrofitting date for global plants under SSP1, 2, 5. In short, default retrofitting date in SSP1 < SSP2 < SSP5 (was recommended by the reviewer). We performed the sensitivity analysis aiming at examining the emission implications by setting different retrofitting dates (2-8 years for either early or late deployment of low carbon technologies). To be more specific:

- In SSP2, the default retrofitting scenario considers that each iron and steel plant will be retrofitted at its planned retrofitting date. The sensitivity analysis examines earlier and later deployment (2-8 years) of retrofitting technologies than the default case (*see Lines 688 – 698*).
- In SSP1 green technologies are adopted sooner, and we have assumed that the retrofitting will be faster than in SSP2. In this case, the default retrofitting scenario considers retrofitting plants 5 years earlier than the planned retrofitting date. The early scenario assumes retrofitting 8 years earlier than the planned retrofitting date whereas the late scenario assumes retrofitting plants 2 years earlier than the planned retrofitting date (see results in *Lines 215-227*).
- In SSP5, reflecting high challenges of mitigation, we have assumed that retrofitting will be deployed later that in SSP2. That is, the default scenario here is 5 years later than the planned retrofitting date. The early-retrofitting scenario is 2 years later than the planned retrofitting date whereas the late-retrofitting scenario is 8 years later than the planned retrofitting date. (see results in *Lines 215–227*).

The authors need to clarify better the discussion of the SSPs and make it clear when they are referring to cumulative emissions that it is actual cumulative emissions or reductions in cumulative emissions.

Many thanks for your comments. We rephrased the legend for Figure 3 to specify the 'cumulative emissions' and 'cumulative emission reductions'. To make it more understandable, cumulative emission reductions are the 'cumulative emissions without any decarbonization intervention (106.3 Gt from 2020 to 2050)' minus the 'cumulative emissions under the low-carbon scenario sets'.

2. I am not convinced by the argument regarding savings/investment in their implementation of the G-RDEM model. It seems that they are largely relying on simulating G-RDEM using default parameterization and there is no discussion of the results—how do domestic/foreign savings and domestic investment as a share of GDP evolve over time? And are the trends plausible? I am not convinced that the drivers in the savings equation are good explanatory variables for savings (they certainly haven't been for Japan), nor convinced of the out-of-sample estimates for the coefficients. Moreover, aggregate savings/investment is only part of the story. The conversion of savings into investment goods also should change over time—away from construction materials towards investment in R & D, information technologies, etc.

We appreciated the questions. Please let us clarify that our aim is not to improve the G-RDEM model, rather we use it to analyse future outputs of iron and steel sector – a default function and output from the model. To the best of our knowledge, G-RDEM is the best tool currently available to perform this task, as it is specifically designed to generate long-term scenarios.

After consulting with the manuscript Handling Editor, we provided more in-depth description and justification for choosing the model in *Lines 504-513*.

"*G-RDEM is a well-designed computable general equilibrium tool for long-term counterfactual analysis and the generation of the economic baseline given gross domestic product (GDP) and population projections. It has been improved in many ways specifically for the generation of long-term scenario. The plausibility of the long-term scenarios generated by G-RDEM have been discussed in detail in many previously published works. For example, BRITZ and ROSON (2019) discussed the long-term scenarios generated by the GRDEM model under the Shared Socio-economic Pathway (SSP) 1-5 and showed that G-RDEM brings about much more plausible results, as well as a more realistic, internally consistent representation of the economic structure in a hypothetical future*".

References:

1. Britz, W. & Roson, R. G-RDEM: A GTAP-Based Recursive Dynamic CGE Model for Long-Term Baseline Generation and Analysis. *Journal of Global Economic Analysis* **4**, 50-96, doi:10.21642/JGEA.040103AF (2019).

G-RDEM has no specific limitation about projecting future steel production. We agree with the reviewer's concern that the model cannot handle some out-of-sample cases, which is now acknowledged in the *Method section (Lines 429-433 in SI)*. Given that future steel production increase will take place in developing countries, we choose the default setting of G-RDEM.

We have added the following sections to the text and SI to improve the manuscript:

- In response to reviewers' concerns about the rationality of using default model settings and parameters, we added justification of model selection in the Methods section *(Lines 504-513)*.
- In response to reviewers' concerns about the lack of discussion of performance of model results (e.g., aggregate savings and investment), we have added more in-depth discussion in the Supplementary Information (*Lines 415-420 in SI*).

- In response to reviewers' concerns about the limitations with the saving equations (and Japan case), we have added a statement of a general limitation of G-RDEM to the Supplementary Information and discussed the potential impact of this limitation on our results *(Lines 429-433 in SI*).
- In response to reviewers' concerns about the conversion of savings into investment goods, we have added a detailed description of the setup about this to the Supplementary Information. *(Lines 421-428 in SI*).

3. I thank the authors for the discussion on 'new' plants, but probably still don't understand exactly what is being done. If I understand correctly, the number of plants is static (in each country), but the number of units within each plant, and its technology can change. What determines the technology of a new unit? The traditional characteristics of the existing plant? Are there any caps on how many units a plant can have?

Please let us clarify that we did NOT discuss 'new plants' in the current manuscript. To our best knowledge, there are no projections for proposed new plants at country / regional / global level, which is also an analysis out of the scope of our paper. The newly added future iron and steel demand will be fulfilled by hypothetically expanding the capacity of the current production plants (i.e. by adding new processing units to existing plants). The number and technology of new units are determined by various parameters under low-carbon retrofitting scenarios, including the plants processing and operating details (current processing routes, year of the latest retrofitting, average operating lifetime), technology adoption availability (development of low-carbon technology and their maturity as time progresses), and national conditions (scrap cumulation, climate policy). We have provided a step-by-step illustration diagram in Extended Data Figure 7, 8 and detailed description with examples in the SI *(Lines 162-235 in SI).*

Here is an example of the response to the process routes vs. retrofittable technology (this example is given in *SI Lines 162-235*): Iron and steel plants with specific processing routes have specific types of processing units.

ArcelorMittal Ghent iron and steel plant in the European Union (EU):

The latest retrofitting time of the ArcelorMittal Ghent iron and steel plant in Belgium with the coal-based BF-BOF steelmaking process is 2015. Considering the average 14-year retrofitting-cycle of iron and steel plants with the BF-BOF steelmaking process, the next retrofitting date for the ArcelorMittal Ghent Iron and steel plant is set as 2029. According to the IEA and the Institute for European Studies' projection, the scrap reserves in the European Union (owned by a company in Luxemburg and located in Belgium) are sufficient before 2030. Therefore, we assume that ArcelorMittal Ghent iron and steel plant will switch directly from the long process of blast furnace to the shorter scrap-based electric-arc-furnace (EAF) one for the low-carbon upgrading. After the first low-carbon retrofitting, ArcelorMittal Ghent iron and steel plant will be fully transformed into a total scrap-based EAF short process steelmaking plant. Accordingly, the average retrofitting-cycle of iron and steel plants with this type of steelmaking process is 12 years. The second retrofitting date of the ArcelorMittal Ghent iron and steel plant is therefore 2041. Since carbon emissions from the total scarp-based EAF, short process steelmaking is close to zero, we assume that the second retrofitting only updates the iron and steel smelting unit, and the steelmaking process remains unchanged.

References:

1. IEA. Iron and Steel Technology Roadmap Towards more sustainable steelmaking. (International Energy Agency (IEA), 2020).

2. Axelson, M., Robson, I., Khandekar, G. & Wyns, T. Breaking Through Industrial Low-CO2 Technologies on the Horizon. (Institute for European Studies, Vrije Universiteit Brusse, 2018)

4. There are still many spots in the paper where the English is rough. Notably, I would suggest re-phrasing the new sentences related to the role of global institutions—some of which is also editorializing. See for examples lines 60-64. See also lines 106-108, which on one reading suggests that India is producing 67% of global steel output. On lines 240-243, this is a trite observation since you say earlier that 8 countries represent the vast majority of emissions

We appreciate the suggestions. We have removed the text related to the role of global institutions following the editor's recommendations. As suggested, we have revised the text in 'Lines 60-64 in the last version' to 'Therefore, the decarbonization of the entire iron and steel industry depends on the efforts undertaken by every single plant.' *(Lines 42-43)*. We revised the sentence in 'Lines 106-108 in the last version' to give a clear account of the high concentration of coal-based DRI plants in India. *(Lines 80-82)*. We removed the repeated expression on the concentration of cumulative reductions *(Lines 240-243* in the last version), and revised to 'The spatial distribution of the hot spots of emissions reduction (countries with large emission reductions, the dark areas in Figure 3) gradually shifts from advanced regions to emerging ones over time.' *(Lines 182-184)*. We've taken the opportunity to thoroughly revise the text for clarity and flow.

Reviewer Reports on the Second Revision:

Referees' comments:

Referee #3 (Remarks to the Author):

This is a carefully thought out exercise and provides detailed scenarios for emissions reduction in a critical sector. Using a CGE model for projecting overall steel demand is appropriate. There is nonetheless much more that could be done--for example looking at more detail on steel demand and how it may evolve with changing GDP and demographics. The authors use default assumptions, which are likely to change between now and 2050.

Author Rebuttals to Second Revision:

Referees' comments:

Referee #3 (Remarks to the Author):

This is a carefully thought out exercise and provides detailed scenarios for emissions reduction in a critical sector. Using a CGE model for projecting overall steel demand is appropriate. There is nonetheless much more that could be done--for example looking at more detail on steel demand and how it may evolve with changing GDP and demographics. The authors use default assumptions, which are likely to change between now and 2050.

We acknowledge the reviewer's concern regarding the projection of steel demand. We have added discussions on the limitations of the CGE model and future directions in the main text *(Lines 251-257)*. The projection of future steel demand in different economies may remain uncertain. We employed a state-of-art computable general equilibrium (CGE) model, i.e., G-RDEM, with default settings of different SSPs to provide the 'most-likely' estimate. But the future is full of varies, such as technological shocks, pandemics, geopolitical conflicts, etc., that may change the regular route of the global economy. The projection of steel demand in the future needs more detailed datasets and real-time economic dynamics to improve and update.