SLACC/MG/3

TOWN AND COUNTRY PLANNING ACT 1990

Application by West Cumbria Mining Ltd

Development of a new underground metallurgical coal mine and associated development at Former Marchon Site, Pow Beck Valley and area from Marchon Site to St Bees Coast

Planning Inspectorate Reference:	**APP/H0900/V/21/3271069**
Local Planning Authority Reference:	**4/17/9007**
Date of Inquiry:	**7th September 2021**

REBUTTAL PROOF OF EVIDENCE

of

Professor Michael Grubb PhD

Professor of Energy & Climate Change, University College London,
Deputy Director, UCL Institute of Sustainable Resources
Eminent Scholar, Economic Sustainability, Kyung-Hee University, Korea

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1. INTRODUCTION

1.1. In this rebuttal evidence I respond to the Proof of Evidence of Caroline Leatherdale [WCM/CL/1] and her Rebuttal Proof of Evidence [WCM/CL/3], the Proof of Evidence of William Tonks [WCM/WLT/1] and his Rebuttal Proof of Evidence [WCM/WLT/3], their appendices, and the Ecolyse Report dated 1 September 2021.

1.2. This rebuttal should be read together with my Proof of Evidence [SLACC/MG/1] ("Main Proof") and Appendices [SLACC/MG/2].

1.3. As with my Main Proof, save where I indicate to the contrary, the facts and matters contained in this proof of evidence are within my own knowledge. Where facts and matters are not within my own knowledge, I have identified my sources of information or understanding.

2. THE ECOLYSE REPORT

2.1. The Proof of Evidence of Caroline Leatherdale attached a report by Ecolyse indicating that it is a "standalone" assessment of the greenhouse gases arising from the Woodhouse Colliery project, which replaces the AECOM Report, which I addressed in my Main Proof (MG/1 sections 4-8).

2.2. During the process of preparing this rebuttal proof a further "Version 2" of the Ecolyse Report dated 1 September 2021 was provided to solicitors for SLACC on the evening of 3 September 2021. ("Ecolyse Version 2" cited as EV2/paragraph number)

2.3. Ecolyse Version 2 states that it was updated to include additional data on the GHG emissions embedded in materials consumed over the operational lifetime of the Development. (EV2/1.9) I note that this appears to have been done in response to my Main Proof where I pointed out that the AECOM Report appeared to omit the embedded carbon emissions of materials for construction of the mine and of mining equipment. (MG/1 paras. 4.08-4.11 and 4.13-4.17).

2.4. Ecolyse Version 2 also provides updated estimates based on the additional emissions included in the assessment and indicates that additional mitigation measures will be employed, as discussed below.

The Ecolyse Scenarios

2.5. Both versions of the Ecolyse Report are based on four scenarios.

2.6. First, is the "**do nothing**" scenario. Whilst it may be obvious, it is perhaps worth noting that Ecolyse acknowledge that the do nothing scenario, without the mine, would have no emissions associated with it (EV2/3.5). So all agree that there is one certain way to avoid greenhouse emissions from the proposed mine: not to grant permission.

2.7. Ecolyse then set out three scenarios for analysis in which the mine is permitted (EV2/3.4):

2.7.1. The "**worst case scenario**" which Ecolyse says includes no mitigation by WCM and assumes no decarbonisation of the electricity grid or transport system.

2.7.2. The "**likely unmitigated scenario**" which Ecolyse indicates accounts for "year year-on-year decarbonisation of the economy including of the national grid and transportation sector consistent with Committee on Climate Change (CCC) and Government published emissions projections". The name appears meant to imply that this scenario reflects the likely emissions from the mine if mitigation was not undertaken by WCM.

2.7.3. The "**likely mitigated scenario**" is "consistent in scope with the likely unmitigated scenario" but also includes reductions applied by Ecolyse to reflect what it says is "mitigation committed to by WCM".

Assessment of Significance

2.8. In my Main Proof I set out why the "significance criteria" adopted by AECOM of 1% of total annual UK carbon budgets was groundless. I note that Ecolyse has not adopted this significance criteria and instead acknowledges that any net increase in GHG emissions should be "treated as having a likely significant effect". (EV2/3.7)

2.9. It therefore appears that WCM now agrees that if the mine leads to an increase in greenhouse gas emissions, this should be treated as significant.

Methodology – general comments

2.10. The methodology of the Ecolyse Report is unclear in many respects. Whilst in some cases, assumptions and emissions factors used in the Report are set out, in other cases they are not and I am then unable to tell what calculations have been performed to arrive at the results, or to consider whether certain figures are reasonable.

2.11. Consequently I focus on key areas, and in particular those which are most likely to alter the results to a significant degree.

2.12. In terms of the methodology for calculating emissions from the enabling and construction phase of the proposed mine, Ecolyse indicate that they have "not reviewed in detail and have [] adopted unchanged" the emissions calculations set out by the AECOM Report. [EV2/2.3] In my Main Proof, I highlighted shortcomings with the AECOM Report's estimates of construction emissions. In particular, the comments I made at paragraphs 4.4, 4.9 and 4.11 have not been addressed. Ecolyse says that the enabling and construction related emissions need not be revisited "because they represent less than 5% of the whole life GHG emissions from the Proposed Development." [EV2/2.3] However, this relies on the assumption that the estimates in the AECOM Report are (at least roughly) accurate, and as I noted in my proof, it is impossible to determine this from the information provided.

2.13. Without delving into the methodology, one can "sense check" the figures. It is striking that, for instance, the assessment asserts that in the "likely mitigated" scenario there would be <u>zero</u> scope 1 and scope 2 emissions during the 2-year period during which the mine is constructed. [EV2/Table 5-2] Given the scale of the works involved and the machinery that will be needed, it is difficult to see how this could possibly be the case.

2.14. Likewise, one may note that the decommissioning emissions are said to be negative in the "likely mitigated" scenario. [EV2/Table 5-2] This appears to be due to a small negative value for land use, and no other emissions estimated to arise. Again, it is no small matter to decommission a site the size of this one, with its many component parts, and it is hard to see how the claim can be made that no emissions will arise from that process. As for the claim that land use after decommissioning could lead to negative emissions, the relevant comparison is not zero, but how much CO_2 might be absorbed from the land (trees, soil etc) over the coming decades in the absence of the mine.

End Use Emissions

2.15. The Ecolyse Report does not assess the end use emissions of the coal on the basis that this is not legally required. (EV2/2.11-2.13) No claim is made by Ecolyse that the end use emissions are zero – the Report only indicates that it is considered appropriate to exclude these from the assessment. (EV2/2.13) Of course I understand that other evidence submitted by WCM does make the claim that the result of the mine is that no net new emissions will arise (or even that there will be a reduction).

2.16. West Cumbria Mining seemed to accept in its previous Environmental Statement chapter on greenhouse gas emissions that the emissions from the end use of the coal "may be capable of being a material planning consideration" (former Environmental Statement, Chapter 19, at paras 10(i), 12, and 65). Ecolyse themselves do not take a position on that issue.

2.17. I repeat the points I made in section 6 of my Main Proof in relation to the magnitude of the end use emissions, the fact that they cannot be “assumed away” and the further point that the political implications of the UK permitting such a mine would undermine efforts to slow the development of coal mines abroad.

2.18. As far as I am aware no one has disputed my calculations of the end use emissions, and nor has anyone taken issue with my statement that there would be political consequences to permitting the mine that would undermine the UK’s climate diplomacy. That, in itself, ought to be enough reason to refuse permission for this mine.

2.19. In relation to the Ecolyse Report, even ignoring all the other shortcomings that I highlight below, one can simply note that attributing the use of only 1% of coal from the mine as net additional coal would result in more than a doubling of the existing Ecolyse estimate for the “likely mitigated” emissions from the mine for every year the mine is operating at full operational capacity. (Compare the figure of 87,994 tonnes CO_2e from my Main Proof para 7.6 with EV2/Table C-6, page 42, final column for the years 2029-2049).

2.20. If “only” 90% substitution took place, the actual emissions from the mine would be more than 11 times the Ecolyse estimates in any year that the mine operates at full capacity.

2.21. And of course, whilst there are proposals to offset the emissions from the operation of the mine (which I address further below), WCM has not made any indication that it would seek to offset the end use emissions of the mine.

Mitigation Measures Relied On

2.22. Table 5-1 of the Ecolyse Report sets out “WCM Proposed Mitigation” for a number of aspects of the greenhouse gases which arise from the mine.

2.23. I am not legally trained, but I understand from SLACC's legal team that currently, a number of these measures are not secured by the conditions and/or legal agreement that WCM has proposed. These include (EV2/Table 5-1):

2.23.1. Proposed use of biodiesel in place of all operational diesel[1] (100% reduction claimed)

2.23.2. Methane capture scheme (95% reduction claimed[2]) – see further discussion below in relation to methane capture

2.23.3. All company vehicles will be electric and be powered through green tariff from the start of the operational phase[3] (100% reduction claimed)

2.23.4. WCM "will work to procure a supplier" of steel rock bolts that can produce these materials using at least 50% recycled steel (reduction not stated, but this leads to the overall figure for "purchased goods and services" dropping by 29% in years the mine operates at full operational capacity[4])

2.24. I also note that there is some irony in the fact that WCM rely on shifting their procurement to recycled steel to reduce their estimated emissions whilst simultaneously arguing that the demand for BF-BOF steel made with metallurgical coal will essentially remain stable over the coming decades.

2.25. As most of the mitigation measures relied upon in the Ecolyse Report do not appear to be actually legally required, it seems highly optimistic to rely on the "likely mitigated" scenario in which it is assumed all of these measures will be implemented.

[1] I understand that this measure is something which is mentioned as a measure which "may be" employed, per Section 106 Agreement, Sch 1 para 12.1.1.

[2] The reduction in methane leakage is claimed to be 95%. Due to the fact that burning the methane results in some emissions, the actual percentage by which the CO_2e figure for methane is reduced is slightly lower than this, as can be seen by comparing the figures in the "fugitive emissions from mining" columns in Tables C-5 and C-6. (No reduction is claimed until the year 2028, as in the initial years, concentrations of methane are considered too small to use the RTOs/gas engine; WLT/1 paras 6.1, 6.3)

[3] I understand that this measure is something which is mentioned as a measure which "may be" employed, per Section 106 Agreement, Sch 1 para 12.1.1.

[4] Compare next-to-last column in EV2/Tables C-4 and C-5 (which show identical figures) with same column in C-6.

2.26. I understand that the only measure set out in Table 5-1 that is actually legally secured is the commitment to a renewable electricity tariff. Even then, I am told by SLACC's legal team that while the commitment in Table 5-1 is that a renewable electricity tariff "will be employed from day 1 of construction…" the condition securing this only requires that details of a renewable electricity tariff "to be used during the Operational Phase of the development" must be submitted to and approved by the Council.[5]

2.27. In relation to the mitigation proposed generally, if the figures in the Ecolyse report reflected only the legally-secured mitigation (i.e. the green tariff electricity), rather than the much longer list of mitigation "proposed," the emissions in "likely mitigated scenario" would be approximately 8.05 million tonnes[6], as compared with 8.65 million in the worst case scenario and 8.20 in the likely unmitigated. This compares with Ecolyse's figure of 1.85 million tonnes in the "likely mitigated" scenario.[7] In other words, using Ecolyse's figures, whilst the Report implies that 77%[8] of the emissions in the "likely unmitigated" scenario would be mitigated by WCM commitments, legally secured commitments amount to less than 2%.[9]

2.28. Separately, I would note that it is not at all clear that it is reasonable to consider that signing up to green tariff electricity or that using biodiesel actually mitigates the greenhouse gas impact of that energy use entirely. There are many different "green tariffs", and there are questions as to whether many of these actually result in additional renewable electricity. A recent call for evidence from the Department of Business Energy and Industrial Strategy, for instance, noted that renewables now account for more than 40% of the UK's electricity mix and that there are concerns about transparency around such tariffs and the "role of green electricity tariffs in a

[5] Draft Condition 101.
[6] This figure can be calculated by assuming that the column labelled "Electricity Consumption" in Table C-5 has a value of zero, but that all other items are unmitigated. (i.e. by subtracting 120,706 from 8.11 million = 7.99 million). Construction/enabling and decommissioning emissions are between 0.05 and 0.09, meaning figures from . It is not possible from the Report to determine how these break down and what portion would be reduced due to green tariff use). [See Tables 4-2 and 5-2]
[7] Table C-6, bottom right cell.
[8] 8.20 – 1.85 = 6.35 Mt mitigated, which is 77% of the 8.2 Mt claimed to arise.
[9] 8.20 – 8.05 = 0.15 Mt mitigated, which is 1.8% of the 8.2 Mt claimed to arise.

world where renewable and low carbon generation become the predominant form of energy in our mix."[10] The BEIS paper also noted that prices for green tariffs have "generally converged with standard tariffs ... most likely reflect[ing] the very small additional costs of procuring" certificates used to denote green supply. There is now sufficient renewable electricity on the grid that suppliers can procure certificates to cover the amount they sell under their green tariff schemes at very low cost, and there is little evidence that such tariffs are leading to new renewable electricity generation capacity.

New figures in relation to embedded carbon

2.29. Ecolyse Version 2 has been updated to contain new figures estimating the embedded carbon of "purchased goods and services," which includes steel rock bolts, concrete and aggregate for roadways and runouts, and steel for mining equipment, as well as certain other items. (EV2/Table B-1, page 27) This is a welcome addition – the omission of certain of these items was something I raised as a concern in my main proof (MG/1 4.16-17)

2.30. Like in many areas, the assumptions behind these newly-included emissions are difficult to consider – in particular it is not clear how the tonnages in the last row of Table B-1 have been arrived at and whether they are reasonable estimates, as there is no methodology setting out how they have been arrived at and showing that this matches the likely operational needs.

2.31. For example, no justification is given for the Ecolyse decision to estimate the emissions from mining equipment simply by taking a raw steel figure and adding 50%, which results in the estimate of 2.7 kgCO2e/kg of machinery. There are many steps between raw steel and final product, including cast-off and much processing and shaping. Whilst not directly comparable, the emissions associated with the mass of cars

[10] DBEIS, Executive Summary, Designing a Framework for Transparency of Carbon Content in Energy Products: A Call for Evidence, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1011032/carbon-content-energy-products-cfe.pdf.

appears to be 4.7 – 5.7 kgCO2e/kg, much greater than the figure used by Ecolyse.[11] Ecolyse's new figures seem likely to underestimate this aspect of the purchased goods and services associated with mining operations.

2.32. I would also note that as the proposal for the very large methane mitigation machinery (the RTOs [pictured WLT/2 pages 7, 9-15) and 40ft containerised gas engines [pictured WLT/2 page 6]) is newly proposed and/or not included in the construction materials set out in the AECOM Report[12] (and so not incorporated in Ecolyse, as the construction emissions were adopted rather than calculated independently), these are omitted from the new calculations as well. These are obviously very large pieces of equipment as can be seen in the diagrams/photos, and will have substantial embedded emissions which do not appear to have been considered.

Methane emission levels

2.33. In its evidence, WCM now indicates that it will institute a methane capture scheme that will capture 95% of the methane emissions from the mine with a proposal to install 10 large regenerative thermal oxidisers (RTOs) in the Clean Coal/Reject Structure [WLT/2 pages 7-11] and install 5 40-foot standard containerised gas engines nearby. [WLT/2 pages 5-6]

2.34. I make the following comments:

2.34.1. I understand that the draft condition & legal obligation that have been suggested by WCM in relation to methane capture simply requires that there be a "mine gas capture scheme" and that whilst WCM's evidence asserts there will be a 95% capture rate, there has not been a commitment by WCM to any

[11] Derived from data in Appendix R2, Appendix A.1, page 94 and associated table.

[12] CD1.145, page 51. The paragraph on construction materials states "*A bill of quantities for the construction materials is not available. Estimates of materials have been made of the buildings, rail line, the concrete culvert and concrete hardstanding, the water tank and the car park. These estimates have been based on dimensions detailed within the Project Description of the Environmental Statement (West Cumbria Mining, 2018a). As other building and infrastructure elements have not yet been designed, this is only a partial calculation.*"

particular level of methane capture in the conditions or legal obligation to reflect this.

2.34.2. Even if such a commitment were made, I cannot see that it would be enforceable without a very significant and sophisticated monitoring system. Mr Tonks provides some detail in relation to methane monitoring systems that are proposed (WLT/1 section 7) but it is important to appreciate that these are all <u>inside</u> the mine. No monitoring is proposed that would provide information on the amount of methane which escapes once the coal comes to the surface, so the methane capture figures appear to be based on a number of assumptions, none of which are to be validated after construction of the mine.

2.34.3. Mr Tonks' calculations [WLT/2 page 2] do not provide sufficient information about how they are derived in order to fully understand or scrutinise their methodology, but it appears to be clear from Mr Tonk's evidence and the Ecolyse Report that the figures used in relation to methane capture rely directly on assumptions (not evidenced anywhere, as far as I can see) that:

2.34.3.1. In relation to the cut coal methane: (1) 85% of the methane from the cut coal will be captured before it leaves the mine[13] (2) that a further 10% will be captured at the coal processing step on the surface[14], leaving only 5% of the methane remaining, (3) that the captured methane will be sent to the RTO units without any leakage, and (4) it will be destroyed in the proposed RTO units with 100% efficiency.

2.34.3.2. In relation to the methane drainage system for the pillar coal methane: (1) there will be no leakage in the system and (2) the methane will be destroyed in the gas engines with 100% efficiency.

[13] WLT/1 para 5.2; EV2/Table B-5, page 32, rows 4-5.
[14] WLT/1 para 5.2; EV2/Table B-5, page 32, rows 4-5.

2.34.3.3. More generally, it is also assumed that the technology is fully implemented, works as promised (100% of the time), and there are no human or other failures in the systems.

2.34.3.4. All of these assumptions are open to question.

2.34.3.5. By way of example, it is well-documented in the oil and gas context that significant fugitive methane escape can occur at sealed joints, flanges, valves, and other equipment, and regular leak detection and repair (LDAR) systems are often mandated to ensure that leaks are minimised. No such systems appear to be proposed here and leaks are assumed not to occur.

2.34.3.6. Another well-documented cause of methane release is due to the need to release the gas during times of equipment failure or maintenance. Any such failures could lead to significant emissions, even if only for a short period.

2.34.3.7. It is not clear on what evidence Mr Tonks asserts that 95% of the methane in the coal will have been released by the time it leaves the processing plant, but if this assumption were wrong, this would lead to additional methane release from the coal which would not be captured (e.g. during conveyance to the rail loading facility or later transport). Even an additional 1% loss would increase the calculated methane emissions from the cut coal by 20% (from 5% to 6%).

2.34.3.8. No evidence is given to substantiate the claim that the RTOs and gas engines would destroy 100% of the methane, and again, if this efficiency was even slightly reduced, this could increase the actual methane emissions significantly.

2.34.3.9. Further, as I have mentioned, without a sophisticated monitoring program to identify and estimate losses from leaks, equipment failure, release of methane from the coal that comes to the surface but is not captured in the processing plant, or releases which occur after leaving the processing plant, it will never become apparent to anyone that the methane capture and destruction rates are not as claimed.

2.34.3.10. I address the issue of offsets below (and the inappropriate way they have been applied to methane emissions), but I understand that the legal obligation that WCM propose is to offset only those emissions as calculated by the Ecolyse Report or a later "GHG Report" for which the "methodology, approach and structure" should be "in general conformity" with the Ecolyse Report.[15] Again, I do not seek to legally analyse this provision, only to note that if future reports which form the basis for the offset calculation use the same methodology and approach, it will simply be assumed that 95% methane capture is taking place without any evidence to validate this assumption.

2.34.3.11. Based on the information provided by WCM, I do not consider one can safely rely on the figures they provide in relation to methane capture. Nor can one credit the claim that the full emissions of the mine will be offset, if lower levels of capture would never be discovered.

Methane arising during construction of the access drifts

2.35. The methane emissions figures are also dependent on the assumption that no methane will arise at all from excavation of the access drifts during the two-year construction period of the mine. This is despite the fact that during this time new

[15] Section 106 agreement page 34.

drifts will be driven to the offshore and onshore coal mining areas (as seen in green outline at Figure 5.4 of Chapter 5 of the Environmental Statement) which are anticipated to excavate 272,000 cubic metres of excavation wastes.

2.36. The evidence of Stuart Haszeldine shows that WCM intend to target the Main Band and Bannock Band coal seams. [SLACC/SH1 para 6.3 and preceding figure, reproduced immediately below] As can be seen in that figure, the planned drift will enter the coal measures long before it reaches the target seams, and indeed will enter the target seams well before the location where mining will start.

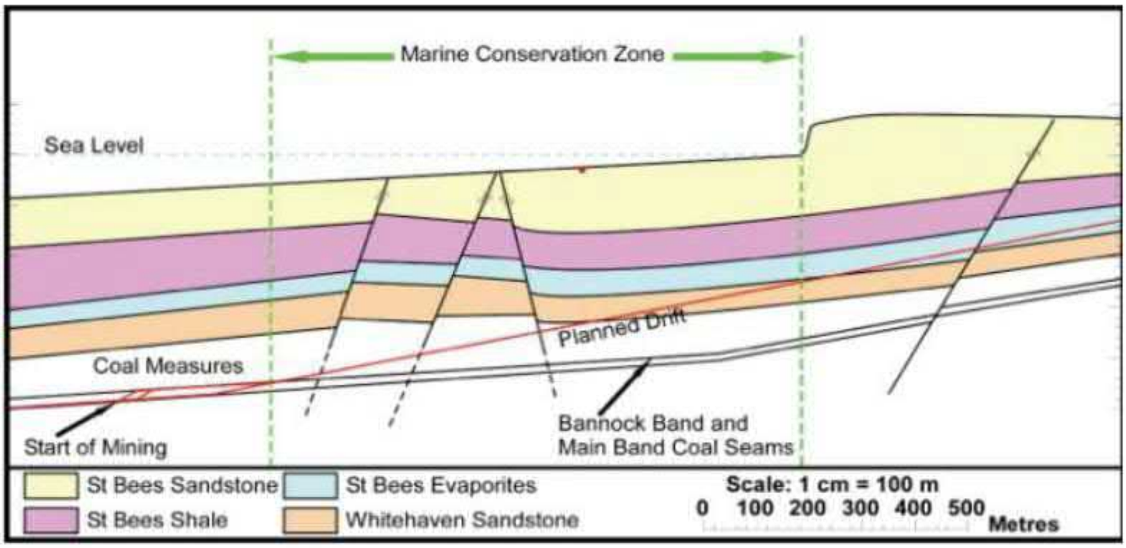
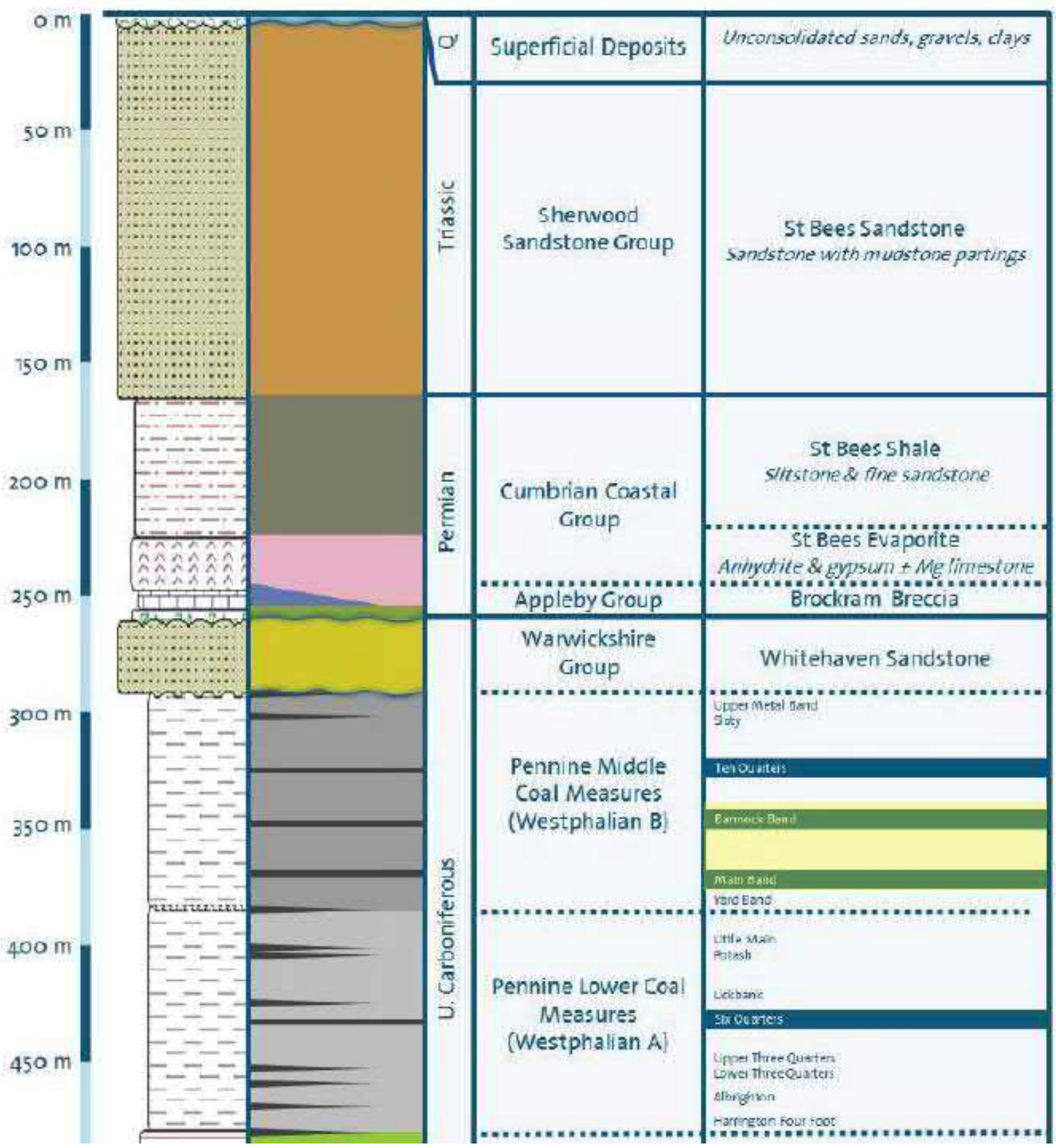


Figure 4: The Geology through which the cross-measure tunnels pass

Figure from ES Chapter 5, Appx B, Subsidence Briefing Note, page 51 (CD1.83)

2.37. Figure 5.1 from Chapter 5 of the Environmental Statement, an extract of which is pasted below (highlighting added to Main and Bannock Bands for ease), also shows that in order to access these coal seams, one must pass through the upper portions of the "Pennine Middle Coal Measures".

Figure 5.1: CMCP Regional Stratigraphy Applicable to Onshore Mining Area



2.38. Given that significant excavation will take place in the coal measures during the two-year construction of the mine – before the methane capture infrastructure is in place and operating – it is not clear how Mr Tonks and Ecolyse can reasonably use a methane emission figure of zero in these years.

Methane content of the coal

2.39. The methane emissions figures are also dependent upon the methane content of the coal. For instance, as 95% capture of the methane from the cut coal is assumed, the GHG emission figures which appear under the "fugitive emissions from mining" heading in Tables C-4, C-5 and C-6 of the Ecolyse Report (EV2/pages 40-42) are dependent upon the methane content of that coal. If the methane content were assumed to be higher, the emissions attributed to the loss of 5% of that methane would raise proportionally.

2.40. Mr Tonks states in his Proof [WLT/1 para 4.1] that:

> "The mined coal has an inherent methane gas content which can be measured, catalogued, mapped, interpolated and hence can be predicted as the mining progresses.
> Core drilling has been carried out since 2014 in the Woodhouse Colliery proposed footprint. The drilling has brought to the surface stratigraphic cores of rock and coal. The coal content has been analysed regarding its in-situ gas content using the desorption method, by which recovered coal is analysed in a laboratory to arrive at a "gas content" of cubic metres of methane per tonne of coal (m3 /t). The shallow onshore drilling carried out indicated the target seam (Main Band) with a gas content of 2m3/t whilst the deeper offshore drilling documentation indicated a target seam with a gas content of 6m3/t. These figures are within the norm of the UK gas contents where there is a range between less than 1m3/t up to as high as over 22m3/t. These figures are reflected in the spreadsheet at Appendix A."

2.41. Chapter 5 of the Environmental Statement shows that at least 19 borehole samples were taken by WCM, at Table 5.1 (reproduced below)

Table 5.1
Summary of Phase 1 – 4 WCM Borehole data

Phase	Date (Purpose)	Boreholes	Additional Information
Phase 1	**October 2014 – March 2015** (Coal seam distribution onshore)	GA03C	
		GA04C	
		GA05C	
		GA06C	
Phase 2	**June 2016 – October 2016** (Offshore data acquisition)	GA07CR	Directional borehole
		WCMOS02C	Offshore borehole
		GA08C	
		GA09C	
		GA11C	Directional borehole
Phase 3	**June 2016 – November 2016** (Consolidation of geological information in early target mining areas)	GA11DNC	Daughter borehole (north) of GA11C
		GA11DSC	Daughter borehole (south) of GA11C
		WCM01C	
		WCM02C	
		WCM03C	
Phase 4	**May 2017 – October 2017** Final Offshore drilling Programme	WCMOS03C	Offshore Borehole
		WCMOS04C	Offshore Borehole
		WCMOS05C	Offshore Borehole
		WCMOS06C	Offshore Borehole
		WCMOS09C	Offshore Borehole

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2.42. Despite obviously having significant data in his possession, Mr Tonks provides only two figures: one for the methane content of the shallow coal and one for the methane content of the deeper offshore coal. No information is given about how these figures are derived from the sampling data. It is not clear, for instance, whether these figures represent median values, average values, or something else. If they are median values, the average value could be much higher (because medians do not take account of the variability of data), and this could therefore underestimate the actual methane likely to be released from the coal. Mr Tonks notes that methane content in UK coals is known range up to 22 m3/t – if even a small portion of the coal seam has a content nearer this value, that could increase the overall methane content of the coal significantly, and thus the proportion which escapes the mine.

2.43. Again, though, there does not seem to be any mechanism by which anyone (aside from *perhaps* WCM internally, due to safety monitoring internal to the mine) would become aware of greater methane content in the coal than the figures anticipate if this is encountered, or the resulting increase in emissions. And nor does there appear to be a mechanism to require that any such additional emissions be reported to anyone or offset.

2.44. This is another reason why I lack confidence in the methane emissions figures and mitigation scenarios.

Post-closure methane emissions

2.45. In my Main Proof I noted that fugitive methane emissions from closed coal mines is a well-recognised and significant concern. [MG/1 para 4.27-4.29] Mr Tonks' rebuttal proof now sets out a proposal for sealing and capping the mine to prevent post-closure methane emissions. [WLT/3 section 4] He further states that "any residual uncertainty can be avoided through post-closure monitoring to ensure that the seal is effective in preventing methane leakage."

2.46. It is of course possible in theory to seal a mine against most leakage after it is closed, and to continue monitoring the mine and the area. However, I do not see in this evidence a clear and binding guarantee that this will happen in practice. I note that Mr Tonks refers to the role of the Coal Authority, so I presume that WCM relies on transferring responsibility for post-mine emissions – presumably decades hence - to the Coal Authority, which I am unable to evaluate.

3. OFFSETTING

3.1. I have set out above why I consider that the Ecolyse Report's estimates of the greenhouse gas emissions from the proposed mine do not appear to be reliable.

3.2. However, it is the Ecolyse methodology that will be used to calculate the offsets required. Quite apart from any other concerns about offsetting, the fact that the Ecolyse estimates emit or underestimate multiple categories of emissions means that – unless the methodology is updated to account for each of these omissions – offsets would only apply to a portion of the *actual* emissions of the mine. This fatally undermines claims that the mine would be "net zero".

Offsetting methane emissions

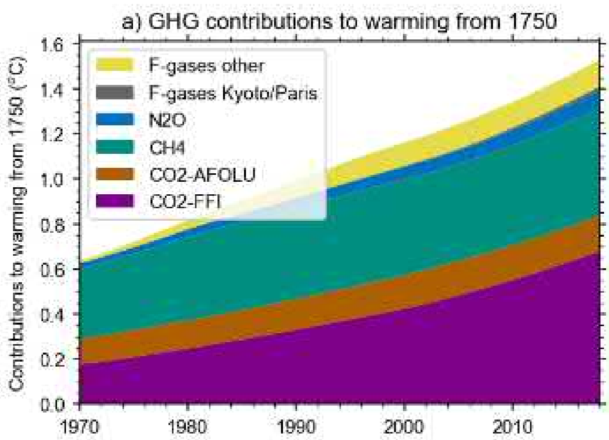
3.3. My Main Proof noted that methane is a major contributor to climate change and that global methane emissions may be decisive in whether global temperatures exceed 1.5C in the next couple of decades. (MG/1 para 4.20)

3.4. I therefore noted that most forms of offsetting focus on avoiding, reducing or absorbing CO2 emissions, and assess their contributions using the 100-year Global Warming Potential (GWP). Any offsets would only partially offset the impact of methane leakage on climate change over the lifetime of the mine.

3.5. Caroline Leatherdale responds by stating that "the agreed international metric for reporting GHG emissions is based on the 100-year GWP. The UK's legislated net zero target, carbon budgets, and annual reporting is therefore all presented as CO2e based on 100-year GWP." [CL/3 para 4.12]

3.6. First, it may be the case that the most common metric used is GWP-100, but that does not mean that shorter-term global warming potentials are not also used and considered to be "agreed international metrics". For instance, the latest IPCC Sixth Assessment Report: Working Group I: The Physical Science Basis, at Chapter 7, s. 7.6.1.4 headed "comparing long-lived with short-lived greenhouse gases" notes that using GWP-100 has the effect of "understating the effect of any new methane emission source by a factor of 4-5 over the 20 years following the introduction of the new source."[16]

3.7. More generally, Ms Leatherdale's response fails to grapple with my material point. Substantively, the warming impacts of methane are real and significant. The below figure extracted from Appendix R1 (Minx et al, 2021, Figure 4) shows the significant contribution of methane to warming. Methane's outsize role (in green) can be clearly seen.



3.8. 100-year global warming potential (GWP) does not adequately represent the impact of methane over the critical next few decades – and consequently it does not address either near- to mid-term rates of climate change nor the temperature goals of the Paris agreement, which if industrial emissions are not greatly mitigated would be

[16] https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Full_Report.pdf

breached within about one (for 1.5C) to a few (for “well below 2C”) decades - not a century.

3.9. Nor, for the same reason, would such methane emissions be completely countered by the proposed offsetting. Even assuming the proposed offsetting is effective, actually offsetting the effects of the methane emissions over the life of the mine would require using a much higher, short-term GWP.

3.10. I would also note in response to Ms Leatherdale that – in relation to her preferred metric, the 100-year GWP of methane, there is significant scientific uncertainty about the actual value, which may be +/- 50% of the currently-adopted estimate. (Appendix R1, page 54) So, I would submit that adopting a precautionary approach to ensure that the mine’s emissions are offset should involve a higher figure than the central estimate in any event.

4. CCS/CCUS

4.1. I note that both Ms Leatherdale’s and other evidence submitted relies heavily on an assumption that CC(U)S is available to capture CO2 use from coal at the required scale and cost. [CL/1 3.23-27] The reliance on utilisation is obviously flawed because the volume of captured CO2 that could be plausibly utilised is very much smaller than the volume emitted, or that would need to be captured in most of the global scenarios that rely significantly on carbon capture. This would be very much magnified in relation to the huge volumes of CO2 that would need to be captured on a blast furnace steel manufacturing site. So, the only plausible option for the decarbonisation of large industry would have to involve capture and disposal, not significant utilisation.

4.2. In relation to CCS, I concur with Professor John Barret that CCS on this scale is reasonably called commercially unproven. Indeed, having seen promises about CCS for over quarter of a century, the striking thing is how few of these promised projects have come to fruition. As with nuclear projections from decades ago, stating that CCS forms an important role in many scenarios says almost nothing about whether or when it will in reality come to pass, or at what scale or cost. Putting something in a scenario does not guarantee the technology will succeed as projected, as underlined by the history of CCS projections to date.

5. THE CLIMATE IMPACT OF THE MINE

5.1. In the proof of evidence of Jim Truman, the claim is made that "the cost reduction following the development of the Woodhouse mine would be negligible and likely to have no impact on the cost-competitiveness of BF-BOF steel production in Europe" and that the mine would not therefore slow down the transition towards low-carbon steel production in Europe in the future. [JT/1 para 7.8]

5.2. The economics of this statement are addressed in evidence from my colleague Paul Ekins, and the key point made that the sorts of costs savings Mr Truman himself asserts will occur, amounting to millions of pounds per year for each Mt of steel produced [JT/1 para 7.7] would not – if achieved – seem "negligible".

5.3. More generally, I would like to address the underlying assumption that underpins the view that the Woodhouse Colliery will reduce emissions, and its basic risk. It depends not only on assumptions that all the plans to reduce its direct emissions are realised and successful, to a degree greater than any other mines, and that offsets are purchased at a scale adequate for any residual emissions.[17] It also hinges on core assumptions about the future of coking coal demand in the UK and Europe, and that approval of the mine would have no impact on this.

5.4. It is highly reminiscent of the arguments strenuously put forward by E.On in the 2000s for building a new coal power plant at Kingsnorth. It was argued that the UK would continue to have an absolute need for baseload coal power production at scale for decades, putting forward evidence that renewable energy and gas could not possibly supply the UK's electricity needs and would be far more expensive. Consequently,

[17] I have set out above why the current Ecolyse Report would allow WCM to purchase offsets that do not cover the full emissions of the mine, and would also be inadequate to counter the methane emissions WCM/Ecolyse acknowledge will arise.

they argued that by building a new plant with the most advanced and efficient power generation technology, it would displace older and less efficient coal plants, and thereby reduce emissions.

5.5. Thankfully, these arguments did not succeed. In 2008 E.On abandoned its plans. Barely ten years later, coal was almost entirely phased out of UK electricity to a degree that was unimaginable to the incumbent power generator at the time. It is worth considering what might have happened had Kingsnorth proceeded – not only the wasted investment, but also the political pressures that would have arisen to keep coal in the electricity system so as not to bankrupt a brand new "state of the art" power station. Instead, at the site of the old and now-demolished Kingsnorth station, a developer is now reported to be looking to build a mixed-use development on the land including a clean energy hub, and it is reported that more than 2,000 jobs could be created.[18]

6. CONCLUSION

6.1. The proofs of evidence to which I have responded do not provide a convincing case that the mine will be 'greenhouse-gas neutral', even aside from the wider impact of adding more supply of coking coal to the European and world markets. Key elements of the "likely mitigation" scenario do not seem to be legally assured; estimates of emissions associated with the construction of the mine seem incomplete or inadequately justified; assurances of very high levels of methane capture are unconvincing particularly in the absence of whole-site, independent monitoring; and commitments to offset residual emissions with carbon offsets would not, in fact, achieve the 'climate neutrality' that WCM seek to imply.

6.2. Instead, proceeding with mine construction would create an obvious risk of emissions associated with construction and operation of the mine, in addition to its wider impact on the market for coking coal. Approval and licencing would moreover undermine the

[18] https://www.kentonline.co.uk/medway/news/ambitious-plans-for-former-power-station-site-241959/

credibility of the UK government's stance on climate change, while the vested interests created by the investment would inevitably encourage continuation of blast furnace steel operations, potentially at the expense of cleaner steel technologies to which the world must anyway move over time.

Declaration

The evidence which I have prepared and provide for this appeal reference APP/H0900/V/21/3271069 in this proof of evidence is true, and I confirm that the opinions expressed are my true opinions.

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A comprehensive dataset for global, regional and national greenhouse gas emissions by sector 1970-2019

Jan C. Minx[1,2,*], William F. Lamb[1,2,*], Robbie M Andrew[3], Josep G. Canadell[4], Monica Crippa[5], Niklas Döbbeling[1], Piers M. Forster[2], Diego Guizzardi[4], Jos Olivier[6], Glen P. Peters[3], Julia Pongratz[7,8], Andy Reisinger[9], Matthew Rigby[10], Marielle Saunois[11], Steven J. Smith[12], Efisio Solazzo[5], Hanqin Tian[13]

[1] Mercator Research Institute on Global Commons and Climate Change, Berlin, 10827, Germany
[2] Priestley International Centre for Climate, School of Earth and Environment, University of Leeds, Leeds; LS2 9JT, UK
[3] CICERO Center for International Climate Research, Oslo, 0318 Norway
[4] Global Carbon Project, CSIRO Oceans and Atmosphere, Canberra, Australia
[5] European Commission, Joint Research Centre, Ispra, Italy
[6] PBL Netherlands Environmental Assessment Bureau, the Hague, the Netherlands
[7] Ludwig-Maximilians-Universität München, Luisenstr. 37, 80333 Munich, Germany
[8] Max Planck Institute for Meteorology, Bundesstrasse 53, 20146 Hamburg, Germany
[9] Institute for Climate, Energy and Disaster Solutions, Fenner School of Society & Environment, Building 141, Linnaeus Way, The Australian National University, Canberra, ACT, 2600, Australia
[10] School of Chemistry, University of Bristol, Bristol, BS8 1TS, UK
[11] Laboratoire des Sciences du Climat et de l'Environnement, LSCE-IPSL (CEA-CNRS-UVSQ), Université Paris-Saclay 91191 Gif-sur-Yvette, France
[12] Joint Global Change Research Institute, Pacific Northwest National Laboratory, College Park, MD 20740 USA
[13] International Center for Climate and Global Change Research, School of Forestry and Wildlife Sciences, Auburn University, Auburn, AL 36849, USA
[*] *Correspondence to*: Jan C. Minx (minx@mcc-berlin.net) and William F. Lamb (lamb@mcc-berlin.net)

Abstract

To track progress towards keeping warming well below 2°C, as agreed upon in the Paris Agreement, comprehensive and reliable information on anthropogenic sources of greenhouse gas emissions (GHG) is required. Here we provide a dataset on anthropogenic GHG emissions 1970-2019 with a broad country and sector coverage. We build the dataset from recent releases of the "Emissions Database for Global Atmospheric Research" (EDGAR) for CO_2 emissions from fossil fuel combustion and industry (FFI), CH_4 emissions, N_2O emissions, and fluorinated gases, and use a well-established fast-track method to extend this dataset from 2018 to 2019. We complement this with data on net CO_2 emissions from land use, land-use change and forestry (LULUCF) from three bookkeeping models. We provide an assessment of the uncertainties in each greenhouse gas at the 90% confidence interval (5th-95th percentile) by combining statistical analysis and comparisons of global emissions inventories with an expert judgement informed by the relevant scientific literature. We identify important data gaps: CH_4 and N_2O emissions could be respectively 10-20% higher than reported in EDGAR once all emissions are accounted. F-gas emissions estimates for individual species in EDGARv5 do not align well with atmospheric measurements and the F-gas total exceeds measured concentrations by about 30%. However, EDGAR and official national emission reports under the UNFCCC do not comprehensively cover all relevant F-gas species. Excluded F-gas species such as chlorofluorocarbons (CFCs) or hydrochlorofluorocarbons (HCFCs) are larger than the sum of the reported species. GHG emissions in 2019 amounted to 59±6.6 $GtCO_2eq$: CO_2 emissions from FFI were 38±3.0 Gt, CO_2 from LULUCF 6.6±4.6 Gt, CH_4 11±3.3 $GtCO_2eq$, N_2O 2.4±1.5 $GtCO_2eq$ and F-gases 1.6±0.49 $GtCO_2eq$. Our analysis of global, anthropogenic GHG emission trends over the past five decades (1970-2019) highlights a pattern of varied, but sustained emissions growth. There is high confidence that global anthropogenic greenhouse gas emissions have increased every decade. Emission growth has been persistent across different (groups of) gases. While CO_2 has accounted for almost 75% of the emission growth since 1970 in terms of CO_2eq as reported here, the combined F-gases have grown at a faster rate than other GHGs, albeit starting from low levels in 1970. Today, F-gases make a non-negligible contribution to global warming – even though CFCs and HCFCs, regulated under the Montreal Protocol and not included in our estimates, have contributed more. There is further high confidence that global anthropogenic GHG emission levels were higher in 2010-2019 than in any previous decade and GHG emission levels have grown across the most recent decade. While average annual greenhouse gas emissions growth slowed between 2010-2019 compared to 2000-2009, the absolute increase in average decadal GHG emissions from the 2000s to the 2010s has been the largest since the 1970s – and within all human history as suggested by available long-term data. We note considerably higher rates of change in GHG emissions between 2018 and 2019 than for the entire decade 2010-2019, which is numerically comparable with the period of high GHG emissions growth during the 2000s, but we place low confidence in this finding as the majority of the growth is driven by highly uncertain increases in CO_2-LULUCF emissions as well as the use of preliminary data and extrapolation methodologies for these most recent years. While there is a growing number of countries today on a sustained emission reduction trajectory, our analysis further reveals that there are no global sectors that show sustained reductions in GHG emissions. We conclude by highlighting that tracking progress in climate policy requires substantial investments in independent GHG emission accounting and monitoring as well as the available national and international statistical infrastructures. The data associated with this article (Minx et al., 2021) can be found at https://doi.org/10.5281/zenodo.5053056.

[NOTE TO REVIEWERS: Data on CO_2 emissions from fossil fuel combustion and industry, methane emissions and nitrous oxide emissions are from the most recent EDGARv6 data. As EDGARv6 data is still being compiled for F-gases, this manuscript contains EDGARv5 estimates for these, but we will update to EDGARv6 during the revision process. This procedures has been agreed upon with David Carlson – one of the chief editors of the journal – before manuscript submission]

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1 Introduction

By signing the Paris Agreement, countries acknowledged the necessity to keep the most severe climate change risks in check by limiting warming to well below 2°C and pursue efforts to limit warming to 1.5°C (UNFCCC, 2015). This requires rapid and sustained greenhouse gas (GHG) emission reductions towards net zero carbon dioxide (CO_2) emissions well within the 21st century along with deep reductions in non-CO_2 emissions (Rogelj et al., 2015, 2018a). Transparent, comprehensive, consistent, accurate and up-to-date inventories of anthropogenic GHG emissions are crucial to track progress by countries, regions and sectors in moving towards these goals.

However, tracking the recent GHG performance of countries and sectors has been challenging. While there is a growing number of global emissions inventories, only very few of them provide a wide coverage of gases, sectors, activities, and countries or regions that are sufficiently up-to-date to aid discussions in science and policy on progress tracking. Table 1 provides an overview of global emission inventories. Many inventories focus on individual gases and subsets of activities. Few provide sectoral detail and particularly for non-CO_2 GHG emissions there is often a considerable time-lag in reporting. Similarly, GHG emissions reporting under the United Nations Framework Convention on Climate Change (UNFCCC) provides reliable, comprehensive and up-to-date statistics for Annex I countries across all major GHGs, but there remain substantial gaps for non-Annex I countries, which often lack a well-developed statistical infrastructure to provide detailed reports (Janssens-Maenhout et al., 2019).

Here we describe a new, comprehensive dataset for global, regional and national greenhouse gas emissions by sector for 1970-2019. Our focus is on anthropogenic GHG emissions only. We build the dataset from recent releases of the “Emissions Database for Global Atmospheric Research” (EDGAR) for CO_2 emissions from fossil fuel combustion and industry (FFI), CH_4 emissions, N_2O emissions, and fluorinated gases (F-gases). We use a well-established fast-track method to extend this dataset to 2019 (Crippa et al., 2020, 2021). For completeness we add net CO_2 emissions from land use, land-use change and forestry (CO_2-LULUCF) from three bookkeeping models (Gasser et al., 2020; Hansis et al., 2015; Houghton and Nassikas, 2017). We provide an assessment of the uncertainties in each greenhouse gas at the 90% confidence interval (5th-95th percentile) by combining statistical analysis and comparisons of global emissions inventories with an expert judgement informed by the relevant scientific literature.

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Table 1 – Overview of global inventories of GHG emissions

Dataset Name	Short Name	Version	Gases	Geo-graphic coverage	Activity split	Time period	Emission factors	Depend-encies	Reference	Link
Emissions Database for Global Atmospheric Research	EDGAR	6.0	CO_2-FFI, CH_4, N_2O	208 countries; global	5 main sectors	1970-2019 for CO2; 1970-2015 for other GHG		IEA, BP, USGS, IFA, GGFR/NOAA, UNFCCC	(Crippa et al., 2021)	https://data.jrc.ec.europa.eu/collection/EDGAR
Potsdam Real-time Integrated Model for probabilistic Assessment of emissions Paths	PRIMAP-hist	2.2	CO_2-FFI, CH_4, N_2O	All UNFCCC member states, most non-UNFCCC territories	5 sectors	1850-2018		Andrew (2019), BP, CDIAC, EDGAR, EDGAR-HYDE, FAOSTAT, RCP, UNFCCC	Gütschow et al. (2016, 2019, 2021)	https://www.pik-potsdam.de/paris-reality-check/primap-hist/
Community Emissions Data System	CEDS	v_2021_02_05	SO_2, NO_x, BC, OC, NH_3, NMVOC, CO, CO_2, CH_4, N_2O	221 countries	60 sectors	1750-2019 (1970-2019 for CH4 and N2O)	ECLIPSE V5a combustion emission factors, IMOGHG v4 shipping emission factors, country specific data	IEA, BP, ECLIPSE, EDGAR, UNFCCC and other country inventory data	Hoesly et al. (2018); McDuffie et al. (2020); O'Rourke et al. (2021)	http://www.globalchange.umd.edu/ceds/
UNFCCC: Annex I Party GHG Inventory Submissions		2021	CO_2, CH_4, N_2O, NO_x, CO, NMVOC, SO_2	Parties included in Annex I to the Convention	Energy, industry, agriculture, LULUCF, waste	1990-2018		Country inventory submissions		https://unfccc.int/ghg-inventories-annex-i-parties/2021
Global Carbon Budget	GCP	2020	CO_2-FFI, CO_2-LULUCF	Global, 259 countries for FFI	5 main categories	CO2-LULUCF: 1850-2019 CO2-FFI: 1750-2019		CDIAC, UNFCCC, Andrew (2019), BP, and other country inventory data; for LULUCF FAO/FRA and LUH2 land-use	Friedlingstein et al. (2019b, 2020)	https://doi.org/10.18160/GCP-2020

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								forcing data		
Global, Regional, and National Fossil-Fuel CO2 Emissions	CDIAC-FF	V2017	CO_2-FFI	259 countries, global	5 main categories	1751-2017			Gilfillan et al. (2020)	https://energy.appstate.edu/research/work-areas/cdiac-appstate
Energy Information Administration International Energy Statistics	EIA		CO_2-FFI	230 countries, global	3 fuel types	1980-2018; 1949-2018 (global)				https://www.eia.gov/international/data/world
BP Statistical Review of World Energy	BP	2020 | 69th edition	CO_2-FFI	108 countries, 7 regions	8 activities, 3 fossil and 3 other fuel types	1965-2019	IPCC default emission factors			https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html
International Energy Agency CO2 Emissions from Fuel Combustion	IEA		CO_2-FFI	190 countries	3 fossil fuels, 6 sectors	1971-2019; OECD: 1960-2019	2006 GLs for National Greenhouse Gas Inventories			https://webstore.iea.org/co2-emissions-from-fuel-combustion-2019-highlights
PKU-FUEL			CO_2, CO, $PM_{2.5}$, PM_{10}, TSP, BC, OC, SO_2, NO_x, NH_3, PAHs		6 sectors, 5 fuel types,	1960-2014				http://inventory.pku.edu.cn/
Carbon Monitor			CO_2-FFI	11 countries, global	6 sectors	2019-		EIA, EDGAR, GCP	Liu et al. (2020)	https://carbonmonitor.org/
Bookkeeping of land-use emissions	BLUE		CO_2-LULUCF			1500-2012		LUH2 land-use forcing data	Hansis et al. (2015)	https://doi.org/10.18160/GCP-2020
OSCAR – an Earth system	OSCAR		CO_2-LULUCF			1750-2010		FAO/FRA and LUH2 land-use	Gasser et al. (2017, 2020)	https://doi.org/10.18

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compact model								forcing data		160/GCP-2020v
Houghton and Nassikas Bookkeeping Model	H&N		CO_2-LULUCF			1850-2015		FAO/FRA land-use forcing data	Houghton and Nassikas (2017)	https://doi.org/10.18160/GCP-2020
The Greenhouse gas – Air pollution INteractions and Synergies Model	GAINS		CO_2, CH_4, N_2O, F-gases	83 countries/regions					Höglund-Isaksson (2012)	
EPA-2020: Greenhouse gas emission inventory	US-EPA		CO_2, CH_4, N_2O, F-gases	USA	6 sectors	1990-2019			EPA (2021)	https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2019
GCP – global nitrous oxide budget	GCP/INI		N_2O	10 land regions and 3 oceanic regions	21 natural and human sectors	1980-2016		FAOSTAT, GAINS, EDGAR	Tian et al. (2020)	https://www.globalcarbonproject.org/nitrousoxidebudget/
FAOSTAT inventory		2020	CO_2, CH_4, N_2O, F-gases	Global (198 countries)	4 agricultural sectors	1990-2017		PRIMAP-hist	Frederici et al. (2015), Tubiello et al. (2013), Tubiello (2019)	http://www.fao.org/faostat/en/#data/EM/metadata
Fire Inventory from NCAR	FINN		CO_2, CH_4, N_2O	Global					Wiedinmyer et al. (2011)	
Global fire assimilation system	GFAS		CO_2, CH_4, N_2O	Global					Kaiser et al. (2012)	
Global fire emissions database	GFED		CO_2, CH_4, N_2O	Global					Giglio et al. (2013)	
Quick fire emissions dataset	QFED		CO_2, CH_4, N_2O	Global					Darmenov and da Silva (2015)	

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2 Methods and Data

2.1 Overview

Our dataset provides a comprehensive set of estimates for global anthropogenic GHG emissions disaggregated by 30 economic sectors and 226 countries. The focus of the data is on anthropogenic GHG emissions originally regulated under the Kyoto Protocol: natural sources and sinks are not considered, and nor are ozone depleting substances regulated under the Montreal Protocol such as chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs). We distinguish five groups of gases: (1) CO_2 emissions from fossil fuel combustion and industry (CO_2-FFI); (2) CO_2 emissions from land use, land-use change and forestry (CO_2-LULUCF); (3) methane emissions (CH_4); (4) nitrous oxide emissions (N_2O); (5) the group of fluorinated gases (F-gases) comprising hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) as well as sulphur hexafluoride (SF6). We do not cover NF_3 emissions [NOTE TO REVIEWERS: Our update of F-gas emissions to EDGAR v6 will also add NF3 emissions to our data], which are also covered under the Paris Agreement. We provide and analyse the GHG emissions data both in native units as well as in CO_2-equivalents (see Section 3.7) as commonly done in wide parts of the climate change mitigation community using global warming potentials with a 100 year time horizon from the IPCC Fifth Assessment Report (Myhre et al., 2013). We briefly discuss the impact of alternative metric choices in tracking aggregated GHG emissions over the past few decades and compare the emissions with estimated anthropogenic warming.

We report the annual growth rate in emissions *E* for adjacent years (in percent per year) by calculating the difference between the two years and then normalizing to the emissions in the first year: $((E_{(t0+1)}-E_{t0})/E_{t0})\times 100$. We apply a leap-year adjustment where relevant to ensure valid interpretations of annual growth rates. This affects the growth rate by about 0.3%yr^{-1} (1/366) and causes calculated growth rates to go up by approximately 0.3% if the first year is a leap year and down by 0.3% if the second year is a leap year. We calculate the relative growth rate in percent per year for multi-year periods (e.g. a decade) by fitting a linear trend to the logarithmic transformation of E across time (see Friedlingstein et al., 2020).

Our dataset draws from three underlying sources: (1) the full EDGARv6 release for CO_2-FFI as well as non-CO_2 GHGs covering the time period 1970-2018 (Crippa et al., 2021). Note that currently F-gas data from EDGARv6 is still being prepared. In the meantime, we use EDGARv5 data covering the time period 1970-2015 (Crippa et al., 2019); (2) EDGAR fast-track extensions for CO_2-FFI, CH_4 and N_2O emissions for 2019 as well as 2016-2019 for F-gas emissions based on Olivier et al. (2005) and Crippa et al. (2020) [NOTE TO REVIEWERS: F-gas emissions in EDGARv6 are currently being revised and will be included in the revised version of this manuscript. F-gases will then also have a fast-track extension from 2018 to 2019]; (3) CO_2-LULUCF as the average of three bookkeeping models, consistent with the approach of the global carbon project (Friedlingstein et al., 2020). As shown in

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Table 2, sectoral detail is organised along five major economic sectors as is common in IPCC reports on climate change mitigation (IPCC, 2014): energy supply, buildings, transport, industry as well as Agriculture, Forestry and Other Land-Use Changes (AFOLU). We devise a classification for assigning our 226 countries to regions, combining the standard Annex I/non-Annex I distinction with geographical location. We provide other common regional classifications from the UN and the World Bank as part of the supplementary files. The dataset including the sector and region classification can be found at https://doi.org/10.5281/zenodo.5053056.

Table 2 – Overview of the two-level sector aggregation with reference to assigned source/sink categories conforming to the IPCC reporting guidelines (IPCC, 2006, 2019) as well as relevant greenhouse gases. Note that EDGAR v6 distinguishes biogenic CO_2 and CH_4 sources with a "bio" label, with all other sectors "fossil" by default.

Sector	Sub-sector	IPCC (2006)	Gases
AFOLU (Agriculture, Forestry and Other Land-Use Changes)	Biomass burning	3.C.1.b (bio)	CH4, N2O
	Enteric Fermentation	3.A.1.a.i (fossil), 3.A.1.a.ii (fossil), 3.A.1.b (fossil), 3.A.1.c (fossil), 3.A.1.d (fossil), 3.A.1.e (fossil), 3.A.1.f (fossil), 3.A.1.g (fossil), 3.A.1.h (fossil)	CH4
	Managed soils and pasture	3.C.4 (fossil), 3.C.5 (fossil), 3.C.6 (fossil), 3.C.3 (fossil), 3.C.2 (fossil)	CO2, N2O
	Manure management	3.A.2.a.i (fossil), 3.A.2.a.ii (fossil), 3.A.2.b (fossil), 3.A.2.c (fossil), 3.A.2.i (fossil), 3.A.2.d (fossil), 3.A.2.e (fossil), 3.A.2.f (fossil), 3.A.2.g (fossil), 3.A.2.h (fossil)	CH4, N2O
	Rice cultivation	3.C.7 (fossil)	CH4
	Synthetic fertilizer application	3.C.4 (fossil)	N2O
	Land-use change		CO2
Buildings	Non-CO2 (all buildings)	2.F.3 (fossil), 2.F.4 (fossil), 2.G.2.c (fossil)	c-C4F8, C4F10, CF4, HFC-134a, SF6
	Non-residential	1.A.4.a (bio), 1.A.4.a (fossil)	CO2, CH4, N2O
	Residential	1.A.4.b (bio), 1.A.4.b (fossil)	CO2, CH4, N2O
Energy systems	Biomass energy systems	1.A.1.a.i (bio), 1.A.1.a.ii (bio), 1.A.1.a.iii (bio), 1.A.1.b (bio), 1.A.1.c.ii (bio), 1.A.1.c.i (bio), 1.A.4.c.i (bio), 1.A.5.a (bio), 1.B.1.c (bio), 1.B.2.a.iii.2 (bio)	CH4, N2O
	Coal mining fugitive emissions	1.B.1.a (fossil), 1.B.1.c (fossil)	CO2, CH4
	Electricity & heat	1.A.1.a.i (fossil), 1.A.1.a.ii (fossil), 1.A.1.a.iii (fossil)	CO2, CH4, N2O
	Oil and gas fugitive emissions	1.B.2.a.iii.2 (fossil), 1.B.2.a.iii.3 (fossil), 1.B.2.a.iii.4 (fossil), 1.B.2.b.iii.2 (fossil), 1.B.2.b.iii.4 (fossil), 1.B.2.b.iii.5 (fossil), 1.B.2.b.iii.3 (fossil), 1.B.2.b.ii (fossil), 1.B.2.a.ii (fossil)	CO2, CH4, N2O
	Other (energy systems)	1.A.1.c.ii (fossil), 1.A.1.c.i (fossil), 1.A.4.c.i (fossil), 1.A.5.a (fossil), 2.G.1.b (fossil), 5.B (fossil), 5.A (fossil)	CO2, CH4, N2O, SF6
	Petroleum refining	1.A.1.b (fossil)	CO2, CH4, N2O

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Industry	Cement	2.A.1 (fossil)	CO2
	Chemicals	1.A.2.c (bio), 1.A.2.c (fossil), 2.A.2 (fossil), 2.A.4.d (fossil), 2.A.4.b (fossil), 2.A.3 (fossil), 2.B.1 (fossil), 2.B.2 (fossil), 2.B.3 (fossil), 2.B.5 (fossil), 2.B.8.f (fossil), 2.B.8.b (fossil), 2.B.8.c (fossil), 2.B.8.a (fossil), 2.B.4 (fossil), 2.B.6 (fossil), 2.B.9.b (fossil), 2.D.3 (fossil), 2.G.3.a (fossil), 2.G.3.b (fossil)	CO2, CH4, N2O, HFC-23, SF6
	Metals	1.A.1.c.i (fossil), 1.A.1.c.ii (fossil), 1.A.2.a (bio), 1.A.2.a (fossil), 1.A.2.b (bio), 1.A.2.b (fossil), 1.B.1.c (fossil), 2.C.1 (fossil), 2.C.2 (fossil), 2.C.3 (fossil), 2.C.4 (fossil), 2.C.5 (fossil), 2.C.6 (fossil)	CO2, CH4, N2O, C2F6, CF4, SF6
	Other industry	1.A.2.d (bio), 1.A.2.d (fossil), 1.A.2.e (bio), 1.A.2.e (fossil), 1.A.2.f (bio), 1.A.2.f (fossil), 1.A.2.k (fossil), 1.A.2.i (fossil), 1.A.5.b.iii (fossil), 2.F.1.a (fossil), 2.F.2 (fossil), 2.F.5 (fossil), 2.E.1 (fossil), 2.E.2 (fossil), 2.E.3 (fossil), 2.G.1.a (fossil), 2.G.2.c (fossil), 2.G.2.b (fossil), 2.G.2.a (fossil), 2.D.1 (fossil), 5.A (fossil)	CO2, CH4, N2O, c-C4F8, C2F6, C3F8, C4F10, C6F14, C7F16, CF4, HFC-125, HFC-134a, HFC-143a, HFC-152a, HFC-227ea, HFC-23, HFC-236fa, HFC-245fa, HFC-32, HFC-365mfc, HFC-43-10-mee, SF6
	Waste	4.A.1 (fossil), 4.D.2 (fossil), 4.D.1 (fossil), 4.C.1 (fossil), 4.C.2 (bio), 4.C.2 (fossil), 4.B (fossil)	CO2, CH4, N2O
Transport	Domestic Aviation	1.A.3.a.ii (fossil)	CO2, CH4, N2O
	Inland Shipping	1.A.3.d.ii (bio), 1.A.3.d.ii (fossil)	CO2, CH4, N2O
	International Aviation	1.A.3.a.i (fossil)	CO2, CH4, N2O
	International Shipping	1.A.3.d.i (bio), 1.A.3.d.i (fossil)	CO2, CH4, N2O
	Other (transport)	1.A.3.e.i (bio), 1.A.3.e.i (fossil), 1.A.4.c.ii (fossil), 1.A.4.c.iii (bio), 1.A.4.c.iii (fossil)	CO2, CH4, N2O
	Rail	1.A.3.c (bio), 1.A.3.c (fossil)	CO2, CH4, N2O
	Road	1.A.3.b (bio), 1.A.3.b (fossil), 2.G.2.c (fossil)	CO2, CH4, N2O, SF6

2.2 The Emissions Database for Global Atmospheric Research (EDGAR)

EDGAR emission estimates included in our dataset are derived from two methodologies: a) full bottom-up emission inventory data; b) fast-track emission inventory data imputed from incomplete input data. As described in Janssens-Maenhout et al. (2019), the EDGAR bottom-up emission inventory estimates are calculated from international activity data and emission factors following the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006) - updated according to the latest scientific knowledge. Emissions (EMs) from a given sector *i* in a country C accumulated during a year *t* for a chemical compound *x* are calculated with the country-specific activity data (AD), quantifying the activity in sector *i*, with the mix of *j* technologies (TECH) and with the mix of *k* (end-of-pipe) abatement measures (EOP) installed with the share *k* for each technology *j*, the emission rate with an uncontrolled emission factor (EF) for each sector *i* and technology *j* and relative reduction (RED) by abatement measure *k*, as summarised in the following formula:

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$$EM_i(C,t,x) = \sum_{j,k} \left[AD_i(C,t) \cdot TECH_{i,j}(C,t) \cdot EOP_{i,j,k}(C,t) \cdot EF_{i,j}(C,t,x) \cdot \left(1 - RED_{i,j,k}(C,t,x)\right)\right]$$

The activity data are sector dependent and vary from fuel combustion in energy units (TJ) of a particular fuel type, to the amount (ton) of products manufactured, or to the number of animals or the area (hectares) or yield (ton) of cultivated crops. The technology mixes, (uncontrolled) emission factors and end-of-pipe measures are determined at different levels: country-specific, regional, country group (e.g. Annex I/non-Annex I), or global. Technology-specific emission factors are used to enable an IPCC tier-2 approach, taking into account the different management and /technology processes or infrastructures (e.g., different distribution networks) under specific "technologies", and modelling explicitly abatements/ emission reductions, e.g. the CH_4 recovery from coal mine gas at country level under the "end-of-pipe measures". As with national inventories, emissions are accounted over a period of one calendar year in the country in which they took place (i.e. a territorial accounting principle) (IPCC, 2006, 2019). A full description of data sources and methodology for EDGARv6 is provided in Crippa et al. (2021).

Extensions to 2019 are derived using a "fast-track methodology", which is designed to update full EDGAR inventories to more recent years based on less information (Crippa et al., 2020; Olivier et al., 2005; Olivier and Peters, 2020). The underlying idea is to extrapolate emissions trends based on observed activity trends in key sectors. For CO_2-FFI emissions, the fast track estimates were based on the latest BP coal, oil and natural gas consumption data (BP, 2019). Updates for cement, lime, ammonia and ferroalloys production are based on US Geological Survey statistics, urea production and consumption on statistics from the International Fertilizer Association, gas used from flaring on data from the Global Gas Flaring Reduction Partnership, steel production on statistics from the World Steel Association, and cement clinker production on UNFCCC data. For methane and nitrous oxide emissions, fast-track extensions are based on detailed agricultural statistics from FAO (CH4 and N2O), fuel production and transmission statistics from IEA and BP (CH_4) as well as UNFCCC-CRF data for Annex I countries on coal production (CH_4 recovery) and the production of chemicals (N_2O abatement). Finally, for F-gas emissions, a more extensive fast-track extension covering 2016-2019 was undertaken. For Annex I countries, these fast-track extensions were based on the most recent national emission inventories, submitted under the UNFCCC (up to 2018). For all remaining countries and years, simple extrapolation was used given the absence of international statistics. Available fast-track data is from EDGARv5, which we link to the full EDGARv6 release by calculating the county and sector specific emissions growth between 2018 and 2019 and multiplying it with the 2018 values in our data.

2.3 Accounting for CO_2 emissions Land Use, Land-Use Change and Forestry (CO_2-LULUCF)

We consider all fluxes of CO_2 from land use, land-use change and forestry. This includes CO_2 fluxes from the clearing of forests and other natural vegetation (by anthropogenic fire and/or clear-cut), afforestation, logging and forest degradation

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(including harvest activity), shifting cultivation (cycles of forest clearing for agriculture, then abandonment), and regrowth of forests and other natural vegetation following wood harvest or abandonment of agriculture, and emissions from peat burning and drainage. Some of these activities lead to emissions of CO_2 to the atmosphere, while others lead to CO_2 sinks. CO_2-LULUCF therefore is the net sum of emissions and removals from all human-induced land use changes and land management. Note that CO_2-LULUCF is referred to as (net) land-use change emissions, ELUC, in the context of the global carbon budget (Friedlingstein et al., 2020). Agriculture per se, apart from conversions between different agricultural types, does not lead to substantial CO_2 emissions as compared to land-use changes such as clearing or regrowth of natural vegetation. Therefore, CO_2 fluxes in the AFOLU sector refer mostly to forestry and other land use (changes), while the agricultural part of the sector is covered by CH_4 and N_2O emissions.

Since in reality anthropogenic CO_2-LULUCF emissions co-occur with natural CO_2 fluxes in the terrestrial biosphere, models have to be used to distinguish anthropogenic and natural fluxes (Friedlingstein et al., 2020). CO_2-LULUCF as reported here is calculated via a bookkeeping approach, as originally proposed by Houghton et al. (2003), tracking carbon stored in vegetation and soils before and after land-use change. Response curves are derived from literature and observations to describe the temporal evolution of the decay and regrowth of vegetation and soil carbon pools for different ecosystems and land use transitions, including product pools of different lifetimes. These dynamics distinguish bookkeeping models from the common approach of estimating "committed emissions" (assigning all present and future emissions to the time of the land use change event), which is frequently derived from remotely-sensed land use area or biomass observations (Ramankutty et al., 2007). Most bookkeeping models also represent the long-term degradation of primary forest as lowered standing vegetation and soil carbon stocks in secondary forests, and include forest management practices such as wood harvesting.

Following the approach taken by the global carbon budget (Friedlingstein et al., 2020), we take the average of three bookkeeping estimates: the bookkeeping of land use emissions model, BLUE (Hansis et al., 2015), H&N (Houghton and Nassikas, 2017), and OSCAR (Gasser et al., 2020). Key differences across these estimates, including land-use forcing, are summarised in Table 4. Since bookkeeping models do not include emissions from organic soils, emissions from peat fires and peat drainage are added from external datasets: Peat burning is based on the Global Fire Emission Database (GFED4s; (van der Werf et al., 2017)) and introduces large interannual variability to the CO_2-LULUCF emissions due to synergies of land-use and climate variability particularly in Southeast Asia, strongly noticeable during El-Niño events such as 1997. Peat drainage is based on estimates by Hooijer et al. (2010) for Indonesia and Malaysia in H&N, and added to BLUE and OSCAR from the global FAO data on organic soils emissions from croplands and grasslands (Conchedda and Tubiello, 2020).

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3. Uncertainties in GHG emission estimates

Estimates of historic GHG emissions – CO_2, CH_4, N_2O and F-gases – are uncertain to different degrees. Assessing and reporting uncertainties is crucial in order to understand whether available estimates are sufficiently accurate to answer, for example, whether GHG emissions are still rising, or if a country has achieved an emission reduction goal (Marland, 2008). These uncertainties can be of a scientific nature, such as when a process is not sufficiently understood. They also arise from incomplete or unknown parameter information (activity data, emission factors etc.), as well as estimation uncertainties from imperfect modelling techniques. There are at least three major ways to examine uncertainties in emission estimates (Marland et al., 2009): 1) by comparing estimates made by independent methods and observations (e.g. comparing top-down vs bottom-up estimates; modelling against remote sensing data) (Petrescu et al., 2020c, 2020a; Saunois et al., 2020; Tian et al., 2020); 2) by comparing estimates from multiple sources and understanding sources of variation (Andres et al., 2012; Andrew, 2020a; Ciais et al., 2021; Macknick, 2011); 3) by evaluating multiple estimates from a single source (e.g. Hoesly and Smith, 2018) including approaches such as uncertainty ranges estimated through statistical sampling across parameter values, applied for example at the country or sectoral level (e.g. Andres et al., 2014; Monni et al., 2007; Solazzo et al., 2021), or to spatially distributed emissions (Tian et al., 2019). This section assesses the relevant peer-reviewed literature on uncertainties in historic GHG emission estimates and places an expert judgement on the uncertainties for the different (groups of) GHGs.

Uncertainty estimates can be rather different depending on the method chosen. For example, the range of estimates from multiple sources is bounded by their interdependency; they can be lower than true structural plus parameter uncertainty estimates or than estimates made by independent methods. In particular it is important to account for potential bias in estimates, which can result from using common methodological or parameter assumptions across estimates, or from missing sources, which can result in a systemic bias in emission estimates (see N_2O discussion below). Independent top-down observational constraints are, therefore, particularly useful to bound total emission estimates (Petrescu et al., 2020c, 2020b).

Solazzo et al. (2021) evaluated the uncertainty of the EDGAR's source categories and their totals for all the main GHGs (CO_2-FFI, CH_4, N_2O). The study is based on the propagation of the uncertainty associated with input parameters (activity data and emission factors) as estimated by expert judgement (tier-1) and complied by IPCC (2006, 2019). A key methodological challenge is determining how well uncertain parameters are correlated between sectors, countries, and regions. The more highly correlated parameters (e.g. emission factors) are across scales, the higher the resulting overall uncertainty estimate. Solazzo et al. (2020) assume full covariance between same source categories where similar assumptions are being used, and independence otherwise. For example, they assume full covariance where the same emission factor is used between countries or sectors, while assuming independence where country-specific emission factors are used. This strikes a balance between extreme assumptions (full independence or full covariance in all cases) that are likely unrealistic, but still leans towards higher uncertainty estimates. When aggregating emission sources, assuming covariance increases the resulting uncertainty estimate.

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Uncertainties calculated with this methodology tend to be higher than the range of values from ensemble of dependant inventories (Saunois et al., 2016, 2020). The uncertainty of emission estimates derived from ensembles of gridded results from bio-physical models (Tian et al., 2018) adds an additional dimension of spatial variability, and is therefore not directly comparable with aggregate country or regional uncertainty, estimated with the methods discussed above.

We adopt a 90% confidence interval (5th-95th percentile) to report the uncertainties in our GHG emissions estimates, i.e., there is a 90 % likelihood that the true value will be within the provided range if the errors have a Gaussian distribution, and no bias is assumed. This is in line with previous reporting in IPCC AR5 (Blanco G. et al., 2014; Ciais et al., 2014). The uncertainties reported here combine statistical analysis, comparisons of global emissions inventories and expert judgement of the likelihood of results lying outside this range, rooted in an understanding gained from the relevant literature. At times, we also use a qualitative assessment of confidence levels to characterize the annual estimates from each term based on the type, amount, quality, and consistency of the evidence as defined by the IPCC (IPCC, 2014).

3.1 CO_2 emissions from fossil fuels and industrial processes

Several studies have compared estimates of annual CO_2-FFI emissions from different global inventories (Andres et al., 2012; Andrew, 2020a; Gütschow et al., 2016; Janssens-Maenhout et al., 2019; Macknick, 2011; Petrescu et al., 2020c). However, estimates are not fully independent as they all ultimately rely on many of the same data sources. For example, all global inventories use one of four global energy datasets to estimate CO_2 emissions from energy use, and these energy datasets themselves all rely on the same national energy statistics, with few exceptions (Andrew, 2020a). Divergence between these estimates (see Figure 1) are mainly related to differences in the estimation methodology, conversion factors, emission coefficients, assumptions about combustion efficiency, and calculation errors (Andrew, 2020a; Marland et al., 2009). Key differences for nine global datasets are highlighted in

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Table 3 (see also Table 1 for further information on the inventories). Another major source of divergence between datasets is differences in their respective system boundaries (Andres et al., 2012; Andrew, 2020a; Macknick, 2011). Hence, differences across CO_2-FFI emissions estimates do not reflect full uncertainty due to source data dependencies. At the same time, the observed range across estimates from different databases exaggerates uncertainty, to the extent that they largely originate in system boundary differences (Andrew, 2020a; Macknick, 2011).

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Table 3 - System boundaries and other key features of global FFI-CO_2 emissions datasets. Comparison of some important general characteristics of nine emissions datasets, with green indicating a characteristic that might be considered a strength. Columns four to six refer to CO_2 emission estimates for industrial processes and product use. Since all datasets are under development, these details are subject to change. Further information on the individual inventories can be found in Table 1. Based on Andrew (Andrew, 2020a)

	Primary source	Uses IPCC emission factors	Includes venting & flaring	Includes cement	Includes other carbonates	Non-fuel use based on	Reports bunkers separately	By fuel type	By sector	Includes official estimates
CDIAC	yes	no	yes	yes	no	national data	yes	yes	no	no
BP	yes	yes	no	no	no	national data	no	no	no	no
IEA	yes	yes	no	no	no	national data	yes	yes	yes	no
EDGAR	yes	yes	yes	yes	yes	national data	yes	no	yes	no
EIA	yes	no	yes	no	no	US data	no	yes	no	no
GCP	partial	no	yes	yes	partial	national data	yes	yes	no	yes
CEDS	mostly	no	yes	yes	yes	national data	yes	yes	yes	yes
PRIMAP-hist	no	no	yes	yes	yes	national data	yes	no	yes	yes
UNFCCC CRFs	yes	partial	yes	yes	yes	national data	yes	yes	yes	yes

Across global inventories, mean global annual CO_2-FFI emissions track at 34.4±2 $GtCO_2$ in 2014, reflecting a variability of about ±5.4% (Figure 1). However, this variability is almost halved when system boundaries are harmonised (Andrew, 2020a). EDGARv6 CO_2-FFI emissions as used in this report track at the top of the range as shown in Figure 1. This is partly due to the comprehensive system boundaries of EDGAR, but also due to the assumption of 100% oxidation of combusted fuels as per IPCC default assumptions. Once system boundaries are harmonised EDGAR continues to track at the upper end of the range, but no longer at the top. EDGAR CO_2 FFI estimates are further well-aligned with emission inventories submitted by Annex I countries to the UNFCCC – even though some variation can occur for individual countries (Andrew, 2020a). Differences in FFI-CO_2 emissions across different version of the EDGAR dataset are shown in the Supplementary Material (see Fig. SM-1).

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Uncertainties in CO_2-FFI emissions arise from the combination of uncertainty in activity data and uncertainties in emission factors including assumptions for combustion completeness and non-combustion uses. CO_2-FFI emissions estimates are largely derived from energy consumption activity data, where data uncertainties are comparatively small due to well established statistical monitoring systems, although there are larger uncertainties in some countries and time periods (Andres et al., 2012; Andrew, 2020a; Ballantyne et al., 2015; Janssens-Maenhout et al., 2019; Macknick, 2011). Most of the underlying uncertainties are systematic and related to underlying biases in the energy statistics and accounting methods used (Friedlingstein et al., 2020). Uncertainties are lower for fuels with relatively uniform properties such as natural gas, oil or gasoline and higher for fuels with more diverse properties, such as coal (IPCC 2006; Blanco G. et al. 2014). Uncertainties in CO_2 emissions estimates from industrial processes, i.e. non-combustive oxidation of fossil fuels and decomposition of carbonates, are higher than for fossil fuel combustion. At the same time, products such as cement also take up carbon over their life cycle, which are often not fully considered in carbon balances (Guo et al., 2021; Sanjuán et al., 2020; Xi et al., 2016). However, recent versions of the global carbon budget include specific estimates for the cement carbonation sink and estimate average annual CO_2 uptake at 0.70 $GtCO_2$ for 2010-2019 (Friedlingstein et al., 2020).

Uncertainties of energy consumption data (and, therefore, CO_2-FFI emissions) are generally higher for the first year of their publication when less data is available to constrain estimates. In the BP energy statistics, 70% of data points are adjusted by an average of 1.3% of a country's total fossil fuel use in the subsequent year with further more modest revisions later on (Hoesly and Smith, 2018). Uncertainties are also higher for developing countries, where statistical reporting systems do not have the same level of maturity as in many industrialised countries (Andres et al., 2012; Andrew, 2020b; Friedlingstein et al., 2019, 2020; Gregg et al., 2008; Guan et al., 2012; Janssens-Maenhout et al., 2019; Korsbakken et al., 2016; Marland, 2008). Example estimates of uncertainties for CO_2 emissions from fossil fuel combustion at the 95% confidence interval are ±3-5% for the U.S., ±15 - ±20% for China and ±50% or more for countries with poorly developed or maintained statistical infrastructure (Andres et al., 2012; Gregg et al., 2008; Marland et al., 1999). However, these customary country groupings do not always predict the extent to which a country's energy data has undergone historical revisions (Hoesly and Smith, 2018). Uncertainties in CO_2-FFI emissions before the 1970s are higher than for more recent estimates. Over the last two to three decades uncertainties have increased again because of increased production in some developing countries with less rigorous statistics and more uncertain fuel properties (Ballantyne et al., 2015; Friedlingstein et al., 2020; Marland et al., 2009).

The global carbon project (Friedlingstein et al., 2019, 2020; Le Quéré et al., 2018) assesses uncertainties in global anthropogenic CO_2-FFI emissions estimates within one standard deviation (1σ) as ±5% (±10% at 2σ). This is broadly consistent with the ±8.4% uncertainty estimate for CDIAC (Andres et al., 2014) as well as the ±7 - ±9% uncertainty estimate for EDGARv4.3.2 and v5 (Janssens-Maenhout et al., 2019; Solazzo et al., 2021) at 2σ. It remains at the higher end of the ±5% - ±10% range provided by Ballantyne et al. (2015). Consistent with the above uncertainty assessments, we present uncertainties

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for global anthropogenic CO_2 emissions at ±8% for a 90% confidence interval in line with IPCC AR5 and the UN emissions gap report (Blanco G. et al., 2014; UNEP, 2020).

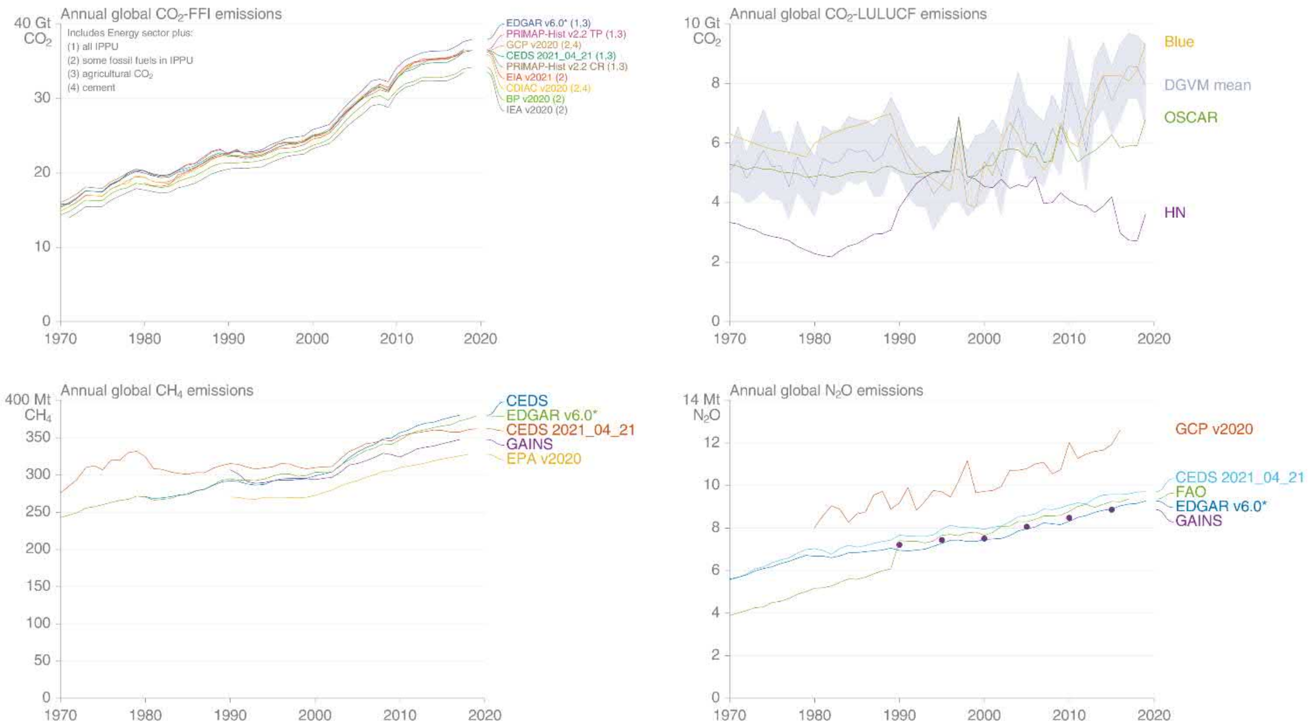

Figure 1 - Estimates of global anthropogenic greenhouse gas emissions from different data sources 1970-2019. Top-left panel: CO_2 FFI emissions from: EDGAR - Emissions Database for Global Atmospheric Research (this dataset) (Crippa et al., 2021); GCP – Global Carbon Project (Friedlingstein et al., 2020); CEDS - Community Emissions Data System (Hoesly et al., 2018; O'Rourke et al., 2021); CDIAC Global, Regional, and National Fossil-Fuel CO_2 Emissions (Gilfillan et al., 2020); PRIMAP-hist - Potsdam Real-time Integrated Model for probabilistic Assessment of emissions Paths (Gütschow et al., 2016, 2019); EIA - Energy Information Administration International Energy Statistics (EIA, 2021); BP - BP Statistical Review of World Energy (BP, 2020); IEA - International Energy Agency CO_2 Emissions from Fuel Combustion (IEA, 2020); IPPU refers to emissions from industrial processes and product use. Top-right panel: CO_2-LULUCF emissions from: BLUE – Bookkeeping of land-use emissions (Hansis et al., 2015); DGVM-mean – Multi-model mean of CO_2-LULUCF emissions from dynamic global vegetation models (Friedlingstein et al., 2020); OSCAR – an earth system compact model (Gasser et al., 2020); HN – Houghton and Nassikas Bookkeeping Model (Houghton and Nassikas, 2017); Bottom-left panel: Anthropogenic methane emissions from: EDGAR (above); CEDS (above); GAINS - The Greenhouse gas – Air pollution INteractions and Synergies Model (Höglund-Isaksson, 2012); EPA-2020: Greenhouse gas emission inventory (EPA, 2021); Bottom-right panel: Anthropogenic nitrous oxide emissions from: GCP – global nitrous oxide budget (Tian et al., 2020); CEDS (above); EDGAR (above); GAINS (above); FAO – N_2O emissions from the FAOSTAT inventory (Tubiello et al., 2013). Differences in emissions across different versions of the EDGAR dataset are shown in the Supplementary Material (Fig. SM-1)

3.2 Anthropogenic CO_2 emissions from land use, land use change and forestry (CO_2-LULUCF)

CO_2-LULUCF emissions are drawn from three global bookkeeping models. For 1990-2019, average net CO_2-LULUCF emissions are estimated at 6.1, 4.3, and 5.6 $GtCO_2\ yr^{-1}$ for BLUE, H&N, and OSCAR (Friedlingstein et al., 2020). Gross emissions 1990-2019 for BLUE, H&N, OSCAR are 17, 9.6 and 19 $GtCO_2\ yr^{-1}$, while gross removals are 11, 5.3, 13 $GtCO_2$ yr-

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^{1} respectively. For 1990-2019 maximum average differences are 9.1 and 7.8 $GtCO_2\ yr^{-1}$ for gross emissions and removals, respectively (Friedlingstein et al., 2020). Note that 2016-2019 is extrapolated in H&N and 2019 in OSCAR based on the anomalies of the net flux for the gross fluxes. Differences in the models underlying this observed variability are reported in Table 4. In the longer term, a consistent general upward trend since 1850 across models is reversed during the second part of the 20th century. Since the 1980s, however, differing trends across models are related to, among other things, different land-use forcings (Gasser et al., 2020). Further differences between BLUE and H&N can be traced in particular to: (1) differences in carbon densities between natural and managed vegetation, or between primary and secondary vegetation; (2) a higher allocation of cleared and harvested material to fast turnover pools in BLUE compared to H&N; and (3) to the inclusion sub-grid scale transitions (Bastos et al., 2021).

Uncertainties in CO_2-LULUCF emissions can be more comprehensively assessed through comparisons across a suite of dynamic global vegetation models (DGVM) (Friedlingstein et al., 2020). DGVM models are not combined in the CO_2-LULUCF mean estimate in our data because the typical DGVM setup includes the loss of additional sink capacity, which makes up about 40% of the DGVM estimate in recent years (Obermeier et al., 2020) and is excluded in bookkeeping estimates. Nonetheless, a CO_2-LULUCF estimate from the DGVM multi-model mean remains consistent with the average estimate from the bookkeeping models, as shown in Figure 1. Variation across DGVMs is large with a standard deviation at around 1.8 $GtCO_2\ yr^{-1}$, but is still smaller than the average difference between bookkeeping models at 2.6 $GtCO_2\ yr^{-1}$ as well as the current estimate of H&N (Houghton and Nassikas, 2017) and its previous model versions (Houghton et al., 2012). DGVMs differ in methodology, input data and how comprehensively they represent land-use-related processes. In particular land management, such as crop harvesting, tillage, or grazing (all implicitly included in observation-based carbon densities of bookkeeping models) can alter CO_2 flux estimates substantially, but are included to varying extents in DGVMs, thus increasing model spread (Arneth et al., 2017). For all types of models, land-use forcing is a major determinant of emissions and removals, and its high uncertainty impacts CO_2-LULUCF estimates (Hartung et al., 2021). The reconstruction of land-use change of the historical past, which has to cover decades to centuries of legacy LULUCF fluxes, is based on sparse data or proxies (Hurtt et al., 2020; Klein Goldewijk et al., 2017), while satellite-based products suffer from complications in distinguishing natural from anthropogenic drivers (Hansen et al., 2013; Li et al., 2018) or accounting for small-scale disturbances and degradation (Matricardi et al., 2020). Lastly, regional carbon budgets can be substantially over- or underestimated when carbon embodied in trade products is not accounted for (Ciais et al., 2021).

We base our uncertainty assessment on Friedlingstein et al. (2020) and take ±2.6 $GtCO_2\ yr^{-1}$ as a best-value judgement for the ±1σ uncertainty range (thus ±5.1 $GtCO_2\ yr^{-1}$ for ±2σ) in CO_2-LULUCF emissions, constant over the last decades. This absolute uncertainty estimate presented above corresponds roughly to a relative uncertainty of about ±50% over 1970-2019, which is much higher than for most fossil-emission terms, but reflects the large model spread and large differences between the current estimate of H&N and its previous model version (Houghton et al., 2012). This corresponds to a relative uncertainty of about

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±80% for a 90% confidence interval (5th-95th percentile) and is larger but still broadly in line with the upper end of the relative uncertainty of ±50 - ±75% considered in AR5 (Blanco G. et al., 2014). Much larger uncertainties in CO_2-LULUCF emissions have been identified across the literature, but were traced back to different definitions used in various modelling frameworks (Pongratz et al., 2014) as well as inventory data (Grassi et al., 2018). Overall, we use a relative uncertainty estimate of about ±70% for a 90% confidence interval. This recognizes the choice of a constant absolute uncertainty estimate taken elsewhere (Friedlingstein et al., 2020) and in recognition of a possible trend towards higher CO_2-LULUCF emissions estimates in more recent years.

Finally, note that attempts to constrain the estimates of CO_2-LULUCF emissions by observed biomass densities have been undertaken, but were successful only in some non-tropical regions (Li et al., 2017). While providing valuable independent and observation-driven information, remote-sensing derived estimates have limited applicability for model evaluation for the total CO_2-LULUCF flux, since they usually only quantify vegetation biomass changes and exclude legacy emissions from the pre-satellite era. Further, with the exception of the (pan-tropical) estimates by Baccini et al. (2012) they either track committed instead of actual emissions (e.g. Tyukavina et al., 2015), combine a static carbon density map with forest cover changes, or include the natural land sink (e.g. Baccini et al., 2017) to infer fluxes directly from the carbon stock time series – none of which fully distinguishes natural from anthropogenic disturbances.

Table 4 - Key differences between global bookkeeping estimates for CO_2-LULUCF emissions. Notes: DGVM – dynamic global vegetation model; LUH2 and FAO refer to land-use forcing datasets; arrows indicate tendency of process to increase or decrease emissions compared to the other estimates' choice.

	Bookkeeping model		
	BLUE[a]	**H&N**[b]	**OSCAR**[c]
Geographical scale of computation	0.25 degree gridscale	country	10 regions and 5 biomes
Carbon densities of soil and vegetation	literature-based	based on country reporting	calibrated to DGVMs
Land-use forcing	LUH2[d,e]	FAO[f]	LUH2 and FAO[d,e, f]
Representation of processes (indicative effect on AFOLU CO_2 emissions)			
Sub-grid scale ("gross") land-use transitions	yes (↑)	no (↓)	yes (↑)
Pasture conversion	From all natural vegetation types proportionally (↑)	from grasslands first (↓)	from all natural vegetation types proportionally (↑)

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Distinction rangeland vs pasture	yes (↓)	no (↑)	no (↑)
Coverage peat drainage (as in Global Carbon Budget 2020)	World (↑)[g]	South East Asia (↓)[h]	World (↑)[g]

Literature: [a] (Hansis et al., 2015); [b] (Houghton and Nassikas, 2017); [c] (Gasser et al., 2020); [d] (Hurtt et al., 2020); [e] (Chini et al., 2020); [f] (Nations, 2015); [g] (Conchedda and Tubiello, 2020); [h] (Hooijer et al., 2010)

3.3 Anthropogenic CH_4 emissions

About 60% of total global methane emissions come from anthropogenic sources (Saunois et al., 2020). These are linked to a range of different sectors: agriculture, fossil production and use, waste as well as biomass and biofuel burning. Methane emissions can be derived either using bottom-up (BU) estimates that rely on anthropogenic inventories such as EDGAR (Janssens-Maenhout et al., 2019), land surface models that infer part of natural emissions (Wania et al., 2013) or observation-based upscaling for some specific sources such as geological sources (e.g. Etiope et al., 2019). Alternatively, top-down (TD) approaches can be used, such as atmospheric transport models that assimilate methane atmospheric observations to estimate past methane emissions (Houweling et al., 2017). Some TD systems aim to optimize certain emission sectors based on differences in their spatial and temporal distributions (e.g. Bergamaschi et al., 2013), while other only solve for net emissions at the surface. Then the partitioning of TD posterior (output) fluxes between specific source sectors (e.g. *Fossil* vs. *BB&F*) is carried out with various degrees of uncertainty depending of the methods and the degree of refinement of sectors, but often rely on ratios from the prior knowledge of fluxes. Comprehensive assessments of methane sources and sinks have been provided by Saunois et al. (2016, 2020) and Kirschke et al. (Kirschke et al., 2013).

EDGAR (Crippa et al., 2019; Janssens-Maenhout et al., 2019) is one of multiple global methane BU inventories available. Other inventories – namely GAINS (Höglund-Isaksson, 2012), US-EPA (EPA, 2011, 2021), CEDS (Hoesly et al., 2018; McDuffie et al., 2020; O'Rourke et al., 2020) as well as FAOSTAT-CH_4 (Federici et al., 2015; Tubiello, 2018; Tubiello et al., 2013) – can differ in terms of their country and sector coverage as well as detail. EDGAR, CEDS, US-EPA and GAINS cover all major source sectors (fossil fuels, agriculture and waste, biofuel) – except large scale biomass burning – but this can be added from different databases such as FINN (Wiedinmyer et al., 2011), GFAS (Kaiser et al., 2012), GFED (Giglio et al., 2013) or QFED (Darmenov and da Silva, 2013). Much like CO2 FFI, these inventories of anthropogenic emissions are not completely independent as they either follow the same IPCC methodology to derive emissions, rely on similar data sources (e.g., FAOSTAT activity data for agriculture, reported fossil fuel production), or draw on reported country inventory data. However, they may differ in the assumptions and data used for the calculation. While the US-EPA inventory uses the reported emissions by the countries to UNFCCC, other inventories produce their own estimates using a consistent approach for all countries, and country specific activity data, emission factor and technological abatement when available. FAOSTAT and

EDGAR mostly apply a Tier 1 approach to estimate methane emissions while GAINS uses a Tier 2 approach (Höglund-Isaksson et al., 2020). CEDS is based on pre-existing emission estimates from FAOSTAT and EDGAR and then scales these emissions to match country-specific inventories, largely those reported to UNFCCC.

Global anthropogenic CH_4 emission estimates are compared in Figure 1. EDGARv5 has revised total global CH_4 emissions about 10 Mt CH_4 yr^{-1} higher than EDGARv4.3.2 due to a higher estimate for the waste sector (see supplementary material). Subsequent revisions of the estimation methodology in EDGARv6 in alignment with the IPCC guidelines refinement (IPCC, 2019) lead to very substantial differences in total CH_4 emissions of up to 50 $MtCH_4yr^{-1}$ before the 1990s, but these differences are smaller ranging from 1-13 $MtCH_4yr^{-1}$ since the 2000s. The cause of these differences is a new procedure to separately estimate of the venting component for gas and oil, in the venting and flaring sector (1B2a/b2). Differences across different versions of the EDGAR dataset are shown in the Supplementary Material (Fig. SM-1). US-EPA show the lowest estimates probably due to missing estimates from a significant number of countries not reporting to UNFCCC (US-EPA2020 includes estimates from only 195 countries) and incomplete sectoral coverage. EDGARv6 estimates of anthropogenic CH_4 emissions, as used here, are in the upper range of the different inventories across most anthropogenic sources. However, they do not cover CH_4 emissions from forest and grassland burning, which amount about 10-12 Mt per year.

Saunois et al (2020) provide estimates of methane sources and sinks based on BU and TD approaches associated with an uncertainty range based on the minimum and maximum values of available studies (because for many individual source and sink estimates the number of studies is often relatively small). Thus, they do not consider the uncertainty of the individual estimates. As shown in Table 5, uncertainties in total global methane emissions across all anthropogenic and natural sources are comparatively small at ±6% - a range larger than errors in transport models only (Locatelli et al., 2015). However, uncertainty in the chemical sink was not fully considered in the TD estimates in Saunois et al (2020). Uncertainty on the global burden of OH is about 10-15%, which translates to an uncertainty of approximately ±9% on total global emissions (Zhao et al., 2020). Based on both TD and BU ensemble, uncertainty (reported as the minimum- maximum range across estimates) on the global anthropogenic methane emissions is about ±10% to ±30% depending on the category, with larger uncertainty in the fossil fuel sectors than in the agriculture and waste sector (Saunois et al., 2020). However, these uncertainties are underestimated as they do not consider the uncertainty in each individual estimate, which includes potential uncertainties in activity data, emission factors, and equations used to estimate emissions.

Uncertainties in EDGARv5 CH_4 emissions using a Tier 1 approach are estimated at -33% to +46% at 2σ, but there is great variability across individual sectors ranging from ±30% (agriculture) to more than ±100% (fuel combustion), with high uncertainties in oil and gas sector (±93%) and coal fugitive emissions (±65%) (Solazzo et al., 2021). Inventories at national scale, such as in the USA also show large uncertainties depending on the sector (NASEM, 2018), though the activity data uncertainty may be lower than those for less developed countries. For example, global inventories, such as EDGAR, estimate

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uncertainties in national anthropogenic emissions of about ± 32% for the 24 member countries of OECD, and up to ±57% for other countries, whose activity data are more uncertain (Janssens-Maenhout et al., 2019).

Table 5 - Uncertainties estimated for methane sources at the global scale: based on ensembles of bottom-up (BU) and top-down (TD) estimates, national reports and specific uncertainty assessments of EDGAR

	Estimated uncertainty in USA inventories [a]	Estimated uncertainty in EDGAR [d]	Estimated uncertainty in EDGAR [e]	Global inventories uncertainty range [b]	Saunois et al. (2020) BU uncertainty range[c]	Saunois et al. (2020) TD uncertainty range[c]
Total global anthropogenic sources (incl. Biomass burning)				-	±6%	±6%
Total global anthropogenic sources (excl. Biomass burning)		±47%	-33% to +46%	±8%		
Agriculture and Waste					±8%	±8%
Rice	na	±60%	31-38%	±22%	±20%	-
Enteric fermentation and manure management	±10 to 20% ± 20% and up to ± 65%		±5%	±8%	-	
Landfills and Waste	±10% but likely much larger	±91%	78-79%	±17%	±7%	-
Fossil fuel production & use					±20%	±25%
Coal	-15% to +20%	±75%	65% 60-74%	±40%	±28%	-
Oil and gas	-20 % to +150%	93%	±19%	±15%	-	
Other	na	±100%	±100%	±64%	±130%[*]	-
Biomass and biofuel burning				-	±25%	±25%
Biomass burning				-	±35%	-

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Biofuel burning	Included in "Other"	147%	+/-24%	±17%	-

[a] Based on (NASEM, 2018)

[b] Uncertainty calculated as ((min-max)/2)/mean*100 from the estimates of year 2017 of the six inventories plotted in Figure 1. This does not consider uncertainty on each individual estimate.

[c] Uncertainty calculated as ((min-max)/2)/mean*100 from individual estimates for the 2008-2017 decade. This does not consider uncertainty on each individual estimate, which is probably larger than the range presented here.

[d] Based on EDGARv432 for year 2010 (Janssens-Maenhout et al., 2019).

e Based on Solazzo et al. (2021)

[*] Mainly due to difficulties in attributing emissions to small specific emission sector.

The most recent UN emissions gap report (UNEP, 2020) gives an uncertainty range for global anthropogenic methane emissions with one standard deviation of ±30% (i.e. ±60% for 2σ), which is slightly higher than recent estimates in the literature. On the other hand, IPCC AR5 provides a comparatively low estimates at ±20% for a 90% confidence interval. Overall, we apply a best value judgment of ±30% for global anthropogenic methane emissions for a 90% confidence interval. This is justified by the large uncertainties reported in the methane budgets (Kirschke et al., 2013; Saunois et al., 2016, 2020) as well as for FAO activity statistics by Tubiello et al. (Tubiello et al., 2015), is broadly in line with the uncertainties quantified for EDGARv5.

3.4 Anthropogenic N_2O emissions

Anthropogenic N_2O emissions occur in a number of sectors, namely agriculture, fossil fuel and industry, biomass burning, and waste. The agriculture sector consists of four components: direct and indirect emissions from soil and water bodies (inland, coastal, and oceanic waters), manure left on pasture, manure management, and aquaculture. Besides these main sectors, a final 'other' category represents the sum of the effects of climate, elevated atmospheric CO_2, and land cover change. This is a new sector that was developed as part of the global nitrous oxide budget (Tian et al., 2020) – a recent assessment to quantify all sources and sinks of N_2O emissions, updating previous work (Kroeze et al., 1999; Mosier et al., 1998; Mosier and Kroeze, 2000; Syakila and Kroeze, 2011). Overall, anthropogenic sources contributed just over 40% to total global N_2O emissions (Tian et al., 2020).

There are a variety of approaches for estimating N_2O emissions. These include inventories (Janssens-Maenhout et al., 2019; Tian et al., 2018; Tubiello et al., 2013), statistical extrapolations of flux measurements (Wang et al., 2020), andas process-based land and ocean modelling (Tian et al., 2019; Yang et al., 2020). There are at least five relevant global N_2O emissions inventories available: EDGAR (Crippa et al., 2019, 2021; Janssens-Maenhout et al., 2019), GAINS (Höglund-Isaksson, 2012), FAO-N_2O (Tubiello, 2018; Tubiello et al., 2013), CEDS (Hoesly et al., 2018; McDuffie et al., 2020; O'Rourke et al., 2020) and GFED (Giglio et al., 2013). While EDGAR and GAINS cover all sectors except biomass burning, FAOSTAT-N_2O is

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focused on agriculture and biomass burning and GFED on biomass burning only. As shown in Figure 1 EDGAR, GAINS, CEDS and FAOSTAT emissions are consistent in magnitude and trend. Recent revisions in estimating indirect N_2O emissions in EDGARv6 lead to an average increase of 1.5% yr^{-1} in total N_2O emissions estimates between 1999 and 2018 compared to EDGARv5 (differences before 1999 were negligible at less than 1% yr^{-1}). Differences across different versions of the EDGAR dataset are shown in the Supplementary Material (Fig. SM-1). The main discrepancies across different global inventories are in agriculture, where emission estimates from the global nitrous oxide budget (also referred to as "GCP") (Tian et al., 2020) and FAOSTAT are on average 1.5 Mt N_2O yr^{-1} higher than those from GAINS and EDGAR during 1990-2016, due to much higher estimates of direct emissions from fertilised soils and manure left on pasture. GCP provides the largest estimate, because it synthesised from the other three inventories and further informed by additional bottom-up modelling estimates – and is as such more comprehensive in scope (Figure 1). In particular, it includes an additional sector that considers the sum of the effects of climate, elevated atmospheric CO_2, and land cover change (Tian et al., 2020). EDGAR estimates of anthropogenic N_2O emissions as used in this dataset should therefore be considered as lower bound estimates.

Anthropogenic N_2O emissions estimates are subject to considerable uncertainty – larger than those from FFI-CO_2 or CH_4 emissions. N_2O inventories suffer from high uncertainty on input data, including fertiliser use, livestock manure availability, storage and applications (Galloway et al., 2010; Steinfeld et al., 2010) as well as nutrient, crops and soils management (Ciais et al., 2014; Shcherbak et al., 2014). Emission factors are also uncertain (Crutzen et al., 2008; Hu et al., 2012; IPCC, 2019; Yuan et al., 2019) and there remains several sources that are not yet well understood (e.g. peatland degradation, permafrost) (Elberling et al., 2010; Wagner-Riddle et al., 2017; Winiwarter et al., 2018). Model-based estimates face uncertainties associated with the specific model configuration as well as parametrisation (Buitenhuis et al., 2018; Tian et al., 2019, 2020). Total uncertainty is also large because N_2O emissions are dominated by emissions from soils, where our level of process understanding is rapidly changing.

For EDGARv4.3.2 uncertainties in N_2O emissions are estimated based on default values (IPCC, 2006) at ±42% for 24 OECD90 countries and at ±93% for other countries for a 95% confidence interval (Janssens-Maenhout et al., 2019). However, Solazzo et al. (2021) arrive at substantially larger values for EDGARv5 allowing for correlation of uncertainties between sectors, countries and regions. At a sector level, uncertainties are larger for agriculture than for biomass burning, fossil fuel and industry, and waste. In the recent Emissions Gap Report (UNEP, 2020) relative uncertainties for global anthropogenic N_2O emissions are estimated at ±50% for a 68% (1σ) confidence interval. This is larger than the ±60% uncertainties reported in IPCC AR5 for a 90% confidence interval (Blanco G. et al., 2014), but is comparable with the ranges for anthropogenic emissions in the global N_2O budget (Tian et al., 2020). Overall, we assess the relative uncertainty for global anthropogenic N_2O emissions at ±60% for a 90% confidence interval.

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Table 6 - Comparison of four global N_2O inventories: EDGAR (Crippa et al. 2019a; Janssens-Maenhout et al. 2019); GCP (Tian et al. 2020); GAINS (Höglund-Isaksson 2012); FAOSTAT (Tubiello 2018; Tubiello et al. 2013)

Name	Time coverage	Geographical coverage	Activity split	IPCC	Reported emissions in 2015 (in MtN_2O)					
				emissions factors	agriculture	Fossil fuel and industry	Biomass burning	Waste and waste sector	other	Total
EDGAR	1970-2018	Global, 226 countries	4 main sectors, 24 sub-sectors	Yes	6	2.4	0.05	0.4	-	8.9
GCP	1980-2016	Global, 10 regions	5 main sectors, 14 sub-sectors	no	8.4	1.6	1.1	0.6	0.3	11.9
GAINS	1990-2015 (every 5 years)	Global, 172 regions	3 main sectors, 16 sub-sectors	no	6.8	1.3	-	0.7	-	8.8
FAOSTAT	1961-2017	Global, 231 countries	2 main sectors, 9 sub-sectors	Yes	8.3	-	0.9	-	-	9.2

3.5 Fluorinated gases

Fluorinated gases comprise over a dozen different species that are released mainly in the industry sector for use as refrigerants, solvents and aerosols. Here we compare global emissions of F-gases estimated in EDGARv5 to top-down values from the 2018 World Meteorological Organisation's (WMO) Scientific Assessment of Ozone Depletion (Engel and Rigby, 2018; Montzka and Velders, 2018). The top-down estimates were based on measurements by the Advanced Global Atmospheric Gases Experiment (AGAGE, Prinn et al., 2018) and National Oceanic and Atmospheric Administration (NOAA, Montzka et al., 2015), assimilated into a global box model (using the method described in Engel and Rigby, et al., 2018 and Rigby et al., (2014)). Uncertainties in the top-down estimates are due to measurement and transport model uncertainty, but as F-gas emissions are entirely anthropogenic in nature they are much better known than CO_2, CH_4, N_2O, where there are also large natural fluxes. For substances with relatively short lifetimes (~50 years or less), uncertainties are typically dominated by uncertainties in the atmospheric lifetimes. Comparisons between the EDGARv5 and WMO 2018 estimates were available for HFCs 125, 134a, 143a, 152a, 227ea, 23, 236fa, 245fa, 32, 365mfc and 43-10-mee, PFCs CF_4, C_2F_6, C_3F_8 and c-C_4F_8, and SF_6. For the higher molecular weight PFCs (C_4F_{10}, C_5F_{12}, C_6F_{14}, C_7F_{16}), top-down estimates were not available in WMO (2018). Top-down estimates have previously been published for these compounds (e.g. Ivy et al., 2012), however, this comparison is

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not included here due to their very low emissions. For a small number of species, global top-down estimates are available for some years, based on an independent atmospheric model to that used in WMO (2018), although most of these inversions use similar measurement datasets; Fortems-Cheiney, et al. (2015) for HFC-134a, Lunt, et al. (2015) for HFC-134a, -125, -152a, -143a and -32 and Rigby, et al (2010) for SF_6.

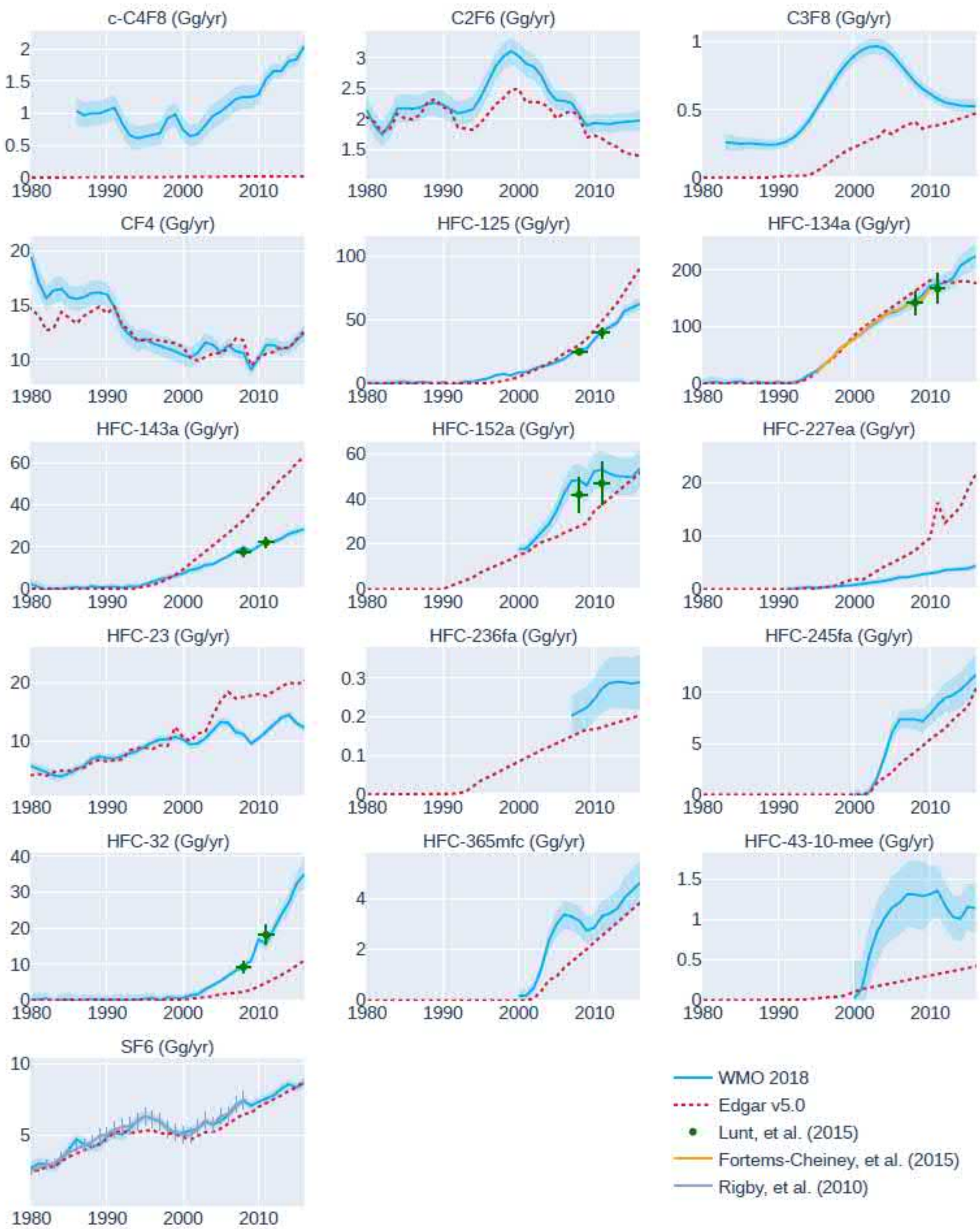
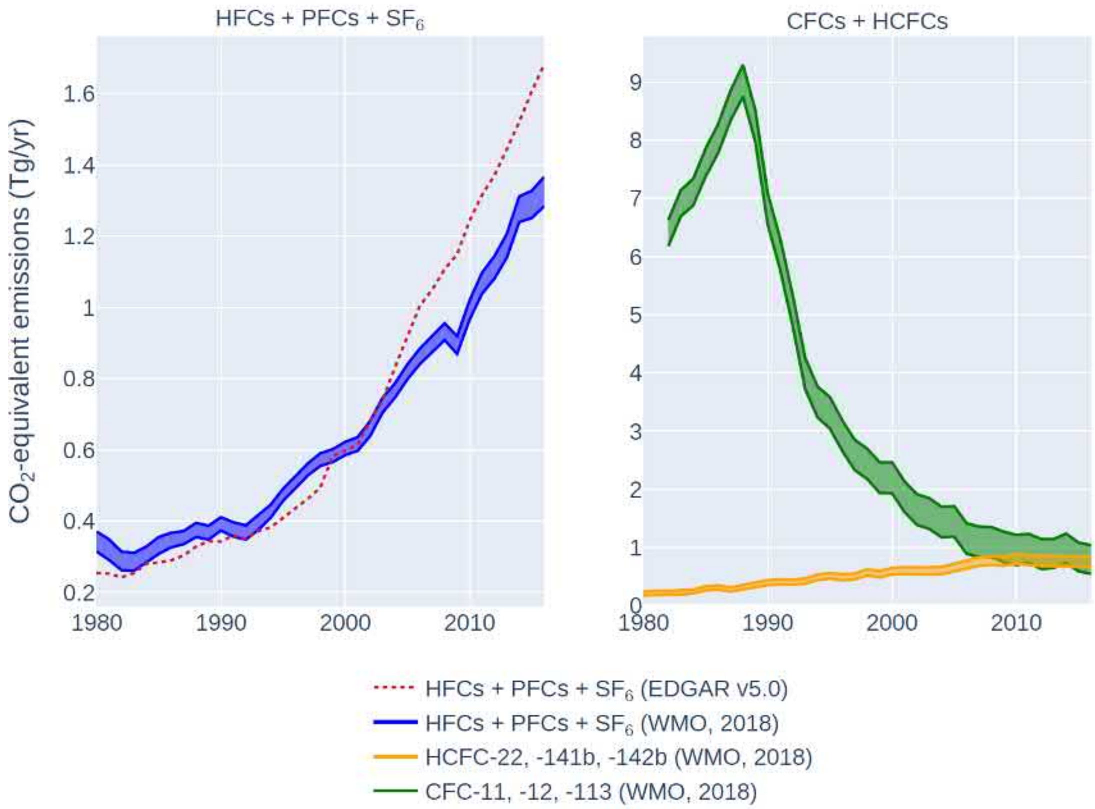


Figure 2 - Comparison of top-down and bottom-up estimates for individual species in EDGARv5. C_4F_{10}, C_5F_{12}, C_6F_{14} and C_7F_{16} are excluded. Top-down estimates from WMO 2018 (Engel and Rigby, 2018; Montzka and Velders, 2018) are shown as blue lines with blue

shading indicating 1-sigma uncertainties. Bottom-up estimates from EDGARv5 are shown in red dotted lines. Top-down estimates for some species are shown from Rigby, et al. (2010), Lunt, et al. (2015) and Fortems-Cheiney, et al. (2015).



565 **Figure 3 – Comparison between top-down estimates and bottom-up EDGARv5 inventory data on GHG emissions.** Left panel: Total GWP100-weighted emissions of F-gases in EDGARv5 (red dashed line, excluding C_4F_{10}, C_5F_{12}, C_6F_{14} and C_7F_{16}) compared to top-down estimates based on AGAGE and NOAA data from WMO (2018) (blue lines; Engel and Rigby, (2018); Montzka and Velders (2018)). Right panel: Top-down aggregated emissions for the three most abundant CFCs (-11, -12 and -113) and HCFCs (-22, -141b, -142b) not covered in bottom-up emissions inventories are shown in green and orange, with the area between the two respective lines representing 1-sigma
570 uncertainties.

The comparison of global top-down and bottom-up emissions for each EDGARv5 F-gas species (excluding heavy PFCs) is shown in Figure 2 for the years 1980 – 2016 (or a subset thereof, depending on the availability of the top-down estimates). Where available, the various top-down estimates agree with each other within uncertainties. The magnitude of the difference between WMO (2018) and EDGARv5 estimates varies markedly between species; for CF_4, the median annual ratio between
575 the top-down and bottom-up estimates is close to 1.0, whereas for c-C_4F_8 it is more than 100. Such differences have been previously noted, for example, by Mühle, et al. (2019) as well as in some earlier papers. For SF_6, the relatively close agreement between a previous version of EDGAR (v4) and a top-down estimate has been discussed in Rigby, et al. (2010). They estimated uncertainties in EDGARv4 of ±10% to ±15%, depending on the year, and indeed, top-down values were consistent within these uncertainties. For CF_4, these is close agreement between EDGARv4 and atmospheric observations after 1991, while for
580 C_2F_6 there is closer agreement before 1991 (Mühle et al., 2010). This remains the case here for EDGARv5. However, it should

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be noted that some assumptions within EDGAR had previously been validated against atmospheric observations, hence EDGARv4 might be considered a hybrid of top-down and bottom-up methodologies for these species, as some parameters may have been chosen based on comparison with atmospheric observations. Mühle, et al. (2010) noted a substantial gap between EDGARv4 and top-down estimates (with EDGARv4 emissions being less than 30% of the top-down values before 2008), which has apparently closed considerably in recent years in EDGARv5. However, for this species, as for many others, the cause of this discrepancy is not known.

When species are aggregated into an F-gas total, weighted by their 100-year GWPs (Figure 3), the EDGARv5 estimates are around 10% lower than the WMO 2018 values in the 1980s. Subsequently, EDGARv5 estimates grow more rapidly than the top-down values and are almost 30% higher than WMO 2018 by the 2010s. Given that detailed uncertainty estimates are not available for all EDGAR F-gas species, we base our uncertainty estimate solely on this single comparison with the top-down values, and therefore suggest an uncertainty in aggregated F-gas emissions of ±30% for a 90% confidence interval. For individual species, the magnitude of this discrepancy can be orders of magnitude larger.

The F-gases in EDGARv5 do not include chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs) and some perfluorinated species such as NF_3 – most of these species being regulated under the Montreal Protocol. Historically, total CO_2-equivalent F-gas emissions have been dominated by the CFCs (Engel and Rigby, 2018). In particular, during the 1980s, peak annual emissions due to CFCs reached 9.1±0.4 $GtCO_2eqyr^{-1}$ (Figure 3), comparable to that of CH_4, and substantially larger than the 2019 emissions of the gases included in EDGARv5 (1.6 $GtCO_2eq$) (Table 7). Subsequently, following the controls of the Montreal Protocol, emissions of CFCs declined substantially, while those of HCFCs and HFCs rose, such that CO_2eq emissions of the HFCs, HCFCs and CFCs were approximately equal by 2016, with a smaller contribution from PFCs, SF_6 and some more minor F-gases. Therefore, the GWP-weighted F-gas emissions in EDGARv5, which are dominated by the HFCs, represent less than half of the overall CO_2eq F-gas emissions in 2018.

3.6 Aggregated GHG emissions

Based on our assessment of relevant uncertainties above, we apply constant, relative uncertainty estimates for GHGs at a 90% confidence interval that range from relatively low for CO_2 FFI (±8%), to intermediate values for CH_4 and F-gases (±30%), to higher values for N_2O (±60%) and CO_2 from LULUCF (±70%). To aggregate these and estimate uncertainties for total greenhouse gases in terms of CO_2eq emissions, we taking the square root of the squared sums of absolute uncertainties for individual (groups of) gases, using 100-year Global Warming Potentials (GWP100) to weight emissions of non-CO_2 gases but excluding uncertainties in the metric itself (see Section 3.7). Overall, this is broadly in line with IPCC AR5 (Blanco G. et al., 2014), but provides important adjustments both in the evaluation of uncertainties (CH_4, F-gases, CO_2-LULUCF) as well as the approach in reporting total uncertainties across greenhouse gases.

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3.7 GHG emission metrics

GHG emission metrics are necessary if emissions of non-CO_2 gases and CO_2 are to be aggregated into CO_2eq emissions. GWP-100 is the most common metric and has been adopted under the transparency framework for the Paris Agreement (UNFCCC, 2019), but many alternative metrics exist in the scientific literature. The most appropriate choice of metric depends on the climate policy objective and the specific use of the metric to support that objective (i.e. why do we want to aggregate or compare emissions of different gases? What specific actions do we wish to inform?)

Different metric choices and time horizons can result in very different weightings of the emissions of Short-lived Climate Forcers (SLCF), such as methane. For example, 1t CH_4 represents as much as 86t CO_2eq if a Global Warming Potential is used with a time horizon of 20 years and including climate-carbon cycle feedbacks, or as little as 4t CO_2eq if the Global Temperature change Potential (GTP) is used with a time horizon of 100 years and excluding climate-carbon cycle feedbacks (Myhre et al., 2013). More recent metric developments that compare emissions in new ways – e.g. the additional warming from sustained changes in SLCF emissions compared to pulse emissions of CO_2 – increase the range of metric values further and can even result in negative values, if SLCF emissions are falling rapidly (Allen et al., 2018; Cain et al., 2019; Collins et al., 2019; Lynch et al., 2020).

The contribution of SLCF emissions to total GHG emissions expressed in CO_2eq thus depends critically on the choice of GHG metric and its time horizon. However, even for a given choice, the metric value for each gas is also subject to uncertainties. For example, the GWP-100 for methane has changed from 21 based on the IPCC Second Assessment Report in 1995 to 28 or 34 based on the IPCC AR5 (including feedbacks). These changes and remaining uncertainties arise from parametric uncertainties, differences in methodological choices, and changes in metric values over time, due to changing background conditions.

- Parametric uncertainties arise from uncertainties in climate sensitivity, radiative efficacy and atmospheric lifetimes of CO_2 and non-CO_2 gases, etc. The IPCC AR5 assessed the parametric uncertainty of GWP for methane as ±30% and ±40% for time horizons of 20 and 100 years, and ±20% and ±30% for gases with atmospheric lifetimes of a century or more. The uncertainty of GTP-100 for methane was estimated at ±75% (Myhre et al., 2013), which is larger than the uncertainty in a forcing-based metric due to due to uncertainties in climate responses to forcing (e.g., climate sensitivity). Further changes in metric values for methane and other gases within this uncertainty range are likely, given recent re-evaluations of the direct forcing of methane (Etminan et al., 2016) and adjustment of effective radiative forcing (Smith et al., 2020).
- Methodological choices introduce a different type of uncertainty, namely which indirect effects are included in the calculation of metric values and the strength of those feedbacks. For methane, indirect forcing caused by

photochemical decay products (mainly tropospheric ozone and stratospheric water vapour) contributes almost 40% of the total forcing from methane emissions. More than half of the changes in GWP-100 values for methane in successive IPCC assessments from 1995 to 2013 are due to re-evaluations of these indirect forcings. These uncertainties are incorporated in the above uncertainty estimates. In addition, warming due to the emission of non-CO_2 gases extends the lifetime of CO_2 already in the atmosphere through climate-carbon cycle feedbacks (Friedlingstein et al., 2013). Including these feedbacks results in higher metric values for all non-CO_2 gases, but the magnitude of this effect is uncertain; e.g. the IPCC AR5 found the GWP-100 value for methane without climate-carbon cycle feedbacks to be 28, whereas including this feedback would raise the value to between 31 and 34 (Gasser et al., 2016; Myhre et al., 2013; Sterner and Johansson, 2017).

- A third uncertainty arises from changes in metric values over time. Metric values depend on the radiative efficacy of CO_2 and non-CO_2 emissions, which in turn depend on the changing atmospheric background concentrations of those gases. Rising temperature can further affect the lifetime of some gases and hence their contribution to forcing over time (Reisinger et al., 2011). Successive IPCC assessments take changing starting-year background conditions into account, which explains part of the changes in GWP-100 metric values in different reports. Current IPCC convention calls for metrics to be calculated using constant background concentrations. Using time-changing background concentrations for the future, i.e. using a specific future concentration scenario, will result in additional changes in metric values. Applying a single metric value to a time series of emissions is therefore only an approximation of the correct metric value for any given emissions year, as e.g. the correct GWP-100 value for methane emitted in the year 1970 will be different to the GWP-100 value for an emission in the year 2018. However, the literature does not offer a complete set of GWP-100 metric values for past concentrations and climate conditions.

Overall, we estimate the uncertainty in GWP-100 metric values, especially if applied to extended emission time series, as ±50% for methane and other SLCFs, and ±40% for non-CO_2 gases with longer atmospheric lifetimes (specifically, those with lifetimes longer than 20 years). If uncertainties in GHG metrics are considered, the overall uncertainty of total GHG emissions in 2018 increases from ±11% to ±24%. (However, in the following sections we do not include GWP uncertainties in our global, regional or sectoral estimates).

For the purpose of this paper, we use GWP-100 metric values from the IPCC AR5 (Myhre et al., 2013) without climate-carbon cycle feedbacks. Even though climate-carbon cycle feedbacks are considered a robust feature of the climate system, the issue was only emerging during the IPCC AR5 and the methodology used to include this in metric calculations was indicative only. Subsequent studies (Gasser et al., 2016; Sterner and Johansson, 2017) suggest that revisions to the simple estimation method in IPCC AR5 are necessary.

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As mentioned above, the most appropriate metric to aggregate GHG emissions depends on the objective. One such objective can be to understand the contribution of emissions in any given year to warming, while another can be to understand the contribution of cumulative emissions over an extended time period to warming. Sustained emissions of SLCFs such as methane do not cause the same temperature response as sustained emissions of CO_2. Showing superimposed emission trends of different gases over multiple decades using GWP-100 as equivalence metric therefore does not necessarily represent the overall contribution to warming from each gas over that period. In Figure 4 we therefore also show the modelled warming from emissions of each gas or group of gases - calculated using the reduced-complexity climate model FAIRv1.6 and calibrated to reproduce the pulse-response functions for each gas consistent with the IPCC AR5 (Myhre et al., 2013). Despite some differences compared to the contribution of each gas, based on GHG emissions expressed in CO_2eq using GWP-100 (see Fig. 3), Figure 4 highlights that GWP-100 does not provide a vastly different story than modelled warming with CO_2 being the dominant and CH_4 being the second most important contributor to GHG-induced warming. Other metrics such as GWP* (Cain et al., 2019) offer an even closer resemblance between cumulative CO_2eq emissions and temperature change if that is the key objective, especially if emissions are no longer rising but potentially falling, as in mitigation scenarios.

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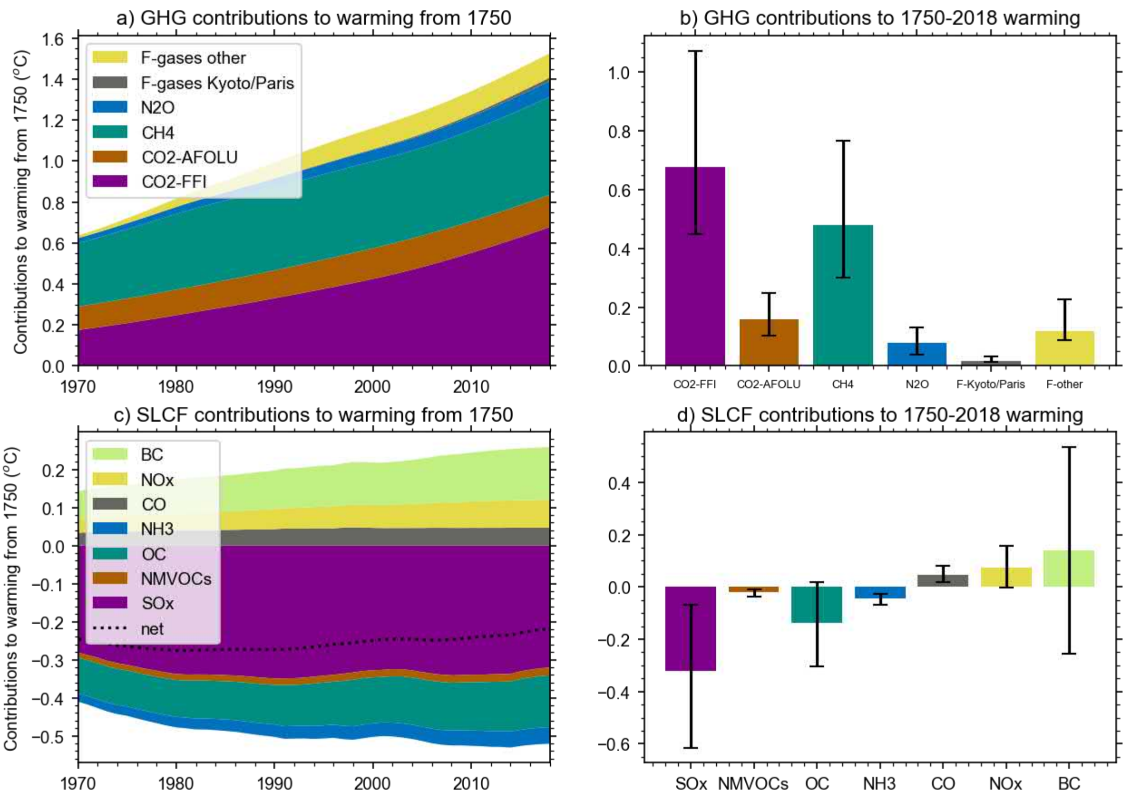

Figure 4 - Contribution of different greenhouse gases to global warming over the period 1750 to 2018. Top row: contributions from estimated with the FAIR reduced-complexity climate model. Major GHGs and aggregates of minor gases as a timeseries in a) and as a total warming bar chart with 5 % to 95 % uncertainty range added in b). Bottom row: contribution from shortshort-lived climate forcers as a timeseries in c) and as a total warming bar chart with 5 % to 95 % uncertainty range added in d). The dotted line in c) gives the net temperature change from short-lived climate forcers. F-Kyoto/Paris includes the gases covered by the Kyoto Protocol and Paris Agreement, while F-other includes the gases covered by the Montreal Protocol.

4 Results

Here we analyse global trends in anthropogenic GHG emissions in three time periods: (1) 1970-2019 to characterise the main trends in the data; (2) 2010-2019 to focus on the last decade and developments since IPCC AR5, which had its data cut-off for the year 2010 (Blanco G. et al., 2014); and (3) 2019 emission levels.

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4.1 Global anthropogenic greenhouse gas emissions for 1970-2019

There is high confidence that global greenhouse gas emissions have increased every decade from an average of 32±4.3 $GtCO_2eqyr^{-1}$ for the decade of the 1970s to an average of 56±6.0 $GtCO_2eqyr^{-1}$ during 2010-2019 as shown in Table 7. The decadal growth rate initially decreased from 1.7% yr^{-1} in the 1970s (1970-1979) to 0.9% yr^{-1} in the 1990s (1990-1999). After a period of accelerated growth during the 2000s (2000-2009) at 2.4%yr^{-1}, triggered mainly by growth in CO_2-FFI emissions from rapid industrialisation in China (Chang and Lahr, 2016; Minx et al., 2011), relative growth has decreased again to 1.1% yr^{-1} during the most recent decade (2010-2019). Uncertainties in aggregate GHG emissions have decreased over time as the share of less uncertain CO_2-FFI emission estimates increased and the share of more uncertain emission estimates such as CO_2-LULUCF or N_2O decreased.

Table 7 – Average annual anthropogenic GHG emissions and emissions growth by decade and (groups of) gases for 1970-2019: CO_2 from fossil fuel combustion and industrial processes (FFI); CO_2 from land use, land-use change and forestry (LULUCF); methane (CH_4); nitrous oxide (N_2O); fluorinated gases (F-gases). Aggregate GHG emission trends by groups of gases reported in $GtCO_2eq$ converted based on global warming potentials with a 100-year time horizon (GWP-100) from the IPCC Fifth Assessment Report (Myhre et al., 2013). Uncertainties are reported for a 90 % confidence interval (see Section 3). Levels and growth are average values over the indicated time period. Additional supplementary tables show similar average annual GHG emissions by decade also for major sectors (Table SM-2) and regions (Table SM-2).

	Average annual emissions levels ($GtCO_2eq\ yr^{-1}$) and emissions growth (%)											
	CO_2 FFI		CO_2 LULUCF		CH_4		N_2O		Fluorinated gases		GHG	
	Levels	Growth	Levels	Growth	Levels	Growth	Levels	Growth	Levels	Growth	Levels	Growth
2019	38±3.0		6.6±4.6		11±3.3		2.5±1.5		1.6±0.49		59±6.6	
2010-2019	36±2.9	1.0%	5.7±4.0	1.8%	10±3.1	0.9%	2.3±1.4	1.2%	1.4±0.41	4.6%	56±6.0	1.1%
2000-2009	29±2.3	3.0%	5.3±3.7	0.4%	9.2±2.8	1.6%	2.1±1.2	1.3%	0.77±0.23	7.8%	47±5.3	2.4%
1990-1999	24±1.9	1.2%	5.0±3.5	-0.1%	8.5±2.5	0.3%	1.9±1.1	0.9%	0.39±0.12	5.2%	39±4.9	0.9%
1980-1989	21±1.6	1.6%	4.7±3.3	1.8%	7.9±2.4	1.0%	1.8±1.1	0.7%	0.26±0.078	3.8%	35±4.5	1.4%
1970-1979	18±1.4	2.8%	4.6±3.2	-1.6%	7.4±2.2	1.2%	1.6±0.98	2.0%	0.17±0.052	6.4%	32±4.3	1.7%
1970	16±1.3		5.0±3.5		6.9±2.1		1.5±0.89		0.13±0.038		29±4.3	

There is high confidence that emission growth has been varied, but persistent across different groups of gases. Decade-by-decade increases in global average annual emissions have been observed consistently across all (groups of) greenhouse gases (Table 7), apart from CO_2-LULUCF emissions, which have been more stable, albeit uncertain, and only recently started to show an upward trend. The pace and scale of emission growth has varied across groups of gases. While average annual

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emissions of all greenhouse gases together grew by about 70% from 32±4.3 $GtCO_2eqyr^{-1}$ during the 1970s (1970-1979) to 56±6.0 $GtCO_2eqyr^{-1}$ during the 2010s (2010-2019), CO_2-FFI emissions doubled from 18±1.4 to 36±2.9 $GtCO_2eqyr^{-1}$ and F-gases grew more than sevenfold from 0.17±0.052 to 1.4±0.41 $GtCO_2eqyr^{-1}$ across the same time period. In fact, persistent and fast growth in F-gas emissions has resulted in emissions levels that are now tracking at about 1.6±0.49 Gt CO_2eqyr^{-1} in 2019 – 2.8% of total GHG emissions measured as GWP-100. Increases in average annual emissions levels from the 1970s (1970-1979) to the 2010s (2010-2019) were lower for CO_2-LULUCF (24%), CH_4 (42%) as well as N_2O (44%) (see Table 7).

However, there is low confidence that the reported increases in CO_2-LULUCF emissions by decade actually constitute a statistically robust trend given the large uncertainties involved. In fact, two bookkeeping models underlying the AFOLU data show opposing positive and negative trends (BLUE, H&N, respectively), while the third model (OSCAR), averaging over simulations that use either the same land-use forcing as BLUE (LUH2) or H&N (FAO), tracks the approximate mean of these (see also Section 3.2). Dynamic global vegetation models, which also use the LUH2 forcing, show higher estimates recently, explained by them considering the loss in sink capacity, while the bookkeeping models do not (see Figure 1). Overall, the different lines of evidence are inconclusive with regard to an upward trend in CO_2-LULUCF emissions.

Global anthropogenic greenhouse gas emissions grew continuously slower than world GDP across all (groups of) individual gases resulting in a sustained decline in the GHG intensity of GDP as shown in Figure 5. The only exception is the group of F-gases for which the GHG intensity of GDP has increased year-by-year until 2010 (with a marked acceleration during the 2000s) and started declining thereafter. Per capita GHG emissions have been fluctuating substantially, with a sustained decline in global per capita GHG emissions since the 1970s followed by an approximate 15 year period of continued growth from the 2000s. In recent years, per capita GHG emissions levels have stabilized without clear evidence for peaking. For CO_2-FFI emissions, sustained growth in per capita emissions can be observed since the mid-1990s levelling off during the last decade. Per capita emissions for CO_2-LULUCF, CH_4 and N_2O declined consistently since the 1970, but this trend has flattened out since the mid-1990s or early 2000s. Per-capita F-gas emissions show sustained and rapid growth until 2010 and have stabilized since.

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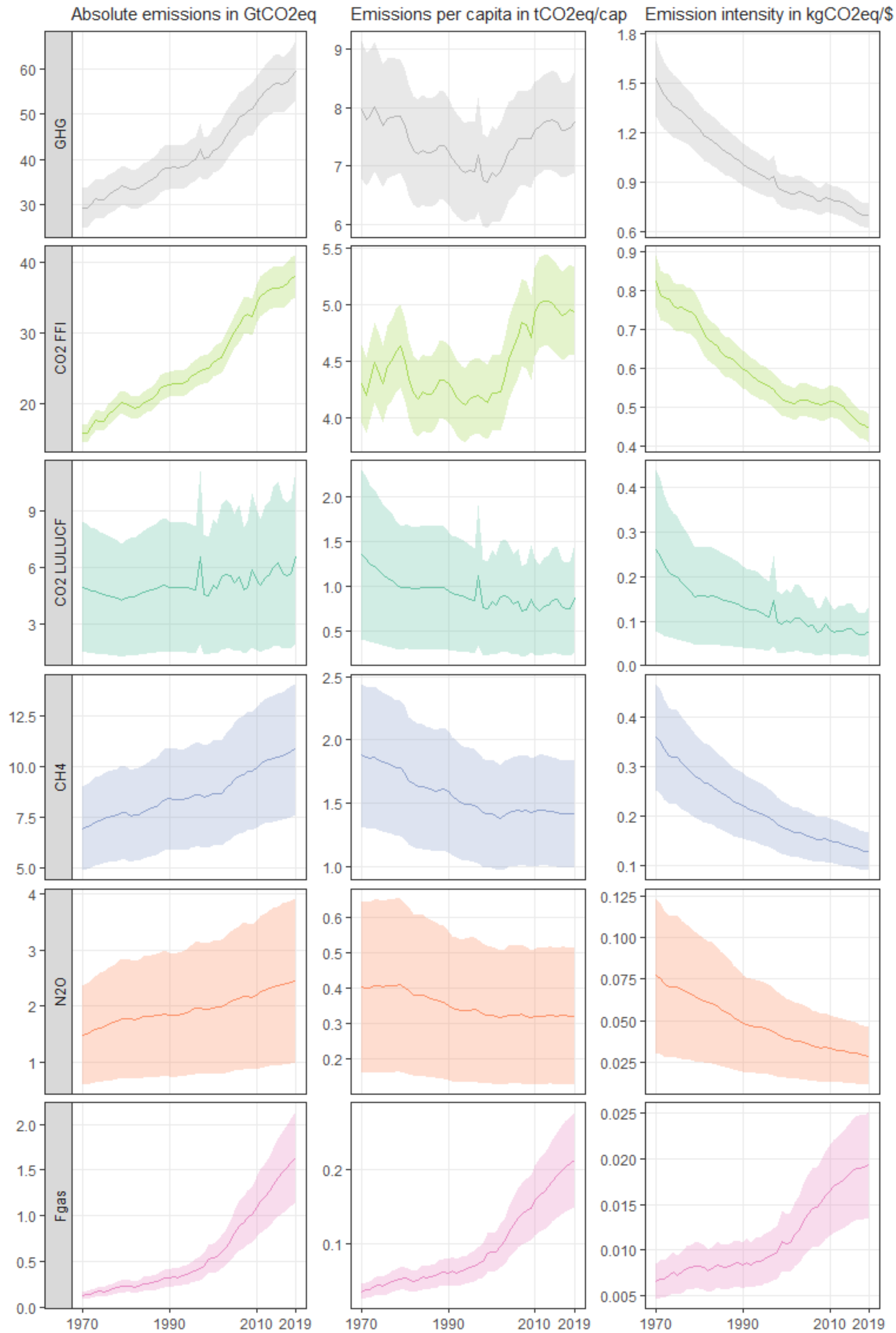

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Figure 5 - Global GHG emissions trends 1970-2019 by individual (groups of) gases and in aggregate: GHGs (black); CO_2-FFI (light green); CO_2-LULUCF (dark green); methane (blue); nitrous oxide (orange); fluorinated gases (pink). Aggregate GHG emission trends by groups of gases reported in $GtCO_2eq$ converted based on global warming potentials with a 100-year time horizon (GWP-100) from the IPCC Fifth Assessment Report (Myhre et al., 2013). Coloured shadings show the associated uncertainties at a 90 % confidence interval without considering uncertainties in GDP and population data (see below). First column shows emission trends in absolute levels ($GtCO_2eq$). Second column shows per capita emissions trends (tCO_2eq/cap) using UN population data for normalization (World Bank, 2021). Third column shows emissions trends per unit of GDP ($kgCO_2eq$/\$) using GDP data in constant 2010 \$ from the World Bank for normalization (World Bank, 2021).

The continuous growth in global anthropogenic GHG emissions since the 1970s was mainly driven by activity growth in three major sectors: energy supply, industry and transportation (see Table SM-2; Fig. SM-4). In energy supply and transportation, average annual emissions were about 2.3 times larger for 2010-2019 than for 1970-1979, growing from 8.5 to 19 $GtCO_2eqyr^{-1}$ and 3.5 to 8.1 $GtCO_2eqyr^{-1}$, respectively. In industry, average annual GHG emissions were 1.9 times larger growing from 7.3 $GtCO_2eqyr^{-1}$ in 1970-1979 to 14 $GtCO_2eqyr^{-1}$ in 2010-2019. At the sub-sector level, electricity & heat and road transport are the largest segments, growing 2.9 and 2.6 times between 1970-1979 and 2010-2019, respectively, from an average 4.6 to 14 $GtCO_2eqyr^{-1}$, and 2.2 to 5.8 $GtCO_2eqyr^{-1}$. The fastest growing sub-sector has been process emissions from cement, which is 4 times larger in 2010-2019 compared to 1970-1979, and currently accounts for an average 1.4 $GtCO_2eqyr^{-1}$. Other rapidly expanding sectors are international aviation (2.9 times larger on 1970-1979 levels), chemicals (2 times larger), metals (1.8 times larger) and waste (1.8 times larger). Growth in GHG emissions in AFOLU and buildings has been much more moderate with average annual GHG emissions only about 25% and 10% higher for 2010-2019 than for 1970-1979.

Most GHG emissions growth occurred in Asia and Developing Pacific as well as the Middle East, where emissions more than tripled from 6.4 $GtCO_2eqyr^{-1}$ and 0.8 $GtCO_2eqyr^{-1}$ in 1970-1979 to 23 $GtCO_2eqyr^{-1}$ and 2.9 $GtCO_2eqyr^{-1}$ in 2010-2019, respectively (see Table SM-1). Over the same time period GHG emissions grew 2.2 times in Africa and 1.7 times in Latin America and the Caribbean, while average annual anthropogenic GHG emissions levels in developed countries and Eastern Europe and West-Central Asia remained stable. However, Figure 6 highlights important variability: first, GHG emissions growth is taking place against the background of large differences in per capita GHG emissions between and within regions. For example, GHG emissions in developed countries have stabilized at high levels of per capita emissions compared to most other regions. Similarly, some countries in the Middle East are among the largest GHG emitters in per capita terms, while other countries of the region such as Yemen have seen comparatively little economic development showing low levels of per capita emissions. Second, the growth in GHG emissions has also been highly varied. For example, several developed countries in Europe such as UK, Germany or France have lower GHG emissions levels today than in the 1970s. In other countries like the US GHG emission levels are still considerably higher today even though they have recently started reducing GHG emissions – unlike Australia or Canada, which have until now only begun stabilizing their GHG emission levels. A comprehensive assessment of country progress in reducing GHG emissions can be found in Lamb et al. (2021b).

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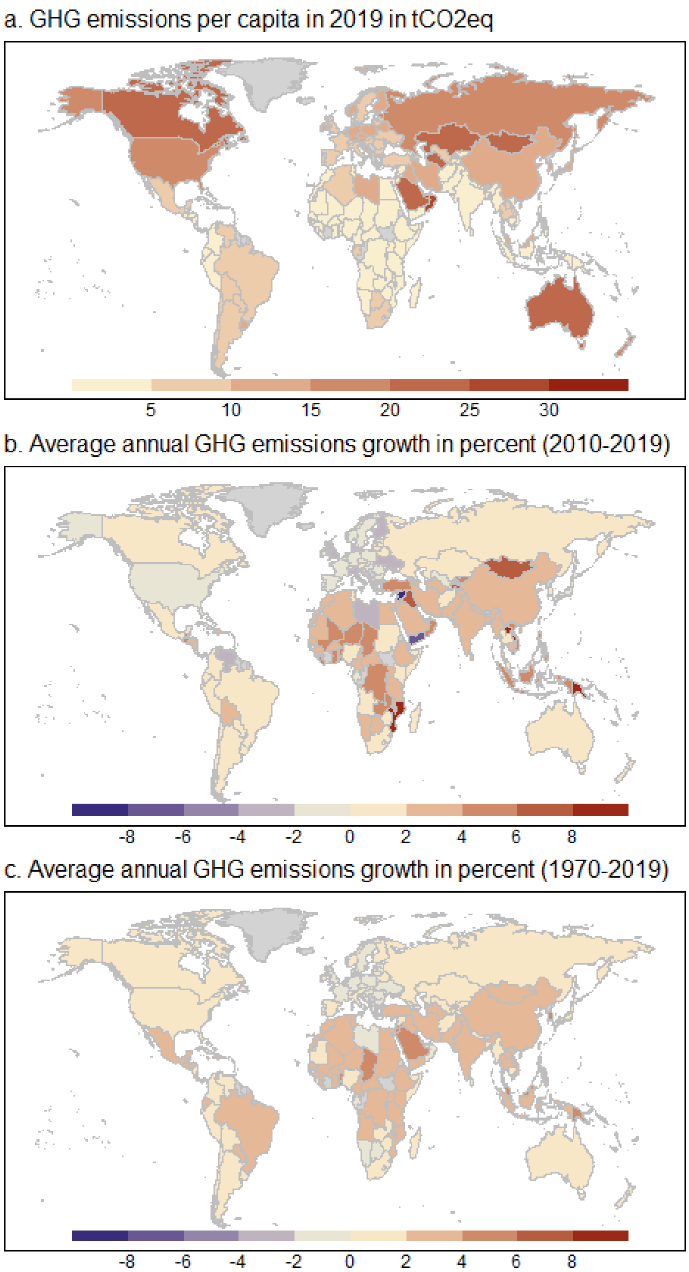

Figure 6 – Levels of and changes in GHG emissions by country. Aggregate GHG emissions are reported in $GtCO_2eq$ converted based on global warming potentials with a 100-year time horizon (GWP-100) from the IPCC Fifth Assessment Report (Myhre et al., 2013). Panel a shows per capita GHG emission levels (tCO_2eq/cap) for the year 2019 using UN population data for normalization (World Bank, 2021). Panel b shows average annual changes (in %) in GHG emissions by countries for 2010-2019. Panel c shows average annual changes (in %) in GHG emissions by countries for 1970-2019.

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In Fig. 7 we compare historic GHG emission trends with different scenarios, to explore how emissions are developing relative to the range of projected future outcomes. The Integrated Assessment Modelling (IAM) community quantified five Shared Socioeconomic Pathways (SSPs) for different levels of radiative forcing in 2100 using six different IAMs (Riahi et al., 2017; Rogelj et al., 2018b). The SSPs are grouped according to their radiative forcing ranging from 1.9 Wm^{-2} to 8.5 Wm^{-2}, aimed at spanning the full range of potential outcomes. The Coupled Model Intercomparison Project Phase 6 (CMIP6) took a subset of these quantified SSPs as the basis for future climate projections (Gidden et al., 2019; O'Neill et al., 2016). In recent years, the use of the very high forcing scenarios – particularly SSP5-8.5 - is being debated in the scientific community (e.g. Hausfather and Peters, 2020b, 2020a; Pedersen et al., 2020; Schwalm et al., 2020).

Historical GHG emissions from our database are consistent with the levels and trends in the scenario data, despite the scenarios being calibrated on older data sources (Gidden et al., 2019) – mainly CEDS (Hoesly et al., 2018). The observed differences are larger for the GHGs with the highest uncertainty, notably CO_2-AFOLU, N_2O and F-gas emissions (Sections 3.2, 3.4 and 3.5). Across the different GHGs, historical emissions track on aggregate with the higher forcing scenarios such as the SSP3-7.0 and SSP5-8.5 markers, in terms of both levels and growth rates. CO_2-FFI emissions still tend towards the higher end of the scenario range shown here, but there are signs that CO_2-FFI emissions are slowing to more moderate forcing levels (e.g., SSP4-6.0 and SSP2-4.5) when considering recent trends (Hausfather and Peters, 2020a). CH_4 and N_2O emissions sit more in the middle and at the lower-end of the scenario range – the latter driven by the lower levels of N_2O emissions in EDGAR – and F-gases are consistent with the scenarios. Total GHG emissions track the higher end scenarios.

Figure 7 highlights the very different future emission trajectories envisioned by IAMs for individual gases – particularly at radiative forcing levels that are consistent with the goal of the Paris Agreement such as SSP1-2.6 and SSP1-1.9. In contrast to CO_2 emission, non-CO_2 forcers such as anthropogenic CH_4 and N_2O emissions are not reduced to zero. However, in many scenarios, F-gases reach zero emissions. N_2O emissions remain at similar levels to today in some of the scenarios with a 1.9 Wm^{-2} forcing at the end of the century, while they are about halved in others. Reductions in methane emissions are a bit more pronounced ranging from about 100 to 200 $MtCH_4yr^{-1}$ in 2100 compared to almost 400 $MtCH_4yr^{-1}$ in 2019. CO_2-AFOLU emission trajectories overlap for different forcing levels, partly reflecting the complexities of modelling land-use change, but overall show a tendency towards a net carbon sink even in SSPs with little or even without climate policy. Given recent trends in land-use change emissions, it could be questioned whether the scenarios adequately explore the uncertainty in future land-use change emissions (Hausfather and Peters, 2020b).

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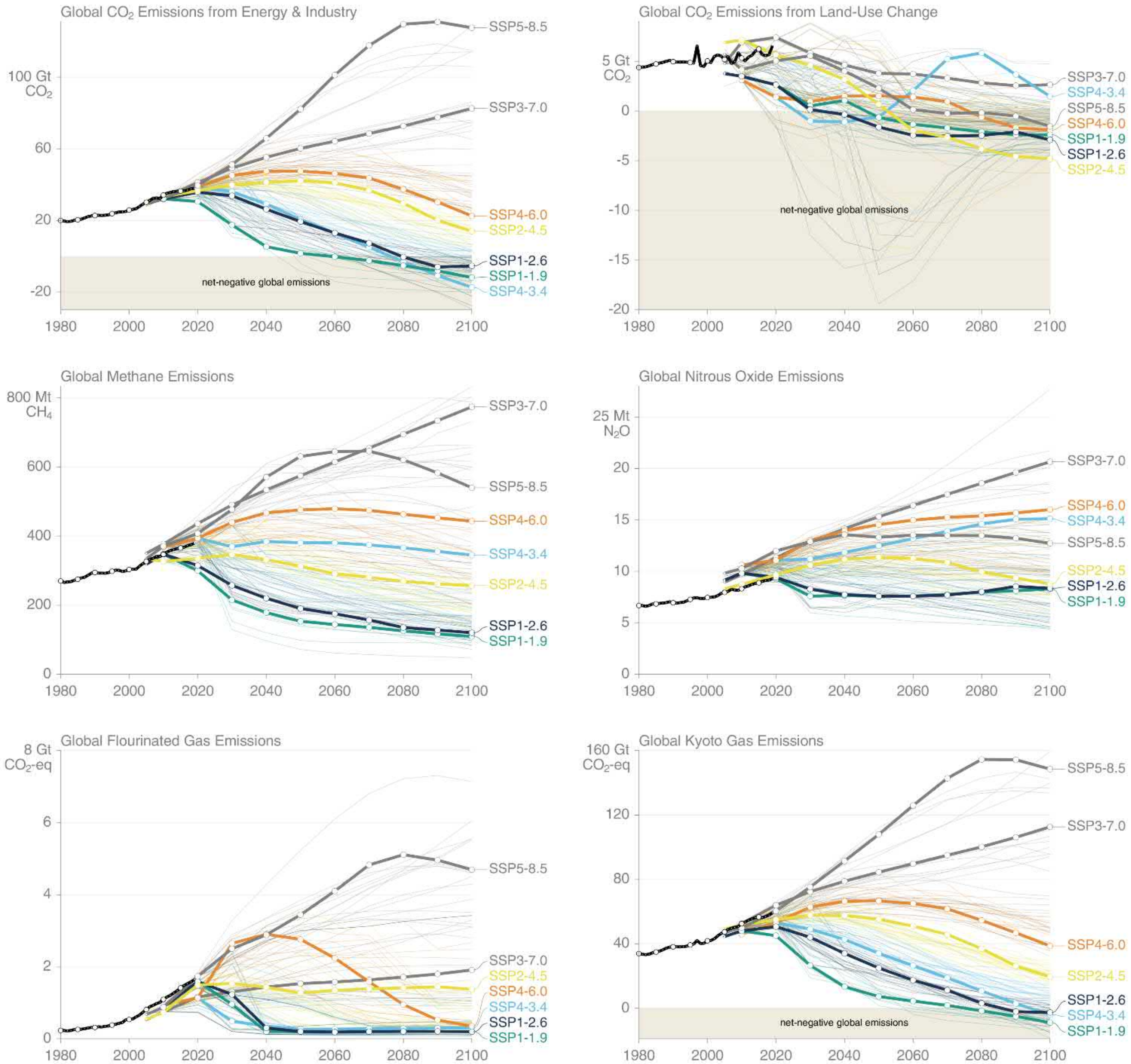

Figure 7 - Historical emissions of GHGs and future projections in socio-economic scenarios. The historical emissions are from this dataset. The Shared Socioeconomic Pathways (SSPs) are from the SSP database version 2 (Riahi et al., 2017; Rogelj et al., 2018b). See also: https://tntcat.iiasa.ac.at/SspDb/). Highlighted scenarios are the markers used in CMIP6 (O'Neill et al., 2016) after harmonisation (Gidden et al., 2019).

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4.1.2 - Global greenhouse gas emissions for the last decade 2010-2019

There is high confidence that global anthropogenic GHG emission levels were higher in 2010-2019 than in any previous decade and GHG emissions levels have grown across the most recent decade. Average annual GHG emissions for 2010-2019 were 56±6.0 $GtCO_2eqyr^{-1}$ compared to 47±5.4 and 39±4.9 $GtCO_2eqyr^{-1}$ for 2000-2009 and 1990-1999, respectively. In 2019 GHG emissions were about 6.8±1.0 $GtCO_2eqyr^{-1}$ or 13% higher than in 2010. F-gas and CO2-LULUCF emissions were 50% and 24% higher in 2019 than in 2010 compared to 12%, 11% and 9% for N_2O, CO_2-FFI and CH_4 emissions, respectively. CO_2 emissions from FFI contributed 3.8±0.3 of the 6.8±1.0 $GtCO_2eqyr^{-1}$ increase in annual GHG emissions with additional contributions of 1.3±0.89 $GtCO_2eqyr^{-1}$ from CO_2-LULUCF, 0.93±0.28 $GtCO_2eqyr^{-1}$ from CH_4, 0.25±0.15 $GtCO_2eqyr^{-1}$ from N_2O and 0.55±016 $GtCO_2eqyr^{-1}$ from F-gases. While average annual greenhouse gas emissions growth slowed between 2010-2019 compared to 2000-2009 from 2.4% to 1.1%, the absolute increase in average decadal GHG emissions by 9.4±0.77 $GtCO_2eqyr^{-1}$ from the 2000s to the 2010s has been the largest since the 1970s – and probably within all human history as suggested by available long-term data (e.g. Friedlingstein et al., 2020; Hoesly et al., 2018).

About 50% of the recent growth in global GHG emissions between 2010 and 2019 came from China (2.7 $GtCO_2eqyr^{-1}$) and India (0.94 $GtCO_2eqyr^{-1}$) (Figure **8**). Among the major emitters, fastest GHG emissions growth was observed for Vietnam with average annual rates of 5.1% yr^{-1} between 2010 and 2019 followed by Turkey (4.6% yr^{-1}), Indonesia (3.8% yr^{-1}), Pakistan (3.4% yr^{-1}), India (3.2% yr^{-1}), Saudia Arabia (2.8% yr^{-1}) and China (2.4% yr^{-1}). GHG emission reductions achieved by countries over the last decade are comparatively small even though there is a growing number of countries on sustained emissions reductions trajectories (Lamb et al., 2021b; Le Quéré et al., 2019b). The US showed the largest net anthropogenic GHG emissions reductions of 0.21 $GtCO_2eqyr^{-1}$ between 2010 and 2019 even though more significant reductions in CO_2 emissions of 0.46 $GtCO_2yr^{-1}$ from a switch from coal to gas in the context of the shale gas expansion was partially compensated by additional CH_4 (0.12 $GtCO_2eqyr^{-1}$) and F-gas (0.13 $GtCO_2eqyr^{-1}$) emissions (Figure **8**). Other countries with decreasing GHG emission levels were Germany (0.13 $GtCO_2eqyr^{-1}$) and the United Kingdom (0.14 $GtCO_2eqyr^{-1}$), where the latter shows the fastest average annual reductions at a rate of 2.6% yr^{-1} in the sample –in line with some GHG emission reduction scenarios that limit global warming to well below 2°C, but those ones that tend to rely more heavily on carbon dioxide removal technologies (Hilaire et al., 2019; Strefler et al., 2018). Further information on country contributions to GHG emission changes since 1990s – an important reference for UN climate policy – are shown in supplementary Fig. SM-2.

Official statistics submitted annually by 43 countries listed in Annex I of the Kyoto Protocol (see Fig. 9) to the UNFCCC (hereafter UNFCCC-CRFs) indicate 1.9% lower emissions over the period 1990-2019. The vast majority of the Annex I countries, which contributed 33.6% of the global GHG emissions in 2019 (according to the dataset presented in this paper), report lower total GHG emissions in 2019 and lower growth (higher reduction) rates between 1990-2019 as compared with the data presented here. The total emissions of the Annex I countries in 2019 stand with 16.8 $GtCO_2eqyr^{-1}$ according to the

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national inventories 5.6% lower than the data presented here for the same countries. The growth rates over the last decade (2010-2019) reported in the national inventories was on average 0.3 percentage points lower than the growth rates for the same set of countries in our dataset (see Figure **8**). Additional analysis comparing our data with UNFCCC-CRF inventories for individual (groups of) gases and countries is provided in supplementary Fig. SM-3.

Sectoral GHG emissions were either stable or increased between 2010 and 2019. There is high confidence that no substantive GHG emissions reductions were observable for entire sectors at the global level (Fig. 8 d and e). The largest sectoral contribution to the 6.8±1.0 $GtCO_2eqyr^{-1}$ increase in GHG emissions levels between 2010 and 2019 was from CO_2-AFOLU with about 1.3 $GtCO_2yr^{-1}$, but this estimate is much more uncertain compared to other sectors. The continued expansion of fossil-fuel based electricity production increased CO_2 emissions by about 1.2 $GtCO_2yr^{-1}$ closely followed by CO_2 emissions from road transport (0.9 $GtCO_2yr^{-1}$) and metal production (0.7 $GtCO_2yr^{-1}$) – the latter being the fastest large emission source in relative terms with 2.1%. Domestic and international aviation are the most rapidly growing sectors (3.8% and 3.7%, respectively), but remain globally small sources of emissions growth (0.1 and 0.17 $GtCO_2yr^{-1}$). Emissions from chemical production and waste treatment are also sizable and comparatively fast growing, contributing 0.47 $GtCO_2yr^{-1}$ at 1.9%yr^{-1} and 0.31 $GtCO_2yr^{-1}$ at 1.6%yr^{-1}, respectively.

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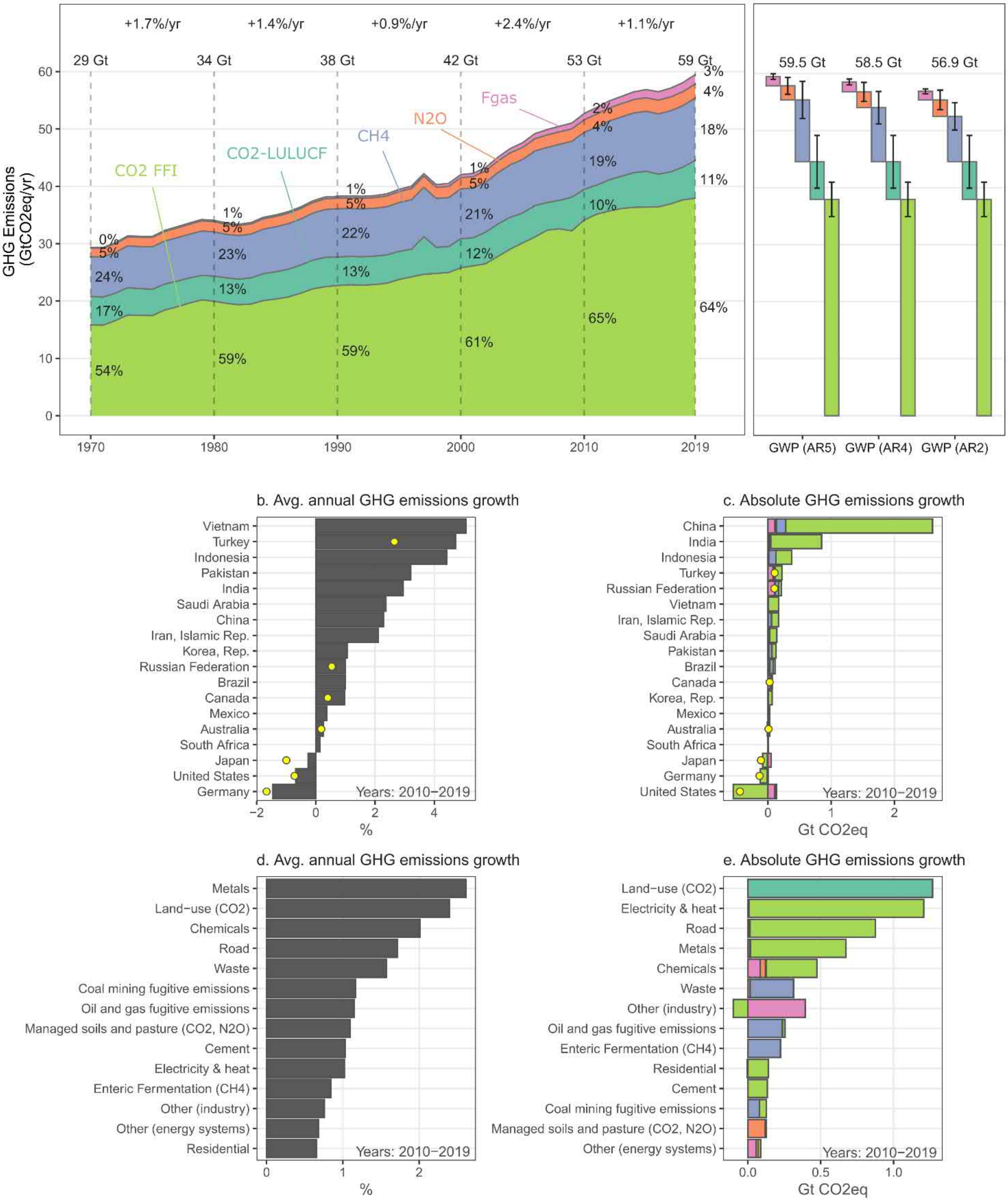

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Figure 8 - **Total anthropogenic GHG emissions (Gt CO_2eq yr-1) 1970-2019: CO_2-FFI (light green); CO_2-LULUCF (dark green); methane (blue); nitrous oxide (orange); fluorinated gases (pink); all greenhouse gases (black). Panel a: Aggregate GHG emission trends by groups of gases reported in GtCO_2eq converted based on global warming potentials with a 100-year time horizon (GWP-100) from the IPCC Fifth Assessment Report (Myhre et al., 2013). Average annual growth rates by decade are reported at the top of the figure (in %yr-1). Waterfall diagrams juxtaposes GHG emissions for the most recent year 2019 in CO_2 equivalent units using GWP-100 values from the IPCC's Second and Fourth Assessment Report, respectively. Error bars show the associated uncertainties at a 90 % confidence interval. Panels b and c show relative (in %) and absolute (in GtCO2eq) changes in GHG emissions for a selection of the largest emitting countries excluding CO2-LULUCF emissions as uncertainties in our estimates are too high for country-level reporting. The yellow dots represent the emissions data according to the national inventories reported by the Annex I countries of the Kyoto Protocol to the UNFCCC (Gütschow et al., 2021; Louise Jeffery et al., 2018). Panels d and e show relative (in %) and absolute (in GtCO2eq) changes in GHG emissions for a selection of the largest emitting sectors (see**

Table 2).

4.1.3 Global greenhouse gas emissions in 2019

Global net anthropogenic greenhouse gas emissions continued to grow and reached 59±6.6 GtCO_2eq in 2019 (Figure **8**). In 2019, CO_2 emissions from FFI were 38±3.0 Gt, CO_2 from LULUCF 6.6±4.6 Gt, CH_4 11±3.3 GtCO_2eq, N_2O 2.4±1.5 GtCO_2eq and F-gases 1.6±0.49 GtCO_2eq. Of the 59±6.6 GtCO_2eq emissions in 2019, 33% (20 GtCO_2eqyr^{-1}) were from energy supply, 24% (15 GtCO_2eqyr^{-1}) from industry, 22% (20 GtCO_2eqyr^{-1}) from AFOLU, 15% (8.7 GtCO_2eqyr^{-1}) from transport, and 5.6% (3.3 GtCO_2eqyr^{-1}) from buildings. In 2019, the largest absolute contributions in GHG emissions were from Asia and Developing Pacific (43%), Developed countries (25%) and Latin America and the Caribbean (10%). China (14 GtCO_2eqyr^{-1}), USA (6.5 GtCO_2eqyr^{-1}) and India (3.7 GtCO_2eqyr^{-1}) and the Russian Federation (2.5 GtCO_2eqyr^{-1}) remained the largest country contributors to global GHG emissions, excluding CO_2-LULUCF as we do have not sufficient confidence to report this data at the country level.

In 2019, emissions were 1.4 GtCO_2eqyr^{-1} or 2.4% higher than the 58±6.1 GtCO_2eq in 2018. Most of this growth (~0.9±0.6 GtCO_2eqyr^{-1}) is related to increases in CO_2-LULUCF, which results in particular from the high peat and tropical deforestation/degradation fires as outlined in Friedlingstein et al. (2020). Growth in CO_2-FFI was very modest at 0.28±0.023 GtCO_2yr^{-1} (Δ0.8%), while F-gas, N_2O and methane grew more rapidly by 3.8%, 1.2% and 1.0% - but at much lower absolute levels. While the rate of GHG emissions change between 2018 and 2019 is numerically comparable with the period of high GHG emissions growth during the 2000s, there is low confidence in the reported value due to the high share of CO_2-LULUCF emissions, which are highly uncertain, and the preliminary nature of the underlying land-use data for 2019 and temporal extrapolation of two of the three bookkeeping estimates. Moreover, given prevailing uncertainties there is low confidence that GHG emissions have never been higher than in 2019 as suggested by the data, but high confidence that average annual GHGs emissions have never been higher for a decade than in 2010-2019 (see Friedlingstein et al., 2020; Hoesly et al., 2018).

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Discussion

In this article we provide a comprehensive, detailed dataset for global, regional, national and sectoral GHG emissions from anthropogenic sources covering the last five decades (1970-2019) built from the EDGARv6 GHG emissions inventory, a fast-track update/projection as well as data on CO_2-LULUCF emissions from global bookkeeping models. We assess uncertainties in our estimates by combining statistical analysis of the underlying data and expert judgement based on an in-depth review of the literature by each gas. We report uncertainties at a 90% confidence interval (5^{th}-95^{th} percentile range). This differs to the uncertainty reported by the Global Carbon Project for the global carbon, methane or nitrous oxide budgets (Friedlingstein et al., 2020; Saunois et al., 2020; Wang et al., 2020), because uncertainties in our dataset are comparatively well characterized (Janssens-Maenhout et al., 2019; Solazzo et al., 2021).

Our uncertainty assessment is broadly consistent with previous assessments focussing on all GHGs (Blanco G. et al., 2014; UNEP, 2020), but we provide some important updates. Our evidence-informed uncertainty judgements are higher for CO_2-LULUCF (±70% rather than ±50%) and CH_4 (±30% rather than ±20%) drawing from work on global carbon (Friedlingstein et al., 2020) and methane (Saunois et al., 2020) budgets. We recognize the vast divergence between bottom-up inventory estimates and top-down atmospheric measurements for individual F-gases. Our revised uncertainty estimate for aggregate F-gas emissions of ±30% (rather than ±20%) reflects the smaller aggregate deviation when all individual species are considered together.

Our analysis involves aggregating GHG emissions into a single unit using GWP-100 values from IPCC AR5 (without carbon cycle feedbacks). By doing so we follow the practice taken in UNFCCC climate diplomacy and large parts of the literature on climate change mitigation. However, we recognise intense scientific and academic debates about the aggregation of GHGs into a single unit and alternative choices of metrics (Myhre et al., 2013) (see Section 3.7). We therefore also use a simple climate model to assess the warming contribution by the individual groups of gases and find that for the historical period when emissions are growing, the GWP-100 gives a reasonable approximation to the warming contributions, but this is not expected to hold when emissions change trajectory under mitigation. In the absence of comprehensive uncertainty analysis that covers CO_2-LULUCF as well as F-gas emissions, we estimate the overall uncertainties of aggregated GHG emissions by simply adding the individual uncertainties judgements by (groups of) gases in quadrature under the assumption of their independence. Comprehensive uncertainty analysis of EDGAR data covering all greenhouse gases should be performed in the future, building on Solazzo et al. (2021). For the first time, we also provide an initial estimate of metric uncertainty arising from the aggregation of individual greenhouse gases into a single unit (see Section 3.7).

Our assessment highlights the comprehensive nature of our dataset covering anthropogenic sources of greenhouse gas emissions. However, there are still some important data gaps. Most recent and comprehensive assessments of the methane

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(Saunois et al., 2020) and nitrous oxide (Tian et al., 2020) budgets suggest that anthropogenic CH_4 and N_2O emissions could be 10-20% higher than reported in EDGAR, respectively. F-gas emissions estimates for individual species in EDGARv5 do not align well with atmospheric measurements and the F-gas aggregate over-reports the measured concentrations by about 30%. However, EDGAR and official national emission reports under the UNFCCC do not comprehensively cover all relevant F-gases species. We also note that our data does not cover species such as chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs) or NF_3 and show that those species, which are regulated under the Montreal Protocol (except NF_3), have contributed more to CO_2eq emissions as well as observed warming. There is an urgent need to dedicate more resources and attention to the independent improvement of F-gas emission statistics, recognizing these current shortcomings and their increasingly important role as a driver of warming.

Our analysis of global, anthropogenic GHG emission trends over the past five decades (1970-2019) highlights a pattern of varied, but sustained emissions growth. There is high confidence that global anthropogenic greenhouse gas emissions have increased every decade. Emission growth has been varied, but persistent across different (groups of) gases. While CO_2 has accounted for almost 75% of the emission growth since 1970 in terms of CO_2eq as reported here, the combined F-gases have grown much faster than other GHGs, albeit starting from very low levels. Today, they make a non-negligible contribution to global warming – recognizing that important species such as CFCs and HCFCs are even not considered. There is further high confidence that global anthropogenic GHG emissions levels were higher in 2010-2019 than in any previous decade and GHG emissions levels have grown across the most recent decade. While average annual greenhouse gas emissions growth slowed between 2010-2019 compared to 2000-2009, the absolute increase in average decadal GHG emissions from the 2000s to the 2010s has been the largest since the 1970s – and within all human history as suggested by available long-term data (e.g. Friedlingstein et al., 2020; Hoesly et al., 2018). We note considerably higher rates of change in GHG emissions between 2018 and 2019 than for the entire decade 2010-2019, which is numerically comparable with the period of high GHG emissions growth during the 2000s, but we place low confidence in this value as the majority is driven by highly uncertain increases in CO_2-LULUCF emissions as well as the use of preliminary data and extrapolation methodologies for these most recent years. While there is a growing number of countries today on a sustained emission reduction trajectory (Lamb et al., 2021b; Le Quéré et al., 2019a), it is important to study the drivers of these reductions as well as patterns of emission growth in other parts of the world (Lamb et al., 2021a). Our analysis further reveals that there are no global sectors that show sustained reductions in GHG emissions.

There is a growing availability of global datasets on anthropogenic emissions sources over the last 10-20 years. However, such global emission inventories have to rely on relatively simple Tier-1 estimation methods and few use more complex Tier-2 methods. Comparison of our estimates with Tier-2 and Tier-3 UNFCCC-CRFs by Annex I countries shows considerable discrepancies for some gases. On aggregate, there is a clear trend towards smaller values for GHG emission reductions and larger values for GHG emission increases in our dataset. Further work needs to be done to fully appreciate underlying

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differences (Andrew, 2020a; Petrescu et al., 2020c, 2020b). Figure 9 further highlights the lack of recent official GHG emissions inventories for many non-Annex 1 countries outside those global emission inventories. Despite the importance of high-quality emission statistics for climate change research and tracking progress in climate policy, our analysis here emphasises considerable prevailing uncertainties and the need for improvement in emission reporting. In sectors where production efficiencies are changing rapidly, as is often the case in developing countries, using emission estimates based on Tier-1 methodologies is likely to mischaracterise trends as both activity data and emission factors change over time (Wilkes et al., 2017). Moving confidently towards net-zero emissions requires high quality emissions statistics for tracking countries' progress based at least on Tier-2, if not on complex Tier-3 estimation models using comprehensive, country-specific activity data and emissions factors (IPCC, 2019). This would also support the formulation of more nuanced climate policy goals that reflect changes in emissions intensity as entry points for more comprehensive and ambitious targets to reduce absolute emissions. However, underpinning such approaches with robust evidence requires the collection of a range of country-specific activity data and development of adequate statistical infrastructure for all countries of the world (FAO and GRA, 2020). Making progress in the implementation of the Paris Agreement and keeping warming well below 2°C requires dedication and cooperation between countries: working together on a robust evidence base in GHG emissions reporting provides one important and often underappreciated step.

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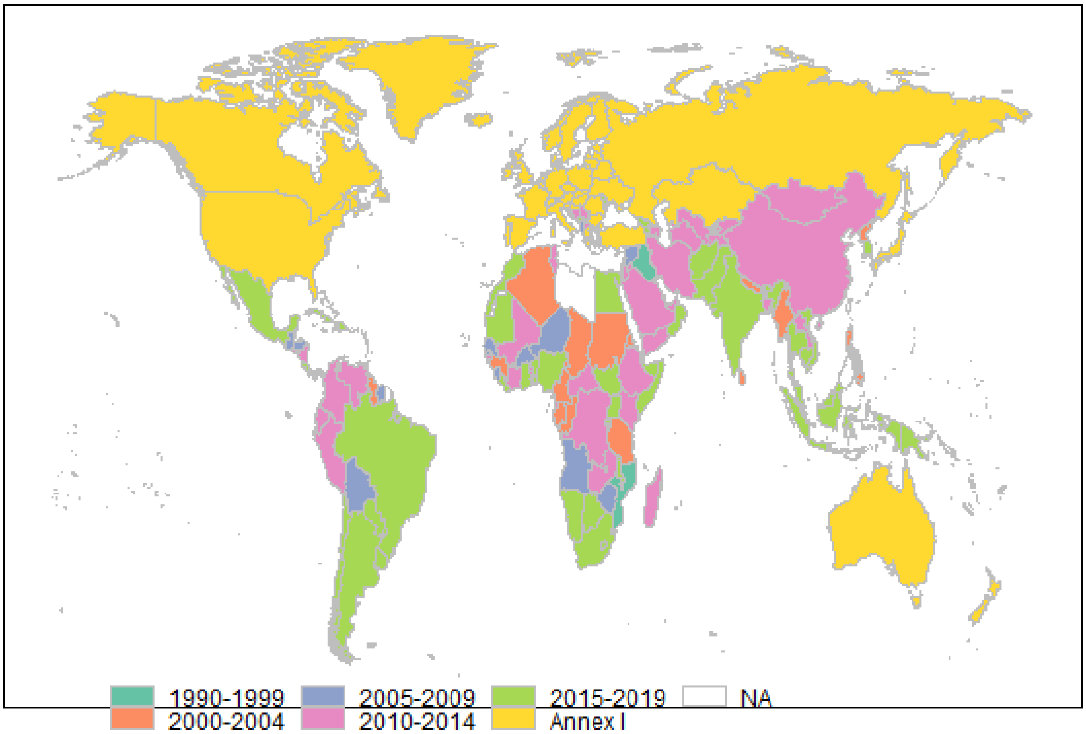

Figure 9 - Overview of most recent GHG emission inventories submitted to the UNFCCC: The map captures the last year for which emission inventories were conducted and published by the UNFCCC on their website (as of 31 May 2021). Annex I countries, according to the UNFCCC definition, have reported their last inventories for 2019. Non-Annex I countries should in principle submit national inventories every two years according to the Paris Agreement. Updated from Janssens-Maenhout et al. (2019)

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Data availability
The emissions dataset used for this study (Minx et al. 2021) is available at https://doi.org/10.5281/zenodo.5053056

[NOTE TO REVIEWERS: Data on CO_2 emissions from fossil fuel combustion and industry, methane emissions and nitrous oxide emissions are from the most recent EDGARv6 data. As EDGARv6 data is still being compiled for F-gases, this manuscript contains EDGARv5 estimates for these, but we will update to EDGARv6 during the revision process. This procedures has been agreed upon with David Carlson – one of the chief editors of the journal – before manuscript submission]

Author contributions
JCM and WFL designed the research. WL, ND, RMA, GPP, MR and PMF generated the figures with support by all other authors (JCM, JGC, MC, DG, JO, JP, AR, MS, SJS, ES, HT). WFL, ND, RMA, GPP, MR and PMF carried out the required computations. JCM led on the analysis in collaboration with all authors (WFL, RMA, JGC, MC, ND, PMF, DG, JO, GPP, JP, AR, MR, MS, SJS, ES, HT) JCM led on the writing of the manuscript in collaboration with all authors (WFL, RMA, JGC, MC, ND, PMF, DG, JO, GPP, JP, AR, MR, MS, SJS, ES, HT).

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WHITE PAPER

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A GLOBAL COMPARISON OF THE LIFE-CYCLE GREENHOUSE GAS EMISSIONS OF COMBUSTION ENGINE AND ELECTRIC PASSENGER CARS

Georg Bieker

www.theicct.org

communications@theicct.org

twitter @theicct

THE INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION

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For additional information:
ICCT – International Council on Clean Transportation Europe
Neue Promenade 6, 10178 Berlin
+49 (30) 847129-102

communications@theicct.org | www.theicct.org | @TheICCT

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EXECUTIVE SUMMARY

If the transportation sector is to align with efforts supporting the best chance of achieving the Paris Agreement's goal of limiting global warming to below 2 °C, the greenhouse gas (GHG) emissions from global road transport in 2050 need to be dramatically lower than today's levels. ICCT's projections show that efforts in line with limiting warming to 1.5 °C mean reducing emissions from the combustion and production of fuels and electricity for transport by at least 80% from today's levels by 2050, and the largest part of this reduction needs to come from passenger cars. Considering the expected future growth of the transport sector, the change needed on a per-vehicle basis will be even higher.

As important as it is to reduce the emissions from fuel and electricity production and consumption, such reduction should of course not come at the cost of higher vehicle production emissions. Taking all together, it is therefore important for policymakers to understand which powertrain and fuel technologies are most capable of shrinking the carbon footprint of cars—and not only the emissions from the tailpipes, but also from fuel and electricity production and vehicle manufacturing.

This study is a life-cycle assessment (LCA) of the GHG emissions of passenger cars in China, Europe, India, and the United States, four markets that are home to the majority of global new passenger car sales and reflect much of the variety in the global vehicle market. The study considers the most relevant powertrain types—internal combustion engine vehicles (ICEVs), including hybrid electric vehicles (HEVs); plug-in hybrid electric vehicles (PHEVs); battery electric vehicles (BEVs); and fuel cell electric vehicles (FCEVs)—and a variety of fuel types and power sources including gasoline, diesel, natural gas, biofuels, e-fuels, hydrogen, and electricity. For each region, the analysis is based on average vehicle characteristics across the most representative market segments and considers fuel and electricity consumption in real-world driving conditions. Additionally, based on stated policies, the study estimates how the life-cycle GHG emissions of cars expected to be registered in 2030 compare with vehicles registered today. For both 2021 and 2030 cars, it considers the changing fuel and electricity mixes during the lifetime of the vehicles.

Key results include the following:

Only battery electric and hydrogen fuel cell electric vehicles have the potential to achieve the magnitude of life-cycle GHG emissions reductions needed to meet Paris Agreement goals.

As shown for average new medium-size cars in Figure ES.1, the assessment finds that the life-cycle emissions over the lifetime of BEVs registered today in Europe, the United States, China, and India are already lower than a comparable gasoline car by 66%–69% in Europe, 60%–68% in the United States, 37%–45% in China, and 19%–34% in India. For medium-size cars projected to be registered in 2030, as the electricity mix continues to decarbonize, the life-cycle emissions gap between BEVs and gasoline vehicles increases to 74%–77% in Europe, 62%–76% in the United States, 48%–64% in China, and 30%–56% in India. As indicated in the figure, a large uncertainty lies in how the future electricity mix develops in each region; the high ends of the error bars reflect more emissions when only considering currently existing and announced policies, and the low ends reflect the implementation of policies the International Energy Agency projects would be required for the power sector to align with Paris Agreement targets.

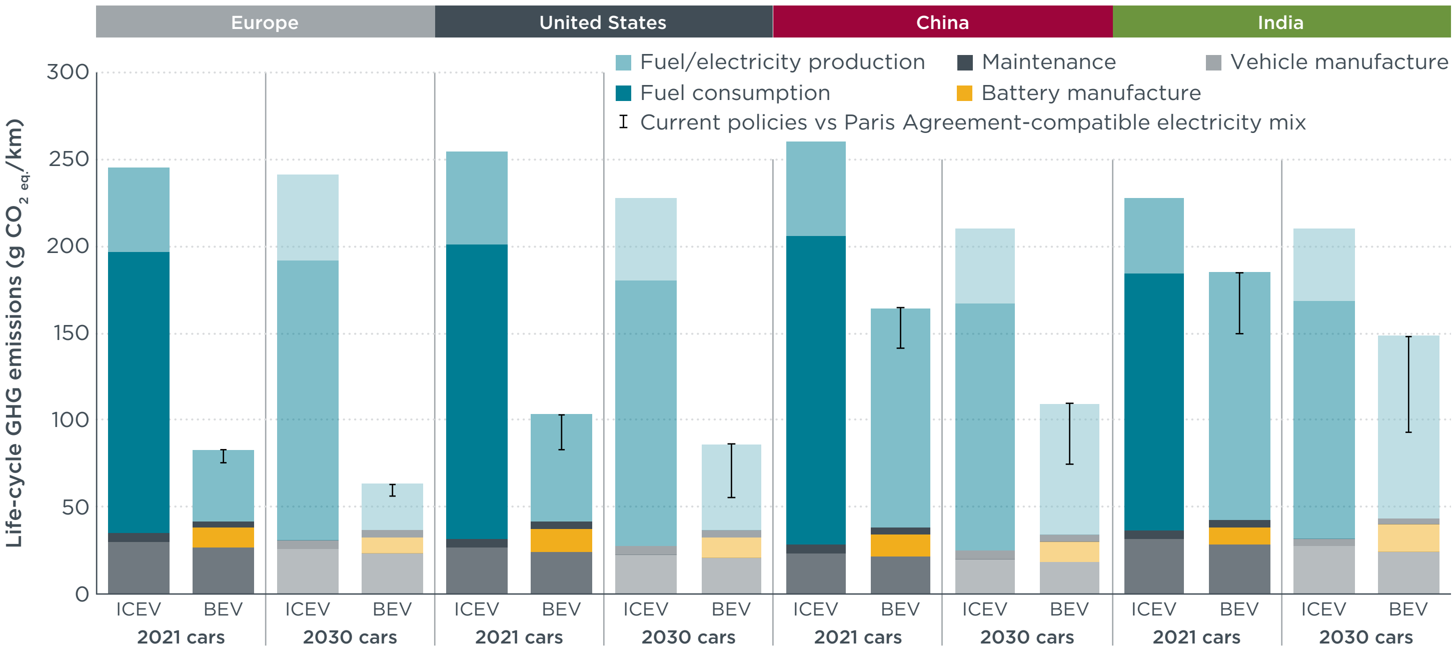

Figure ES.1. Life-cycle GHG emissions of average medium-size gasoline internal combustion engine (ICEVs) and battery electric vehicles (BEVs) registered in Europe, the United States, China, and India in 2021 and projected to be registered in 2030. The error bars indicate the difference between the development of the electricity mix according to stated policies (the higher values) and what is required to align with the Paris Agreement.

While BEVs registered today already produce significantly lower life-cycle GHG emissions on average, the same is not true for FCEVs fueled by hydrogen. This is because the primary source of hydrogen today is through reforming methane from natural gas ("grey hydrogen"), and that results in more modest life-cycle emissions reductions that are about 26%–40% less than for today's average medium-size gasoline vehicles in the respective regions. Utilizing hydrogen produced from renewable electricity ("green hydrogen"), instead, would result in 76%–80% lower life-cycle GHG emissions for FCEVs. Renewable energy powered FCEVs show slightly higher life-cycle emissions than BEVs powered by the same renewable electricity, though; this is because the electricity-based FCEV pathway is approximately three times as energy intensive as the BEV pathway, and as such, we took account of emissions from the construction of additional renewable electricity installations.

There is no realistic pathway for deep decarbonization of combustion engine vehicles. HEVs improve the efficiency of internal combustion engine vehicles by recovering braking energy and storing it in a battery that can then be used to support propulsion with an electric motor. In this study, HEVs are found to reduce life-cycle GHG emissions by only about 20% compared to conventional gasoline cars.

PHEVs have a larger battery that can be charged before driving and they can operate in a predominantly electric mode for a certain range. Also in this drive mode, though, the electric motor is usually supported by the combustion engine, and thus it is not necessarily purely electric driving. In any case, the life-cycle GHG emissions of PHEVs are mostly determined by the electric versus combustion engine drive share in average real-world usage. This is found to vary significantly between regions, and the life-cycle GHG emissions of today's medium-size PHEVs compared to gasoline cars is 42%–46% lower in the United States, 25%–27% lower in Europe, and 6%–12% lower in China, depending on the development of the electricity mix. (PHEVs are hardly registered in India.) Compared to average BEVs in the United States, Europe, and China, the life-cycle GHG emissions for PHEVs are 43%–64%, 123%–138%, and 39%–58% higher for cars registered in 2021 and 53%–100%, 171%–197%, and 94%–166% higher for cars expected to be registered in 2030.

This study also analyzed the development of the average blend of biofuels and biogas in fossil diesel, gasoline, and natural gas based on current policies and projected supply. Across the four regions and all fuel types, the impact of future changes in the biofuel blends driven by current policies range from a negligible influence to a reduction of the life-cycle GHG emissions of gasoline, diesel, or natural gas vehicles by a maximum of 9%, even over the lifetime of cars registered in 2030. Due to a number of factors, including competing demand from other sectors and high cost of production, it is not feasible to supply enough low-carbon biofuels such as residues- and waste-based biodiesel, ethanol, or biomethane to substantially displace fossil fuels in combustion engine cars. Additionally, the very high production cost of e-fuels means they are not likely to contribute substantially to decarbonization of the fuel mix within the lifetimes of 2021 or 2030 cars.

To align with Paris Agreement targets, the registration of new combustion engine vehicles should be phased out in the 2030–2035 time frame. Given average vehicle lifetimes of 15–18 years in the markets analyzed and that Paris Agreement reduction targets need to be met by 2050, only those technologies that can achieve a deep decarbonization should be produced and registered by about 2030–2035. Based on the assessment presented here, BEVs powered by renewable electricity and FCEVs fueled by green hydrogen are the only two technology pathways that qualify. Hybridization can be utilized to reduce the fuel consumption of new internal combustion engine vehicles registered over the next decade, but neither HEVs nor PHEVs provide the magnitude of reduction in GHG emissions needed in the long term. Thus, the registration of new cars with these powertrain types needs to be phased out in the 2030–2035 time frame.

In the meantime, given the life-cycle GHG emission benefits that BEVs already provide today, the transition to electric cars need not wait for future power sector improvements. Indeed, the benefits of a continuously decarbonizing power sector can only be captured in full if the transition to electric vehicles proceeds well ahead of that.

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APPENDIX – DATA AND ASSUMPTIONS

A.1 VEHICLE CYCLE

Glider and powertrain

Table A.1 shows the GHG emissions used for the production and recycling[15] of the glider and powertrain (sans battery and hydrogen system) of lower medium cars in Europe. These values are based on a recent vehicle LCA study by Ricardo AEA, ifeu, and E4Tech (Hill et al., 2020) that focused on the European Union and United Kingdom.

Table A.1. GHG emissions of the production and recycling of the glider and powertrain of lower medium cars in the European Union and the United Kingdom and mass-based GHG emission factors derived from dividing these by the average mass of this segment in the European Union and the United Kingdom in 2019.

	t $CO_{2\ eq.}$	t $CO_{2\ eq.}/t_{vehicle}$
Gasoline ICEV	7.2	5.2
Diesel ICEV	7.2	5.2
CNG ICEV	7.6	5.5
PHEV (without battery)	7.9	5.7
BEV (without battery)	6.5	4.7
FCEV (without hydrogen system)	6.5	4.7

These values are comparable to other recent vehicle LCA studies (e.g., Hall & Lutsey, 2018; Agora Verkehrswende, 2019a; Wietschel et al., 2019a; Wietschel et al., 2019b; Transport & Environment, 2020), and the GREET model (Argonne National Laboratory, 2020). This is especially the case regarding the 10% lower GHG emissions of producing and recycling the glider and electric powertrain for BEVs and FCEVs compared to ICEVs and PHEVs. Dividing the Ricardo AEA values by the average mass in running order of lower medium segment cars in the European Union and United Kingdom in 2019 results in mass specific GHG emission factors. These are applied to the average vehicle mass of the respective segments.

In the European Union and the United Kingdom, the average mass of cars in the small, lower medium, and SUV segments registered in 2019 was 1,155 kg, 1,382 kg, and 1,537 kg, respectively (Díaz et al., 2020). In the United States, the average mass of passenger cars and SUVs[16] in 2019 was 1,593 kg and 1,935 kg, respectively (U.S. Environmental Protection Agency, 2021). For new cars in the A0, A, and SUV segments in China in 2019, the average mass was 1,112 kg, 1,281 kg, and 1,545 kg, respectively (data from China Automotive Technology and Research Center). In India, the average mass of hatchback, sedan, and SUV segment cars registered in FY 2019–20 was 876 kg, 998 kg, and 1,377 kg, respectively (data from Segment Y Automotive Intelligence). For 2030 cars in all four regions, the GHG emissions are assumed to decrease by 15% (Hill et al., 2020).

Hydrogen system

In recent vehicle LCA studies, the GHG emissions of the production of the hydrogen system, which contains a hydrogen tank and a fuel cell, correspond to about 5 t $CO_{2\ eq.}$ (Hill et al., 2020; Wietschel et al., 2019b; Agora Verkehrswende, 2019b) while they

15 There are two different approaches for considering the GHG emissions impact of recycling in an LCA, and both are subject to change over time. One is the cut-off approach, which considers the GHG emissions benefit of using recycled material for the production of the vehicles at one point in time, and the other is the avoided burden approach, which considers the GHG emissions credit of later recycling of parts of the vehicles at the end of life. The Ricardo AEA study used a dynamic, time-sensitive hybrid of the cut-off and avoided burden approaches.

16 Including SUVs from the regulatory classes of cars and trucks.

amount to 3.4-4.2 t $CO_{2\ eq.}$ in the GREET model (Argonne National Laboratory, 2020). These emissions mostly correspond the energy-intensive production of carbon fiber reinforced plastic for the high-pressure hydrogen tank. Using the numbers from the GREET model, this study considers 3.4 t $CO_{2\ eq.}$ for the hydrogen system of medium-size cars (Toyota Mirai, 5 kg hydrogen tank) and 4.2 t $CO_{2\ eq.}$ for SUVs (Hyundai Nexo, 6.3 kg hydrogen tank). For 2030 cars, the capacity of the hydrogen tank is assumed to remain the same, while the GHG emissions of the hydrogen tank and fuel cell manufacturing are considered to be reduced by 20%.

Maintenance

Depending on the powertrain type and segment, GHG emissions of vehicle maintenance during use phase are estimated to be 4–13 g $CO_{2\ eq.}$/km in recent LCA studies (Agora Verkehrswende, 2019a; Hill et al., 2020). Because BEVs and FCEVs use fewer consumables, they have lower maintenance GHG emissions; diesel cars, in contrast, consume urea in the exhaust aftertreatment and thus show higher maintenance emissions. This study assumes maintenance GHG emissions of 5 g $CO_{2\ eq.}$/km for gasoline and CNG powered ICEVs and PHEVs, 7 g $CO_{2\ eq.}$/km for diesel ICEVs, and 4 g $CO_{2\ eq.}$/km for BEVs and FCEVs.

Lifetime mileage

Europe

Cars registered in Europe are considered to be used for an average lifetime of 18 years. This is based on the average age of end-of-life vehicles in several countries: Germany in 2014–2016, which was 17–18 years (Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit, 2020); 19 years in France in 2018 (Taszka & Domergue, 2019); and 20 years in Portugal and Poland in 2015 (Mehlhart et al., 2018b). It is also based on an average vehicle age of 16–17 years in Greece, Romania, Estonia, and Lithuania in 2018 (European Automobile Manufacturers Association, 2019). As these numbers correspond to cars that were registered about two decades ago, and vehicle lifetime has been observed to increase every year (European Automobile Manufacturers Association, 2019), assuming a lifetime of 18 years for cars registered in 2021 and 2030 is considered a conservative estimate.

Lower vehicle lifetimes used in other vehicle LCA studies might refer to the average age of cars that are deregistered in a certain country, for example 13 years in Germany in 2005–2009 (Kraftfahrt-Bundesamt, 2011) or 14 years in the United Kingdom in 2012–2013 (Dun et al., 2015). Especially for countries that export large numbers of second-hand cars, such as Germany (Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit, 2020) and other European countries (Mehlhart et al., 2018a; United Nations Environment Programme, 2020), these cars continue to be used in other countries. Therefore, the numbers of 13–14 years do not cover the full vehicle lifetime.

The average annual mileage of small, lower medium, and upper medium segment cars in Germany in 2011 was found to be similar to the annual mileage in these segments in the average of all EU member states and the United Kingdom that same year (Emisia, 2013). Therefore, German mobility survey data is considered to be representative for the region. In 2014, the average annual mileage of small, lower medium, and SUV segment cars in Germany was 11,000 km/a, 13,500 km/a, and 15,000 km/a, respectively (Bäumer et al., 2017). With an average useful vehicle lifetime of 18 years, the lifetime mileage corresponds to 198,000 km for small, 243,000 km for lower medium, and 270,000 km for SUV segment cars.

From the German mobility survey data, it was further deduced that the annual mileage of passenger cars decreases by about 5% per year. Thereby, the annual mileage of a car in the 18th year, for instance, is only 42% of the annual mileage in the first year.

United States

The 15–16 year average lifetime often associated with passenger cars and light trucks in the United States is based on survival rate data from 2003 (Lu, 2006) and thus corresponds to vehicles that were registered before 1990. This is more than 30 years ago and there is no recent survival rate data available. Considering that the average age of light-duty vehicles in the United States has continuously increased, from 8.4 years in 1995 to 11.8 years in 2019 (U.S. Department of Transportation, 2021), the vehicle lifetime of cars registered today and projected to be registered in 2030 is considered to be higher than it was for pre-1990 cars. This study thus assumes an average lifetime of 18 years.

This study estimates the average lifetime mileage with the accumulated annual mileage per vehicle age over the first 18 years of usage. With annual mileage per vehicle age data from the 2017 National Household Travel Survey (U.S. Department of Transportation, 2017), the average lifetime mileages of passenger cars and SUVs were estimated to 314,000 km and 337,000 km. From the 2017 survey, it was further deduced that the annual mileage decreases linearly in the first 18 years. For both passenger cars and SUVs, the annual mileage is assumed to decrease linearly, by about 500 km/a per year.

China

The useful vehicle lifetime of passenger cars registered in China from the late 1990s to early 2000s was found to be about 15 years (Hao et al., 2011; China Automotive Technology and Research Center, 2017). For cars registered in 2021 and projected to be registered in 2030, it is expected to be significantly higher, in part because vehicle retirement after 15 years that was formerly mandatory was lifted in 2013. In a conservative estimate, however, this study assumes an average useful vehicle life of 15 years.

While the average annual mileage of private and commercial light-duty passenger vehicles varies between provinces, the national average is about 19,000 km/a (China Automotive Technology and Research Center, 2017; Liu et al., 2017; Huo et al., 2012). The study considers this fleet-wide average for A segment cars and SUVs. As passenger cars from small vehicle segments usually have a lower annual mileage, a 10% lower value is assumed for A0 segment cars. This results in a lifetime mileage of 256,500 km for A0 segment cars and 285,000 km for A segment cars and SUVs.

During the 15 years of vehicle usage, the annual mileage is assumed to decrease by 5% each year.

India

Based on ICCT's India Emissions Model (Bansal & Bandivadekar, 2013), an average vehicle lifetime of 15 years and lifetime mileages of 165,000 km for hatchback and sedan segment cars and 188,000 km for SUV segment cars are assumed. The annual mileage is further assumed to decrease by 3% per year.

A.2 FUEL CYCLE

Fuel and electricity consumption

Europe

The average real-world fuel consumption of new gasoline, diesel, and CNG cars in Europe in Table A.2 is derived from the segment-specific average NEDC fuel consumption of new cars registered the European Union and the United Kingdom in 2019 (Díaz et al., 2020) and a consumer-reported real-world to NEDC deviation of +37% for conventional gasoline and CNG cars, +50% for hybrid electric vehicles (HEVs), and +44% for diesel cars (Dornoff et al., 2020).