Core Model Proposal #368: Adding fugitive CO2 emissions from fossil resources

Product: Global Change Analysis Model (GCAM)

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Related sector: emissions

Type of development: data, code

Purpose: This Core Model Proposal adds fugitive CO2 emissions from coal, crude oil, and natural gas resources to the data system. It also includes an improved method to replace outlier emissions factors for fossil resources. Lastly, it makes some minor changes to the data system and Model Interface headers to fix some inconsistencies in how resource technologies are named in the XMLs.

Description of Changes

This CMP is comprised of two main changes: adding fugitive CO2 emissions from fossil resources and implementing a new method to replace outlier emissions factors for fossil resources for non-CO2 GHG and CO2 fugitive emissions.

First, we added fugitive CO2 emissions from fossil resources as a NonCO2 object with the name "CO2_FUG." Emissions factors for coal, natural gas, and crude oil were derived from the CEDS CO2 data ("Fugitive" sectors) and units were converted to MTC to match other CO2 emissions. Fugitive CO2 emissions occur either as CO2 gas contained in either oil, gas, or coal resources is released during the process of extraction, or as other carbon-containing compounds (particularly methane) are flared at the point of extraction (e.g., oil well flares). See the IPCC Guidelines for National GHG Inventories chapter on fugitive emissions for more information on the sources of fugitive CO2 emissions from oil, gas, and coal production. Note that CO2 from abandoned mine methane is not explicitly represented. Additional work would be required to explicitly represent this.

For crude oil, we took additional steps to both disaggregate historical fugitive CO2, CH4, and N2O emissions from conventional and unconventional oil in regions with historical unconventional oil (Canada and South America_Northern) and to assign default emissions factors for all other regions so that fugitive GHG emissions from future unconventional oil development are represented. We first derived two average unconventional oil fugitive emissions factors for each GHG from the IPCC Guidelines for National GHG Inventories chapter on fugitive emission: (1) an emissions factor for oil sands (calculated from the sum of the average unconventional oil exploration factor in Table 1.2.4 and the oil sands production factors in Table 1.2.4A) and (2) an average emissions factor for non-oil-sands unconventional oil (calculated from the sum of the conventional oil exploration factor in Table 1.2.4 and the average of the conventional oil production factors in Table 1.2.4A). In regions with historical unconventional oil (Canada and South America_Northern), we adopted the oil sands emissions factor for unconventional oil, and used this value to split up the CEDS crude oil fugitive GHG emissions into conventional and unconventional oil, subsequently recalculating the conventional oil emissions factor. We chose the oil sands emissions factors since oil sands represents the majority (or all) of historical unconventional oil production in these regions. For other regions, we used a weighted average of the oil sands and non-oil-sands emissions factors; weights came from Wang et al. (2016)'s assessment of global unconventional oil resources which estimated that 14% of the world's recoverable unconventional oil consists of oil sands. These weighted average emissions factors for CO2, CH4, and N2O were assigned to all historical years.

Second, we discovered and resolved an error in how the data system deals with outlier emissions factors (EF) from fossil fuel resources. The method in place was intended to replace each emissions factor above the global 95th percentile (for a given gas and resource) with the global median. However, a bug in the code caused each emissions factor above the global median, rather than the global 95th percentile, to be replaced. We fixed this bug but found that the resulting emissions were unrealistic; in particular, this caused methane emissions to more than double globally, largely due to unrealistically high methane emissions from coal in regions with low coal production (such as Africa_Northern). Therefore, we implemented a new EF outlier replacement approach which aims to account for the fact that some regions with very low production but nonzero emissions have unrealistically high emissions factors; this is an issue that the 95th percentile approach originally intended to address but did not successfully achieve. For the new approach, we implemented a threshold EF for each gas and resource that is defined as the lesser of (1) the 95th percentile EF and (2) the maximum EF within the "top" regions (those accounting for 99.75% of global energy for that resource) (this is a conservative approach to avoid having an overly high default EF). Emissions factors above this threshold are replaced with the median EF of the "top" regions (rather than simply the global median). This resulted in a better match with the historical data and reasonable future projections.

Third, we also fixed an issue with inconsistent technology object types in resource XMLs. Previously, in all_energy_emissions.xml, crude oil, natural gas, and coal followed a resource→ subresource→ technology structure, while the correct structure is resource→ reserve-subresource→ resource-reserve-technology. While the C++ code properly dealt with this, it was potentially confusing. Additionally, some resource tags were written with the nocreate="1" tag and others were not, leading to duplicate subresources and technologies in the XML. We modified the relevant Model Interface (MI) headers and included node equivalences to fix these problems. This doesn't change anything in the model (because of the way objects are read in) but makes the XMLs consistent and less confusing.

1. File changes in gcamdata

Table 1. Changes to chunks

Chunk name Output names(s)	**Changes**
zchunk_L102.nonco2_ceds_R_S_Y L102.ceds_GFED_nonco2_tg_R_S_F	▪ New input file: emissions/CEDS/CO2_total_CEDS_emissions ▪ New Non.CO2: CO2_FUG from CEDS "Fugitive" sectors
zchunk_L112.ceds_ghg_en_R_S_T_Y L112.ghg_tgej_R_en_S_F_Yh_infered_combEF_AP	▪ Included CO2_FUG in relevant output and exclude from other outputs ▪ Used IPCC_unconventional_oil_fug_emfacts.csv and the new default emissions factor in constants.R (see Table 2) to assign CO2_FUG emissions factors for unconventional oil and to split up CEDS fugitive CO2 emissions from conventional and unconventional oil ▪ Implemented new method to replace outlier emissions factors
zchunk_L201.en_nonco2.R L201.ghg_res L201.nonghg_res	▪ Converted CO2_FUG emissions units from Tg to MTC ▪ Added emiss.units column to write emissions-unit tag to all_energy_emissions.xml since CO2_FUG has different units (MTC) than other GHGs from resource production (Tg)
zchunk_batch_all_energy_emissions_xml all_energy_emissions.xml	▪ Used new header "GDPCtrlMaxResReserve" (see table below) for L201.nonghg_max_reduction_res ▪ Added node equivalences for resource, subresource, and technology

Table 2. Other gcamdata changes

File	Changes
constants.R	▪ Added a new constant emissions.UNCONVENTIONAL.OIL.FUG.CO2.EMFAC, the default CO2_FUG unconventional oil emissions factor for regions without historical unconventional oil production (weighted average of emissions factors from the IPCC Guidelines as described above)
emissions/IPCC_unconventional_oil_fug_emfacts.csv	▪ Added this new input file containing fugitive CO2 unconventional oil emissions factors for regions with historical unconventional oil production (oil sands emission factor from IPCC Guidelines as described above)
ModelInterface_headers.txt	▪ Added a new header "GDPCtrlMaxResReserve" that is identical to "GDPCtrlMaxRes" except that it uses reserve-subresource and resource-reserve-technology rather than just subresource and technology ▪ Added nocreate="1" to all resource headers used in zchunk_batch_all_energy_emissions_xml ▪ Added emissions-unit tag to "ResEmissCoef" header
generate_package_data.R	▪ Added new header “GDPCtrlMaxResReserve" to level 2 data names ▪ Modified the header "ResEmissCoef" in level 2 data names to include emiss.units column that writes to emissions-unit XML tag
xml.R	▪ Fixed typo in XML_NODE_EQUIV (replaced resource.reserve.technology with resource-reserve-technology)

2. Updates to C++ code

One C++ file was changed to ensure that the new CO2_FUG emissions are passed to Hector. In `world.cpp`, we added a new `EmissionsSummer` for CO2_FUG and added its emissions to the existing CO2 emissions used to set the climate model.

3. Updates to queries

We updated the queries so that the CO2 emissions from fossil resources (CO2_FUG) are counted as CO2 emissions in the relevant queries. We also added a new query, CO2 emissions by resource production.

Table 3. Changes to queries in Main_queries.xml

Query	Changes
CO2 emissions by region	Edited xPath to include the name "CO2_FUG"
NonCO2 emissions by region	Added a labelRewriteList to rewrite "CO2_FUG" to "CO2" so that the new CO2 emissions are counted in CO2
NonCO2 emissions by resource production	Added a labelRewriteList to rewrite "CO2_FUG" to "CO2" so that the new CO2 emissions are counted in CO2
CO2 emissions by resource production	Added this new query, which includes both fugitive and non-fugitive CO2 emissions by resource production

Scenarios

Name	Description
Ref_old	Default GCAM reference scenario in the master branch
Ref_new	Default GCAM reference scenario with fugitive CO2 resource emissions added and new emissions factor outlier replacement method implemented
2p6_old	GCAM's RCP2.6 scenario in the master branch
2p6_new	GCAM's RCP2.6 scenario with fugitive CO2 resource emissions added and new emissions factor outlier replacement method implemented

Validation

Fugitive CO2 emissions from resource production vary by gas and by region (figure 1). Note the differences in y-axis scales. Globally, fugitive CO2 emissions are highest for coal in future years. Fugitive CO2 emissions for crude oil decline starting in 2030 as crude oil production declines and is replaced by unconventional oil production (figure 7).

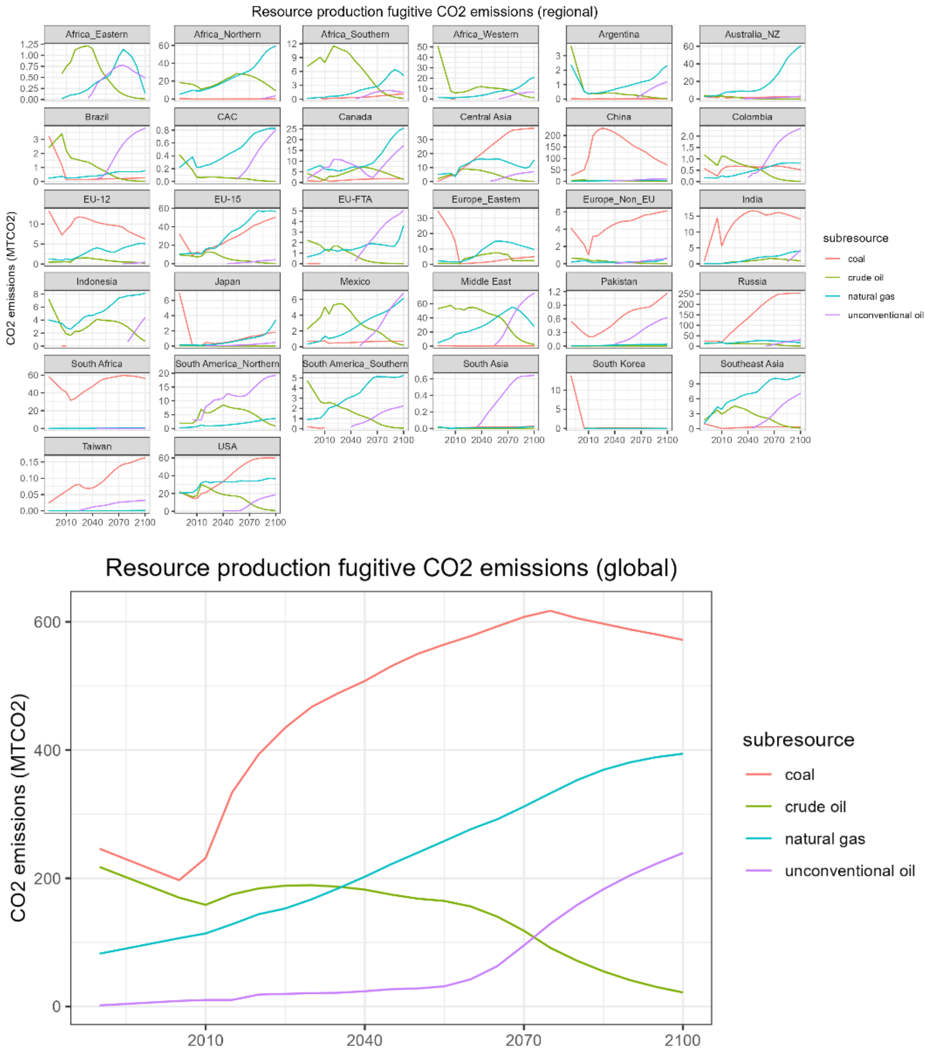

Figure 1 Fugitive CO2 emissions from resource production in the reference scenario.

Without fugitive emissions, the only CO2 emissions from resource production in GCAM were from unconventional oil. When added in, fugitive emissions make up varying proportions of regions' total CO2 emissions from resource production, depending on the amount of unconventional oil, and therefore non-fugitive CO2 emissions, in the region (figure 2: left). By 2100, fugitive emissions make up about 35% of total CO2 emissions from resource production globally (figure 2: right)

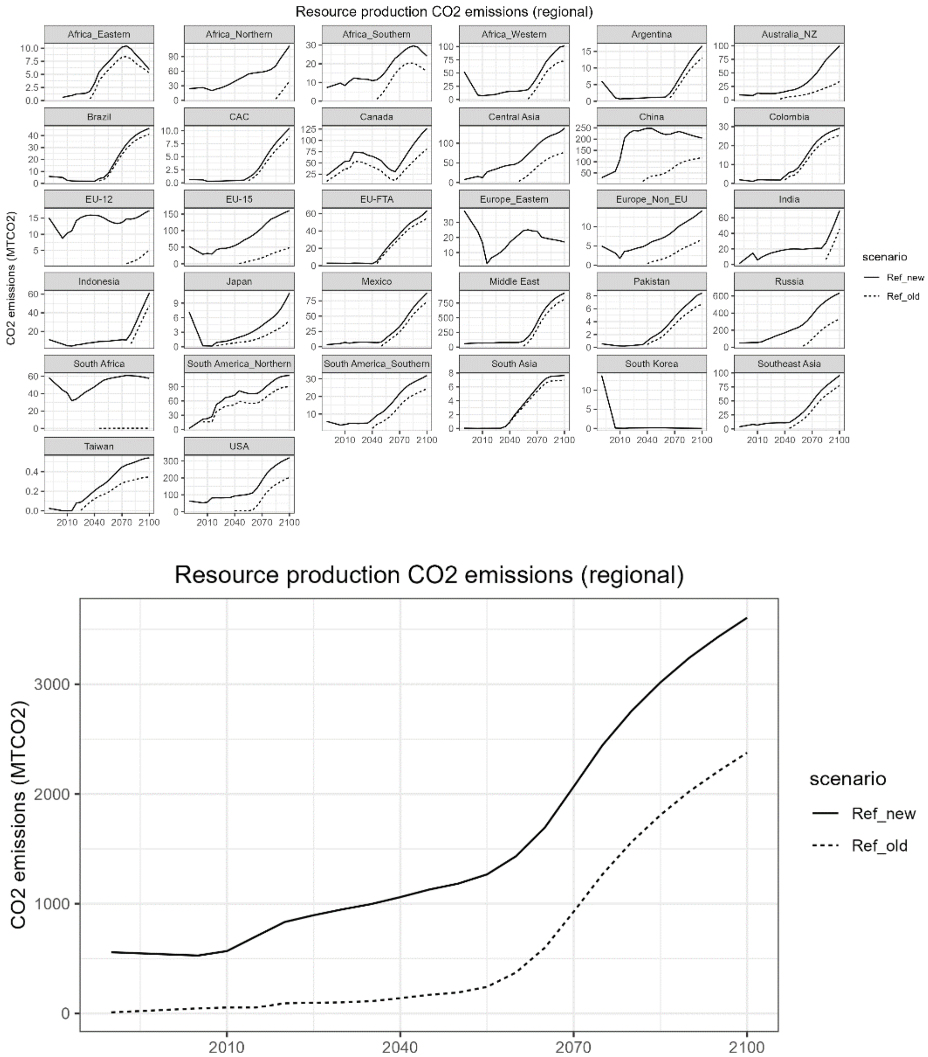

Figure 2. Total CO2 emissions from all resources in the reference scenario, with and without fugitive emissions added. Note that, previously, the only CO2 from resource production was from unconventional oil.

Since this CMP also includes a fix for the median emissions coefficient replacement error, emissions of other GHGs (CH4 and N20) were also impacted. Previously, resource production GHG emissions factors above the global median emissions factor for a given gas in a given historical year were replaced with the global median. The replacement was intended only for emissions factors above the global 95th percentile; with the changes in this CMP, only emissions factors above a newly defined threshold (the smaller of the global median and the maximum of the top 99.75% of producers) are replaced with a lower emissions factor. Therefore, regions whose historical implied emissions factors were between the global median and this new threshold for a given gas now retain their original emissions factors rather than being assigned a lower emissions factor. This results in higher CH4 and N2O emissions in these cases (figures 3 and 4). For regions whose historical implied emissions factors were above the new threshold (e.g., coal CH4 in Africa_Eastern and Taiwan), their adjusted emissions factors and therefore emissions are lower, since the new replacement emissions factor is the median of the top 99.75% of producers rather than the global median. The median of the top 99.75% of producers in 2015 is lower than the global median for all three resources, but particularly for coal (0.246 Tg/EJ vs 0.543 Tg/EJ). For regions whose historical implied emissions factors were below the new threshold, emissions factors and therefore remain the same (e.g., CH4 in USA and N2O in Brazil).

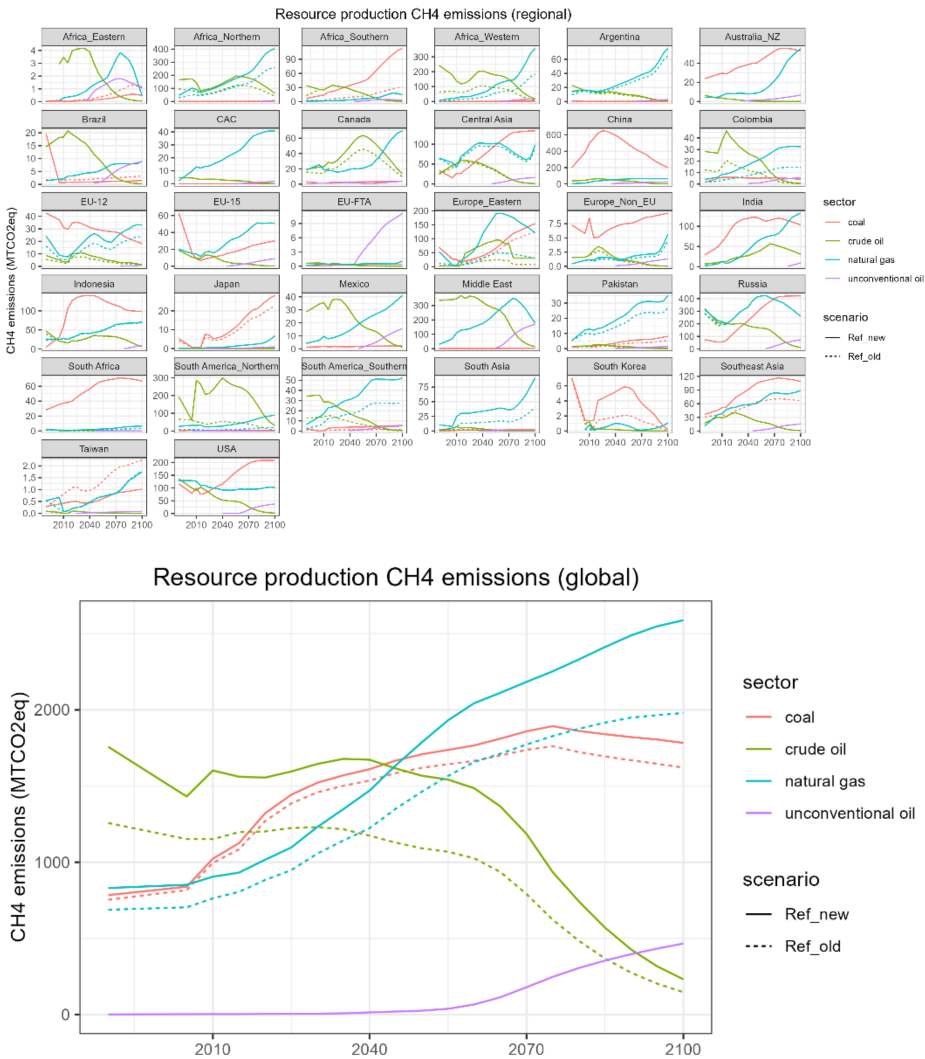

Figure 3. CH4 emissions from resource production in the reference scenario before (dotted lines) and after (solid lines) the 95th percentile median replacement issue was fixed.

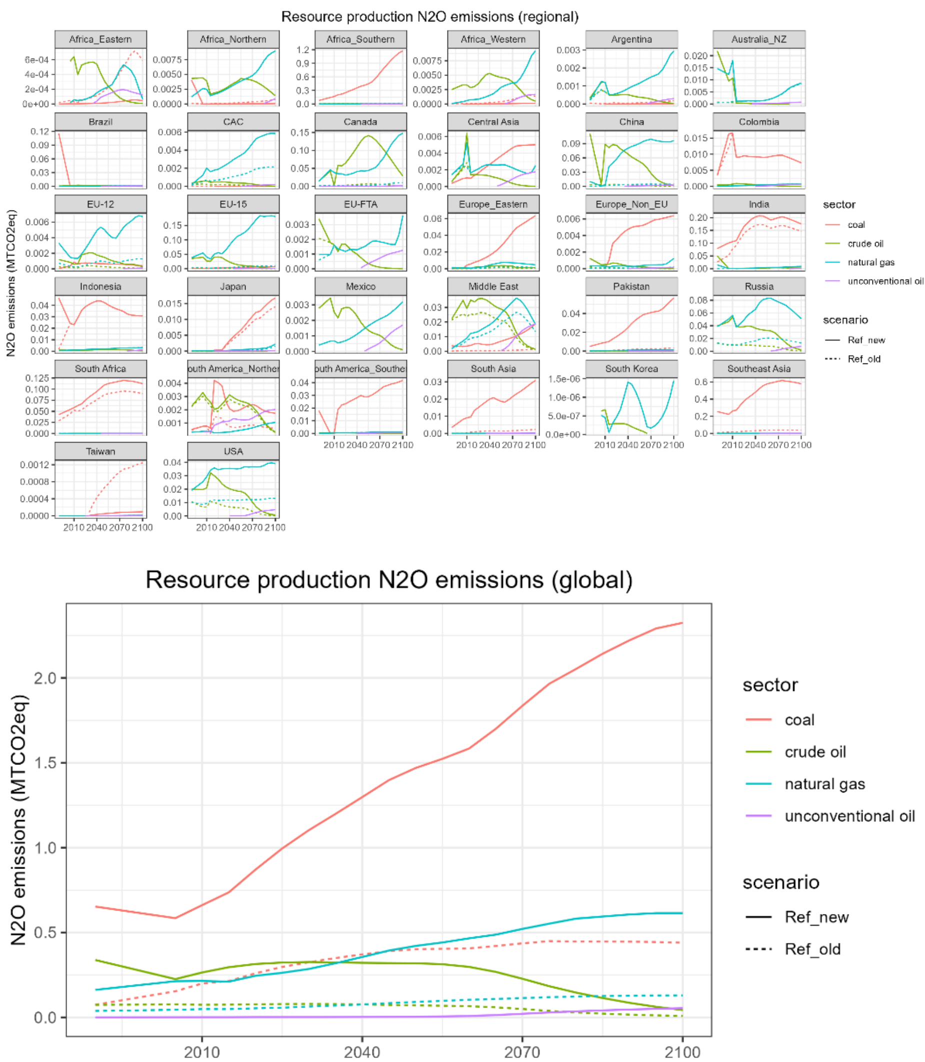

Figure 4. N2O emissions from resource production in the reference scenario before (dotted lines) and after (solid lines) the 95th percentile median replacement issue was fixed.

The figure below shows the total global emissions of CH4, CO2, and N2O without and with the changes in this CMP. Note the different y-axis scales.

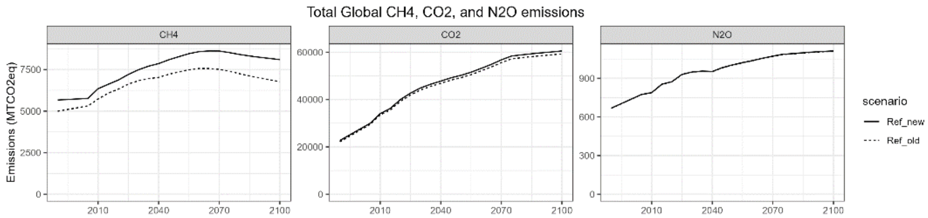

Figure 5. Total global CH4, CO2, and N2O emissions in the reference scenario without and with the changes in this CMP.

The figure below compares CEDS input data with the old and new GCAM output emissions for CH4 and N2O (left), and with the new GCAM output emissions for fugitive CO2 (right) in historical years. Emissions are compared at the CEDS aggregate sector level, which includes a sector for coal and an aggregate sector for conventional oil and natural gas combined. This figure shows that the old emissions factor approach underestimated global nonCO2 GHG emissions from resource production in historical years and that the new approach is a closer match to the input data. With the new approach, GCAM historical emissions are still slightly lower than CEDS emissions, particularly for N20 from coal production. The historical output for the newly added fugitive CO2 emissions matches the CEDS input data relatively well but is slightly lower, like the other GHGs.

This underestimation of historical GHG emissions comes from the fact that resource emissions in GCAM currently include both extraction and refinery emissions. This means that there can be some artificially high emission factors when emissions (extraction plus refinery) are divided by resource production in GCAM. It is these high emission factors that are reset as described above. This results in an underestimate of historical emissions. Once production and refinery sectors are split out in CEDS, these emissions can be more accurately represented in GCAM.

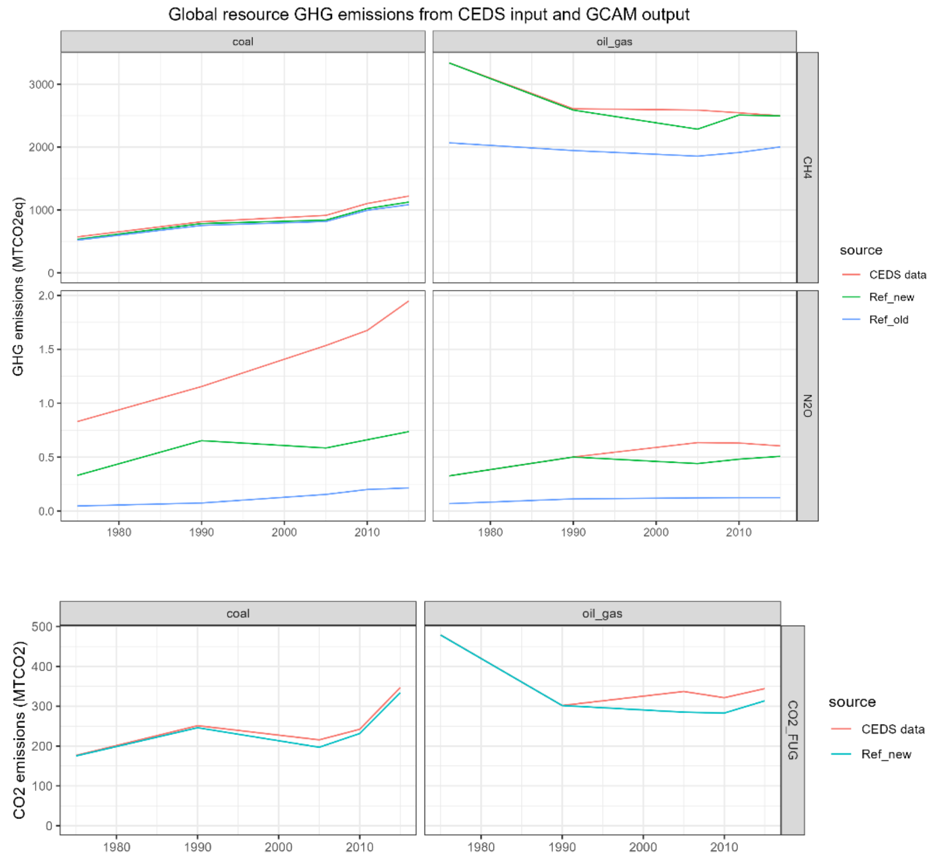

Figure 6. Total global CH4, CO2, and N2O emissions from coal and from the CEDS aggregate sector oil_gas (including conventional oil and natural gas) for historical years. Data are from the old and new GCAM outputs as well as CEDS input data

In the reference scenario, the amount of resource production for coal, oil, and gas is unaffected by the changes in this CMP (Ref_old and Ref_new are identical in figure 7). However, there is slightly less coal, natural gas, and unconventional oil production in the RCP2.6 scenario (figure 7); this because the addition of fugitive CO2 and increase in nonCO2 emissions causes an increase in the carbon price, in turn driving a decline in resource production.

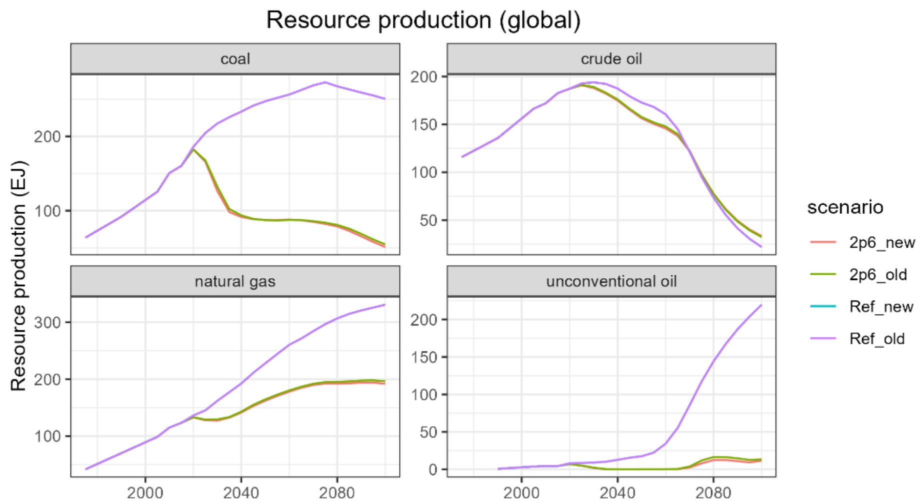

Figure 7. Production of coal, crude oil, natural gas, and unconventional oil in the reference and RCP2.6 scenarios with and without the changes in this CMP.

In the reference case, there is a slight increase in total atmospheric forcing through 2100 due to the increases in GHG emissions from the changes in this CMP, but the increase in atmospheric forcing in the RCP2.6 scenario is minimal (figure 8) despite higher GHG emissions from resource production (figure 9). Figure 10 shows that these increased GHG emissions are offset in the 2p6_new scenario by a decrease in CO2 emissions from electricity production and end-use sectors (industry, transport, buildings) as well as increased BECCS until about 2080. Note the different y-axis scale on the right panel compared to the other two panels.

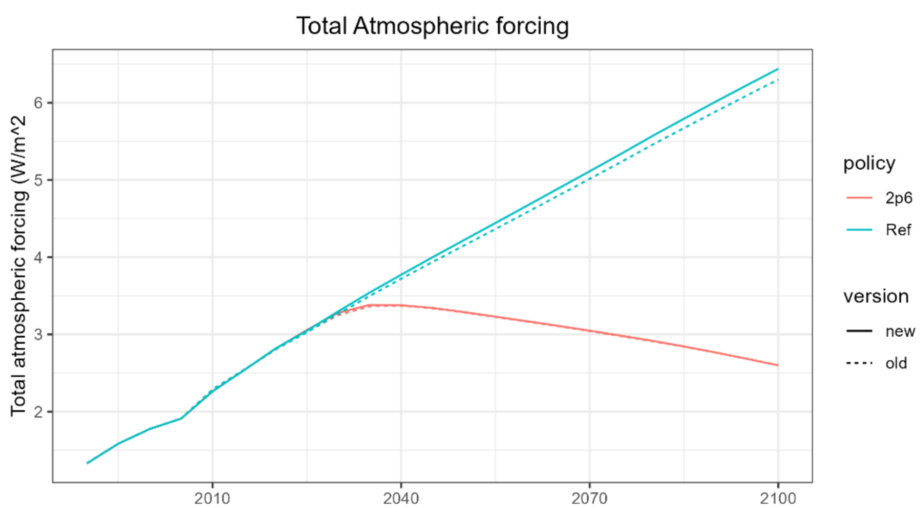

Figure 8. Total atmospheric forcing with and without the changes in this CMP.

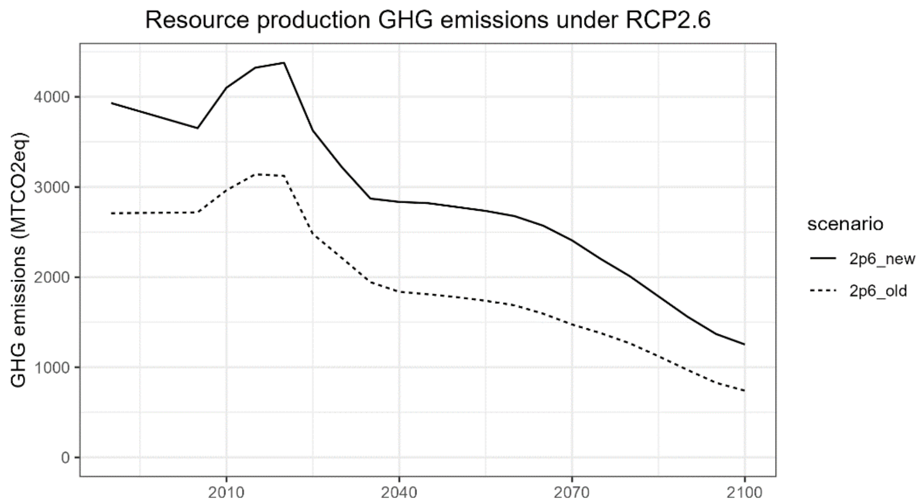

Figure 9. Total resource production GHG emissions under RCP2.6 before and after the changes in this CMP. GHGs include CO2, CH4, and N2O. LUC emissions are excluded.

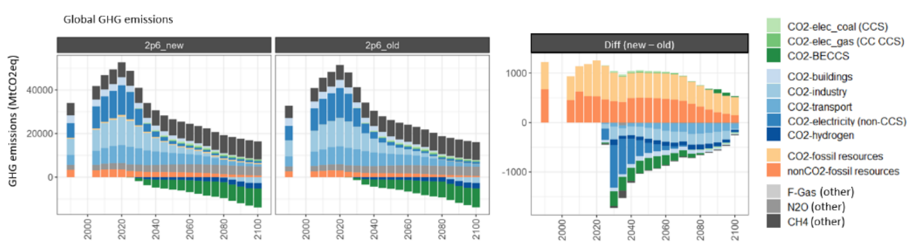

Figure 10. Global GHG emissions by sector under RCP2.6. The middle and left figures show absolute emissions before and after the changes in this CMP, respectively, and the right panel shows the difference between the new and old emissions.