Horizon 2020 Societal challenge 5: Climate action, environment, resource efficiency and raw materials

VERIFY

Observation-based system for monitoring and verification of greenhouse gases

GA number 776810, RIA

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Contributors:	Robbie Andrew (CICERO), Glen Peters (CICERO)
Internal reviewers:	Chapter 2: Philippe Ciais (LSCE), Han Dolman (VU) Chapter 3: Gunnhild Søgaard (NIBIO), Giacomo Grassi (JRC), Roxana Petrescu (VU)

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1. Changes with respect to the DoA

None

2. Dissemination and uptake

(Who will/could use this deliverable, within the project or outside the project?)

This deliverable will be of broad interest amongst those using emission inventory data. There have been several studies that discuss the qualitative differences between different datasets, but in this deliverable, we quantify the differences where possible and provide a much more detailed and specific discussion of differences. Most of the focus is on fossil CO_2 emissions, but we give a detailed conceptual analysis of land-based CO_2 emissions. Non-CO_2 emissions are discussed in a separate deliverable.

3. Short Summary of results (<250 words)

There are many independent estimates of GHG emissions, but very little understanding either qualitatively or quantitatively of the differences between these estimates. One of the biggest reasons for differences between independent estimates is differences in system boundaries. While these issues have been discussed qualitatively before, this report develops this and adds quantitative detail. While this report is focused on the EU, it does consider estimates in other key regions and the global level. We focus on a detailed quantitative comparison of fossil CO_2 emissions, illustrating that even subtle and poorly communicated differences in system boundaries can lead to significant quantitative differences. While uncertainties are rarely reported for different datasets, uncertainties based on comparing independent datasets are probably overestimates. For land-based CO_2 emissions, our comparisons and discussions are more qualitative, but we expand on previous discussions to pay closer attention to Harvested Wood Products and bioenergy. Both these fluxes are important for regional carbon budgets. Follow up work will progressively detail more quantitative analysis of the differences between land-based CO_2 estimates. This report does not discuss non-CO_2 emissions, which are covered in another deliverable. Our analysis highlights the importance of consistency in and awareness of system boundaries when verifying emission estimates. We further outline areas where more research is needed to better detail and understand differences in system boundaries.

4. Evidence of accomplishment

This deliverable will be first submitted as a report. We plan on submitting an abridged version of the fossil CO_2 emission analysis to a peer reviewed journal, and sections of the land-based CO_2 emissions may lead to journal submissions (specifically, bioenergy and forest accounting).

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Version	Date	Description	Author (Organisation)
V0	30/04/2019	Initial submission	Glen Peters (CICERO)
V1	10/05/2019	Formating	Sonia Firion (CEA/LSCE)

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1. Introduction

Emissions of greenhouse gases in the EU28 territory that are reported to the UNFCCC in the Common Reporting Format (CRF) can be grouped into different types (see Figure 1):

- Fossil CO_2 emissions from fuel combustion and industry;
- Non-CO_2 emissions (CH_4, N_2O, and fluorinated gases);
- CO_2 emissions of sources and removals from managed land use, disaggregated into land converted from one type to another, land that remains unchanged, and Harvested Wood Products (HWPs);
- CO_2 emissions from bioenergy, which are reported as a memo to the energy sector;
- Fossil CO_2 emissions from bunker fuel sales, which are reported as a memo to the energy sector.

While all these emissions are reported by countries to the UNFCCC, they are not all accounted for in emission reduction efforts. Fossil CO_2 emissions are the only emissions that are unambiguously allocated and reported for emissions reduction efforts. Emissions from converted and remaining land are based on the concept of 'managed land', which is a proxy for 'anthropogenic', and not all countries reported all their land as managed (Grassi et al., 2017; Grassi et al., 2018a). Bioenergy is reported as a memo in the energy sector, on the basis that any carbon implications are captured in the AFOLU sector. Emissions from bunker fuels occur in international territory and may not be relevant for atmospheric verification of emissions within a geographic territory.

It is important to distinguish between reporting and accounting in the NIR context, as not all reported emissions account towards emission reduction efforts (Grassi et al., 2018b). **Reporting** refers to the inclusion of estimates of anthropogenic GHG fluxes in NIRs, following the methodological guidance provided by the intergovernmental panel on climate change (IPCC). The NIR should, in principle, aim to reflect "what the atmosphere sees" (Peters et al., 2009), within the limits given by the method used and the data available. In the context of mitigation targets (e.g. the Paris Agreement), **accounting** refers to the comparison of emissions and removals with the target and quantifies progress toward the target. For the LULUCF sector, specific *accounting rules* are used to filter reported flux estimates with the aim to better quantify the results of mitigation actions (Grassi et al., 2018b).

The UNFCCC reporting principles allocated emissions to the physical location (and time) that they occur (Peters et al., 2009). It is further possible to allocate emissions to countries in different ways, such as allocation to the products which are consumed within a country or the fuels that are produced from a country (Davis et al., 2011). These different allocations are very useful in some policy contexts, but not as useful in the context of verification and are not discussed in this report.

The definition of the EU28 varies depending on the application, and this is particularly relevant for verification. Formally, emissions are reported differently for the EU28 under the UNFCCC and Kyoto Protocol, additionally, several EU countries (Denmark, France, and the United-Kingdom) have overseas territories that may, or may not, additionally be members of the EU, and further, may be reported differently for the UNFCCC and Kyoto Protocol accounting. Atmospheric modelers may further use a different definition of territory, based on a purely geographic basis. These differences, while sounding rather academic, do make differences of 1-2% to emissions in the affected countries and should not be ignored.

There are many different estimates of the different components of the territorial emissions, and there have been several articles explaining the core qualitative differences particularly for fossil CO_2 emissions (Macknick, 2011; Andres et al., 2012a) and more recently land-based CO_2 emissions (Grassi et al., 2017; Grassi et al., 2018a). The objective of this report is to go beyond qualitative comparisons and isolate the quantitative differences. Many of these differences will relate to system boundary differences, others will relate to methods and data choices. In this report, we will outline these key differences.

This report focuses on “structural uncertainties”, as opposed to “parametric uncertainties”. Structural uncertainties related to system boundaries, what effects are included or excluded, how terms are defined, and similar. Parametric uncertainties relate to the variations in input data, which comes on top of the structural uncertainties. As a concrete example, a structural uncertainty might be whether a fossil CO_2 estimate includes emissions from international aviation, while a parametric uncertainty might be the emission factor for jet fuel. When making comparisons across datasets, or performing verification, it is important to correct for structural uncertainties, to avoid misinterpreting the findings.

This report will place most focus on fossil CO_2 emissions (section 2), but the other components will be covered to the extent they are not covered in other deliverables in VERIFY. Section 3 will be primarily conceptual but will perform some quantitative analysis. A deeper analysis of the land-based emissions will occur in VERIFY Work Package 3 and in later phases of Work Package 5. Non-CO_2 emissions will not be covered in this report, as they are covered elsewhere (Petrescu et al., 2018).

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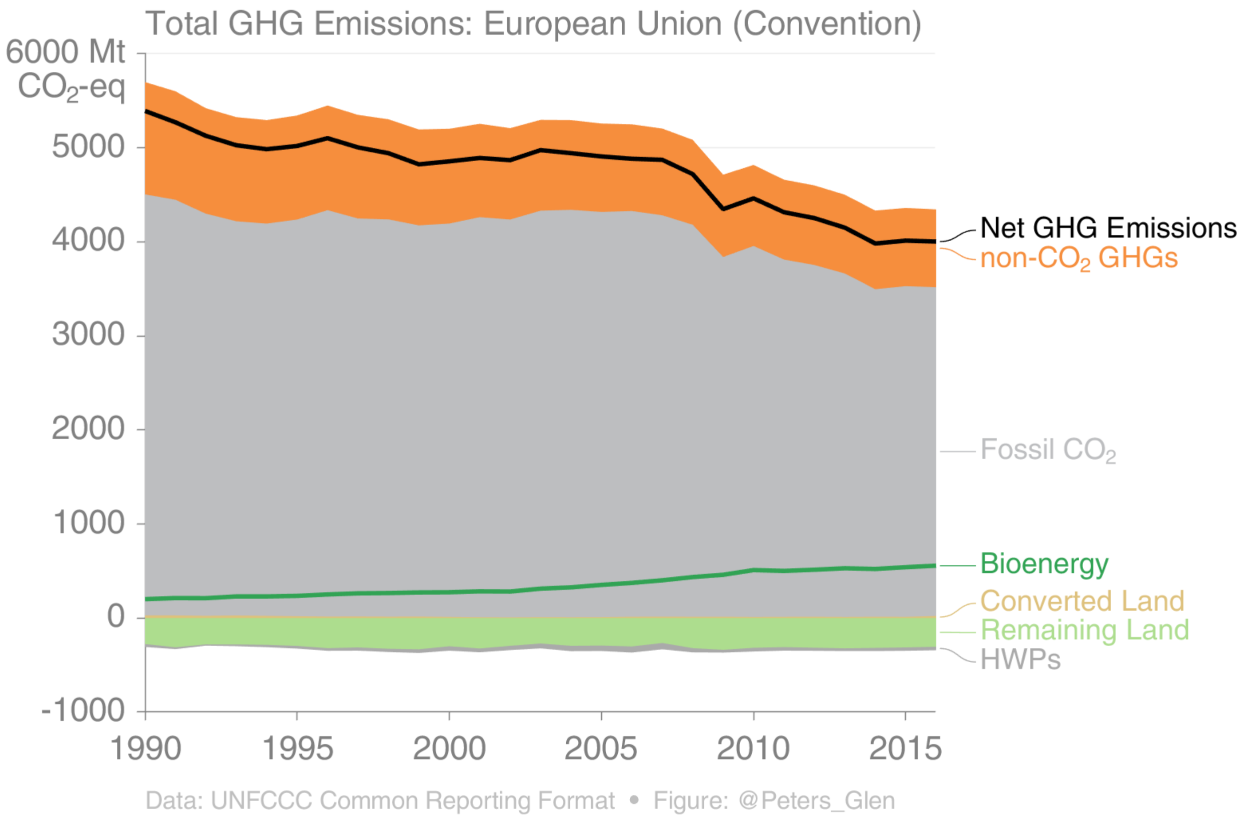

Figure 1: GHG emissions reported to the UNFCCC by the EU28. Fossil and non-CO_2 emissions are routinely considered, but other components are less discussed outside of specific inventory circles. Emissions from bioenergy are reported but not allocated to countries as they are captured in the land fluxes. The land-use components (converted and remaining land, and HWPs) are not always (fully) allocated for emission reduction efforts.

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2. Fossil CO_2 Emission

Fossil CO_2 emissions occur when fossil carbon compounds are broken down via combustion or other forms of oxidation. Most of these fossil compounds are in the form of fossil fuels, such as coal, oil, and natural gas. In addition are fossil carbonates, such as calcium carbonate and magnesium carbonate, which are used as feedstocks in industrial processes, and whose decomposition also leads to emissions of CO_2.

Because fossil fuel CO_2 emissions are largely connected with energy, which is a closely tracked commodity group, there is a wealth of underlying data that can be used for estimating emissions. However, differences in collection, treatment, interpretation, inclusion, and various factors such as carbon contents and fractions of oxidised carbon, lead to significant differences in estimates of emissions between datasets.

While comparisons of datasets are often made, in this report we attempt to explain the key reasons behind differences between these datasets, including descriptions of their data sources, construction, and, importantly, system boundaries.

Several comparisons have been performed before, notably Marland et al. (1999), who compared CDIAC and EDGAR, Andres et al. (2012b), who made a high-level comparison of several datasets, and Ciais et al. (2010), who compared datasets for the EU.

2.1. System Boundaries

Here we use the term 'system boundary' to describe the categories of emissions that are included in each dataset, and the way in which they are distinguished when presented in more detail. There are many aspects to these, which we will discuss in turn, limiting ourselves to CO_2 emissions data.

System Boundary issues:

- Fossil fuels, land-use change, carbonates
- Combustion vs Oxidation
- Inventories vs Accounts
- Sectoral vs Reference Approach
- Bunker fuels
- Time periods
- Sector definitions
- Country definitions
- Confidential emissions

There are three main physical sources of anthropogenic carbon dioxide: decomposition of fossil fuels, land-use change (e.g., deforestation), and decomposition of (fossil) carbonates. All emissions datasets include fossil fuels, while fewer include either land-use change or carbonates.

Decomposition of carbonates occurs in cement production, lime production, glass production, but also in steel manufacture where carbonates are used as a flux agent to facilitate removal of impurities. Carbonates are also found to varying degrees in coal deposits and CO_2 emissions from carbonate decomposition are therefore generated when coal is combusted. Datasets may include emissions only from cement production, or from all carbonate decomposition.

Several emissions datasets are relatively simple extensions of energy datasets (IEA, EIA, BP), and their primary purpose is to show the emissions associated with consumption of energy, rather than to provide a comprehensive picture of all emissions of CO2. Of course, most emissions of CO_2 are from fossil fuels, with emissions from land-use change and carbonates combined currently amounting to about 15% of the global total.

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While most datasets focus on combustion of fossil fuels, some extend the definition to all oxidation of fossil fuels. While combustion is one form of oxidation, other forms exist, such as in chemical processes where hydrocarbons are used as a source of carbon or as a reducing agent. This distinction generally hinges on whether the fossil fuel is primarily required as an energy source (energy released by combustion) or as an agent in a chemical process.

Particularly coal consumption in the metals industry can be considered as either combustion or as a chemical feedstock. Coke used in refining iron ore is critical as a reducing agent, but also serves as an energy source. However, when coal is used to make carbon anodes for aluminium smelting, the oxidation of the anode that occurs during production is not considered combustion.

The entities to which emissions are assigned vary between datasets. Some parties have different geographic and economic extents under the Kyoto Protocol and the UNFCCC, and therefore submit more than one inventory to the UNFCCC. These include Denmark (DNM "KP-CP2" is Denmark; DKE "KP-CP1" is Denmark + Greenland; DNK "Convention" is Denmark + Greenland + Faroe Islands), France (FRK "KP" is France + all overseas areas that are part of the EU, such as Réunion; FRA "Convention" is FRK + all other overseas areas, such as New Caledonia), and the United Kingdom (GBK "KP" is UK + Channel Islands + Caymans + Falklands + Gibraltar; GBR "Convention" is as GBK + Bermuda). These make differences of less than 2% for individual countries. The European Union also submits two sets of inventories: EUA (Convention: strictly EU territory) and EUC (Kyoto Protocol: includes also Iceland and overseas territories). Similarly, the United States reports include Puerto Rico and other territories when submitted to UNFCCC.

Moreover, emissions can be limited either to geographical areas or economic activities. *Inventories*, as for example submitted to the UNFCCC, cover geographical areas (akin to Energy Balances), while *Accounts* cover economic activities (akin to Energy Accounts). Accounts must be adjusted for the activities of foreign nationals and companies within the territory (e.g. emissions from tourists driving cars), and activities of nationals and national companies in other territories. Accounts follow the definitions of the System of National Accounts, used, among other things, for calculating GDP.

With regard to these country definitions, the allocation of emissions from combustion of international bunker fuels has been particularly problematic. While energy data are collated as to which country sells bunker fuels, this is very poorly related to which country has responsibility for the combustion of those fuels. Various methods have been proposed to allocate these emissions, such as to the country whose flag a ship operates under, or that which the owner of the ship is a tax resident in, or those that operate the ship, of even those who purchase the goods borne by the ship. However, none of these is clearly superior to the others, and they can result in very different distributions of these emissions. This is in effect why the international aviation and maritime industries have been largely excluded from negotiations, and are now being forced to act independently on a global basis.

By including emissions from bunker fuel sales in a country's totals, significant deviations appear for some countries (Figure 2, Figure 3). There is not yet any international agreement on which party should include emissions from bunker fuels in its accounts, and their inclusion by BP and EIA produces emissions estimates at odds with current rules on national emissions responsibility.

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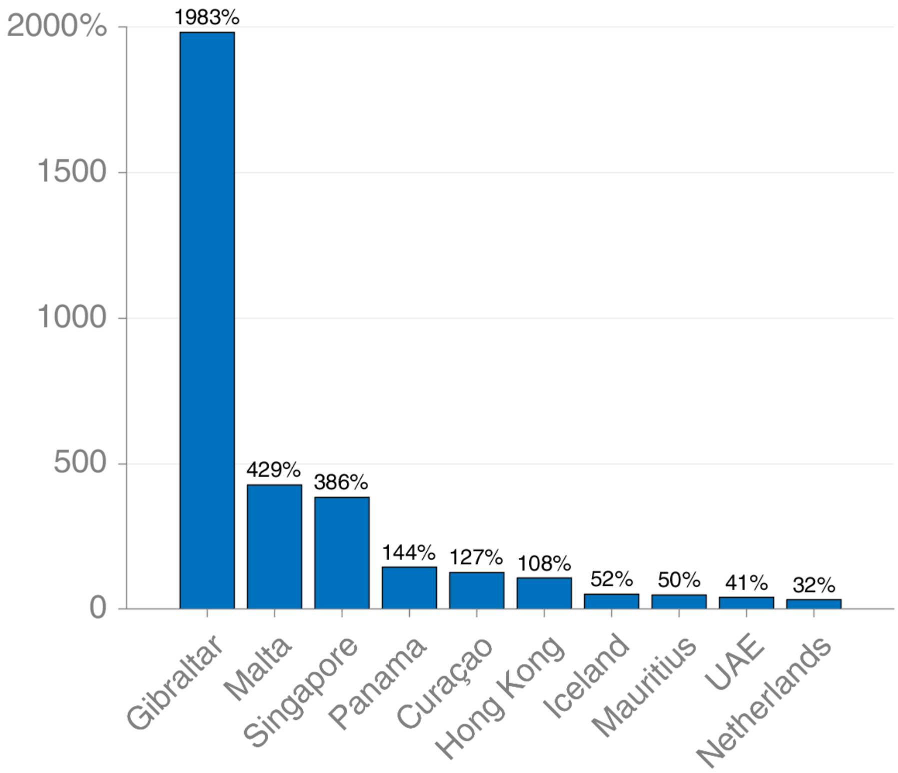

Figure 2: Emissions from sales of international marine and aviation bunker fuels as a proportion of total domestic emissions, top ten countries, using IEA data.

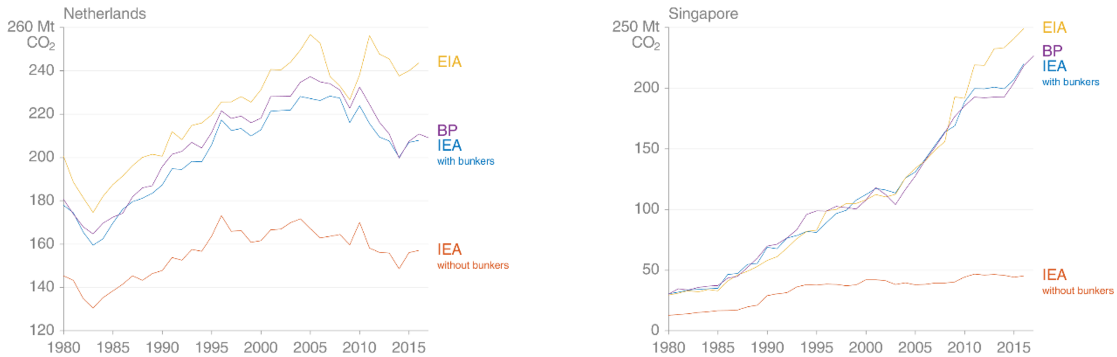

Figure 3: The consequences of inclusion/exclusion of bunker fuels varies by country, but is particularly marked for the Netherlands and other, smaller maritime nations.

Further methods of allocating emissions have been devised, such as re-allocating through economic supply chains to the point of final consumption, so-called consumption-based emissions, and variants (e.g., Davis and Caldeira, 2010; Andrew et al., 2013). These alternatives have not yet obtained international acceptance.

The ways in which national or global emissions are presented in more detailed form can vary substantially between datasets. While the IPCC Guidelines set a clear method for differentiating between “sectors of [the] economy” (Penman et al., 2006, p. 4), these sectors are quite different to those understood by economists. The Energy sector, for example, includes most combustion of energy, whether the activities are undertaken by enterprises

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whose main activity is energy production or not. All private combustion of gasoline is included in the Energy sector, whereas under economic accounts private activities would be accounted to households. Agricultural emissions, under the IPCC methodology, do not include such activities as driving tractors or heating glasshouses. Other datasets do assign emissions to economic activities. Further, breakdown by type of fossil fuel can vary, with the use of Solid, Liquid, Gas as distinct from Coal, Oil, Natural Gas.

The time period over which emissions are accounted can vary. While all present annual emissions, some also report sub-annual periods. More importantly, while most countries' data are reported for calendar years (from 1 January to 31 December), some are reported for financial years. In the IEA's data, which probably represents most datasets because of non-independent original sources, non-calendar year data are reported for Bangladesh, Egypt, India, Nepal. For India, by far the most significant of these, the 2016 year represents the financial year 1 April 2016 – 31 March 2017 (the majority of this period falling in 2016), which would be called the 2017 year in India (the financial year ending in 2017).

One final category of system boundaries is the inclusion of confidential data. At detailed levels some countries may withhold and aggregate reporting of emissions from certain activities for strategic reasons. While these are generally included at aggregate level, emissions from military activities are known sometimes to be withheld entirely. The IEA "has found that in practice most countries consider information on military consumption as confidential and therefore either combine it with other information or do not include it at all" (IEA, 2018c, p. 55).

Different methods can be used to estimate emissions, based on different original data sources. The most important distinction is between the Sectoral Approach and the Reference Approach, applying only to emissions from fossil fuels. While the Sectoral approach is based on detailed demand-side energy data (a bottom-up calculation, starting with as much detail as possible, typically sales data), the Reference approach is based on much less detailed supply-side data (a top-down calculation, typically using national production, international trade, and stock change data). While the estimates generated by the Sectoral Approach are definitive, those under the Reference Approach are used as a partially independent cross check.

2.1.1. System boundaries of selected data sets

Figure 4 compares seven data sources' emissions estimates for the EU28 for the single year 2016, the most recent common year in all datasets. The figure attempts to show the differences in both system boundaries and estimates. However, the estimates from BP, EIA, and EDGAR used here do not provide disaggregated estimates in the same way; while both BP and EIA include emissions from sales of bunker fuels, those emissions are not presented separately, nor do the energy data distinguish bunker fuel sales. Other versions of EDGAR do provide sufficient disaggregation, but are currently only updated to 2012. Bunkers are normally excluded from national statistics, but are shown here for comparison with EIA and BP to give an indication of how much those sources' totals would be bunkers.

The CRFs (Common Reporting Format datasets under the UNFCCC), following the IPCC 2006 Guidelines (Eggleston et al., 2006), report Fuel Combustion within the Energy sector: 1A. However, some fuel combustion can be reported instead in the Industrial Processes sector

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because it is used both as an energy source and as a chemical carbon source. For example, the IPCC Guidelines state that coke used in smelting iron ore in a blast furnace should not be reported in the Energy sector, but rather “All carbon used in blast furnaces should be considered process-related IPPU emissions” (Eggleston et al., 2006, p. 4.11).

The estimate of combustion (Energy sector 1A) emissions from the IEA is a little less than the Energy Combustion estimate in the CRFs, and their estimate of emissions in the Metals sector (part of IPPU) is slightly larger than that in the CRF.

Only the CRFs, GCP and CDIAC include flaring emissions, although it appears that CDIAC’s are underestimated here. CDIAC’s flaring estimates are derived from the UN energy statistics for flaring but also include assumed immediate oxidation of vented methane.

GCP’s total emissions are by design equal to those of the CRF. However, the distribution among subcomponents is different: GCP attempts to follow CDIAC’s definitions of solid, liquid, and gas as the oxidation of these fuel categories, rather than only their combustion (Le Quéré et al., 2018a). Therefore, more of industrial processes are accounted against those fuel categories, and in the blue bar in the figure, than in the CRFs. Moreover, GCP does not retain the distinction between other industrial processes and agricultural and waste emissions, grouping them together in an ‘others’ category, shown red in the figure. While GCP sources cement emissions from Andrew (2018), for Annex-1 countries those in turn are sourced from the CRFs for the period covered by the latter.

While BP’s total matches very closely that of CRFs without bunkers, BP’s estimate includes bunkers, indicating that their estimate is probably on the low side.

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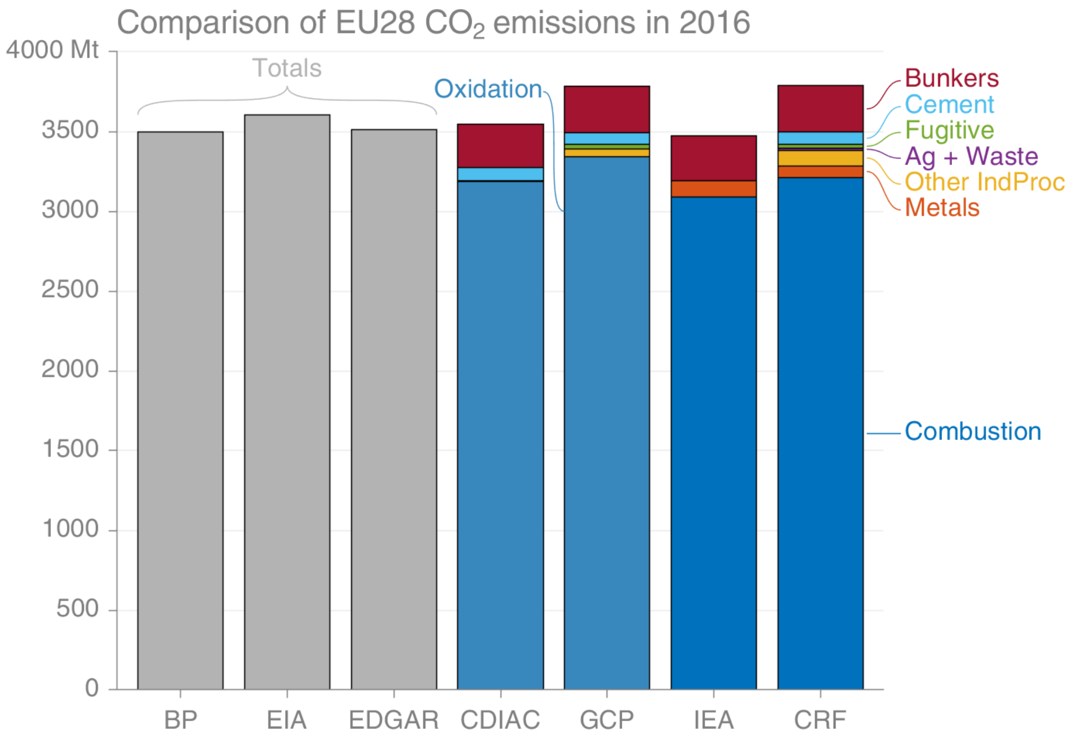

Figure 4: Comparison of seven emissions datasets, showing subcategories. BP and EIA are available divided only by fuel type, while EDGAR (v5.0 FT2017) is only divided into five economic sectors. 'Other IndProc' is other emissions in the IPCC's Industrial Process and Product Use sector.

2.2. IPCC Inventory Guidelines

The Intergovernmental Panel on Climate Change (IPCC) provides comprehensive guidance for compiling emissions inventories for all sources of emissions.

The Guidelines are built on decades of efforts and expertise in compiling emissions estimates and are designed to be flexible to suit countries' specific needs. Work began on The Guidelines in 1991 by Working Group 1 of the IPCC under the IPCC/OECD/IEA Programme on National Greenhouse Gas Inventories, with the first edition approved in 1994 and adopted the following year. A revision to these was published in 1996 (Houghton et al., 1996), and a new edition published in 2006 (Eggleston et al., 2006), with later amendments (e.g., the wetlands supplement, Hiraishi et al., 2013).

The methodology is divided into three 'Tiers', where Tier 1 uses supplied default emission factors applied to national activity data, Tier 2 uses national emission factors, and Tier 3 uses national models and/or direct measurements. The Tier 1 approach is often used by compilers of international inventories because they can do so using precompiled international datasets of activity, such as energy or agriculture databases.

While the 1996 Guidelines included a fraction of carbon stored (sequestered) from non-energy use (allowing for some to be oxidised at some point), the 2006 Guidelines removed these, effectively setting the fraction stored to 1.0 for all products. This was because "in

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most instances, emission inventory compilers had no "real" information as to whether this correction was actually applicable" (IEA, 2018a, p. I.22).

2.3. Detailed descriptions of global emissions data sources

Figure 5 provides an overview of some general characteristics of six global emissions datasets.

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

Figure 5: Comparison of general characteristics of six global emissions datasets, with green indicating advantage.

Figure 6 shows the main global energy datasets, primary global emissions datasets, and secondary (derived from primary) emissions datasets. The most important data source type for emissions estimates is energy data, which are ultimate derived from heterogeneous national sources. However, these national sources are highly heterogeneous. The IEA and Eurostat have developed questionnaires that are sent to at least 61 countries (all members of OECD, EU, UNECE, "and a few others"), and these identically completed questionnaires are submitted to the IEA, the UN, and (for certain countries) Eurostat[1].

[1] See https://www.iea.org/statistics/resources/questionnaires/

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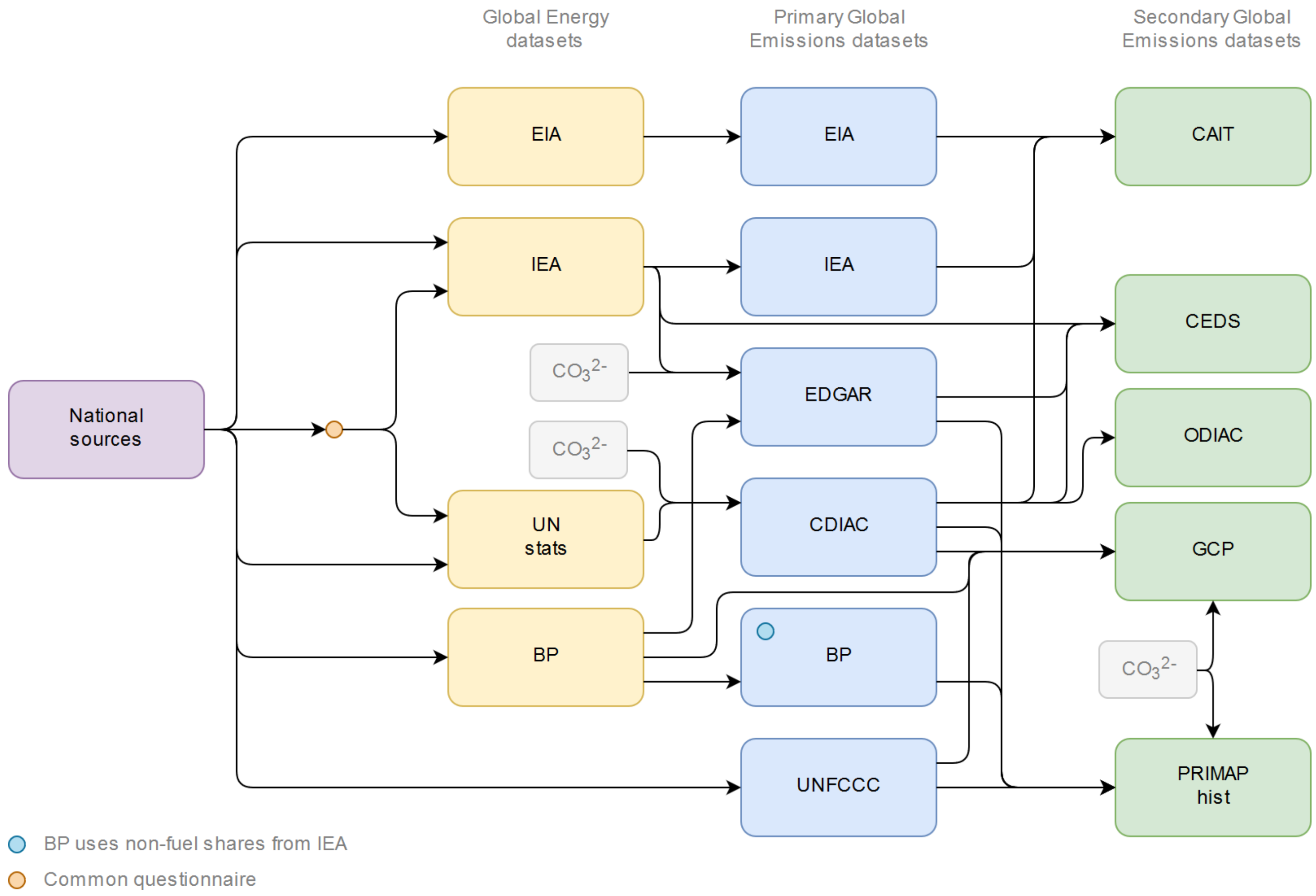

Figure 6: Dependencies of selected global energy and CO_2 emissions datasets. Here a 'primary' emissions dataset is one that calculated emissions directly from energy data, rather than collating emissions estimates from other sources. In addition to energy data sources, some emissions datasets include emissions from carbonates, which rely on other data sources. Some national data are first collated by regional organisations.

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2.3.1. IEA

The International Energy Agency (IEA), established in 1974, is an intergovernmental organisation whose membership draws from members of the Organisation for Economic Cooperation and Development (OECD). The IEA collects energy data for about 150 countries. There are five annual questionnaires for members of the OECD, EU, and UNECE: one each for coal, oil, natural gas, electricity and heat, and renewables. The completed questionnaires are submitted directly to IEA, UN, and (if European) Eurostat. These data are submitted in gross energy terms (gross calorific value).

Questionnaire data are supplemented with information directly from national administrations, and, where necessary, industry[2]. "The commodity balances for all other countries are based on national energy data of heterogeneous nature, converted and adapted to fit the IEA format and methodology" (IEA, 2018d, p. I.17).

The IEA calculates CO_2 emissions directly from energy data in TJ (NCV) using IPCC 2006 Tier 1 and default CO_2 emission factors from Table 2.2 of the 2006 Guidelines, with both bioenergy combustion and non-energy use resulting in zero emissions. Because the IEA defines natural gas production as marketable production, natural gas "extraction losses and quantities reinjected, vented or flared" are not included in the category 'Indigenous Production', but are reported separately.

There are three variants of IEA's emissions database:

- *Detailed estimates* (IEA, 2018a, c): includes emissions from 1960 (for OECD members, and 1971 for non-members), 181 countries/regions, 47 products, 41 flows. Paid service.
- *2006 Guidelines*: includes emissions from 1970, 185 countries/regions, 5 products, 13 flows (Fuel Combustion (IPCC Energy+IPPU), Reference Approach (IPCC Energy), Sectoral Approach (IPCC Energy), and various additional details). Paid service.
- *CO_2 Highlights (IEA, 2018b)*: includes emissions from 1971, 180 countries/regions, 3 products, 1 flow (total fuel combustion emissions by the sectoral approach). Freely available.

The IEA has three main total emissions definitions (IEA, 2018c):

- CO_2 Fuel combustion: Both that which would be included in IPCC category 1A (Energy: Fuel combustion), and any fuel combustion in IPPU
- CO_2 Sectoral Approach: Fuel combustion only in IPCC category 1A (Energy: Fuel combustion). This excludes certain emissions in the metals industry.

[2] See https://www.transparency-partnership.net/sites/default/files/u2620/the_iea_energy_data_collection_and_co2_estimates_an_overview__iea__coent.pdf.

- CO_2 Reference Approach: Fuel combustion calculated using energy supply data. Will therefore include some fugitive emissions (e.g. from refineries), in addition to differing by statistical differences (the difference between supply-side and demand-side data).

These are represented in Figure 7.

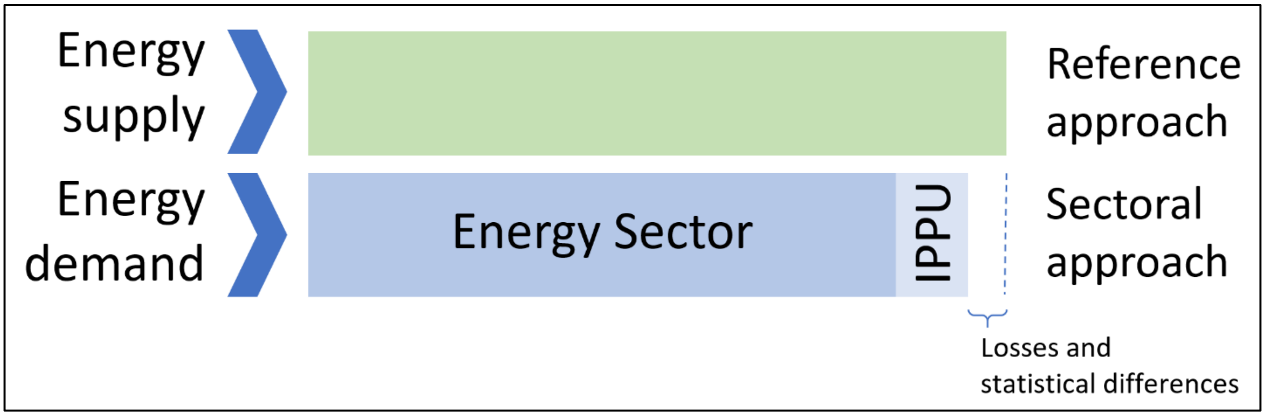

Figure 7: Schematic explanation of IEA's emissions estimates totals. IEA reports emissions from fuel combustion, using a Reference Approach, based on energy supply-side data (production, trade, stock changes), and a Sectoral Approach, based on energy demand-side data (largely sales). The latter is also subdivided between emissions that fall under the IPCC's Energy Sector and those that fall under the Industrial Processes and other Product Use (IPPU) sector (largely in the metal industry).

The process of data harmonisation actively driven by the IEA means that other organisations that collect directly from national agencies obtain better quality data, benefitting from the IEA's efforts.

The IEA provides no quantitative assessment of uncertainty associated with its emissions dataset.

IEA emissions reconstruction

Replicating the methodology used by IEA to generate emissions estimates from energy data is a good test of precise understanding.

In the following figure, global emissions reported by IEA are compared with global emissions calculated directly from IEA's energy data using their reported methodology. The difference is never more than 100 kt/yr, and the reason for this residual is that the published energy data do not differentiate between two products for which IEA uses two separate emission factors, Orimulsion and Other Hydrocarbons, such that a single emission factor is used for these different fuels. In IEA's energy data Orimulsion is included in Other Hydrocarbons. For countries with no, or very low, use of other hydrocarbons, estimates differ only because of rounding in the data reported by IEA. Few countries report use of these hydrocarbons – Canada, Denmark, Guatemala, Italy, South Korea, Lithuania, and UK – and only over a limited period.

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In the subsequent figures two examples are presented, China and USA, where the absolute error between IEA's reported emissions estimates and our replicated estimates are never more than 0.04 kt CO_2/yr, demonstrating clearly that the methodology is well documented.

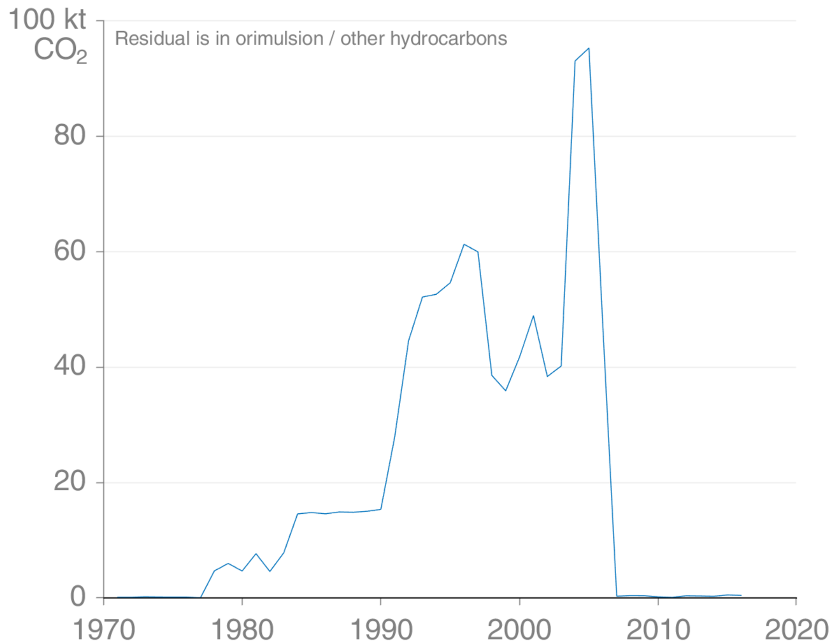
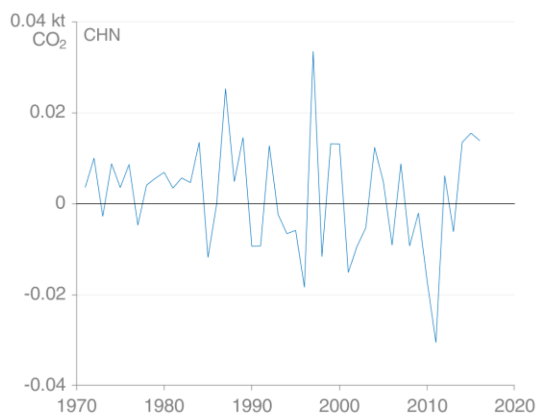


Figure 8: Difference between IEA's reported global CO_2 emissions and those obtained by replicating IEA's methodology applied to energy data. The residual can't be avoided because IEA do not provide energy consumption data separating Orimulsion from other hydrocarbons.



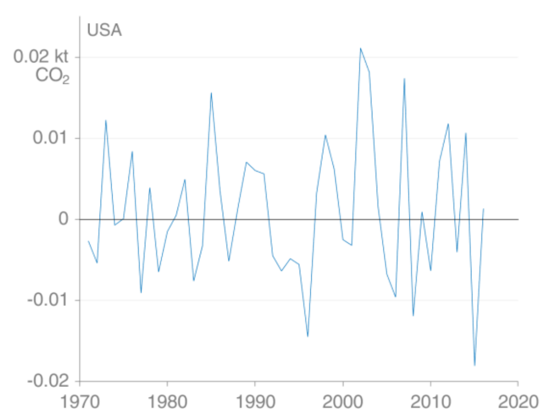


Figure 9: Difference between IEA's reported CO_2 emissions for China and those obtained by

Figure 10: Difference between IEA's reported CO_2 emissions for the USA and those obtained

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replicating IEA's methodology applied to energy data.	**by replicating IEA's methodology applied to energy data.**

2.3.2. UNFCCC (CRFs)

Since 2003, Annex-1 parties to the UN Framework Convention on Climate Change (UNFCCC) have submitted national inventory reports for the period 1990 to two years before the submission year. These reports, consisting of both a document and data in spreadsheet form, are due 15 April every year (UNFCCC, 2014). At present there are 42 countries submitting, in addition to the EU's combined submission, since the EU is also a party to the UNFCCC in its own right.

These spreadsheets, known as the Common Reporting Format (CRF), are normally generated using software developed by the UNFCCC Secretariat following the structure presented by the IPCC Guidelines (see section 2.2), but are in a relatively poor format for comprehensive analysis, with the 2018 edition's dataset spread over 126,920 spreadsheets in 1,336 separate Excel files. However, some data are available through the UNFCCC's data interface[3], and Jeffery et al. (2018) have produced a flat-record format dataset from these files, facilitating more widespread analysis. Revised inventories are typically submitted several times through the year as corrections are made.

Since the 2015 edition, following decisions made at COP19,[4] inventories must follow the methodology described in the 2006 IPCC Guidelines (Eggleston et al., 2006), with the exception that the CRF retains the 1996 distinction between Agriculture and LULUCF instead of the new (2006) AFOLU sector[5]. All anthropogenic sources and sinks of greenhouse gases are included. Energy emissions must be estimated using both the Sectoral Approach and the Reference Approach, with the former used as the official estimate and the latter as a cross-check.

Some of the most important changes in the CRFs from 2015 are:

- Use of new global warming potentials (from AR2 to AR4), although this has no effect for CO_2
- Consolidation of sector "Solvent and Other Product Use" with "Industrial Processes" to give "Industrial Processes and other Product Use"

[3] http://di.unfccc.int/time_series

[4] https://unfccc.int/resource/docs/2013/cop19/eng/10a03.pdf#page=2

[5] This represents a distinction between then UNFCCC Annex I reporting guidelines as determined in negotiation between parties and the UNFCCC, and the IPCC Reporting Guidelines. The UNFCCC Secretariat developed new tables for AFOLU in 2010 (https://unfccc.int/sites/default/files/set_2_afolu_final.pdf) but these were not introduced to reporting requirements.

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- Reallocation of CO_2 emissions from Urea and Lime application from LULUCF to Agriculture. Previously no CO_2 emissions were reported under Agriculture.
- The 2006 Guidelines changed all default energy carbon oxidation factors to 1.0 (see section 2.2)

The purpose of the Reference Approach is as a quality check using somewhat independent data and a simplified methodology. When two approaches differ markedly the UNFCCC Secretariat may ask parties to explain and to reduce deviations.

Non-Annex-I parties (parties to the UNFCCC that are not listed in Annex I of the Convention treaty text) are requested to submit National Communications and BURs, for which the requirements are less stringent than the CRF. At COP24 in Poland, agreement was reached that non-Annex-I parties must submit at least biennial transparency reports and national inventories at the latest by 31 December 2024, although it is unclear whether data should be in machine-readable form (UNFCCC, 2018) p64.

Each Annex-1 country estimates uncertainties associated with each emissions estimate, and aggregated uncertainties for totals, following the uncertainty guidelines provided by the IPCC (Frey et al., 2006).

Henceforth in this report we analyse Annex-1 emissions reports and refer to them as 'CRF'.

2.3.3. EDGAR

The Emissions Database for Global Atmospheric Research (EDGAR) is an important database of global and country-level emissions of all greenhouse gases, used by the IPCC.

The Netherlands Environment Agency (PBL) published the first version in 1995, limited to emissions from aviation, spatially distributed on a 5°x5° grid for the year 1990 (Olivier, 1995). Version 2.0 was published the following year on a 1°x1° grid for 1990, with sectoral, grid and per-country data (Olivier et al., 1996; Olivier et al., 1999).

EDGAR is now maintained by the Joint Research Centre of the European Commission, with continued input by PBL. The most recent fully documented version is v4.3.2, documented as a journal article currently in review (Janssens-Maenhout et al., 2019). This version presents emissions for 1970–2012.

The EDGAR database is released in more than one format, with the fully disaggregated dataset updated less frequently. A 'Fast Track' version is produced every year using a variant method, and released at a much lower level of detail. The most recently published version is v5.0_FT2017, used by Muntean et al. (2018), for which the publicly available version includes total fossil CO_2 (fossil fuels and carbonates) for five sectors, 208 countries plus bunker fuels, for 1970–2017.

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Energy emissions are derived using the IPCC Tier 1 approach according to the 2006 Guidelines from the IEA's energy data (v4.3.2 used IEA's 2014 edition, while v5.0_FT2017 used the 2017 edition), while carbonate emissions are largely based on production data from the USGS. In the fast-track versions some smaller emissions categories are extrapolated from the full EDGAR database using proxy data and growth rates.

EDGAR is unique among the CO_2 datasets here in including global estimates of emissions from all carbonate decomposition, not just cement production.

EDGAR estimates uncertainty on CO_2 emissions by assigning 2σ values that vary by country/region and time (Table 2b in Janssens-Maenhout et al., 2019). Global uncertainty on CO_2 emissions is calculated by assuming all errors are independent to be ±9% at 2σ.

2.3.4. BP

BP produced its first limited-circulation Statistical Review of World Energy in 1952 (BP, 2011). In recent years the BP Review has been highly anticipated primarily because it is the earliest data release to cover global energy and fossil-fuel CO_2 emissions, published in June of each year with data up to the previous year. The dataset is widely used, something that is facilitated by its being freely available, and its publication in Excel spreadsheet format.

Since 2007 the Review has been produced in collaboration with the Centre for Energy Economics Research and Policy (CEERP) at Heriot-Watt University, Scotland (Heriot Watt University, 2017).

Energy data are sourced directly from countries, although there is little documentation of specific sources. In the most recent edition, data were reported for 80 separate countries in addition to further regional groupings, from 1965 to 2017 (BP, 2018).

It appears that emissions were first included in the 2009 edition. Prior to the 2016 edition, emissions of CO_2 were calculated simply using a single emission factor for each of oil, gas, and coal, taking no account of consumption for non-combustion purposes (e.g., bitumen). From 2016 this has been revised to use the default emission factors for each product type from the IPCC 2006 Guidelines, with biofuels assumed to be carbon neutral. In addition, non-combusted energy has been removed using shares from IEA's energy balances (BP, 2017). The main consequence of this change is a decrease in emissions from oil in particular, because of high non-fuel use in oil.

BP provides national total emissions, without a breakdown by fuel type or sector. It includes international bunker fuels unseparated from national emissions. Emissions from venting and flaring are excluded, while own use (e.g., on oil rigs) is included (pers. comm., CEERP).

BP have energy data at a more disaggregated level than just coal, oil, and gas, and calculate emissions at this more disaggregated level. While oil is fully disaggregated, Coal is divided into Hard Coal and Brown Coal (coke is assigned to hard coal), and Gas is just Natural Gas (pers.

comm., CEERP). This means that both the non-fuel-use (NFU) shares and the emission factors are applied at these disaggregated levels. A consequence of this is that Gas and Oil should be fairly close to IEA's CO_2 estimates, with the differences deriving from energy data differences, while Coal might deviate because of a lower level of disaggregation. The NFU share from the most recent IEA data year are used in cases where BP data extend beyond the IEA data (pers. comm., CEERP).

BP provides no quantitative assessment of uncertainty associated with its emissions dataset.

2.3.5. CDIAC

The emissions dataset of the Carbon Dioxide Information Analysis Center (CDIAC) at Oak Ridge National Laboratory has been widely used, and some aspects of its construction methodology were used for the Tier 1 approach in the first IPCC Guidelines (Haukås et al., 1997). The IPCC's Fifth Assessment Report used CDIAC's emissions estimates when reporting both long-term and short-term emissions trends (Ciais et al., 2013).

The dataset has a long heritage[6], with David Keeling's work in 1973 as the starting point (Keeling, 1973). From then, Ralph Rotty, who had assisted Keeling with the 1973 paper, continued to update the dataset, adding flaring estimates (Rotty, 1973), making the first sub-global estimates (Rotty, 1983), and collaborating with Gregg Marland at the Institute for Energy Analysis at Oak Ridge. Still later, Andres et al. (1994; 1999) added emissions estimates from 1751–1949, and this long time-series with a consistent methodology is one of the core reasons the CDIAC dataset remains widely used.

The CDIAC dataset was updated annually, with the most recent official release in 2017 with data for 1751–2014. In 2016 it was announced that the US Department of Defense would be withdrawing funding for CDIAC, throwing the dataset's future into doubt, but it has since been taken up again by Appalachian State University (ASU). The 2018 release is available from the ASU website[7], and it is expected to be updated regularly in future.

CDIAC's estimates are derived from UN energy data, which in more recent years were in most cases identical with IEA data (see Figure 6). The emissions data include estimates in five categories: Solid, Liquid, Gas, Cement, and Flaring.

Separate methods are used to derive global and national estimates. For global estimates, CDIAC decided that more accurate results would be obtained by using energy production data as opposed to consumption data, because consumption data are derived using more uncertain international trade data. In addition, global average factors are used for non-energy uses. So

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[6] Some further details of CDIAC's history are discussed here: http://folk.uio.no/roberan/t/EarlyEstimates1.shtml

[7] https://energy.appstate.edu/CDIAC

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global energy production are adjusted first by global changes in stocks, and then multiplied by the carbon contents and fractions of oxidised carbon provided in table 13 of Marland and Rotty (1984).

For national emissions, apparent gross energy consumption is calculated from production plus imports, less exports, less supply to bunkers, less changes in stocks. From this gross figure all consumption of specific fuel types is subtracted as being ‘stored’ (not oxidised): for liquid fuels these include lubricants, petroleum coke, other petroleum products, petroleum waxes, white spirit, and bitumen asphalt[8]. The same carbon contents from table 13 of Marland and Rotty (1984) are used, but the fraction of oxidised carbon for liquid fuels represent only incomplete combustion and not non-energy uses and is therefore 98.5% instead of 91.8%.

For cement, production in tonnes is multiplied by 0.136 g C/g cement (Boden et al., 1995). A number of authors have raised questions about the accuracy of CDIAC’s cement emissions estimates, particularly for China (e.g., Lei, 2012; Ke et al., 2013; Liu et al., 2015). Andrew (2018) has covered the reasons for CDIAC’s cement estimates being inflated.

The method used for estimating flaring emissions is not clearly documented, but is known to include vented methane, which is assumed to oxidise to CO_2 within the same year it is emitted.

Andres et al. (2012b) reported uncertainty on global emissions as ±10% at 95%/2sd, while this was subsequently updated by Andres et al. (2014) to ±8.4% at 95%/2sd.

CDIAC emissions reconstruction

To test our understanding of CDIAC’s methodology, the documentation for which is spread across several documents (Marland and Rotty, 1984; Marland and Boden, 1993; Boden et al., 1995), we can compare CDIAC’s reported global emissions with those estimated directly from UN energy data, although only the most recent four years’ data are publicly available in each UN Yearbook. Here using the 2018 edition we see that our estimates are within 0.6%. One potential reason for residual differences is that CDIAC have access to data on consumption for non-energy uses by detailed fuel type, which do not appear in the Year Book.

However, here we have not followed precisely CDIAC’s described methodology for liquids: while Marland and Rotty (1984) say 6.7% is non-energy (stored) plus 1.5% non-oxidised (incomplete combustion), we have assumed complete combustion of energy use, which provides much closer results to CDIAC’s numbers. It appears that the 2012 edition was produced without the assumption of complete combustion for liquid fuels (i.e. both 6.7% and 1.5% factors were used), so the method has most likely changed between these two editions.

[8] Marland and Boden (1993) state that all non-fuel use indicated by the UN is assumed not oxidized, but data from CDIAC seen by CICERO indicates some deviation from this.

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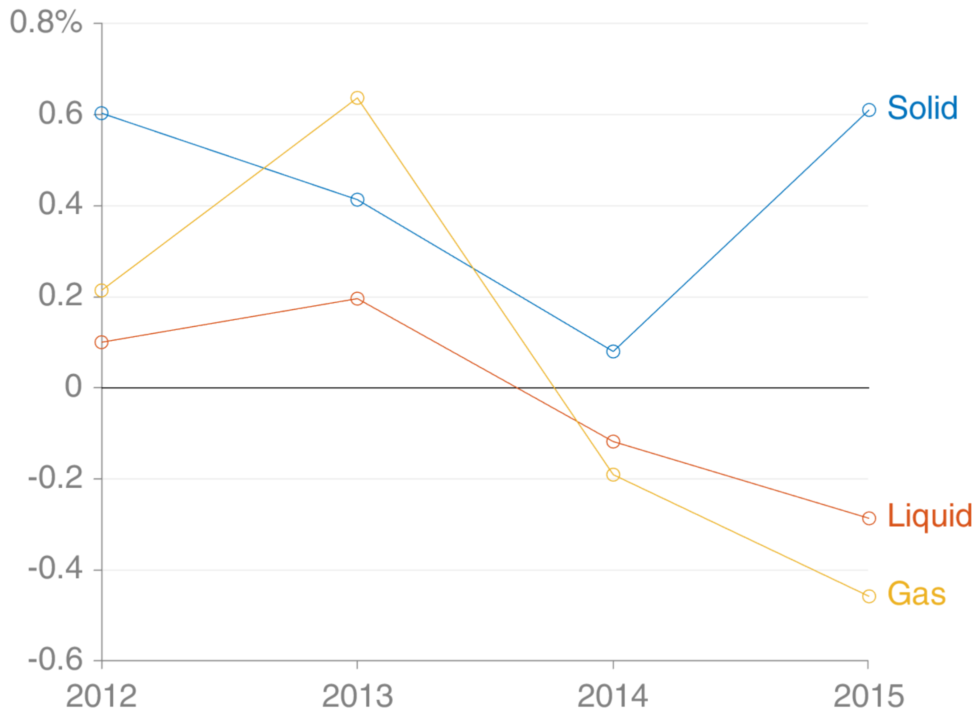

Figure 11: Difference between CDIAC's global emissions estimates from the 2018 edition and those obtained by applying CDIAC's described method directly to UN energy data.

2.3.6. EIA

The US Energy Information Administration (EIA) is primarily concerned with tracking energy markets, as are BP and IEA, but has all the data required to produce estimates of CO_2 emissions from energy consumption. EIA collect international energy data directly from a large number of sources[9].

The dataset 'Total Carbon Dioxide Emissions from the Consumption of Energy' is part of their International Energy Statistics. The product has been in 'beta' since May 2015, and it is not clear what update frequency is intended; the current data cover the period 1980–2016.

The EIA's emissions estimation methodology is stated to be documented in a 2008 report[10], although this document specifically deals with emissions in the US, and makes no mention of

[9] Detailed here: https://www.eia.gov/beta/international/data/browser/views/partials/sources.html, although this source list doesn't appear to be up-to-date.

[10] See https://www.eia.gov/beta/international/data/browser/views/partials/table_notes.html.

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international emissions (EIA, 2008). EIA say they are working towards a new process that will include more transparency (pers. comm., 19 March 2019).

Because the EIA does not provide international energy consumption data at the detailed fuel level, their CO_2 emissions estimates cannot be precisely replicated using the described methodology.

The EIA's international energy dataset does not indicate non-fuel uses, so the methodology for estimating emissions must first adjust for these. Carbon in natural gas used for manufacturing nitrogenous fertiliser is assumed emitted, otherwise all non-fuel use is assumed to be sequestered. Coke is assumed to be combusted, rather than a non-fuel use.

National emissions include bunker fuels along with flared natural gas and vented CO_2.

The EIA is currently working to streamline the international energy data process, improve transparency, and align the data with those used in their International Energy Outlook[11].

The EIA provides no quantitative assessment of uncertainty associated with its emissions dataset.

2.3.7. Global Carbon Project (GCP)

The Global Carbon Project (GCP) releases a Global Carbon Budget annually, usually timed to coincide with the UNFCCC COP, and one component of this is a CO_2 emissions dataset (Le Quéré et al., 2018a).

GCP's dataset is based primarily on CDIAC, which has been widely used in the carbon-cycle community for many years. In addition, GCP prioritises data from the Annex-I countries' CRF reports to the UNFCCC, overwrites cement emissions from Andrew (2018), and uses energy growth rates from BP to extend time series by two-to-three years.

Combining CRF data with CDIAC for Annex-I countries (38% of CO_2 global emissions in 2017) introduces problems of consistency of system boundaries. That which CDIAC includes as emissions for each fuel category is not the same as what the IPCC Guidelines indicate for the Energy sector (see section 2.1). The pragmatic option chosen by GCP is to use official (CRF) estimates for national total (all sectors) CO_2 emissions, and then to map emissions at lower levels of disaggregation to CDIAC's system boundaries. For example, natural gas includes not only combustion of natural gas but also any use of natural gas that under CDIAC's methodology is assumed to be oxidised in the short-term, such as use in fertiliser manufacture. For liquid fuels, this includes not only combustion of petroleum products, but incineration of plastics; similarly for coal. In addition, GCP includes an 'other' category for CO_2 emissions in the CRF

[11] Pers. comm., Perry Lindstrom, 21 March 2019.

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reports that are outside of CDIAC's system boundary, such as those in quicklime production, urea application, and combustion of peat.

GCP's data period is (in 2018 edition) from 1751–2017, with a global projection to 2018. The dataset is available both as an Excel/CSV download and via web-based interface[12]. Documentation is updated annually through the "living data" process at the journal ESSD.

The GCP assesses uncertainty on global emissions to be ±10% at the 95%/2sd level, after (Andres et al., 2012b), with uncertainty for developed countries at ±10% and for developing countries ±20% (Le Quéré et al., 2018a). Note that GCP reports uncertainties at 68%/1sd level.

2.3.8. CEDS

The Community Emissions Data System (CEDS; Hoesly et al., 2018) is intended to be an open-source emissions data production system, although the full system requires purchase of IEA's energy data. It produces annual national, sectoral, and monthly gridded emissions of a number of greenhouse gases and pollutants, including CO_2.

Emissions of CO_2 are derived from IEA's energy data in physical units, using emission factors from CDIAC and EIA. Cement emissions are taken directly from CDIAC. Estimates for countries for which official (or near official) estimates are available are scaled to those official estimates during the periods they are available.

Emission factors from CDIAC are applied for coal and natural gas combustion, from Marland and Rotty (1984) and Marland and Boden (1993)[13]. For natural gas, the emission factor used is 50.20 tCO_2/TJ GCV[14]. For coal, the emission factor used is 90.5 tCO_2/TJ GCV, applied to hard and brown coal separately[15]. For China a lower coal oxidation factor of 0.96 was used, based on specific research there (Liu et al., 2015). For liquid fuels (heavy, medium, and light oils) and coal

[12] The Global Carbon Atlas: http://www.globalcarbonatlas.org/en/CO2-emissions

[13] The citation given is to Boden et al. (1995), but that is only a minor update to Marland and Rotty (1984) and Marland and Boden (1993), including in addition the method used to calculate emissions from flaring and a slightly revised cement factor.

[14] Marland and Rotty (1984) used a carbon content of 13.7 tC/TJ = 50.23 tCO_2/TJ, and an oxidation fraction of 0.98, giving an emission factor of 49.23 tCO_2/TJ; the IPCC default is 56.1 tCO2/TJ NCV, and using NCV/GCV=0.90 that would be 50.5 tCO_2/TJ GCV.

[15] Energy content of 29.31 GJ GCV/tCoal, carbon content 70.7%, ratio of GCV to NCV 1.055, oxidation fraction 0.982 gives an emission factor of 91.6 tCO2/TJ GCV or 86.9 tCO2/TJ NCV; the lowest IPCC default is 94.6.

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coke, emission factors are taken from the EIA[16]. Emission factors are modified by fuel-specific fractions oxidized, following CDIAC's methodology.

Emissions calculated using IEA energy data are 'default emissions' for 1960/71–2014. These are then scaled to EDGAR, then to 'national inventories' where available, then extrapolated historically using CDIAC, with some minor corrections to CDIAC's data. For China, the emissions dataset MEIC[17] is considered a 'national inventory' and China's emissions are scaled to MEIC for the years 2008, 2010, and 2012.

Hoesly et al. (2018) discuss uncertainty at some length, but quantitative estimates of uncertainty are still in the pipeline.

2.3.9. CAIT

The World Resources Institute (WRI) developed the Climate Analysis Indicators Tool (CAIT), collating data from other emissions datasets: CDIAC, FAO, IEA, EIA, US EPA. The 2015 edition included 185 countries (WRI, 2015), with emissions by sector and gas for 1990–2014, and only country total emissions for 1850–2014.

For CO_2, IEA's sectoral approach emissions estimates are used directly for the 135 countries covered by that dataset, starting from 1971. CDIAC is used from 1850 to 1970 for all countries (estimates prior to 1850 were deemed to have insufficient geographic coverage[18]) and from 1971 to 2011/12 for countries not present in IEA's dataset. EIA is used for Lesotho[19] for 1980 to 2012, and for 2012 for all countries for which 2012 was not present in the other two datasets. UNFCCC inventories are not used in the main dataset because of their limited geographic coverage, but are presented separately.

2.3.10. PRIMAP-hist

The Potsdam Real-time Integrated Model for probabilistic Assessment of emissions Paths (PRIMAP) historical emissions dataset (PRIMAP-hist) is constructed based on a prioritization

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[16] These factors are provided at https://www.eia.gov/environment/emissions/co2_vol_mass.php. The EIA's factors were originally developed to be US-specific averages rather than relying on global average factors from the IPCC (EIA, 1994). They are based on gross heating values.

[17] Multi-resolution emission inventory for China, http://www.meicmodel.org/.

[18] WRI state that "CDIAC covers around 15 CAIT countries in 1850". While this certainly does appear to be very limited coverage, at that time those 15 countries would have represented the vast bulk of all fossil energy consumption, and the assumption of zero for remaining countries is not unreasonable. In particular, oil and gas were essentially zero before 1900.

[19] Lesotho's emissions in CDIAC start in 1990.

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scheme from other emissions datasets (Gütschow et al., 2016). Version 2.0 includes emissions for 1850–2016.

2.3.11. HIDE

The IMAGE 2 'hundred year' (1890-1990) data base of the global environment included historical CO_2 emissions for 13 regions (Klein Goldewijk and Battjes, 1995, 1997), but is no longer emissions. It calculated emissions for 1860–1949 directly from energy production data (Etemad and Luciani, 1991)[20]. For the period 1950–1990 emissions were taken directly from Marland et al. (1994).

2.3.12. MATCH

The Modelling and Assessment of Contributions to Climate Change (MATCH) expert group was established by the UNFCCC in 2001 to generate a historical emissions time series in the wake of Brazil's proposal to include historical emissions in negotiations (Höhne et al., 2011)[21]. It was updated by den Elzen et al. (2013) with data from EDGAR, but is no longer updated.

The dataset included emissions from Energy and industry (CO_2, CH_4, N_2O), Agriculture and waste (CH_4, N_2O), Land use change and forestry (CO_2). Emissions were collated from other datasets with the following order of prioritisation:

- UNFCCC submissions (Annex I: 1990–2004, Non-Annex I: 1994 and earlier where available)
- IEA CO_2 from fuel combustion 1970–2004 + cement emissions from CDIAC
- US EPA 1990–2005 for CH_4 and N_2O
- CDIAC 1751–2003
- EDGAR/HYDE 1890–1990, all sectors, 17 regions
- MNP/RIVM IMAGE 2.2: 1970–2100, all gases, all sectors, 17 regions

2.4. Comparison of emissions data sources

2.4.1. Energy Data

[20] HYDE makes no mention of adjusting for energy trade, which Etemad and Luciani (1991) did not include.

[21] See http://www.match-info.net/.

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All CO_2 emissions estimates ultimately derive the bulk of their data from energy data, and this is therefore the first potential source of deviation. It is also a large potential source of uncertainty, relying as it does on national administrations to report honestly and correctly.

The following figure compares global energy production from three energy datasets, demonstrating general coherence with some deviations.

To make the three datasets comparable it was necessary to convert them all to the same units, EJ of net calorific value. EIA present all their energy data in gross calorific value terms (higher heating value), and GCV are also used in the US' submissions to the UNFCCC. To make this conversion we use the three simple factors suggested by the IPCC: coal 0.95, oil 0.95, gas 0.90 (Eggleston et al., 2006).

In particular, we see a significant deviation of EIA's coal energy data from the other two sources here after 2010, and something of a diverging oil trend between the three after about 2005. That deviation in coal energy in EIA's dataset is propagated through to emissions estimates, and appears to be in data for China, as shown in the subsequent figure.

BP's oil production numbers lie slightly below those of the IEA and EIA over the entire period.

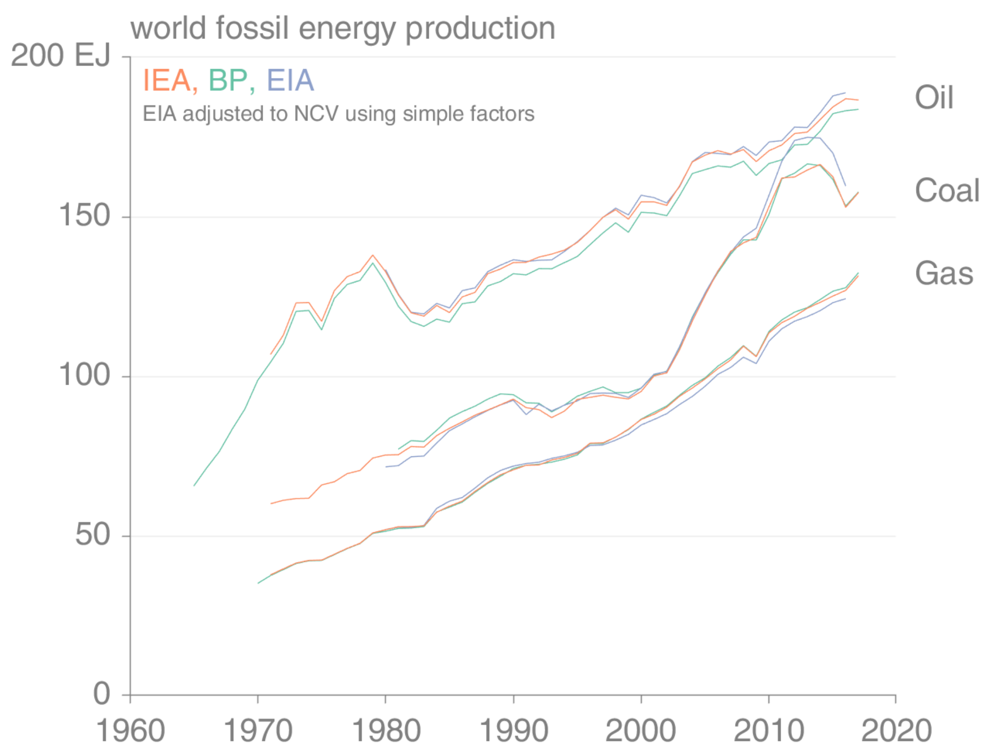

Figure 12: Differences in underlying energy data are the first reason for differences in emissions estimates.

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However, CO_2 emissions estimates are generally derived from energy consumption data, rather than from production data. The exception to this general rule is CDIAC's estimate of global emissions, which they derive from production data, arguing that the generation of energy consumption data requires the introduction of much more uncertain trade data and that the production data are therefore more likely to be accurate. The UN has also produced global energy statistics for many years, but their long time-series is not freely available.

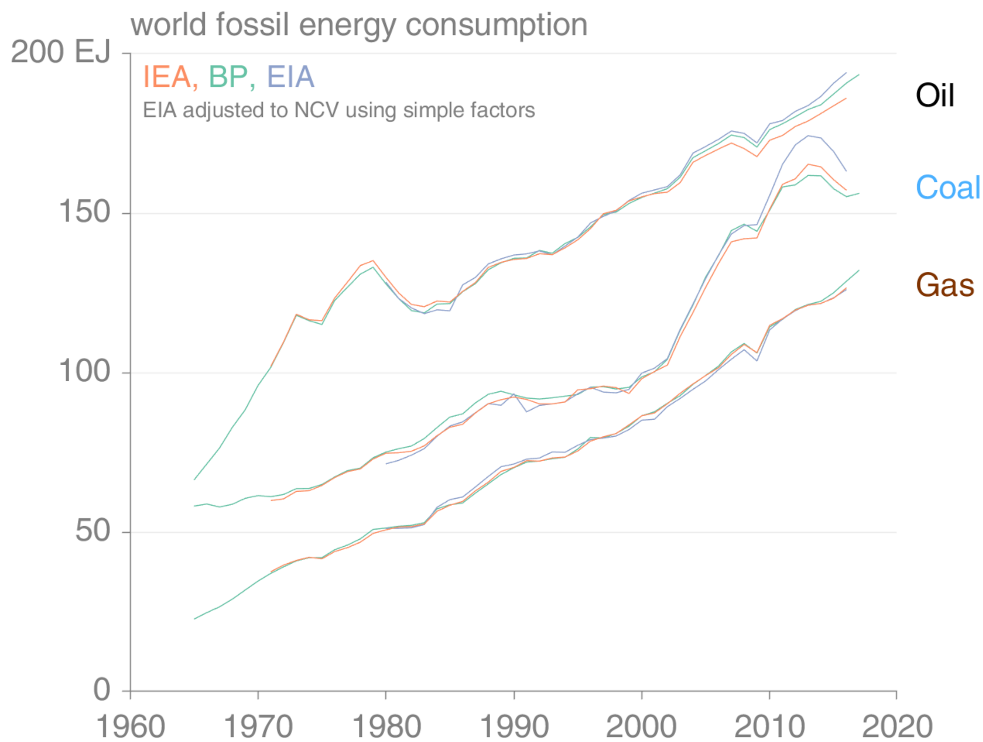

Figure 13: Global energy consumption estimates from three sources.

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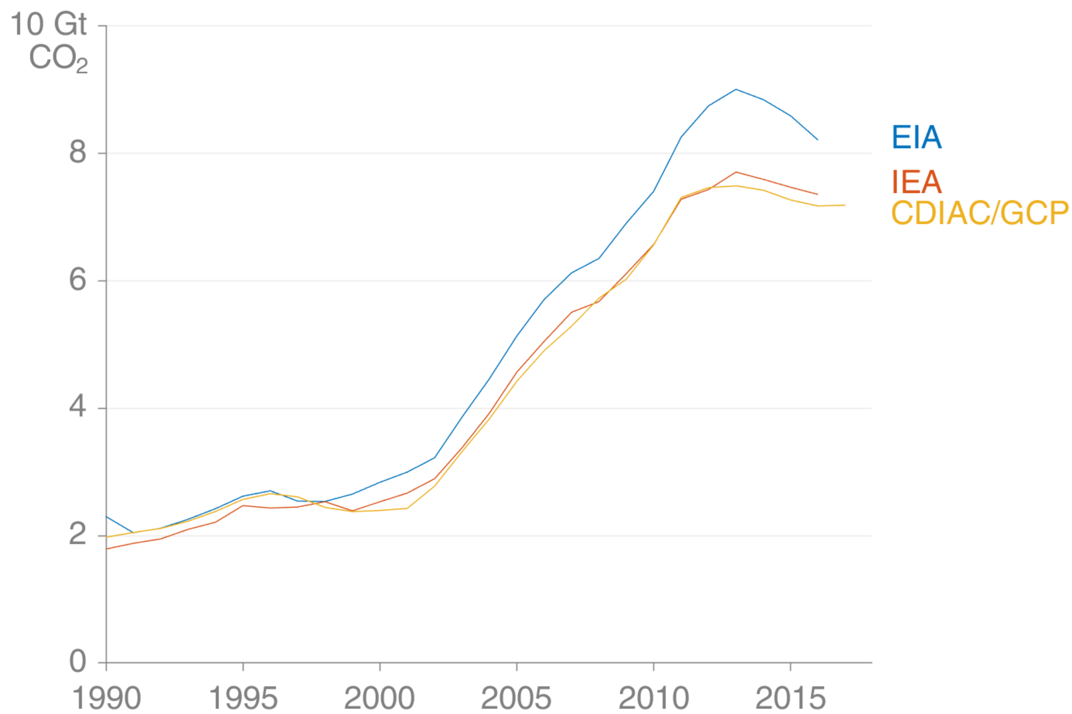

Figure 14: Demonstrating that the deviation of EIA's coal energy data for China are not due to the simple conversion from GCV and NCV that were used in the previous figures. EIA's emissions estimates trends would be closer to the IEA's if that were the case. This appears to indicate a divergence in underlying energy data.

2.4.2. Comparison of IEA and CRF

In determining why global emissions differ between datasets, it is first necessary to compare at country level, since global emissions are always calculated as a sum of all countries' emissions[22].

The emissions estimates made by the IEA are careful and well documented, and here we compare those with the official estimates submitted by countries to the UNFCCC in the Common Reporting Format (CRF).

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[22] While CDIAC state that they calculate global emissions from global energy production, this is equivalent to calculating emissions from country-level energy production and then summing, since global energy production is the sum of country-level energy production.

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Figure 15 and Figure 16 show that in some cases there is relatively strong correlation between the IEA and CRF estimates, while there are clearly some biases and some with very poor correlation.

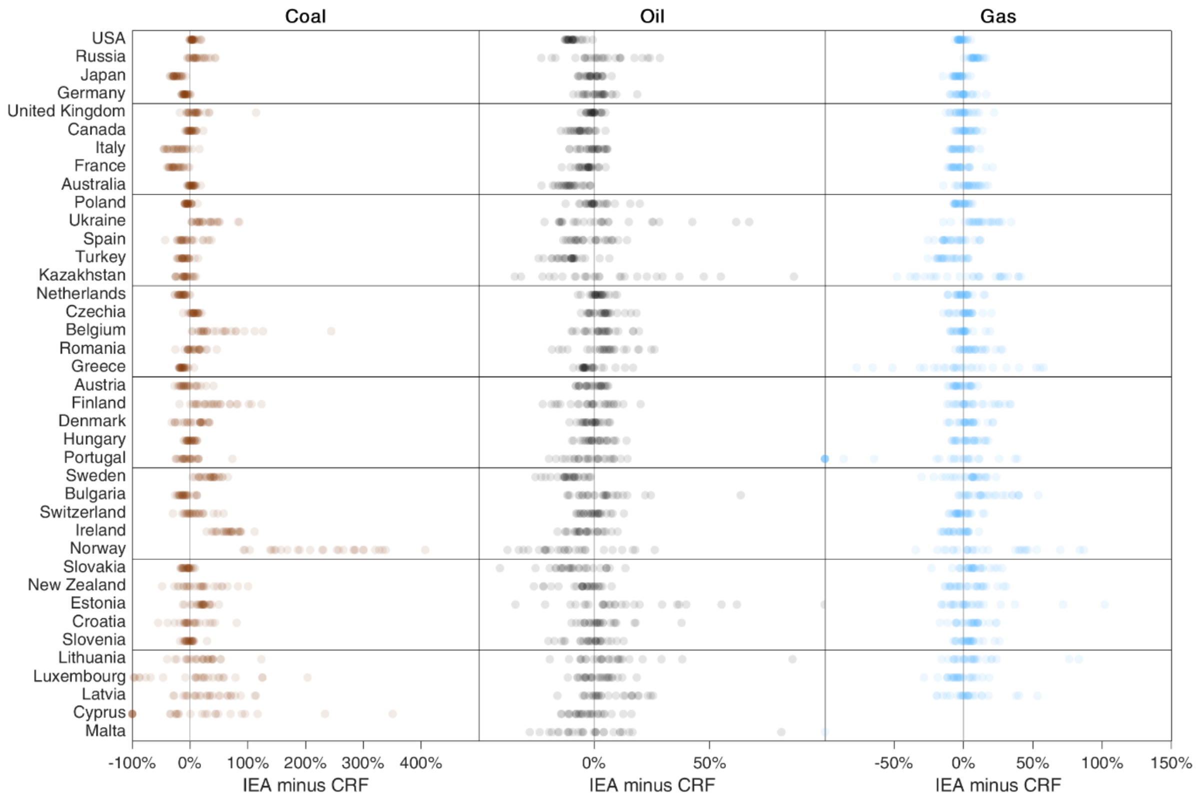

Figure 15: Comparison of emissions from the Reference Approach by IEA and the UNFCCC CRFs. Note scale differences.

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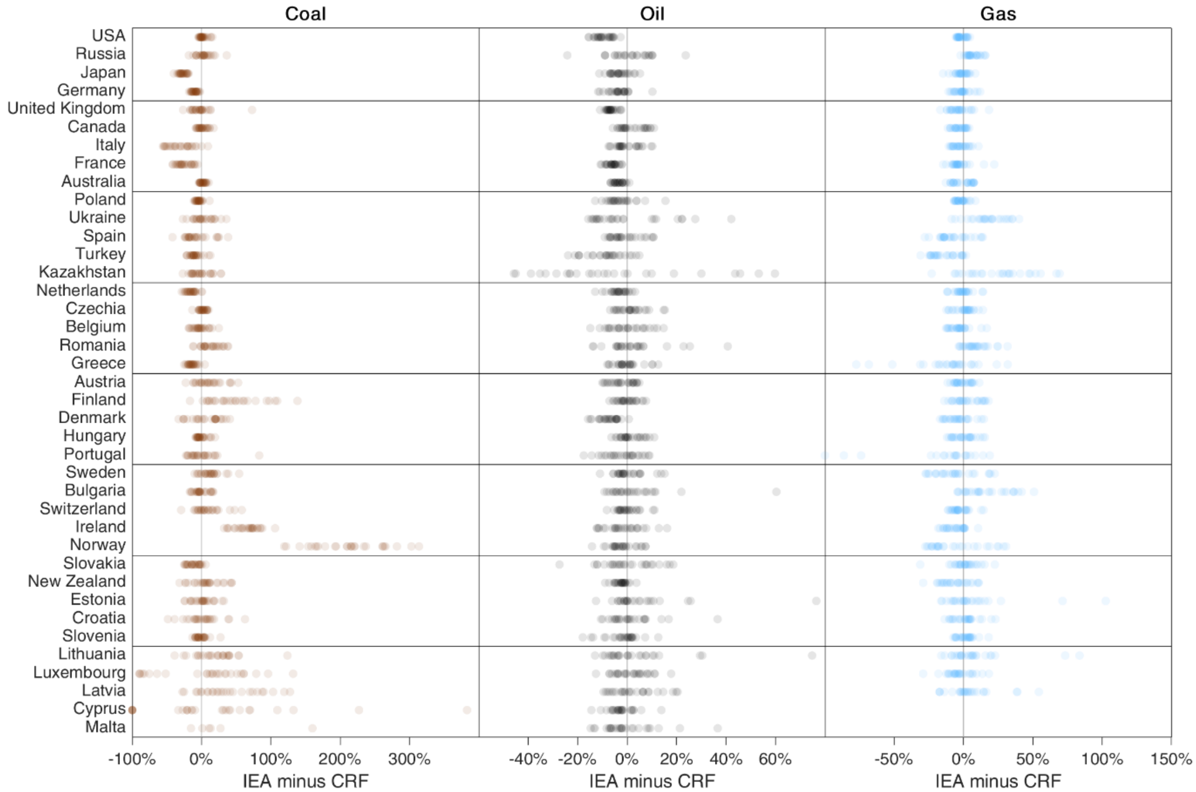

Figure 16: Comparison of IEA and CRF emissions estimates (sectoral approach) for 40 countries. Countries are ordered by total CO_2 emissions in CRF. Note scale differences.

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USA

Figure 17 compares the Sectoral Approach estimates from the CRF and IEA, demonstrating a significant gap between the estimates from liquid fuels. This difference in emissions from oil is almost 300 Mt, or 15%, in later years. Both the IEA (pers. comm.) and EPA (pers. comm.) are planning to investigate this difference.

There are some peculiarities with the US CRF submission. Firstly, what EIA call “Other Liquids” are reported in the category “Orimulsion”, even though the US neither produces nor consumes Orimulsion. The IPCC defines Orimulsion as “A tar-like substance that occurs naturally in Venezuela. It can be burned directly or refined into light petroleum products.” (2006 guidelines, vol1, chapter 1). Other Liquids includes hydrogen, oxygenates, renewables, unfinished oils, and motor gasoline blending components. The EPA (who submit the CRF) have requested that the UNFCCC Secretariat include additional reporting categories to avoid these confusions.

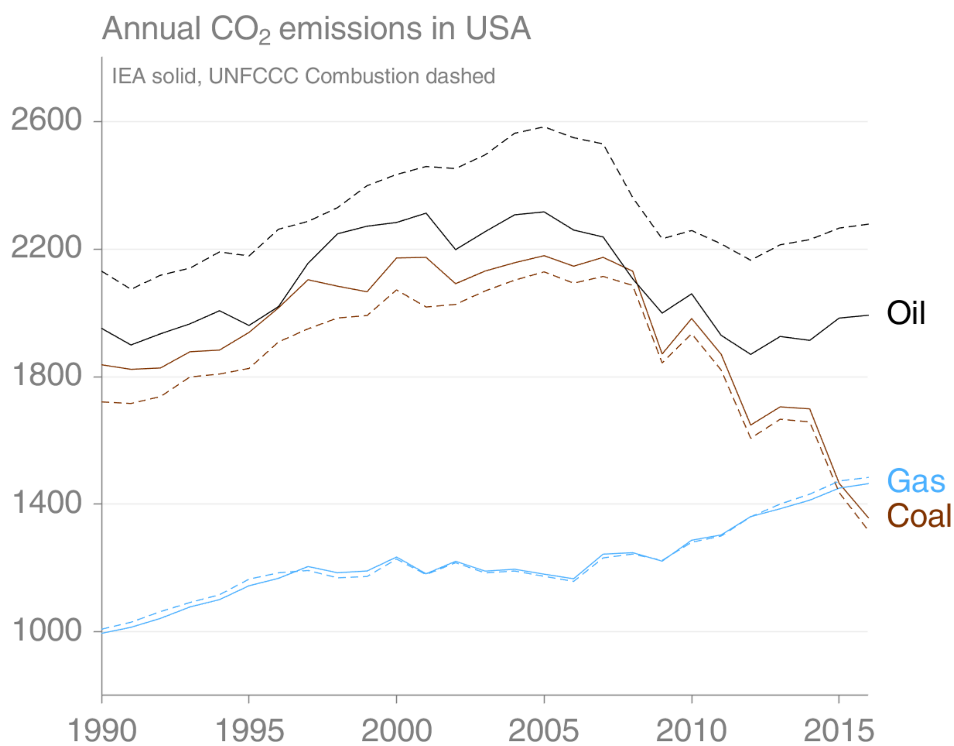

Figure 17: Comparison of emissions estimates for the USA from IEA and UNFCCC.

Secondly, uses of petroleum products in industrial processes are removed from the Reference Approach energy emissions calculation by being added to Stock Changes. These adjustments include petroleum coke for aluminium, ferroalloy, titanium dioxide, and ammonia production; coking coal for iron and steel production; natural gas for ammonia production; and other oil and residual fuel for carbon black production (EPA, 2018).

Natural Gas emissions are usually well estimated in all datasets because there it describes a single energy product, and because energy content exhibits limited regional variation.

Figure 18 focusses on emissions from US consumption of liquid fuels, comparing estimates from the EIA and IEA with those in the CRF (by the US EPA). Clearly the approach used (sectoral vs reference) has little to say in the differences between data sources. Here the IEA assigns zero liquid-fuel emissions to IPPU for the US.

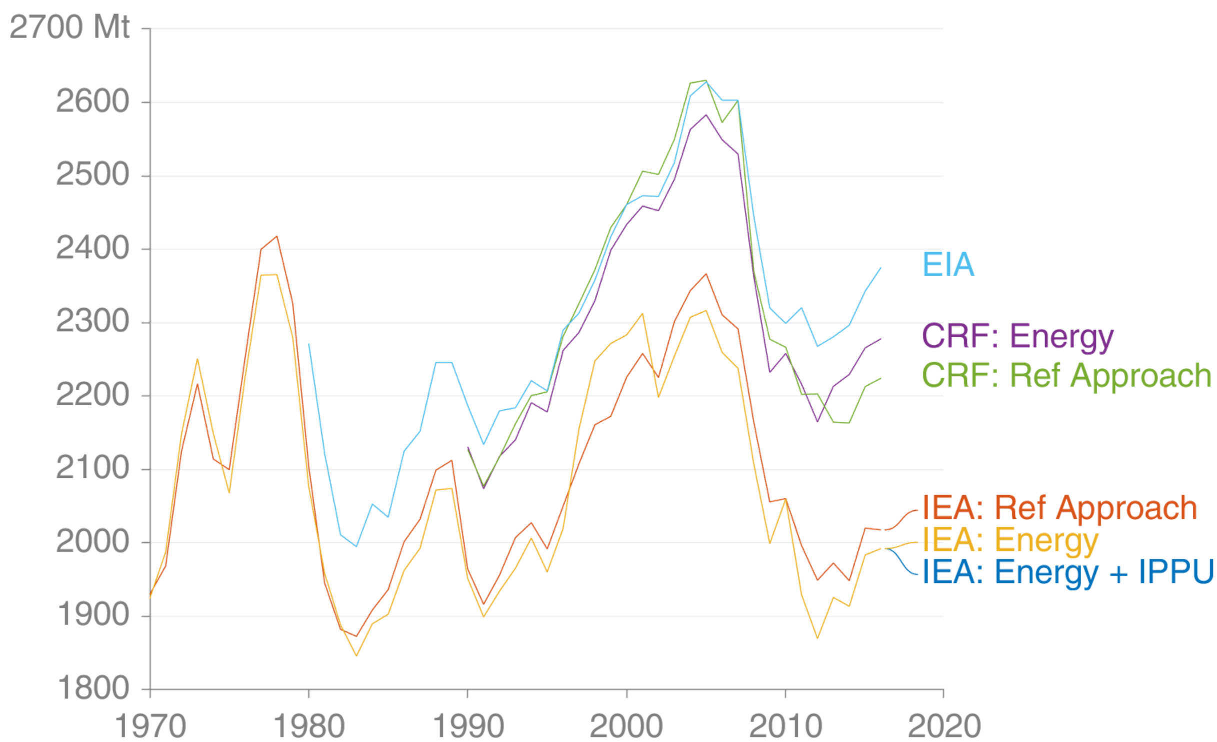

Figure 18: Comparison of estimates for CO_2 emissions from US liquid fuels, from EIA, CRF (EPA), and IEA.

EU28

The IEA's estimates for the EU are relatively close to those in the CRFs. While divergences for gas and coal exhibit no trends, the two estimates for oil appear to be converging over time. This could reflect a reduction in the consumption of a type of fuel for which the two estimates differ.

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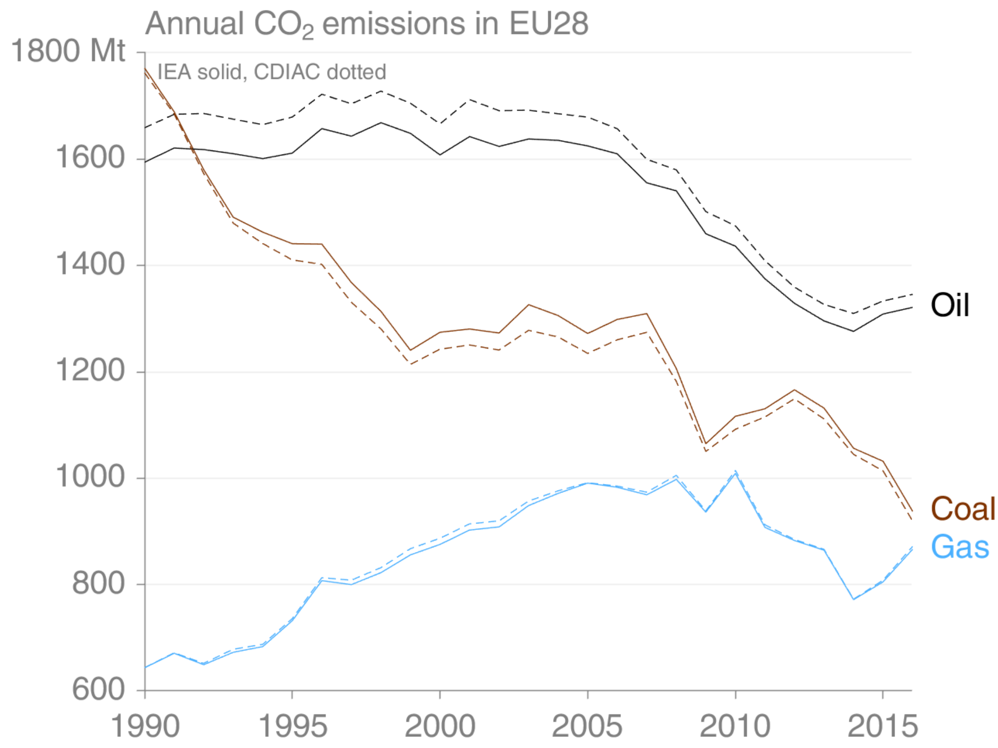

Figure 19: Comparison of annual co2 emissions for the European Union from UNCCC and IEA.

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Annex-1 total

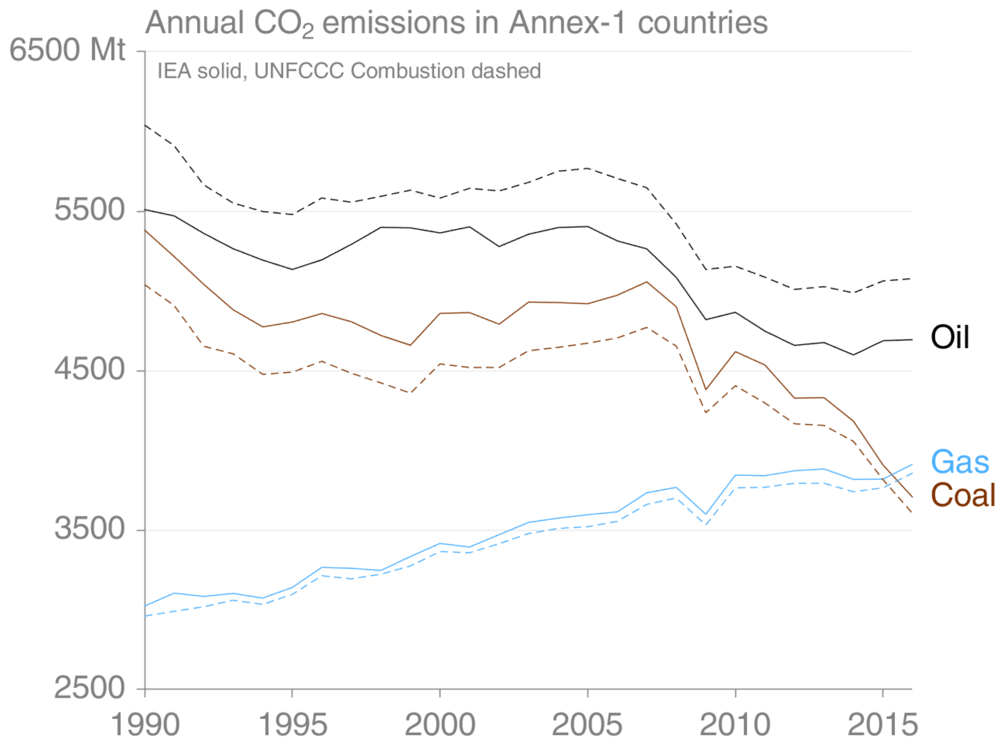

Figure 20: Comparison of annual CO_2 emissions for Annex-1 countries from UNCCC and IEA.

Revisions of CRFs

While the official reporting by Annex-1 countries to the UNFCCC via the CRFs is often seen as the 'gold standard', significant revisions of these estimates do nevertheless occur. Here we demonstrate this with some selected examples, although these should not be taken as representative; in many cases revisions are relatively minor.

As part of the UNFCCC reporting requirements, revisions to previous estimates must be documented and explained.

The first case (Figure 21) shows CO_2 emissions from combustion of gaseous fuels in Germany, which demonstrates that the final year's emissions in each report can be quite heavily revised, despite that year having finished more than 15 months before submission. In this case, however, no revisions are evident in earlier periods.

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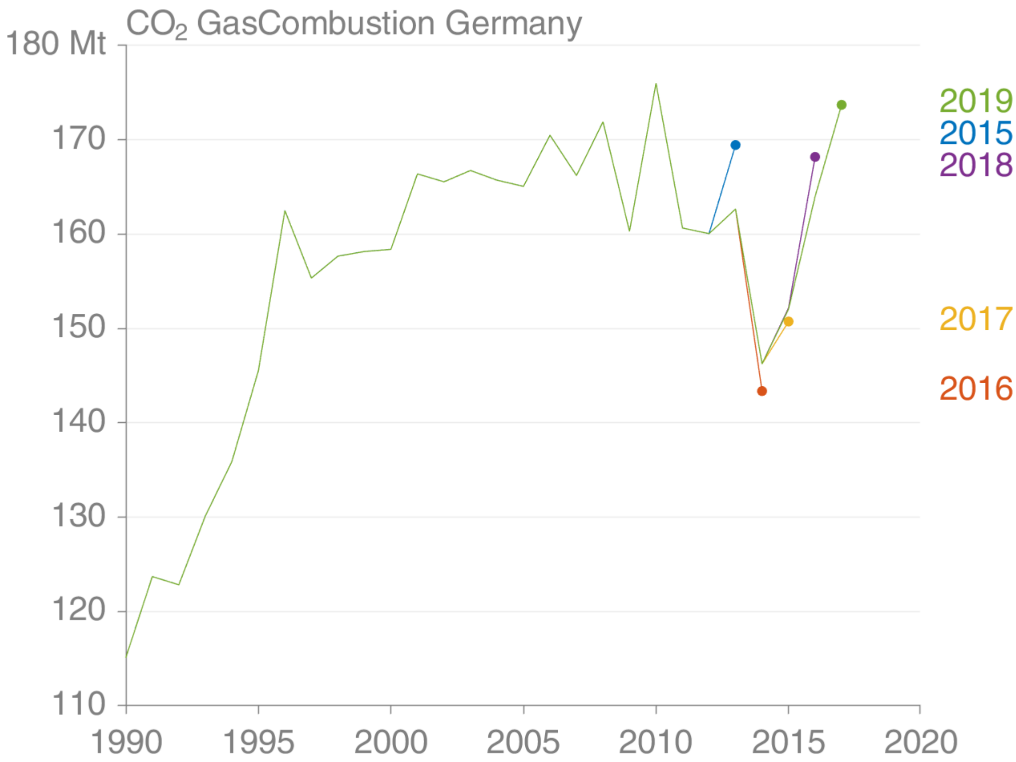

Figure 21: Comparison of the five most recent annual German CRF submissions for CO_2 emissions from gas combustion.

The next example (Figure 22) shows CO_2 emissions from combustion of liquid fuels in France. These are perhaps harder to estimate than emissions from gaseous or solid fuels because they are strongly affected by transport, which can cross international borders; a vehicle transport model is therefore required to derive territorial emissions from national fuel sales and vehicle traffic data.

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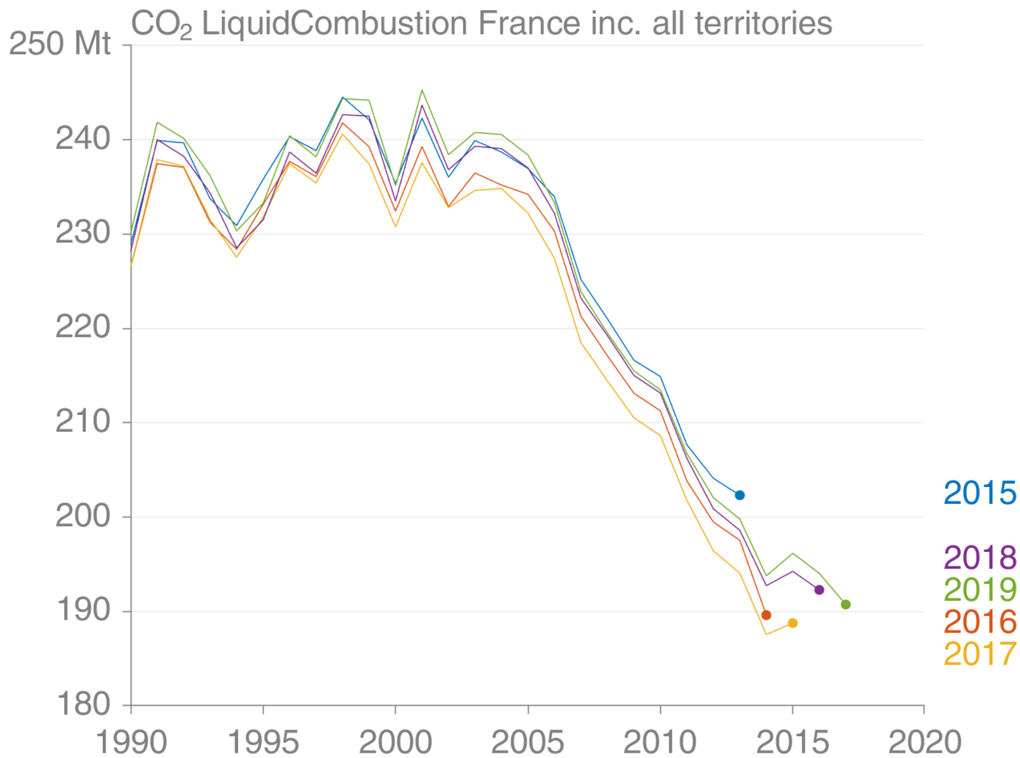

Figure 22: Comparison of the five most recent annual French CRF submissions for CO_2 emissions from liquid fuels combustion.

The final example here (Figure 23) shows CO_2 emissions from combustion of liquid fuels in the Netherlands. Again, there have been some significant revisions, particularly in the early part of the reporting period.

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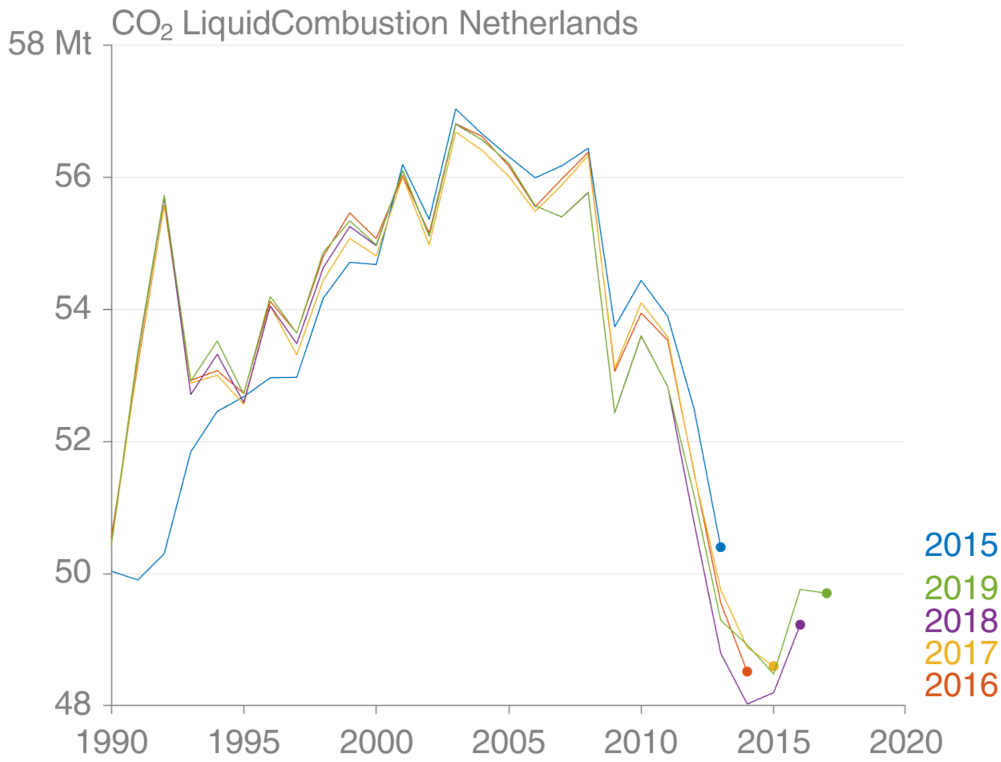

Figure 23: Comparison of the five most recent annual Dutch CRF submissions for CO_2 emissions from liquid fuels combustion.

2.4.3. Comparison of Multiple Sources

Now we compare a larger number of available emissions datasets at the country and region level.

USA

Figure 24 shows these emissions estimates from a number of sources. Some general conclusions can be drawn.

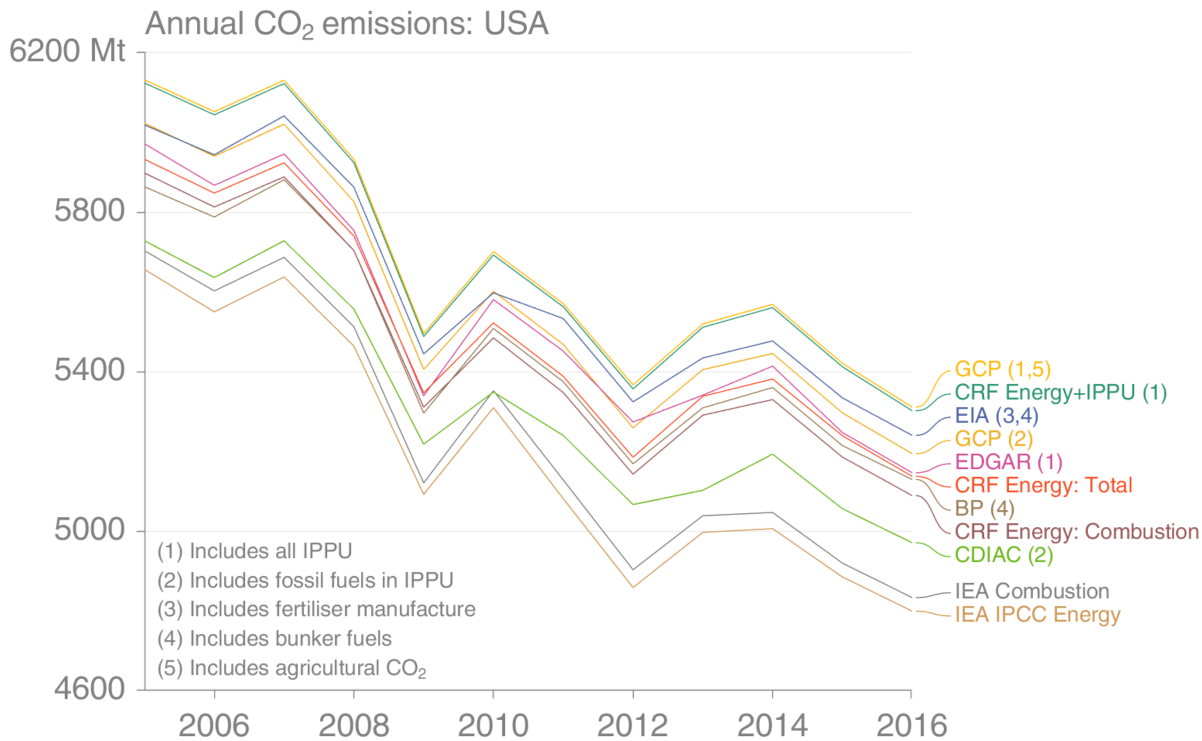

Figure 24: Annual CO_2 emissions for the US from various sources. Data versions: IEA 2018, GCP 2019prelim, CDIAC 2017, BP 2018, EDGAR v5.0_FT2017, EIA 2018, CRF April 2018. CRF here means UNFCCC.

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The highest and lowest estimates in 2016 differ by 358 Mt, or about 7%.

IEA's estimates are lowest, with their headline fuel-combustion emissions slightly higher than their 'energy' emissions because of the addition of some combustion emissions often recorded in IPCC's Industrial Processes sector (e.g. coke use in steel manufacturing).

There is quite a gap between IEA's combustion estimates and those in the US CRF, while these should in theory be relatively close given their basis in the same energy data and use of the same system boundary (see section **Ошибка! Источник ссылки не найден.**).

CDIAC's estimate includes all oxidation of fossil fuels in its system boundary, and is expected to be higher than a combustion estimate. It does sit higher than IEA's combustion estimate, but lower than the CRF estimate. This reflects that CDIAC's energy data source, the UN, is effectively the same as the IEA.

BP's estimate is expected to be higher than a combustion estimate because it also includes emissions from sales of bunker fuels. According to the IEA, emissions from US bunker fuels sales amounted to 128 Mt in 2016.

The US report to the UNFCCC via the CRF is represented three times in the chart: only combustion emissions, total energy-sector emissions, and combined emissions from the energy and industrial process sectors. The second category includes fugitive CO_2 emissions and any emissions from the transport and storage of CO_2 and is therefore higher than combustion emissions alone.

EDGAR's emissions lie very close to the CRF Energy total, but include also all emissions in the Industrial Process sector.

GCP's estimates are presented twice in the figure. The lower estimates theoretically match CDIAC's system boundary, including all oxidation of fossil fuels regardless of which IPCC sector they fall into. The higher estimate, for Annex-I countries, is exactly the CRF total CO_2 emissions across all sectors except LULUCF, meaning they include a small amount of agricultural emissions (from urea and lime use).

EIA's estimates lie towards the top of the range here. They include both emissions from sales of bunker fuels (as with BP) and production/eventual emissions from use of natural gas in the production of fertiliser.

In addition to the differences discussed, some of these estimates include emissions from venting and flaring (of methane and carbon dioxide), while others do not. Neither BP nor IEA include emissions from venting and flaring.

European Union

In the case of the European Union, shown in the following figure, the range in 2016 is about 414 Mt, or almost 13%. We see much less divergence between IEA and CRF estimates; IEA combustion and CRF combustion estimates are very close. IEA IPCC Energy excludes fugitive

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emissions and those from transport and storage of CO2, so are lower than combustion and total energy-sector emissions.

CDIAC's estimates are very close to IEA's combustion estimates, despite including additional fossil-fuel oxidation in its system boundary.

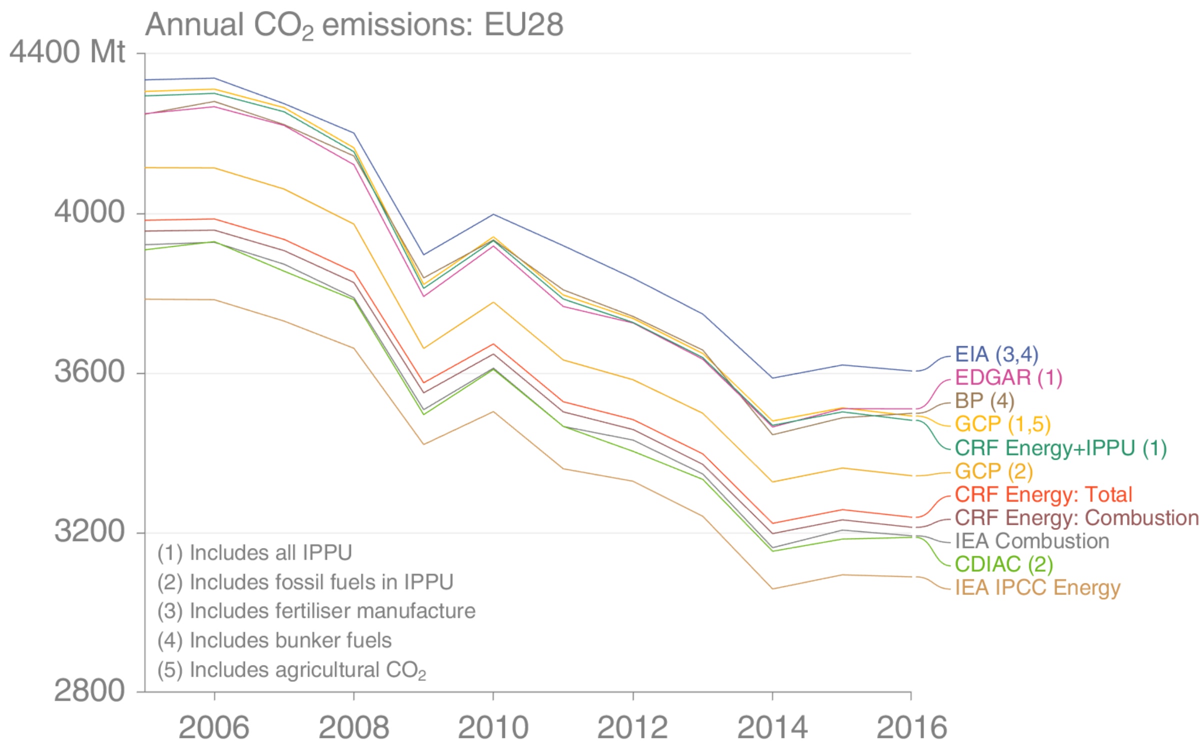

Figure 25: Annual CO_2 emissions for the EU28 from various sources. For details see previous figure's caption.

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EU: Natural Gas

While both coal and oil emissions are subject to particularly strong deviations between datasets with both energy content differences and bunker fuels, natural gas is much more uniform. The following figure shows estimates of the EU's annual CO2 emissions from natural gas from a number of sources.

Here we include also natural gas emissions from BP, which, while not reported by BP, are reproducible using their energy data and methodology.

From our discussion of system boundaries (section 2.1), we would expect the IEA, CRF, and BP estimates to be lowest, given that they include only emissions from combustion, while the other estimates include some additional emissions. The EIA includes natural gas used in fertilizer production, while CDIAC and GCP include all emissions from use of natural gas.

However, we see here that CDIAC's estimates are always lower than those of the EIA, despite including more emissions categories. This reflects the difference in methodology rather than the difference in system boundary.

In the process of producing this analysis, the authors discovered minor errors in the way the Global Carbon Project's emissions accounts were generated from the CRF datasets. As mentioned earlier, the GCP has chosen to replicate the CRFs' totals for each country, representing the official best emissions estimate. But to maintain consistency with the all non-Annex 1 countries (who do not submit CRF-based data), and with data prior to 1990, GCP maps CRF emissions to CDIAC's categories, such that 'natural gas' emissions include all emissions categories that CDIAC is reported to include. However, some errors in those mappings led to some emissions being assigned to natural gas that should have been assigned to oil, and the 'GCP 2019' line on the figure represents a provisional correction of this. These errors did not affect the national total emissions reported by GCP, only the breakdown by fuel category.

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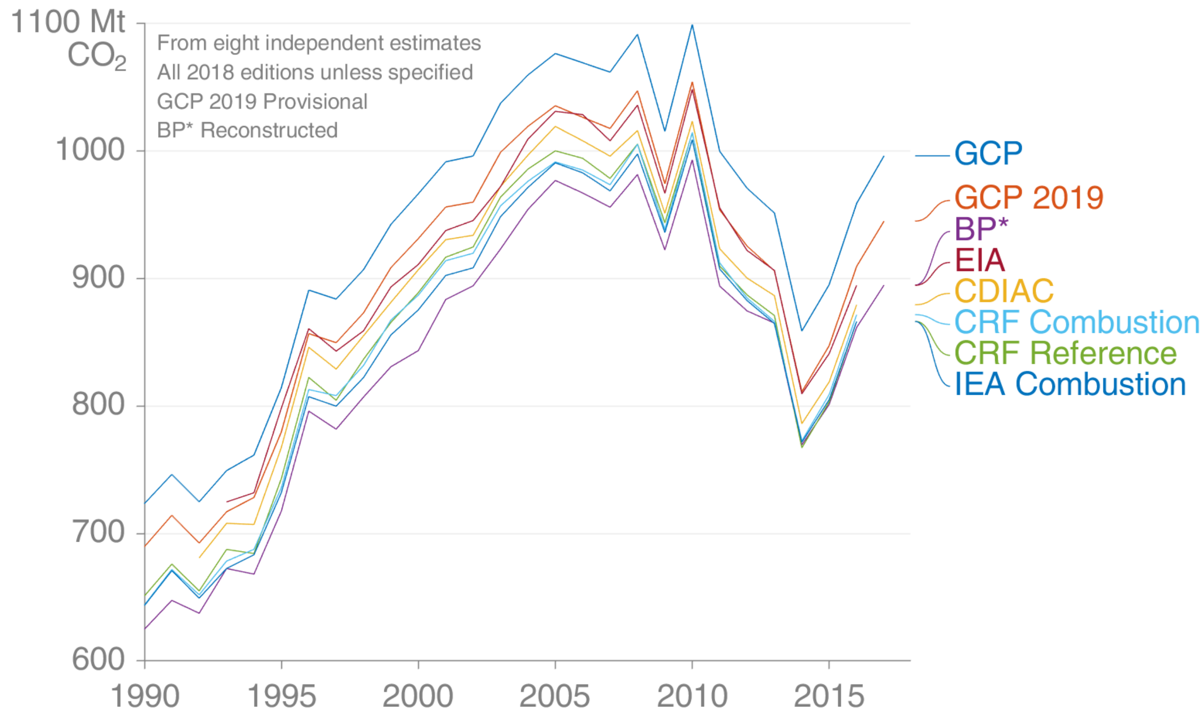

Figure 26: Comparison of estimates of emissions from natural gas in the European Union. BP emissions here are reconstructed using BP's energy data and methodology. The higher GCP line was found to be in error.

China

Turning to China, a non-Annex 1 country, and therefore with different reporting lines and requirements, we see a large range between estimates of 2900 Mt, or 31%. Much of this difference is because carbonate emissions are considerably higher in China than in developed countries: emissions from production of cement and lime form a larger proportion of total emissions.

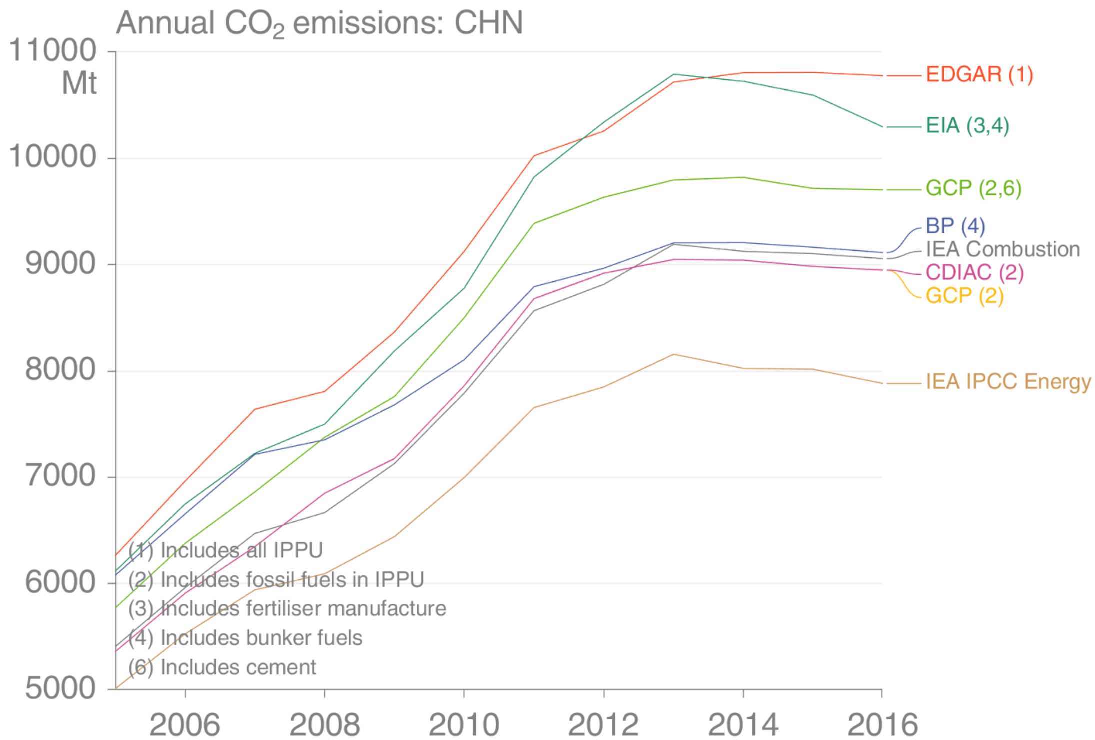

Figure 27: Annual CO_2 emissions for China from various sources.

Again, BP's and EIA's estimates include emissions from sales of bunker fuels, so it is unexpected that BP's estimate in recent years lies so close to the IEA combustion estimate, which does not. Figure 28 shows the underlying energy data from the available primary sources, showing that BP has lower coal consumption in China than IEA in recent years.

EDGAR's estimates are the highest, but they also have the broadest system boundary here, with Other Carbonates included. In contrast to Annex-1 countries, here GCP's estimates come directly from CDIAC, which does not include emissions from non-cement carbonates.

EIA's estimates show a trend in recent years that is at odds with the other emissions sources; this was observed in the underlying energy data shown in section **Ошибка! Источник ссылки не найден.**.

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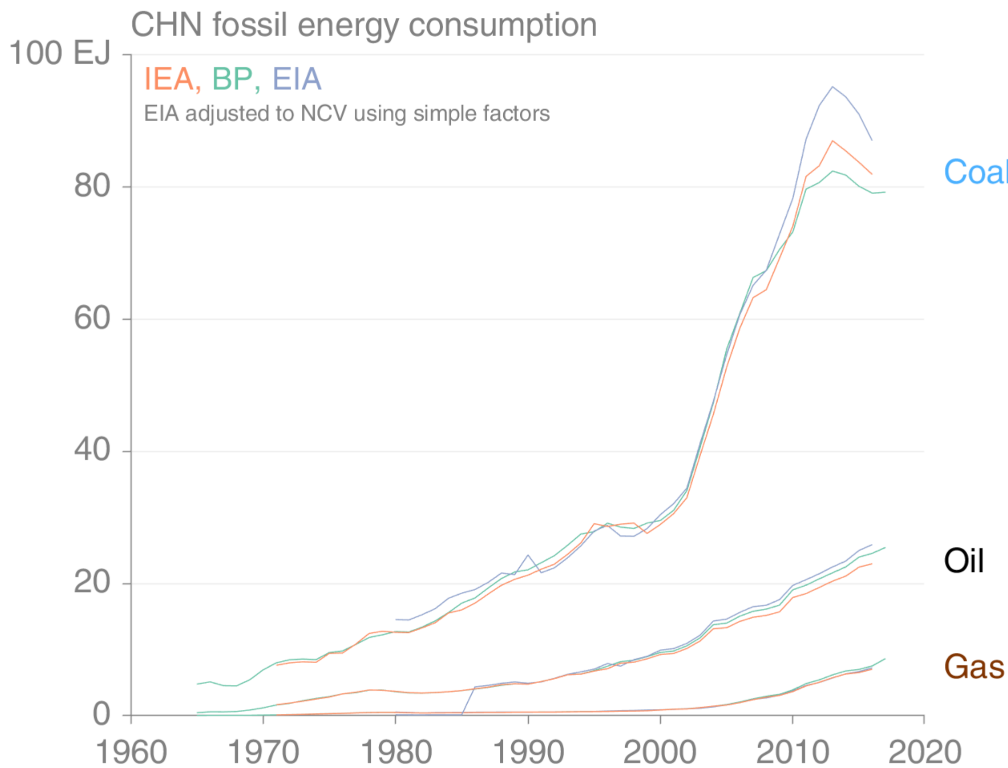

Figure 28: Comparison of fossil energy consumption from IEA, BP, and EIA[23].

Global

Much of the variation between estimates of global emissions is a result of different system boundaries. Figure 29 compares emissions from a number of different datasets, demonstrating a wide spread.

EDGAR has the largest system boundary, including all fossil fuel and carbonate emissions. CDIAC is presented twice, both with and without cement emissions, and cement emissions are overestimated (see section 0). GCP is also presented twice, both with and without cement emissions, and without emissions the global total of GCP is taken directly from CDIAC. The EIA's underlying energy data for China are possibly too high (see section **Ошибка! Источник ссылки не найден.**), pushing it's estimates of global emissions up; it also excludes emissions from carbonates. Neither BP's nor IEA's emissions include any carbonates nor venting and flaring. The IEA's "IPCC Energy" emissions include only emissions that would be included in the IPCC's Energy sector, thereby excluding some use, particularly of coal in industrial processes.

[23] The abnormally low oil consumption in EIA's data until 1985 is not yet explained.

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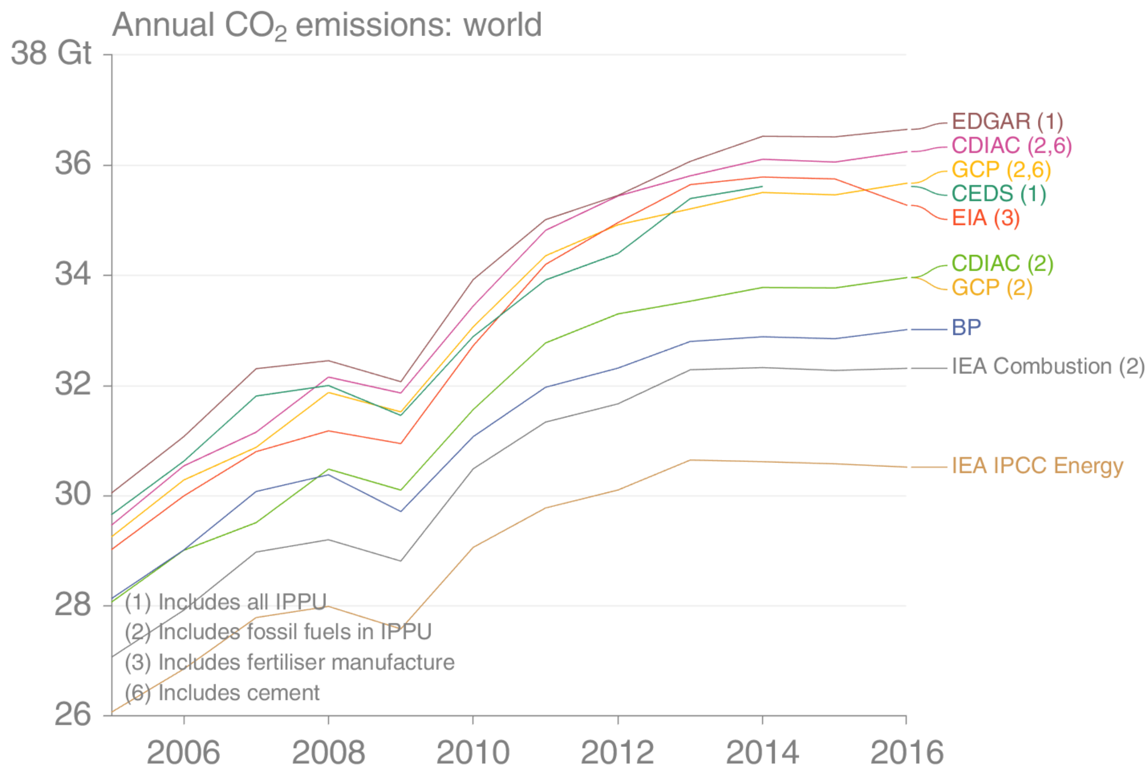

Figure 29: Annual global CO_2 emissions from various sources.

European Union countries

For completeness, the following figures show these comparisons for all 28 countries of the European Union.

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Figure 30: Annual CO_2 emissions for EU28 countries from various sources. For details see text.

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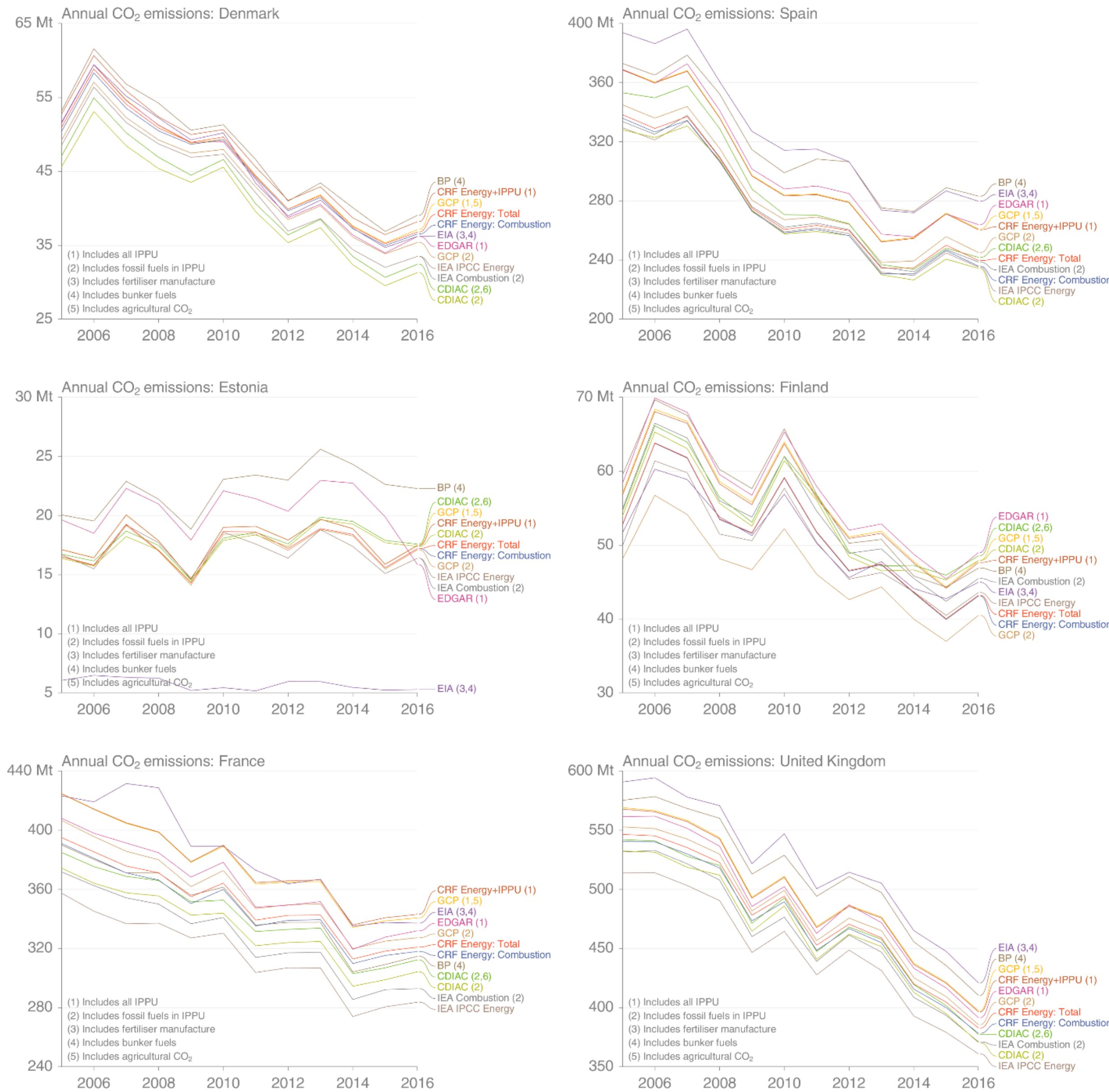

Figure 31: Annual CO_2 emissions for EU28 countries from various sources. For details see text.

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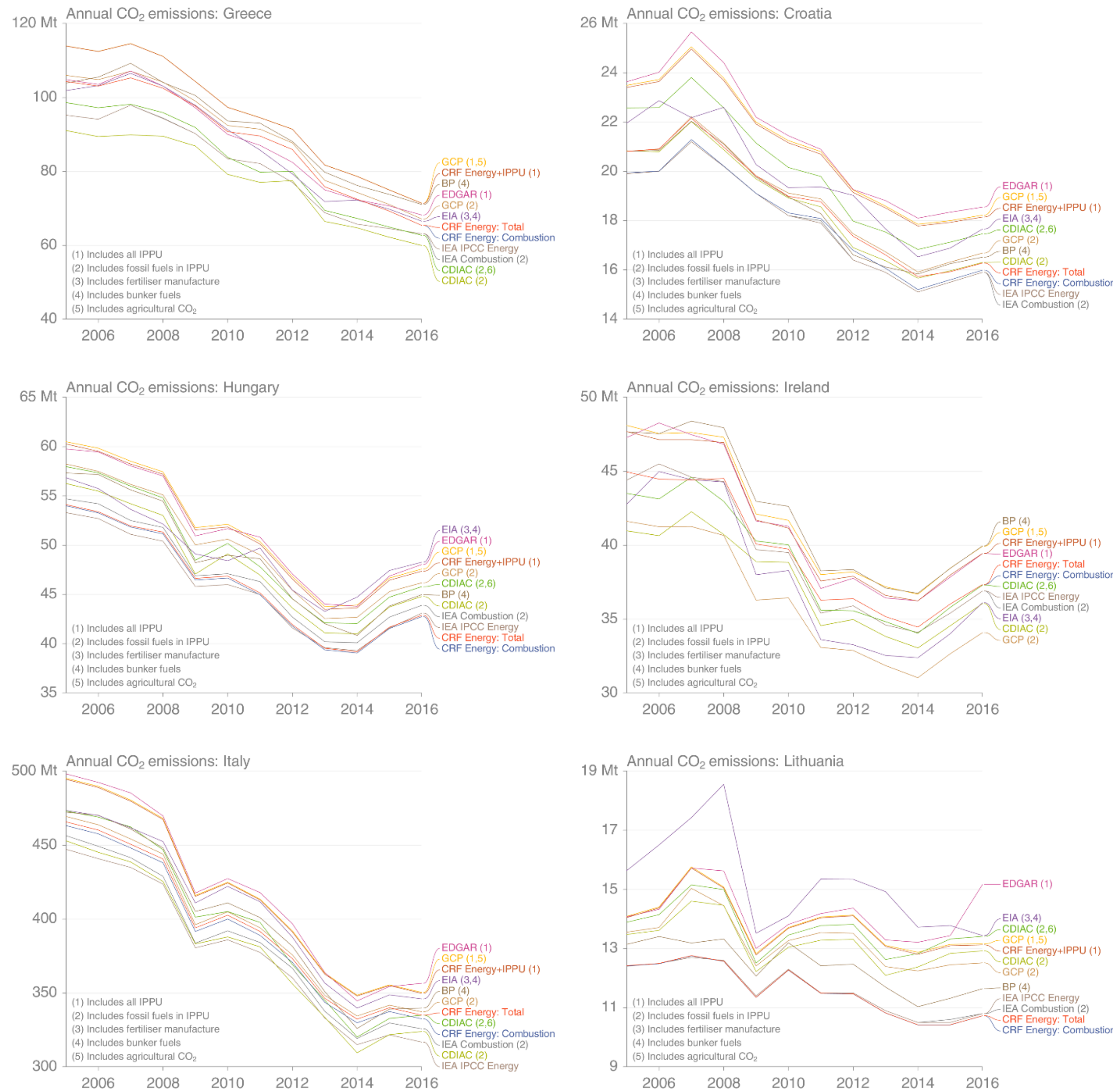

Figure 32: Annual CO_2 emissions for EU28 countries from various sources. For details see text.

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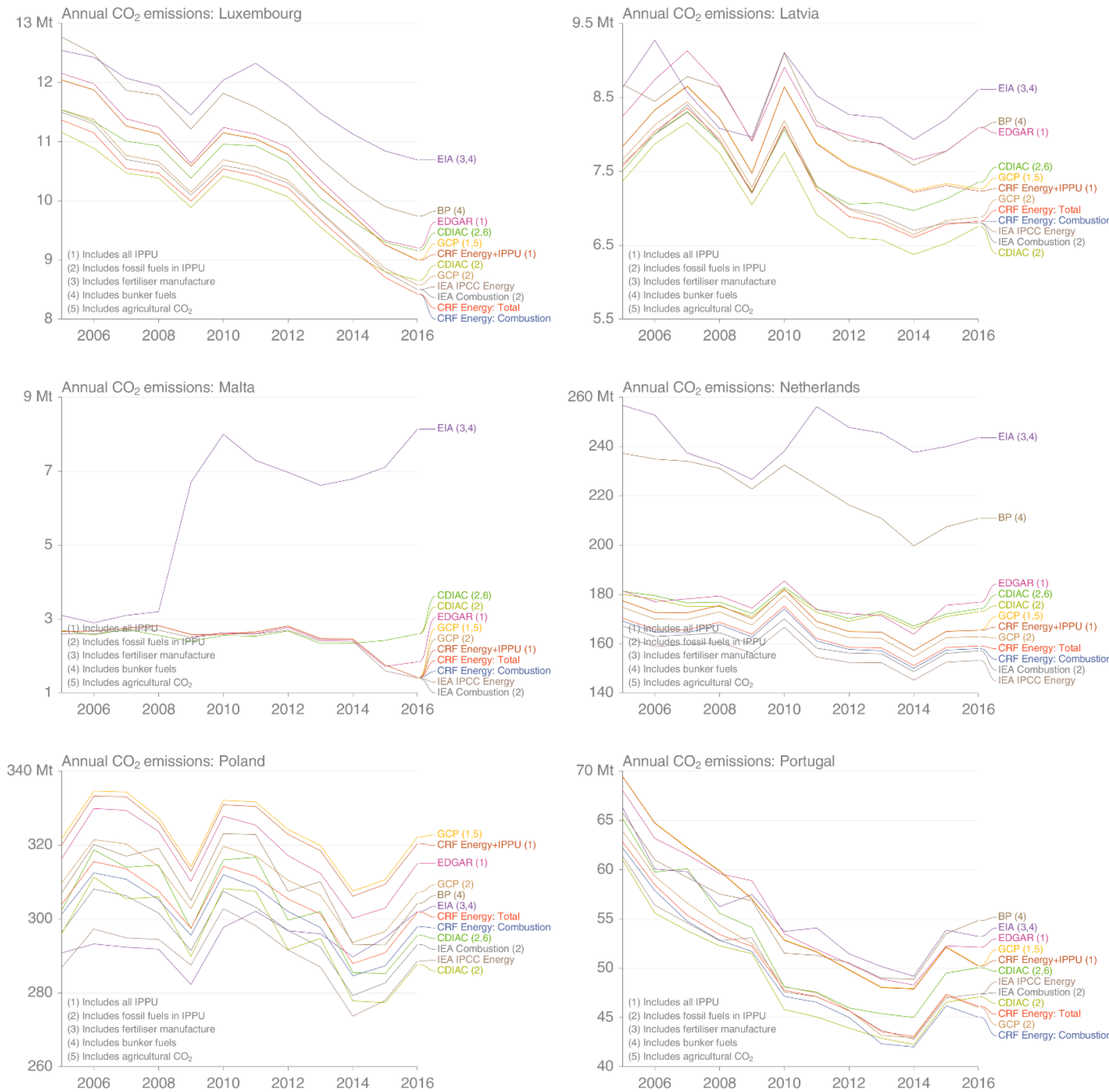

Figure 33: Annual CO_2 emissions for EU28 countries from various sources. For details see text.

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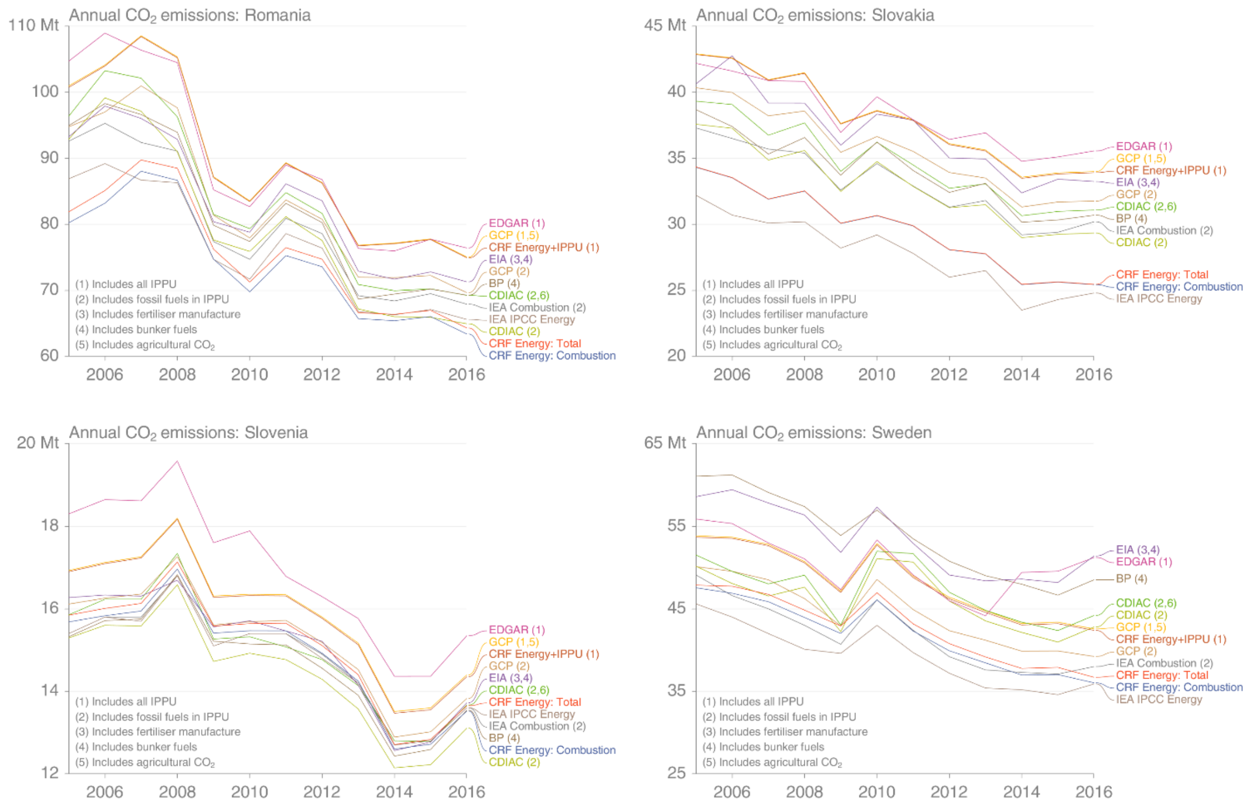

Figure 34: Annual CO_2 emissions for EU28 countries from various sources. For details see text.

2.5. Gridded Emissions Datasets

This section may be expanded in a future revision of this report. A good overview has been made by Andres et al. (2012b).

- CDIAC: initially used gridded population
- ODIAC (Oda and Maksyutov, 2011; Oda et al., 2018): National emissions (CDIAC), nightlight (NOAA/NASA), point-source power plants (CARMA), international shipping (EDGAR v4.1), aviation (AERO2k: 2002 only)
- EDGAR (Janssens-Maenhout et al., 2012): urban and rural population, road network, inland waterways, aviation and international shipping trajectories, along with point locations for individual plants and industrial activity locations, such as power plants, iron and steel plants, cement production facilities, coal mines, and oil and gas production sites.
- FFDAS (Asefi-Najafabady et al., 2014)
- CEDS
- PKU-FUEL (Chen et al., 2016): Peking University http://inventory.pku.edu.cn

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- Data 1960-2014, energy emissions from IEA energy data, implies use of 2016 edition

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3. Land-based CO_2 Emissions

About 10% of global CO_2 emissions are from net-forest loss and around one-quarter of global CO_2 emissions are reabsorbed in the forest sink (Le Quéré et al., 2018b). Land-based CO_2 emissions are clearly important from a climate perspective. While fossil CO_2 emissions currently dominate the emission sources, forests have played a significant role in the past (source), currently (sink), and this role will continue in the future (source and sink). Despite the importance of the forests, it has significant uncertainty in terms of terminology, methods, and data.

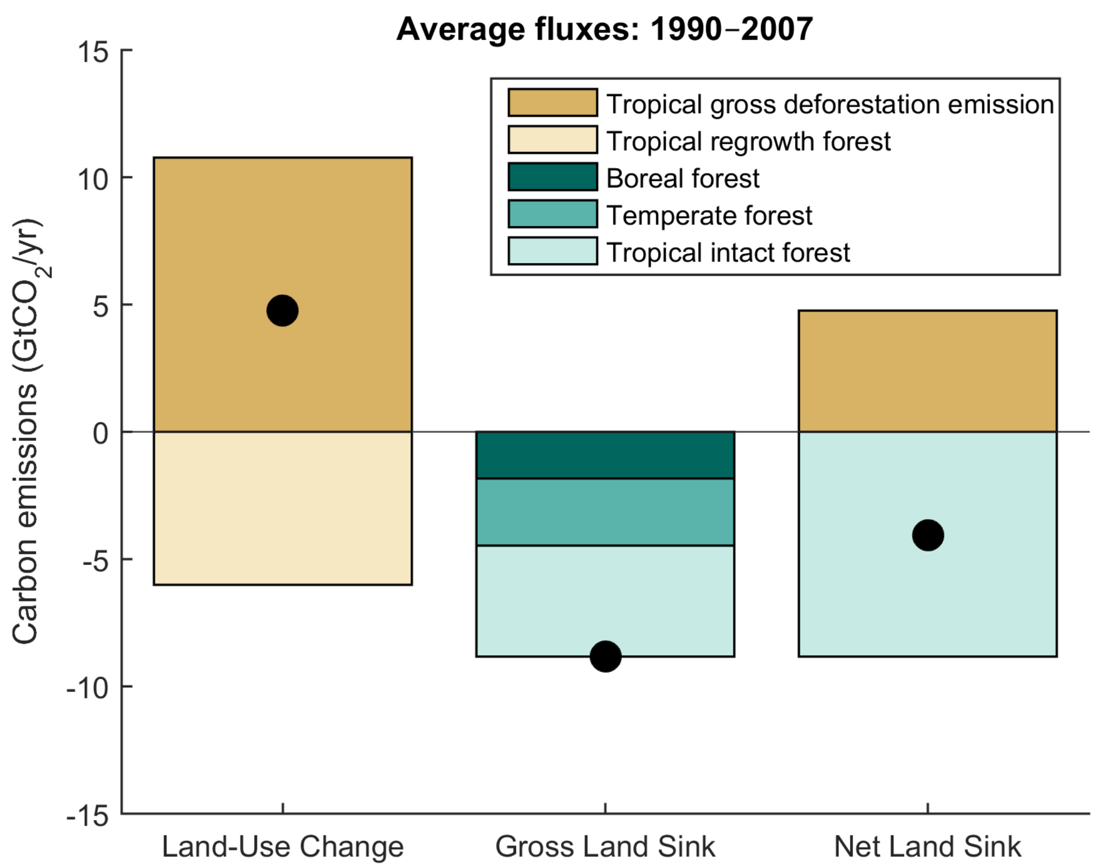

Figure 35: Estimated sources and sinks from forests, showing that direct land-use changes can have positive (deforestation) and negative (afforestation) fluxes, with the sinks primarily driven by environmental factors. While deforestation and afforestation also occurs in boreal and temperate regions, it is only disaggregated for tropical forests (Pan et al., 2011).

In recent decades, about 5GtCO_2 per year are emitted from land-use change (deforestation and afforestation) and about 8GtCO_2 per year taken up in the global forest sink, making forests a net

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sink of around 4GtCO_2 per year (Pan et al., 2011) (Figure 35). However, these numbers hide underlying dynamics. Global forest loss is the difference between deforestation (11GtCO_2 per year) and afforestation (6GtCO_2 per year). Considering afforestation and the forest sink together, they take up nearly 15GtCO_2 per year. Most forest loss is in the tropics, while boreal and temperate forests make meaningful contributions to the sink (about one-half of the sink). Though, the sink may represent a recovery from poor forest management in the past. While there is considerable uncertainty in these global estimates, independent data and models show broadly the same results (Le Quéré et al., 2018b). However, when translating these global numbers to the country level, the uncertainties are magnified considerably. The uncertainty not only lies in the underlying data and methods, but also definitions.

A key point of confusion in the land sector is different definitions used by scientists and inventory experts (Grassi et al., 2018a) (Figure 36). Broadly speaking, land fluxes can be differentiated into three processes: 1) Direct (land-use change, harvest, other management), 2) Indirect (changes induced by climate change, CO_2 fertilisation, etc), 3) Natural effects (disturbances, interannual variability). Compounding these differences are alternatives ways of defining managed land.

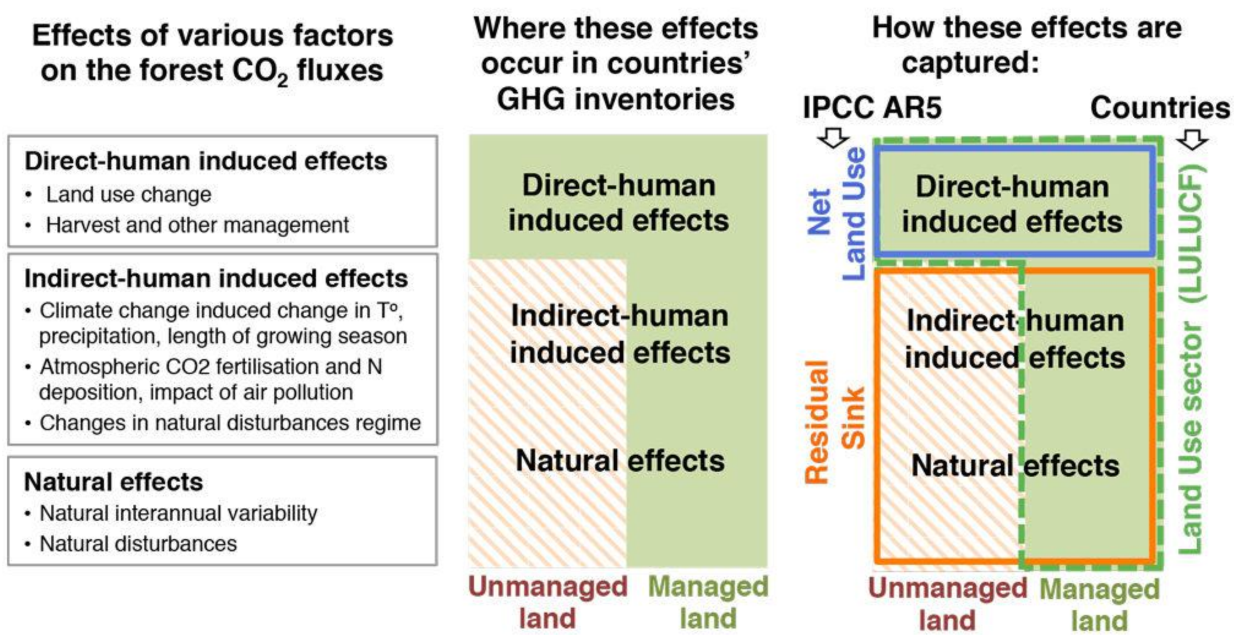

Figure 36: Different definitions of land-use change emissions and the residual land sink between scientific studies and inventory reports.

Scientific studies generally use different definitions of land-use emissions depending on the type of model. *Bookkeeping approaches* consider anthropogenic land-use change emissions to cover only direct effects on managed land (Le Quéré et al., 2018b), with other land areas and processes (indirect and natural) determining the land sink (Figure 35). *Dynamic Global*

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Vegetation Models (DGVMs) can either include direct, indirect, and natural processes on managed land or consider only direct processes on managed land (Le Quéré et al., 2018b).

National Inventory Reports (NIRs) use the notion of "managed land" as a proxy for "anthropogenic" land-use emissions. Managed land is defined as "land where human interventions and practices have been applied to perform production, ecological or social functions" (IPCC, 2006), and covers direct, indirect, and natural processes. Countries determine the anthropogenic emissions for reporting using the notion of managed land, but the definition generally varies by country making comparisons difficult and not all the reported emissions may contribute to a mitigation target (Grassi et al., 2018b).

The differences between scientific studies and NIRs is not trivial, with the current gap between scientific and inventory estimates around 4-5GtCO_2/yr (Grassi et al., 2018a). With more aggressive mitigation targets (e.g., to be consistent with 1.5°C of global warming) or with the need for verification of emissions, whether fossil, bioenergy, or land-based, there is a greater need for comparability between scientific and inventory-based studies.

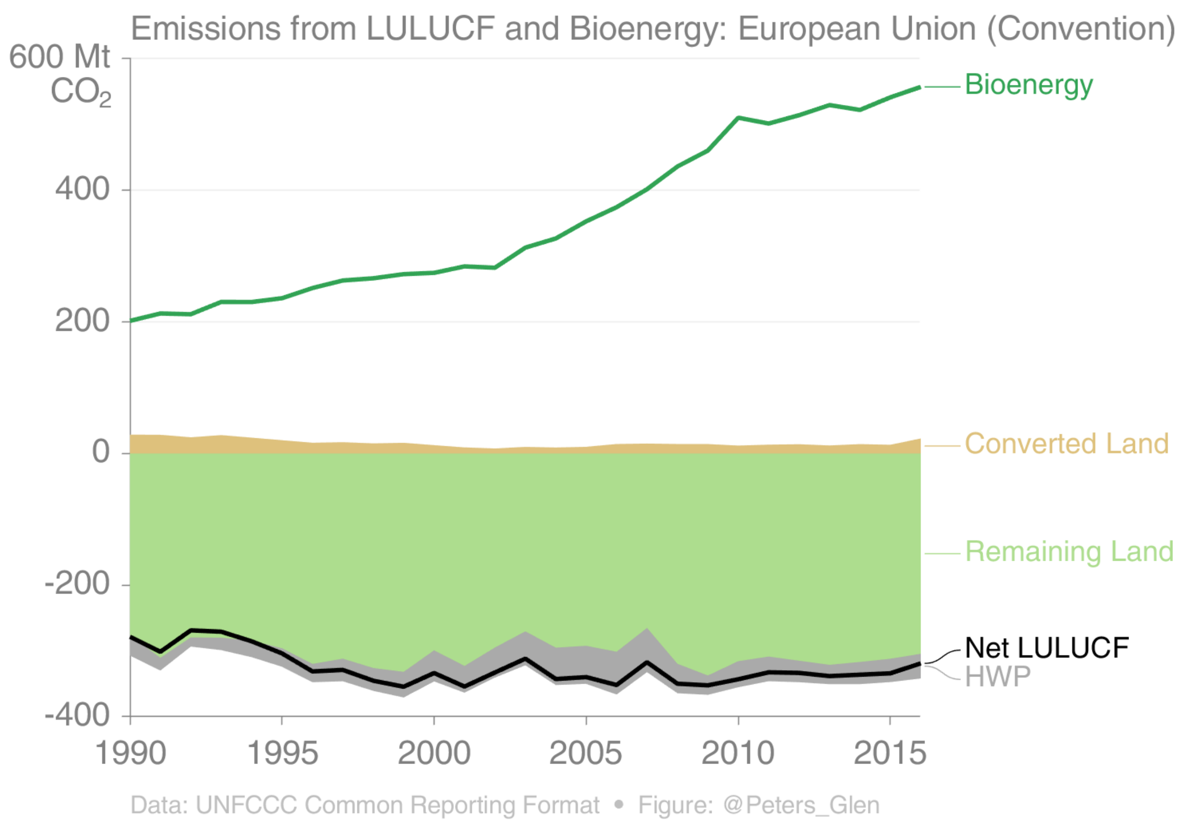

Figure 37: The National Inventory Report for CO_2 emissions from land use, land-use change, and forestry, in addition to the estimate CO_2 emissions from bioenergy use in the EU28.

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In a policy context, the National Inventory Reports (NIRs) to the UNFCCC are a critical reference point for comparability as this defines how countries currently report emissions. The NIRs report emissions from managed land split into forest lands, croplands, grasslands, wetlands, settlements, and other lands. The CO_2 emissions on managed land are separated into land converted from one type to another (Converted Land), land that retains the same land use (Remaining Land), stock changes in Harvested Wood Product (HWP) pools, and CO_2 emissions from bioenergy use (Figure 37). Once land is converted, the IPCC default is that it retains converted status for 20 years before it enters the remaining category. The CO_2 emissions from bioenergy are reported as a memo in the energy sector and not allocated to total emissions as they are implicitly reported in gains and losses of forest (see below). For other land types, the change in biomass is only estimated for perennial woody crops. For annual crops, increase in biomass stocks in a single year is assumed equal to biomass losses from harvest and mortality in that same year. Converted land is where one land type has changed from one category to another in consecutive years (e.g., forest land to cropland), and is, by definition, managed and hence anthropogenic. Land that remains unchanged (e.g., forest land remains forest land) may still be actively managed and have associated emissions (e.g., forestry in the forest land case). Both converted and remaining land include direct effects and most of indirect and natural effects depending on the method used (Grassi et al., 2018a).

The NIRs report carbon stock changes, relating to both harvest, regrowth, and other management (whether production, ecological, or social). The dynamics of harvest and regrowth make definitions ambiguous (Gasser and Ciais, 2013; Pongratz et al., 2014). The harvest leads to an immediate decrease in the carbon stock on the forest, but not necessarily an immediate release of CO_2. Carbon can remain stored in Harvested Wood Products (HWP) for extended periods (Pingoud et al., 2006a). In principle HWPs include all wood material (including bark) that leaves harvest sites, but the lifetime will vary with use. HWPs are split into three semi-finished products, sawn wood, wood-based panels and paper & paperboard, with default half-lives of 35, 25 and 2 years, respectively. The CO_2 emissions from bioenergy, that are either harvested directly or are outputs of the HWPs pool, are reported as a memo, but not allocated to the energy sector on the basis that any associated emissions are already captured in the LULUCF sector. This bioenergy convention can change for emission accounting.

In the following sections, we give an overview of the key challenges with land-based emissions, bioenergy use, and harvested wood products. We will not quantify the differences at the detailed level, as that will be performed in other parts of the VERIFY project.

3.1. Land fluxes

The Global Carbon Budget is based on scientific studies and can be represented by the balance equation

$E_F + E_L = G_{ATM} + S_O + S_L + B_{im}$

where E_F are the fossil-based emissions (section 2), E_L is the CO_2 emissions from land-use change (however defined), G_{ATM} is the atmosphere growth rate, S_O is the ocean sink, S_L is the land sink

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(however defined), and B_{im} is the "budget imbalance". Each term in the Global Carbon Budget is estimated independently, and the budget imbalance is since we can't quantify each term and its variability precisely (Le Quéré et al., 2018b). Prior to the 2017 release, the budget imbalance was not included, and the land sink was taken as the residual of all other components. The net land emissions are taken as $N_L = E_L - S_L$.

The NIRs consider the land flux to be

$E_{NIR} = C + R + H$

where C is the net emissions from converted land, R from remaining land, and H from harvested wood products. Each term includes net emissions from direct, indirect, and natural effects, e.g., $C=C_{direct}+C_{indirect}+C_{natural}$. Bioenergy, B, has emissions reported as a memo in the energy sector, on the assumption that the change in stock in the land sector (emissions from harvest) is captured in converted or remaining land. The E_{NIR} only includes managed land, and uptake in unmanaged land (indirect and natural) would provide the sink, S_{NIR} (not estimates), and the net land sink would be $N_{NIR} = E_{NIR} – S_{NIR}$.

The different definitions and concepts used by the scientific and inventory communities means that the land fluxes, E_L and E_{NIR}, are not comparable, nor are the sinks. The framework developed by Grassi et al. (2018a) can be generalized to make a more direct comparison (Figure 36). Figure 38 disaggregates managed forest land into components that are reported in the UNFCCC NIRs: converted land (e.g., land changing from cropland to forest land), Harvested Wood Products (HWPs), and the remaining land (e.g., forest land remaining forest land) is split into land that is "production" (forestry) or land that is used for "ecological or social functions", based on the definitions of managed land. Unmanaged land cannot have direct human induced effects. The figure conceptually has area along the horizontal axis, the vertical axis represents emissions per unit area, and so the area of each box is the emissions on that land area for each process. The horizontal axis should add to the total forest land (or all land if croplands, grasslands, settlements, wetlands, and other land are included). In the conceptual figure all areas and emissions are identical, which is just for illustrative purposes. In the EU subsection below, the areas of the individual boxes will be discussed in more detail.

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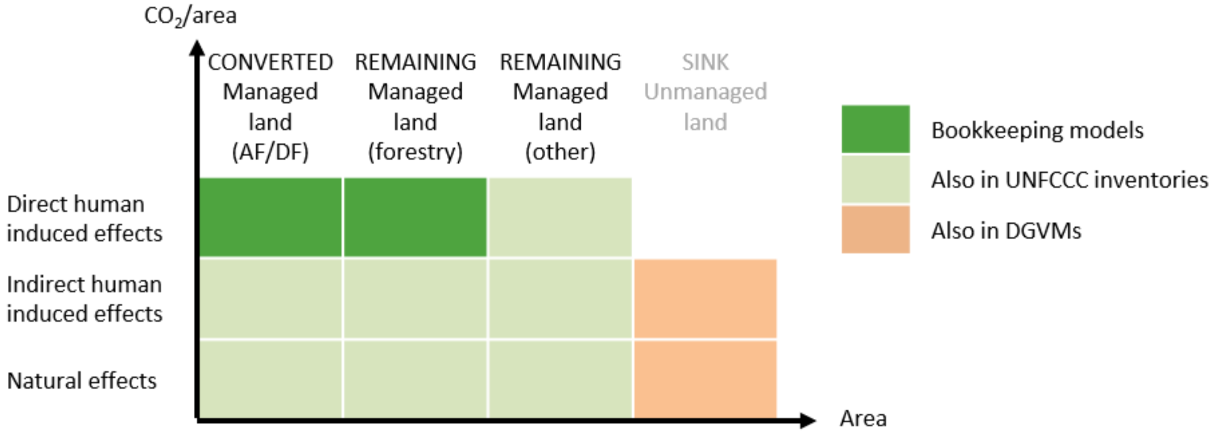

Figure 38: A conceptual extension of Figure 36 to disaggregate the managed land into three different components, showing how they map to components reported in the UNFCCC inventories. The converted land is equivalent to afforestation (AF) plus deforestation (DF). Remaining land is split into forestry and other (ecological and social functions). Bookkeeping models (Hansis et al., 2015; Houghton and Nassikas, 2017) include only the dark green components (direct managed land), NIRs include all green components (direct, indirect, natural on managed land), and DGVMs include all components but often only defined direct managed land as anthropogenic.

Carbon accounting generally considers all gains and losses in forests, and the most significant loss is harvest in most cases (Figure 39). The harvests may either be directly for bioenergy, the HWP pool (semi-finished products), exports, or other (small to negligible). Bioenergy may originate from direct harvest, indirectly as a byproduct, indirectly from energy recovery of HWPs, from other land types (e.g., woody perennials on cropland), other sources (such as cooking oil), or from trade. The HWPs following three semi-finished products represent products removed from domestic forests and produced for domestic consumption and for export. The harvest for direct exports does not enter HWPs. Figure 39 is largely conceptual, but different subsections below will tease out the HWPs and bioenergy.

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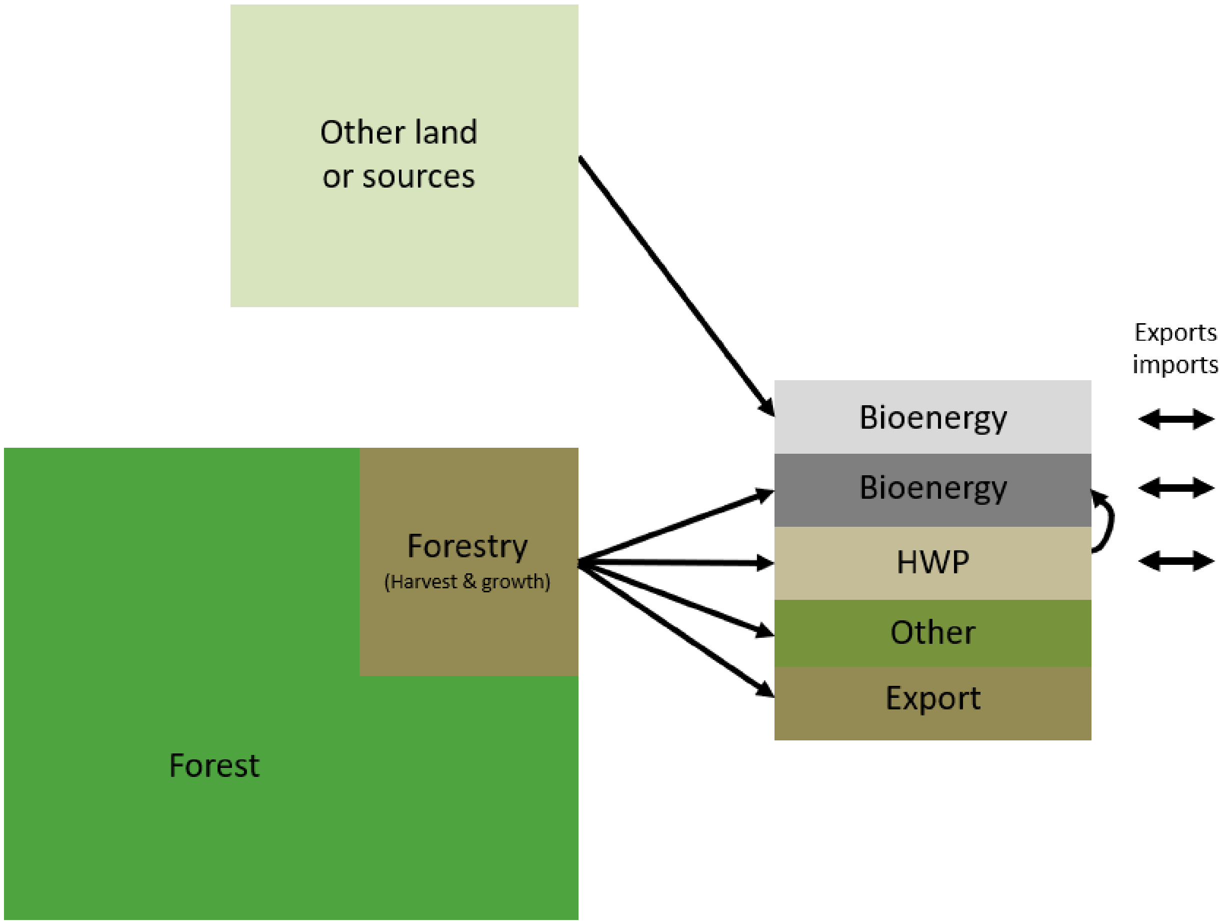

Figure 39: A schematic to illustrate that a section of forests may be harvested, with the harvest going to directly to bioenergy, to HWPs (sawnwood, wood-based panels and paper & paperboard), to export, or other uses not covered (small). Bioenergy can additionally come from non-forest sources (e.g., cropland) or energy-recovery from HWPs. Exports and imports can add to each of these flows.

3.1.1. Comparison of different land fluxes (Global)

Figure 40 shows the land-use change emissions from several independent data sources at the global level. The figures include the following datasets:

- BLUE (Hansis et al., 2015) is a spatially explicit (half degree grid) bookkeeping model that tracks individual histories of successive LULCC events in each grid cell. Estimates for peat burning and peat drainage are included (Le Quéré et al., 2018b);
- Houghton and Nassikas (2017) is a country-level bookkeeping model, that tracks land use and land cover (croplands, pastures, plantations, industrial wood harvest, and

fuelwood harvest) in four carbon pools (living aboveground and belowground biomass; dead biomass; harvested wood products; and soil organic carbon);

- Global Carbon Budget (GCB) is the average of the BLUE and Houghton and Nassikas bookkeeping models (Le Quéré et al., 2018b);
- Food and Agriculture Organization (FAO) tracks net carbon stock change in the living biomass pool (aboveground and belowground) associated with forests and net forest conversion using an IPCC Tier 1 stock difference method (IPCC, 2006) and is based purely on country data;
- TRENDY are the DGVM results presented in the Global Carbon Budget (Le Quéré et al., 2018b) with variations in the coverage of each model (Arneth et al., 2017);
- UNFCCC National Inventory Reports (NIRs) are reported by Annex I (essentially developed) countries following the IPCC guidelines (IPCC, 2006) with results only available for Annex I countries.

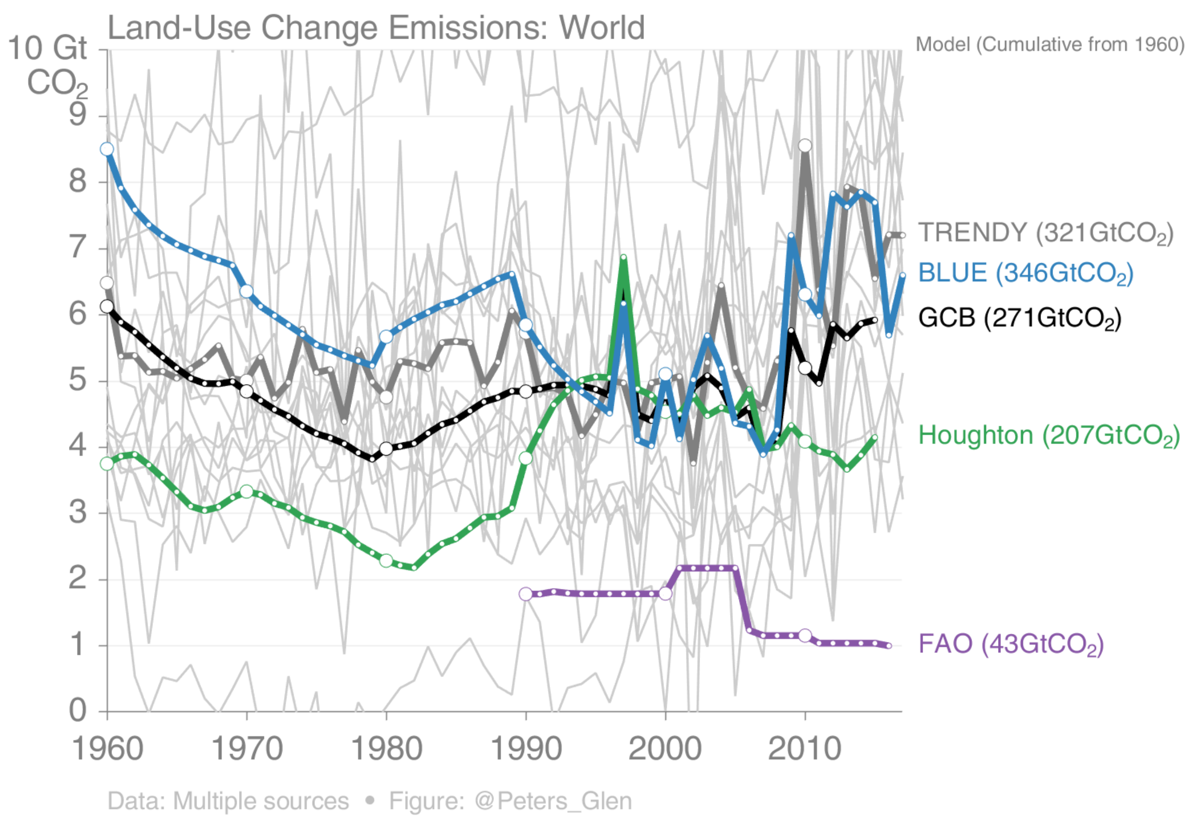

Figure 40: A comparison of independent estimates of the land-use change flux. The heavy grey line (TRENDY) is the average of 16 TRENDY models, shown as thing grey lines. The cumulative emissions for FAO only start in 1990. The text explains each of the models in more detail.

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The estimates in Figure 40 are not directly comparable, because of all the differences in system boundary (Figure 38). The two bookkeeping models consider only direct effects on land managed for production. The FAO estimates follow IPCC reporting guidelines (IPCC, 2006), and therefore include direct, indirect, and natural effects, as well as land managed for ecological and social functions. The DGVMs consider direct, indirect, and natural effects on land managed for production only. Each of the DGVMs also has different system boundaries (Arneth et al., 2017). On top of these differences, each model may use different data or definitions for the land areas (Grassi et al., 2018a). While it may be tempting to assign uncertainties to land-use emissions based on the spread in the figure, in practice, the data should first be corrected to a consistent system boundary (Grassi et al., 2018a).

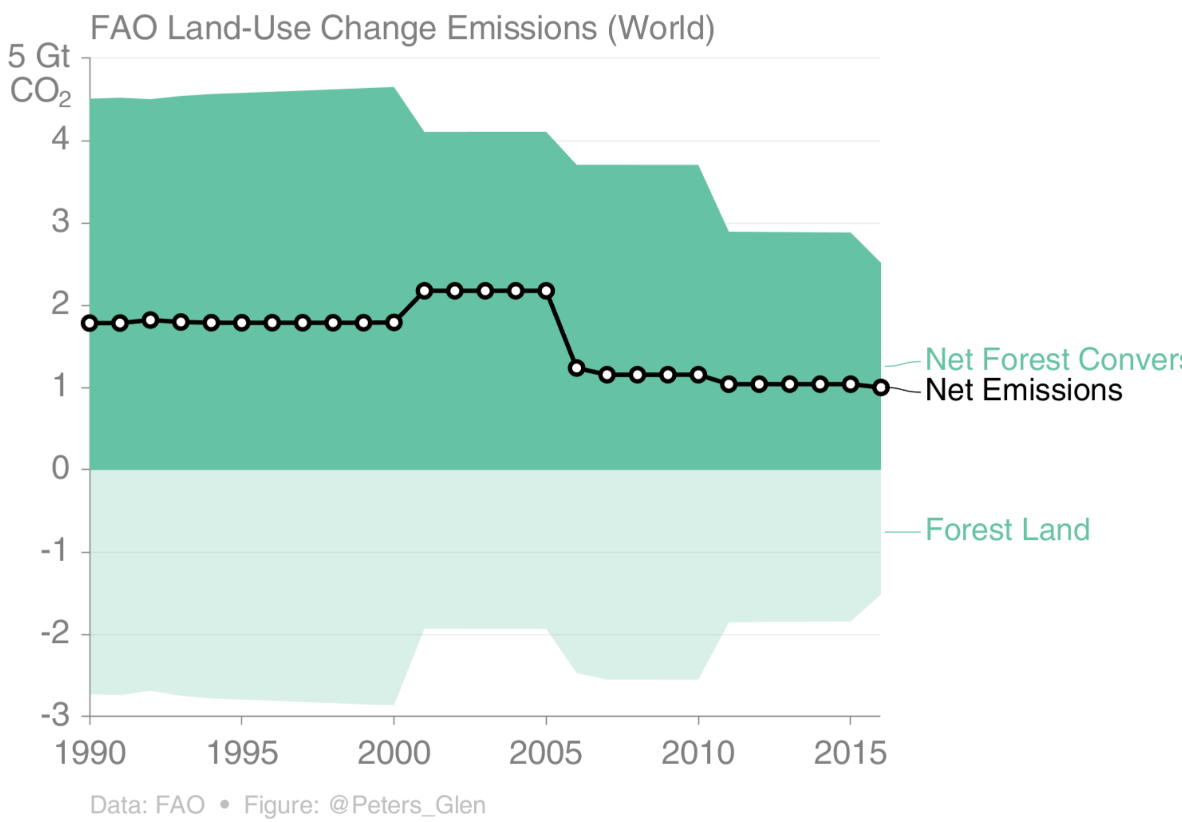

Figure 41: FAO by component, excluding the cropland, grassland, and biomass burning components. The net emissions equal what is shown in the previous figure.

The FAO results are much lower than the others, and approximate the approach used by the UNFCCC NIRs. Figure 41 shows the FAO estimates for forest land, split into a component for net forest conversation (afforestation and deforestation, with direct, indirect and natural effects) and forest land (e.g., forestry and other management including direct, indirect, and natural effects). There are two core differences with other estimates: first, the managed area, and second, the carbon density additionally includes indirect and natural effects. Without similar data from the other estimates, it is not possible to determine whether the net forest conversion

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is higher in other estimates or the forest land smaller. An earlier study shows that both managed areas and indirect and natural effects are both important to explain the differences, though the relative effects vary by region (Grassi et al., 2018a).

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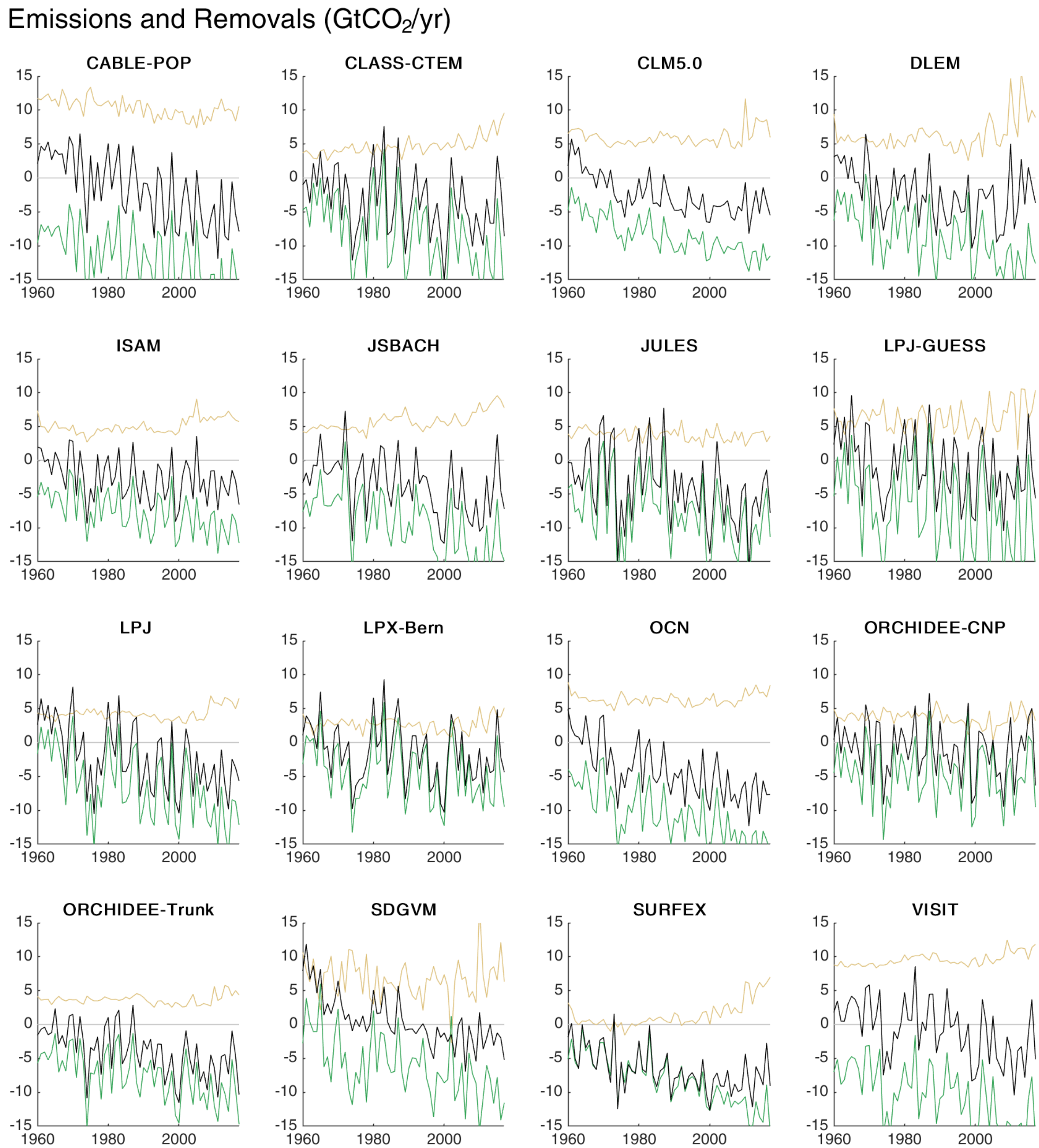

Figure 42: Sixteen TRENDY models used in the 2018 Global Carbon Budget, showing the sources and sinks. The figure shows the anthropogenic land-flux (brown), sink (green), and net (difference of the two).

Only the DGVMs report land fluxes on the (unmanaged) land sink (Le Quéré et al., 2018b). Sixteen TRENDY models were included in the 2018 Global Carbon Budget (Figure 42), with large

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variations in land fluxes and therefore net emissions. Each of these models, in turn, differs from the other available estimates (Figure 40). Understanding these differences (Arneth et al., 2017) is a part of ongoing research (Le Quéré et al., 2018b), including in the VERIFY and other EU projects.

3.1.2. Comparison of different land fluxes (EU28)

Figure 43 shows different independent estimates of the land-use change flux for the EU28, including now the UNFCCC NIRs but excluding the DGVMs. Given the variations at the global level, it is rather surprising that the EU level has similar results across estimates (Grassi et al., 2018a). Given this, it is possible to conceptually detail Figure 38 further by drawing on some quantitative EU28 results. According to FAO and UNFCCC NIRs, the net forest conversion is relatively small in the EU, as is the HWPs net flux (Figure 37). That the UNFCCC NIRs and bookkeeping estimates are similar implies that the managed areas and indirect and natural effects must be of similar magnitude, or balance in ways that give the appearance of similarity. The EU is known to have a very small unmanaged land area. Combining these snippets of information together, it suggests that most of the LULUCF emissions in the EU28 are from direct effects in the forestry sector (Figure 44).

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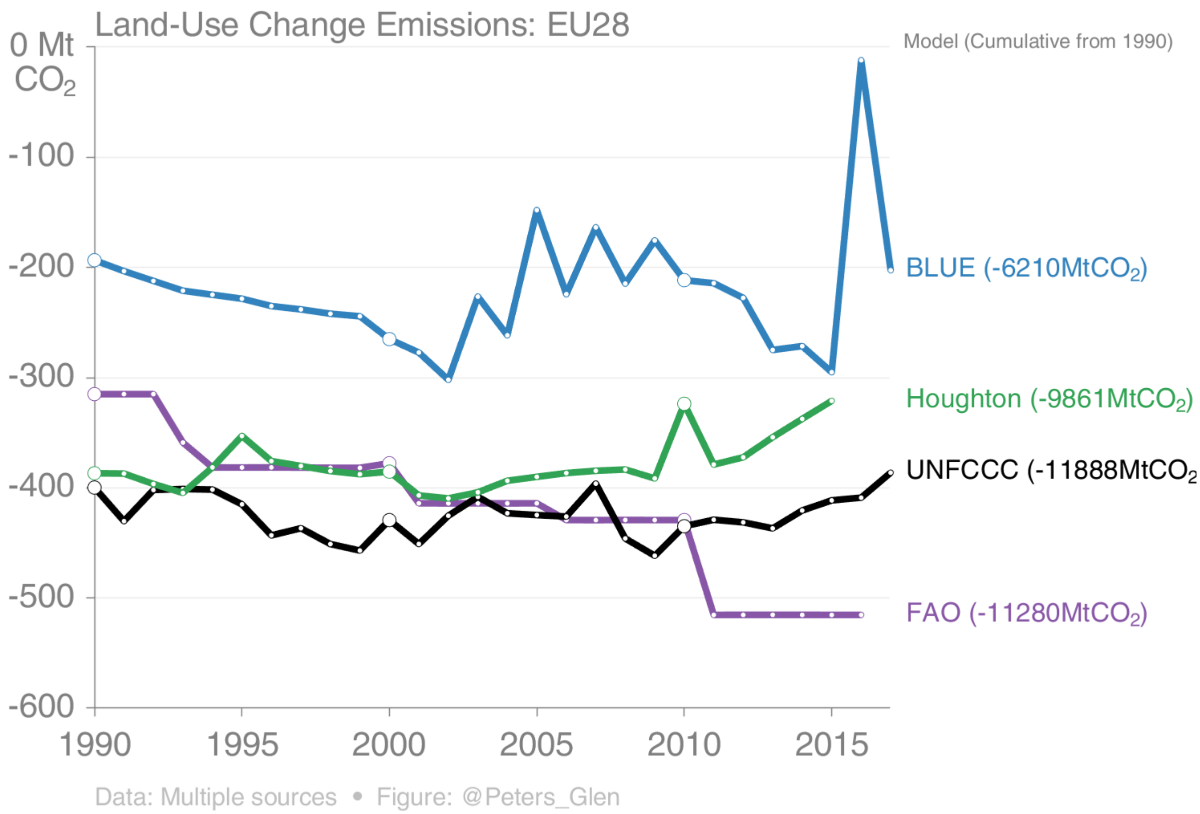

Figure 43: A comparison of independent estimates of the land-use change flux in the EU28. The UNFCCC estimate includes only forests (land converted to forests or land remaining forest).

Even though Figure 44 remains conceptual, it does give an interesting perspective and application of Figure 38. According to this simple analysis the EU land flux is dominated by direct effects in the managed forest sector, with minimal emissions in land conversion (from NIRs). With appropriate data and models, it is theoretically possible to expand enumerate the figure more accurately. This could be repeated for other countries or regions and is one way to provide more detailed and comparable data across independent estimates of land fluxes. Based on the findings in the VERIFY project (WP3), it may be possible to construct this figure more accurately for the case of the EU28.

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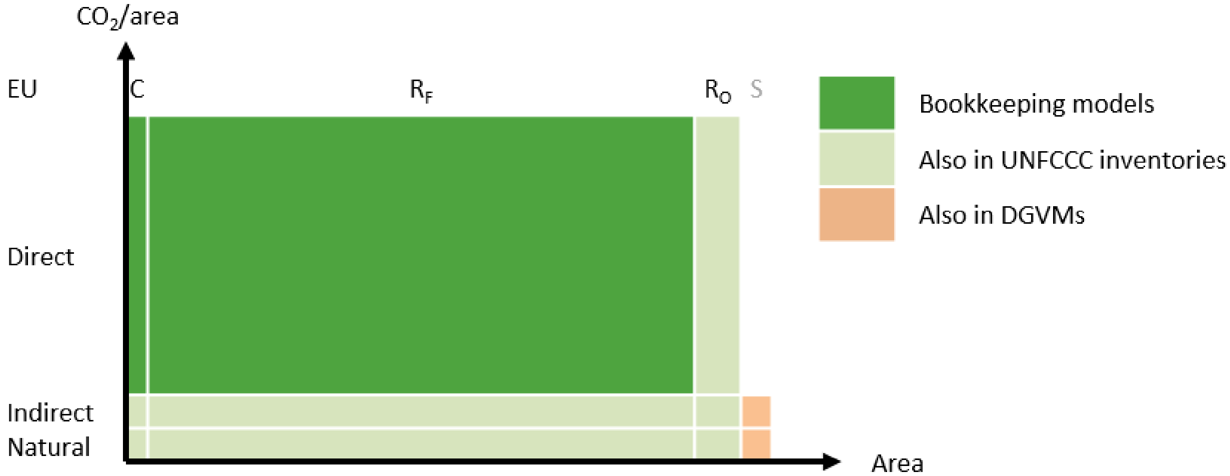

Figure 44: A conceptual extension of Figure 38 to the EU level, using NIRs and bookkeeping models to infer the conceptual differences in magnitude for each factor. It is conceptually possible to estimate each of these terms more concretely, using a combination of models and data.

3.2. Harvested Wood Products

Forest products that are harvested (either deforestation or managed forestry) do not necessarily lead to immediate release of CO_2 emissions. Harvested material (Figure 45) may be used for bioenergy and lead to CO_2 emissions soon after harvest (next section) or enter various products pools that slowly emit CO_2 over an extended period (known as Harvested Wood Products). Harvests that are used for paper may release CO_2 in a matter of years, while harvests that lead to furniture or housing may release CO_2 over decades. The NIR focuses on industrial sawn wood, wood-based panels, and paper and paperboard, and therefor may not capture all harvests. Other than bioenergy, there may be additional harvest associated with clothing, food, or fodder.

Figure 45 shows the complexities of wood harvests for the EU (Cazzaniga et al., 2019). Of the total wood removals (658Mm^3), 42% are used directly for energy while the remainder enter the HWP pool. However, some HWP byproducts or end-of-life products are ultimately used for bioenergy. In 2015, the EU wood removal directly for energy was 279Mm^3, but bioenergy was around 451Mm^3 due to the use of bioenergy as a byproduct or from post-consumer goods. It total, 70% of the EU wood harvest was associated with bioenergy. Some of the flows that receive most attention or debate, such as wood pellets, are only a very small fraction of the total flows.

Accounting for HWPs has always been contentious with many different approaches possible (Pingoud et al., 2006b). There are also considerably challenges in estimating the flows out of the HWP pools (Mason Earles et al., 2012). In the context of verification, it is also important to have a good understanding of the exports and imports of HWPs, in addition to crops (Peters et al.,

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2012). HWP provides an important potential for mitigation by extending the life of products in HWP pools, but also compete with other forest uses (such as bioenergy). The complexities and potential of HWPs have recently been explored for Europe (Pilli et al., 2015). HWPs will not be considered further in this report.

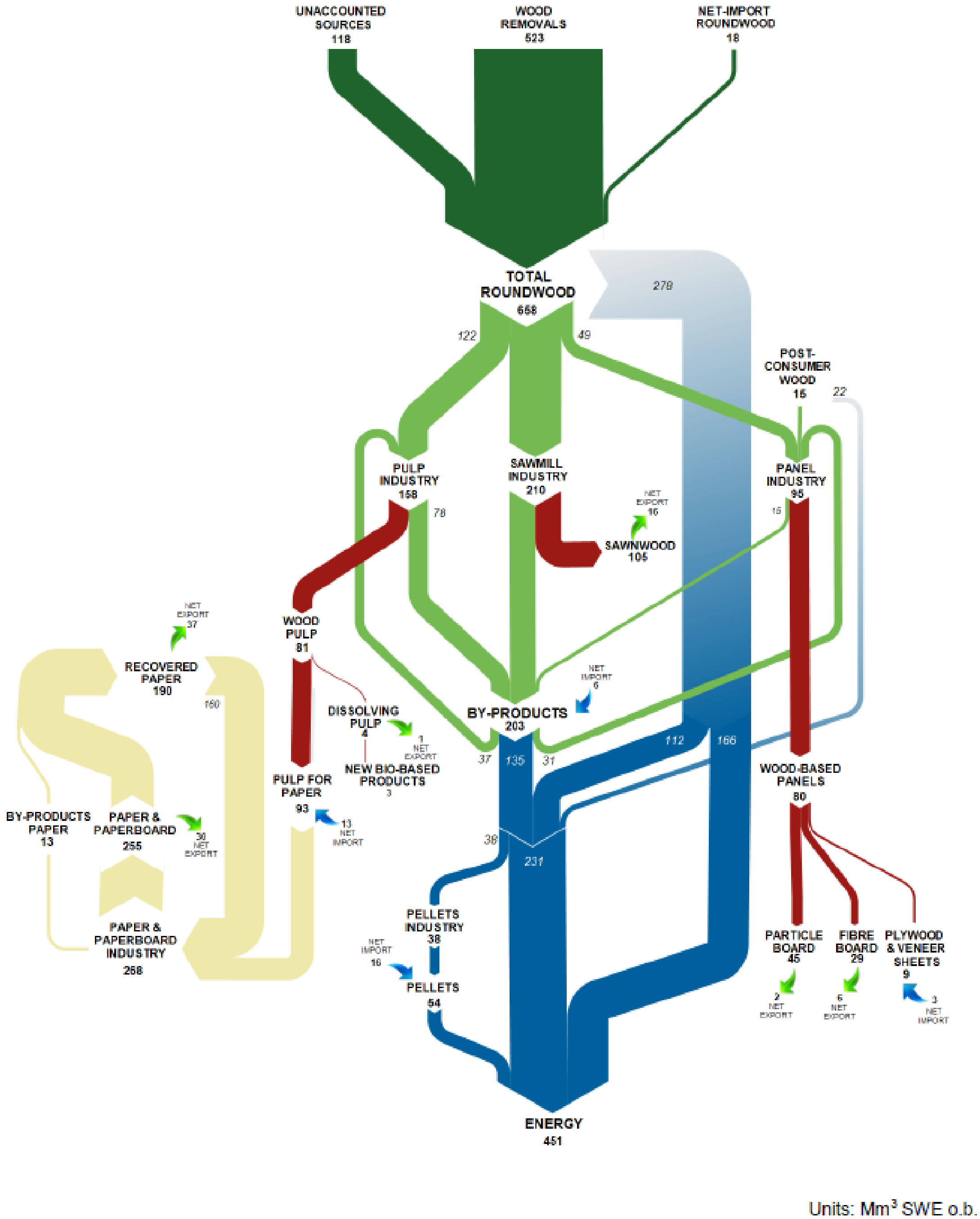

Figure 45: Sankey diagrams of woody biomass flows in the EU-28 (Cazzaniga et al., 2019).

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3.3. Bioenergy

In the IPCC Guidelines, bioenergy emissions are not allocated to the energy sector but are reported as a memo. This implies bioenergy is carbon neutral in the energy sector, but to compensate the emissions are captured as a harvest (stock change) in the LULUCF sector. If the harvest is replaced by regrowth elsewhere in the managed forest (zero stock change), then carbon neutrality is achieved. If the harvest is not replaced by regrowth (reduced carbon stock in managed forests) then carbon neutrality is not achieved. This approach to bioenergy has been heavily critiqued in the past (Searchinger et al., 2009), but was used to deal with the complexities of the interaction between the land and bioenergy sectors and to not penalize bioenergy relative to coal (Pingoud et al., 2010).

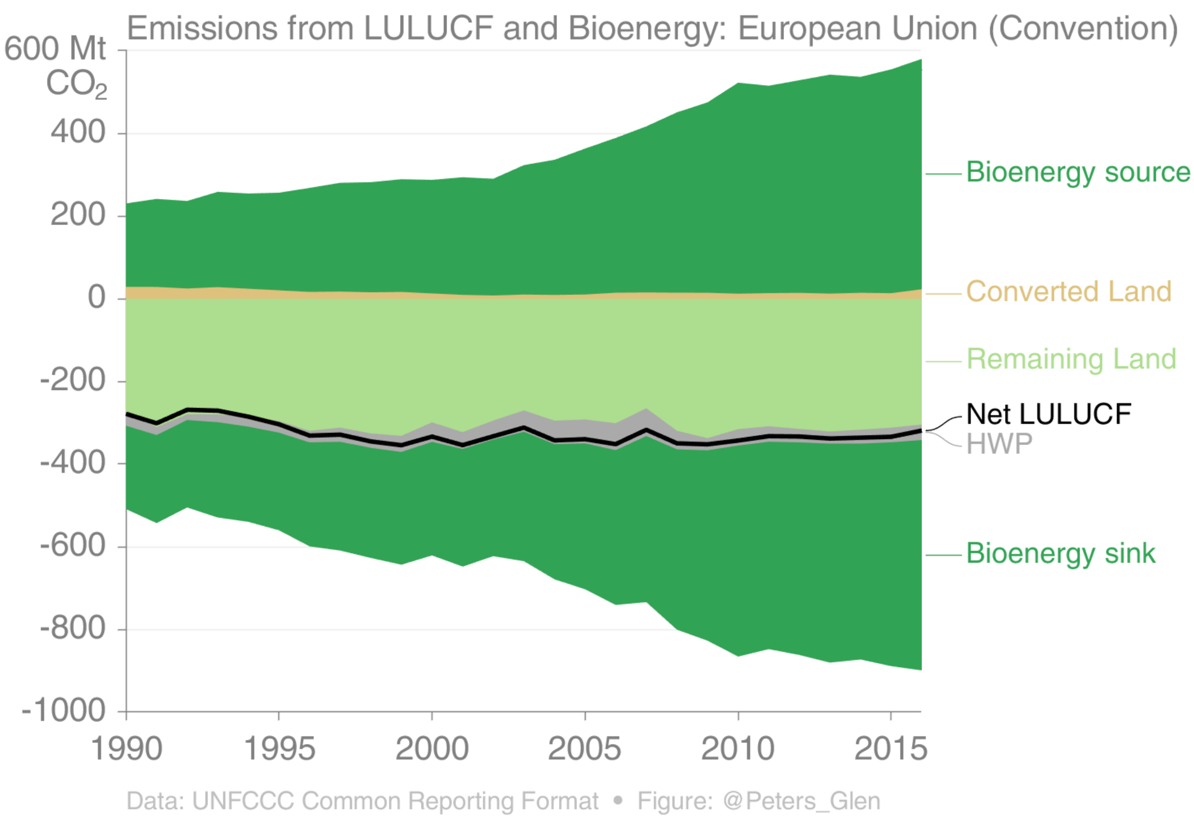

Figure 46: An illustrative extension of the land fluxes in the EU (Figure 37) to show what would happen if the bioenergy was allocated as emissions, and the implied sink that is required to produce the harvested bioenergy. The net emissions are the same, as full carbon neutrality is assumed.

Figure 37 shows the extent of bioenergy (as reported as a memo) compared to the land-flux in the EU. For illustrative purposes, bioenergy is allocated as an emission source, requiring a sink of the same size to achieve carbon neutrality. As the forest is constantly in production (harvest

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and regrowth) it is not possible to determine how large the hypothetical sink would have been to achieve carbon neutrality, but the figure illustrates that bioenergy is the largest in the land sector. If carbon neutrality was achieved, then the total sink (including associated with bioenergy) would be around 900MtCO_2 per year in the EU, much larger than the reported sink of around 300MtCO_2 per year.

Because land used for bioenergy and HWPs is not explicitly tracked, it is difficult to assess carbon neutrality. It may be that the bioenergy is not carbon neutral, but this is offset by other forest sinks (e.g., related to HWPs or conservation). It may be that bioenergy is more than carbon neutral, masked by inefficient harvest of HWPs. A further complexity, is that some bioenergy originates outside of the forest sector, may be imported, or may have formally been an HWP (used for later energy recovery as a byproduct or at end-of-life). The complexity of wood flows indicates the challenges in assessing carbon neutrality (Figure 45). These issues are particularly relevant for verification, as the sources and sinks of bioenergy (and HWP) emissions may be located in the incorrect geographic location, and the associated changes will be mixed with fossil CO_2 emissions.

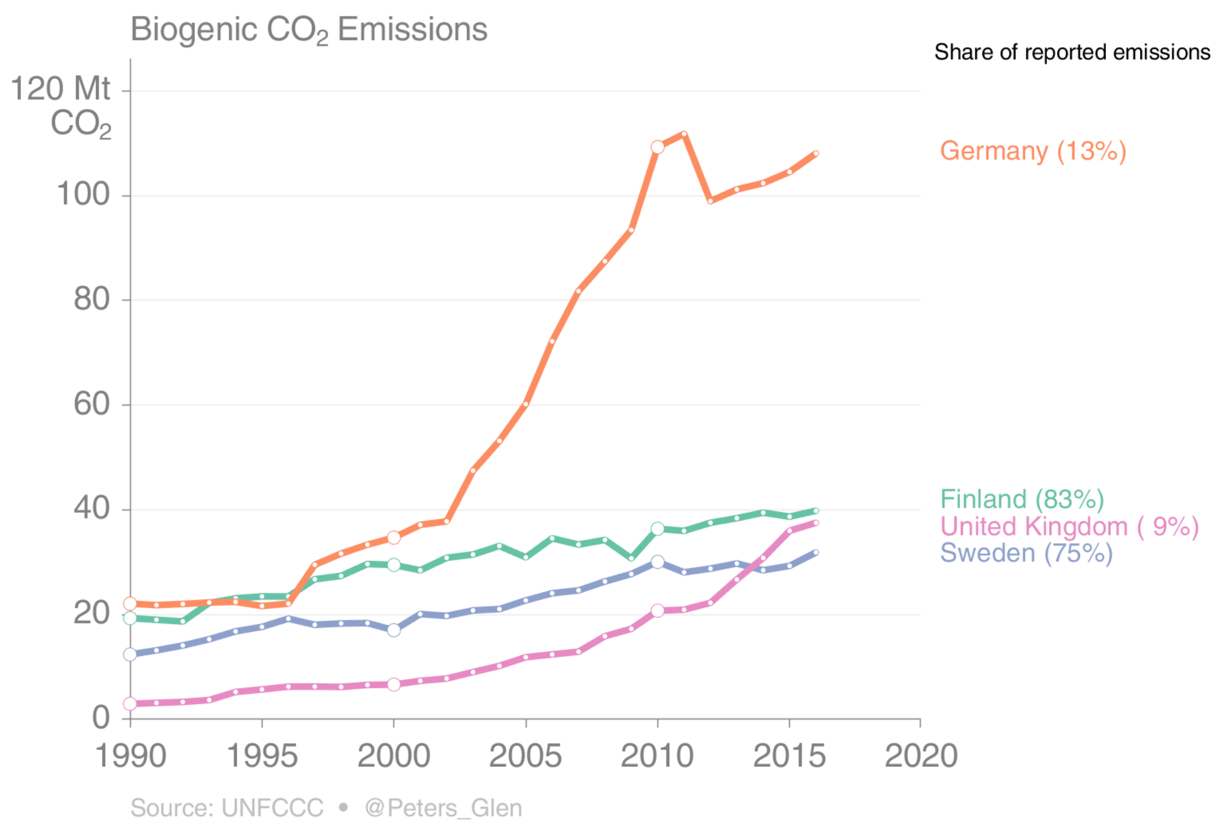

Figure 47: Bioenergy emissions and their share of total emissions for select EU countries indicating the importance of bioenergy compared to fossil CO_2 fluxes.

The potential scale of bioenergy emissions on the land sector is significant in comparison to fossil CO_2 emissions (Figure 47). CO_2 emissions from bioenergy are ~16% the size of fossil CO_2

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emission in the EU, varying considerably by country. In Sweden and Finland, emissions from bioenergy are of a similar size to fossil CO_2 emissions. While for purposes of carbon accounting it may be appropriate to consider bioenergy as a stock change in the land sector, it may be less relevant for top-down verification of CO_2 emissions. It is further a challenge to assess carbon neutrality, as the forest land used for bioenergy is not differentiated from the forest land used for other managed purposes, like HWPs. The possibility to import bioenergy also complicates the assessment of bioenergy and its carbon neutrality. It may therefore be sensible to analyze bioenergy and land interactions outside of the NIR framework, or to extend the framework, to address bioenergy.

Several organizations publish bioenergy use, and thereby it is possible to estimate emissions from independent sources (Figure 48). Not all bioenergy is forest derived or is only indirectly based on forests, potential as a byproduct (Figure 45). Modern biofuels may be based on liquids or other sources (Figure 39), but the largest share of bioenergy in the EU is forest-derived. A small share of the bioenergy is imported (Figure 45).

Input data to bookkeeping models and some other datasets are often based on FAO data, which has less coverage of bioenergy than the IEA (IPCC, 2011). This further complicates the assessment and comparison of the carbon neutrality of bioenergy, across models and sources.

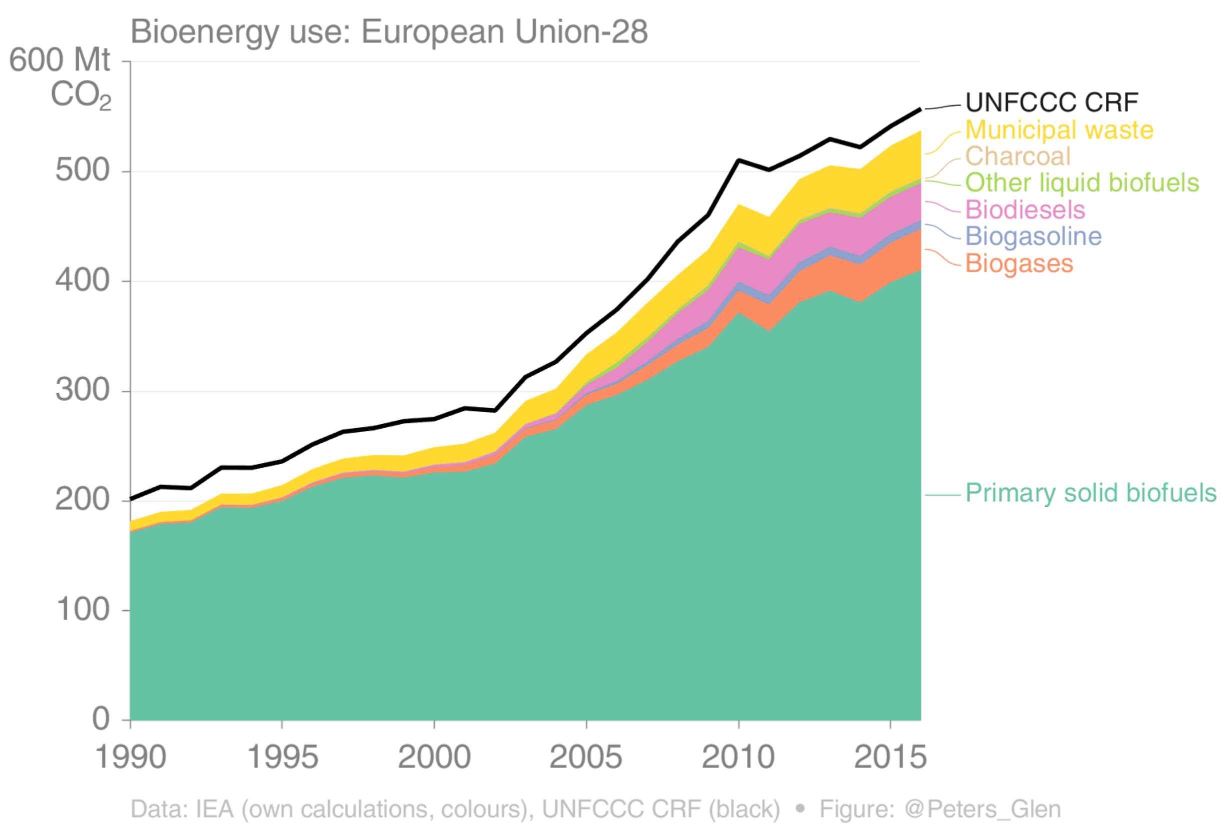

Figure 48: By energy by sources (IEA) compared to UNFCCC CRF.

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It is clear that bioenergy is becoming a more important share of country emissions (Figure 47), and this is likely to increase in a 1.5°C or 2°C world (Rogelj et al., 2018). Due to the way that bioenergy is included in NIRs, it creates challenges with verification and accounting for carbon neutrality (Searchinger et al., 2009). This is further complicated by differences in land-accounting across scientific and inventory approaches (Grassi et al., 2018a). A more detailed assessment of the interaction of bioenergy, HWPs, and the land sector is warranted, and can be undertaken through the GHG budgets in VERIFY (WP5).

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4. Non-CO_2 Greenhouse Gas Emissions

An assessment and discussion of different estimates of non-CO_2 GHG emissions have been discussed in another deliverable (Petrescu et al., 2018).

5. Summary

There are many independent estimates of GHG emissions, but very little understanding either qualitatively or quantitatively of the differences between these estimates. One of the biggest reasons for differences between independent estimates is differences in system boundaries. While these issues have been discussed qualitatively before, this report develops this and adds quantitative detail. This report is focused on the EU, but does consider estimates in other key regions and the global level. We focus on a detailed quantitative comparison of fossil CO_2 emissions, extend previous qualitative and quantitative discussion of land-based CO_2 emissions, but leave non-CO_2 emissions for another deliverable.

For fossil CO_2 emissions, we show that even subtle and poorly communicated differences in system boundaries can lead to significant quantitative differences. While there are underlying source data differences between emissions datasets, the most common reason for divergence is differences in system boundaries: which emissions categories are included. Assessing uncertainty simply by gauging the range of a set of estimates is therefore highly inappropriate: like should be compared with like. In many cases, however, these system boundary differences are not apparent to even the attentive observer, and the example of the large disagreement in emissions estimates for the USA demonstrates this well, with neither the EIA nor the IEA having an explanation for disagreement between their estimates. While uncertainties are rarely reported for different datasets, uncertainties based on comparing independent datasets are probably overestimates. There remains more work to be done in clarifying the differences between emissions datasets, and in particular a more standardised description of data flows in dataset construction – rather than today's prose jungles – would be of enormous benefit.

For land-based CO_2 emissions, our comparisons and discussions are more qualitative, but we expand on previous discussions to pay closer attention to Harvested Wood Products and bioenergy. In recent years there has been increased attention to the quantitative differences between land-based CO_2 emissions, with a much better understanding between inventories and estimates from the scientific community. However, there remain gaps in our understanding of differences between FAO and UNFCCC and between different DGVMs and bookkeeping models. Work is ongoing on several fronts to address these issues. While there is a lot of attention on the gains and losses in forests, there has been less attention on HWPs and bioenergy. We argue that a much deeper analysis of HWPs and bioenergy, and how they interact with the land-based CO_2 emissions is needed to confidently perform verification of land-based CO_2 emissions. There is considerable scope for more work. There is a need to better communicate the idiosyncrasies of different estimates, and a need for more detailed data from each estimate to bridge the differences between them.

The report highlights the importance of consistency in and awareness of system boundaries when verifying emission estimates. More research in this space is still needed to better detail and understand differences in system boundaries, and the consequences this has on verification.

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