Towards near-real time air pollutant and greenhouse gas emissions: lessons learned from multiple estimates during the COVID-19 Pandemic

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Abstract. The 2020 COVID-19 crisis caused an unprecedented drop in anthropogenic emissions of air pollutants and greenhouse gases. Given that emissions estimates from official national inventories for the year 2020 were not reported until two years later, new and non-traditional datasets to estimate near-real time emissions became particularly relevant and widely used in international monitoring and modelling activities during the pandemic. This study investigates the impact of the COVID-19 pandemic on 2020 European (the 27 EU Member States and the UK) emissions by comparing a selection of such near-real time emission estimates, with the official inventories that were subsequently reported in 2022 under the Convention on Long-Range Transboundary Air Pollution (CLRTAP) and the United Nations Framework Convention on Climate Change (UNFCCC). Results indicate that annual changes in total 2020 emissions reported by official and near-real time estimates are fairly in line for most of the chemical species, with NO_x and fossil fuel CO_2 being reported as the ones that experienced the largest reduction in Europe in all cases. However, large discrepancies arise between the official and non-official datasets when comparing annual results at the sector and country level, indicating that caution should be exercised when estimating changes in emissions using specific near-real time activity datasets, such as time mobility data derived from smartphones. Main examples of these differences are observed for manufacturing industry NO_x (relative changes ranging between -21.4% and -5.4%) and road transport CO_2 (relative changes ranging between -29.3% and -5.6%) total European emissions. Additionally, significant discrepancies are observed between the quarterly and monthly distribution of emissions drops reported by the various near-real time inventories, with differences up to a factor of 1.5 for total NO_x during April 2020, when restrictions were at their maximum. For residential combustion, shipping and public energy industry, results indicate that changes in emissions that occurred between 2019 and 2020 were mainly dominated by non-COVID-19 factors including meteorology,

the implementation of the Global Sulphur Cap and the shutdown of coal-fired power plants as part of national decarbonization efforts, respectively. The potential increase in NMVOC emissions from the intensive use of personal protective equipment such as hand sanitizer gels is considered in a heterogeneous way across countries in official reported inventories, indicating the need for some countries to base their calculations on more advanced methods. The findings of this study can be used to better understand the uncertainties of near-real time emissions and how such emissions could be used in the future to provide timely updates to emission datasets that are critical for modelling and monitoring applications.

1 Introduction

Under the United Nations Economic Commission for Europe (UNECE) Convention on Long-Range Transboundary Air Pollution (CLRTAP) (UNECE, 2012) and the United Nations Framework Convention on Climate Change (UNFCCC) (UNFCCC, 1992), as well as corresponding EU legislation (i.e., the National Emission reduction Commitments Directive, European Commission, 2016; the Monitoring Mechanism Regulation, European Commission, 2013), EU Member States and the UK are obliged to report annual emission inventories of air pollutants (AP) and greenhouse gases (GHG). These reported inventories form the basis for monitoring progress towards collective goals as well as national emission ceilings and reduction commitments (e.g., the Effort Sharing Decision, European Commission, 2009). Parties must submit their emission inventories on an annual basis in accordance with the corresponding reporting guidelines and following the emission estimation methodologies described in the European Monitoring and Evaluation Programme/ European Environment Agency (EMEP/EEA) air pollutant emission inventory guidebook (EEA, 2019) for AP and the Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories (IPCC, 2019) for GHG.

Despite providing consistent and robust time series of emission estimates, official emission inventory submissions are reported with a two-year time lag. The lagged reporting deadlines (i.e., reporting in a given year (Y) shall typically include annual emissions estimates from 1990 to Y-2) reflect the time needed to finalize accurate national statistics (e.g., official energy consumption statistics) and the cost, time and effort entailed to collect and process them for compiling emission inventories. As a result, in addition to the inherent uncertainties of emission inventories, this time lag can introduce additional uncertainties when these datasets are used (and extrapolated) in certain modelling applications, mainly air quality forecasting systems, as they may not represent current emission sources accurately (Tong et al., 2012). This limitation can be largely amplified in the event of major and unexpected emission changes, such as during the 2008–2009 global economic recession (Castellanos and Folkert, 2012; Peters et al., 2012) or more recently the COVID-19 pandemic. Given the sharp drop in mobility and associated emissions caused by the COVID-19 crisis, alternative methods to estimate near-real time emissions were developed, with the objective of contributing to numerical modelling exercises aiming at understanding the impact of those emission changes on air quality levels (e.g., Badia et al., 2021; Barré et al., 2021; Gaubert et al., 2021; Schneider et al., 2021). These emission datasets included the use of near-real time activity information that is not traditionally used in official reported inventories, such as mobility data derived from smartphones, congestion statistics obtained from navigation applications or near-real time electricity load and generation statistics published by national transmission system operators, among others. Seminal studies tackling the impact of COVID-19 upon primary emissions include Le Quéré et al. (2020), Forster et al. (2020), Guevara et al. (2020 and 2022), Liu et al. (2020a and 2020b), Doumbia et al. (2021), Harkins et al. (2021) and Zheng et al. (2021). In reaction to the COVID-19 pandemic and the growing interest in near-real time emission estimates, some European countries started to publish quarterly (e.g., UK, BEIS, 2022; the Netherlands, CBS, 2022) and monthly (e.g., France; CITEPA, 2022) estimates of emissions based on preliminary energy data. Results from these studies suggest that near-real time emission estimates could be used to provide timely updates to emission trends, especially in the case of other significant and unexpected anthropogenic emission changes (e.g., economic and energy crisis, armed conflicts). However, before they can be used to complement official emission inventories and be integrated into air quality forecasting systems, an assessment of their reliability and associated uncertainty is needed.

This study provides an intercomparison of 2020 emission changes derived from official reported inventories and multiple near-real time estimates for various AP (i.e., NO_x, NMVOC, SO_2, NH_3, PM10, PM2.5) and GHG (i.e., CO_2 and CH_4) for European Union countries (EU27) plus United Kingdom (EU27 + UK). Specifically, we evaluated the magnitude of relative emission changes reported by both official and non-official estimates for individual pollutant sources. Considering the emission drops associated with COVID-19 restrictions occurred in a heterogeneous way and at specific periods of the year, the study not only focuses on annual emission changes, but also includes comparisons of intra-annual variability reported by the different near-real time emission estimates (i.e., quarterly and monthly level). The results of this inter-comparison exercise are used to produce recommendations on how best to approach near-real time emission estimates.

Section 2 describes the methods and datasets considered for the intercomparison, while Section 3 discusses the results obtained in terms of annual, quarterly and monthly relative emission changes by pollutant, country and sector. The main conclusions and lessons learned from this work are provided in Section 4.

2 Methodology

This study compares AP and GHG emission changes in 2020 as provided by 4 near-real time emission estimates and the official reported inventories under the CLRTAP and UNFCCC, respectively. A description of each dataset and summary of methodologies is provided in Table 1 and sections 2.1 and 2.2.

Table 1 Main characteristics of the emission datasets considered in the intercomparison work

Dataset	Type of data	Spatial coverage (resolution)	Temporal coverage (resolution)	Species	Sectors	Reference
guevaraetal	Relative adjustment factors	Europe (country level)	Jan-Dec 2020 (daily, weekly[*])	AP and GHG [***]	All GNFR sectors except for J_Waste, K_AgriLivestock and L_AgriOther	Guevara et al. (2020 and 2022)
doumbiaetal	Relative adjustment factors	Global (country level)	Jan-Dec 2020 (daily/monthly[**])	AP and GHG [***]	Road transport, aviation shipping, power, industry, residential/commercial	Doumbia et al. (2021)
forsteretal	Relative adjustment factors	Global (country level)	Jan-Dec 2020 (daily)	AP and GHG [****]	Road transport, residential, power, industry and aviation	Forster et al. (2020)
liuetal	Absolute emissions	Global (country level for EU27 plus UK)	Jan 2019 until present day	CO_2	Road transport, residential, power, industry, aviation, shipping	Liu et al. (2020a, 2020b)
emep_ceip	Absolute emissions	Member states under the CLRTAP (country level)	1990-2020 (annual)	NOx, SOx, CO, NMVOC, NH_3, PM10, PM2.5	All GNFR sectors	CEIP (2022)
unfccc	Absolute emissions	Member states under the UNFCCC (country level)	1990-2020 (annual)	CO_2, CH_4, N_2O	All CRF sectors	UNFCCC (2022)

[*] Daily for all sectors except for shipping (weekly)
[**] Daily for all sectors except for shipping and aviation (monthly)
[***] Relative adjustment factors are country-, sector- and species-dependent
[****] Relative adjustment factors are only country and sector-dependent (same factors assumed for all AP and GHG species)

2.1 Officially reported emissions

Officially reported emissions of NOx, NMVOC, CO, SO_2, NH_3 and PM2.5 (reporting year 2022) for 2019 and 2020 were obtained from the EMEP Centre on Emission Inventories and Projections (CEIP, 2022; hereinafter referred to as emep_ceip), containing sectoral emissions following the Gridded Nomenclature For Reporting (GNFR) classification system. Officially reported 2019 and 2020 emissions of CO_2 and CH_4 (reporting year 2022) were obtained from the national inventory submissions to the UNFCCC (UNFCCC, 2022; hereinafter referred to as unfccc). GHGs emission data at the Common Reporting Format (CRF) level was converted to the GNFR classification system according to the CRF-GNFR crosswalk of Kuenen et al. (2022a). A detailed description of the activity data and emission factors used to estimate official reported emissions is provided by each country under the Informative Inventory Reports (IIRs) for the AP (CEIP, 2022) and the National Inventory Reports (NIR) for the GHG (UNFCCC, 2022).

2.2 Near-real time estimates

Methodologies and proxies used by each near-real time database to derive emission estimates are summarised in Table 2.

The Copernicus Atmosphere Monitoring Service (CAMS) COVID-19 emission adjustment factors dataset (Guevara et al., 2022; hereinafter referred to as guevaraetal) is a European dataset of daily sector-, pollutant- and country-dependent emission adjustment factors associated with the COVID-19 mobility restrictions for the year 2020. Adjustment factors are expressed as a percentage of emission changes compared to a 2020 business-as-usual scenario, i.e., the emissions that would have been released in 2020 in the absence of COVID-19 restrictions and under the same meteorological conditions. The resulting dataset covers a total of nine emission sectors, which are grouped according to the GNFR classification system, including road transport, energy industry, manufacturing industry, residential and commercial combustion, aviation, shipping, off-road transport, use of solvents, and fugitive emissions from transportation and distribution of fossil fuels. The adjustment factors were developed considering activity information traditionally used to estimate emissions, such as energy statistics or traffic counts, as well as information derived from Google COVID-19 Community Mobility data (Google LLC, 2021) and machine learning techniques. The adjustment factors developed by Guevara et al. (2022) are pollutant-dependent and consider the heterogeneous impact of the COVID-19 restrictions across the different activities in some sectors (e.g., light-duty vehicles versus heavy-duty vehicles in the road transport sector, GNFR_F, or essential versus non-essential industrial activities in the manufacturing industry sector, GNFR_B).

The COvid-19 adjustmeNt Factors fOR eMissions (CONFORM, Doumbia et al, 2021; hereinafter referred to as doumbiaetal) provides a global dataset of emission adjustment factors per country and sector that quantify relative changes in emissions compared to a business-as-usual situation in 2020. The activity factors are estimated using data from a variety of sources, including google mobility reports for the road transport, residential and commercial and manufacturing industry sectors, total electricity load for the power generation sector, data on air transportation published by the Knowledge Center on Migration and Demography (KCMD) Dynamic Data Hub for the aviation sector and statistics on container ship port calls reported by the United Nations Conference on Trade and Development for maritime emissions. In contrast to the CAMS datasets, for each sector the constructed adjustment factors are homogeneous across species.

Like CONFORM, Forster et al. (2020) report a dataset of global emission adjustment factors that vary per country and sector and cover the whole year 2020 (hereinafter referred to as forsteretal). Adjustment factors are also derived in large part from Google mobility data (i.e., for the surface transport, residential, public and commercial and manufacturing industry sectors). For the power sector, weighted Google mobility data reported for the workplace, residential and retail categories are considered to construct the adjustment factors, which are then scaled to match the CO_2 global emission change reported by Le Quéré et al. (2020). For the air traffic and maritime sector, the Le Quéré et al. (2020) emission trends for international and national aviation and shipping are directly used, which were derived from total number of departing flights reported by the Official Aviation Guide of the Airway (OAG) and shipping activity forecasts provided by the World Trade Organization, respectively. The developed adjustment factors were later used by Lamboll et al. (2021) to produce gridded projections of emission scenarios and run general circulation models to investigate the impact of national lockdown measures on climate. This slightly modified the approach to aviation emissions, which were globally scaled in proportion to the total number of aircraft flying at that time, reported by FlightRadar24.

The Carbon Monitor initiative (Liu et al., 2020a and 2020b; hereinafter referred to as liuetal) provides estimates of global daily CO_2 emissions from fossil fuel combustion and cement production. Daily emissions are estimated from annual emissions from the Emissions Database for Global Atmospheric Research inventory (EDGAR, Crippa et al., 2019) in the base year 2019 and a diverse range of activity data, which are used to downscale and extrapolate in time annual emissions to daily level from each sector. The activity proxies considered include electrical power generation for power plant emissions, production data and production indices of industry processes for industrial manufacturing emissions, mobility indices (TomTom data for > 200 cities in Europe aggregated to country scale) for road transport emissions, flight location data (FlightRadar24 database) for aviation emissions and shipping mobility statistics (metric tons of cargo from the UN COMTRADE Monitor database) for maritime emissions. Residential emissions are assumed to vary only according to population weighted daily temperature. Emissions are reported per sector (for 6 sectors) and country or group of countries. A specific European version of Carbon Monitor was recently released, which reports emissions from each of the individual countries of the EU27 + UK bloc (Ke et al., 2022). The sectors included in the dataset are road transport, energy industry, manufacturing industry, residential and commercial buildings fuel use, aviation and shipping. Unlike the previous three datasets, Carbon monitor does not provide information on relative emission changes but estimates of daily absolute emissions from January 2019 until the present, with a ~ 3 months latency after the time of emission.

Table 2 Summary of the methodologies and proxies considered in the near-real time estimates per sector

Dataset	Energy industry	Residential/commercial combustion	Manufacturing industry	Road transport	Air traffic	Shipping
guevaraetal	Temperature corrected electricity demand data from ENTSO-E [(1)] using population-weighted ERA5 2-m ambient air temperature [(2)]	Google COVID-19 Mobility data [(3)] (average of retail and recreation, residential, and workplaces categories) adjusted with measured residential and commercial energy consumption statistics	Industrial production indexes from Eurostat [(4)]	Google COVID-19 Mobility data (transit stations category) adjusted with measured traffic counts	Airport movement statistics from EUROCONTROL [(7)]	CO2 AIS-based shipping emissions from STEAM (Jalkanen et al. 2016)
doumbiaetal	Electricity demand data from ENTSO-E [(2)]	Google COVID-19 Mobility data [(3)] (residential category)	Google COVID-19 Mobility data [(3)] (workplaces categories)	Google COVID-19 Mobility data [(3)] (transit stations category)	Official Aviation Guide measurements [(8)] in conjunction with data by the Knowledge Center on Migration and Demography Dynamic Data Hub [(9)]	Container ship port calls reported by the United Nations Conference on Trade and Development [(11)]
forsteretal	Google COVID-19 Mobility data [(3)] (average of retail and recreation, residential, and workplaces categories)	Google COVID-19 Mobility data (residential and retail and recreation categories)	Google COVID-19 Mobility data [(3)] (workplaces categories)	Google COVID-19 Mobility data [(3)] (transit stations category)	Relative emission changes reported by Le Quéré et al. (2020)	Relative emission changes reported by Le Quéré et al. (2020)
liuetal	Electricity generation data by production types from ENTSO-E [(1)]	Population-weighted heating degree days assuming no direct effect of COVID and other factors	Industrial production indexes from Eurostat [(4)]	TomTom congestion data [(5)] calibrated against car flux data (Paris) [(6)]	Individual commercial flights tracked by Flightradar24 [(10)]	Metric tons of cargo reported by UN COMTRADE Monitor. [(12, 13)]

[(1)]) ENTSO-E (2022)
[(2)] C3S (2017)
[(3)] Google LCC (2021)
[(4)] Eurostat (2021)
[(5)] https://www.tomtom.com/en_gb/traffic-index/, last access: November 2022
[(6)] https://opendata.paris.fr/pages/home/, last access: November 2022
[(7)] EUROCONTROL (2021)
[(8)] https://www.oag.com/coronavirus-airline-schedules-data, last access: November 2022
[(9)] https://migration-demography-tools.jrc.ec.europa.eu/data-hub/, last access: November 2022
[(10)] https://www.flightradar24.com, last access: November 2022
[(11)] https://unctad.org/news/covid-19-shipping-data-hints-some-recovery-global-trade, last access: November 2022
[(12)] Cerdeiro et al. (2020)
[(13)] https://comtrade.un.org/data/ais, last access: May 2023

2.3 Baseline for the estimation of 2020 relative emission changes

The estimation of relative changes ($RC_{s,c,p}$) in 2020 emissions per GNFR sector *s*, country *c* and pollutant *p* is computed as indicated in Eq.1:

$$RC_{s,c,p} = \left(\frac{Emis2020_{s,c,p} - EmisBaseline_{s,c,p}}{EmisBaseline_{s,c,p}}\right) * 100 \qquad \text{Eq. 1}$$

Where $Emis2020_{s,c,p}$ are the annual emissions reported for 2020 per GNFR sector *s*, country *c* and pollutant *p* and $EmisBaseline_{s,c,p}$ are the annual emissions reported for the baseline scenario per GNFR sector *s*, country *c* and pollutant *p*.

The baseline considered for the official reported emissions (i.e., emep_ceip and unfccc) and liuetal is the year 2019 (from EDGARv4.3 in liuetal) because the three datasets report emissions for that year as well as for 2020. For the three other near-real time datasets (i.e., guevaraetal, doumbiaetla, forsteretal) the baseline considered is the Copernicus CAMS-REG_v5.1 2020 business-as-usual (BAU) emission inventory (Kuenen et al., 2022b), which reports AP and GHG emissions for 2020 ignoring the impact of COVID-19, while 2020 emissions are estimated by combining this inventory with the adjustment factors reported by each dataset.

The use of different baselines implies that the relative changes estimated by official reported emissions and liuetal are not only related to the effect of the COVID-19 restrictions, but also to other factors such as changes in meteorology or the implementation of new emission regulations between 2019 and 2020, while the computed relative changes for guevaraetal, doumbiaetla and forsteretal only account for the COVID-19 effect. Consequently, this comparison brings the opportunity of disentangling the COVID-19 impacts from other effects on 2020 emissions.

3 Comparison of changes in 2020 emissions

In this section, we compare relative changes in 2020 emissions as reported by the official and non-official estimates described in Sect. 2. The comparison focuses on EU27 + UK and is performed at the annual (Sect. 3.1) and monthly (Sect. 3.2) scale.

3.1 Annual emission changes

Annual changes in NO_x, NMVOC, CO, SO_2, $PM_{2.5}$, NH_3, CO_2 and CH_4 emissions per GNFR sector at the EU27+UK level are summarised in Table 3 and Table 4. Figure 1 shows the relative contribution [%] of each GNFR sector to total 2019 emissions at the EU27 + UK level to support the analysis performed.

CO_2 (-12.2%) and NO_x (-11.3%) are the pollutants that experienced the largest reduction in Europe according to official estimates (unfccc and emep_ceip, respectively), the values reported by doumbiaetla and liuetal for CO_2 (-12.2% and -11.6%, respectively) and guevaraetal for NO_x (-10.5%) being the ones closer to them. These findings are in line with the fact that road transport contributes substantially to CO_2 and NO_x emissions (Fig. 1) and, at the same time, was the most affected sector by the COVID-19 restrictions, after aviation. Also, in agreement with official estimates, NH_3 and CH_4 are reported by the near-real time datasets as the species that experienced the lowest reductions (i.e., -1.1% and -1.4% according to official estimates and between -0.9% and 0.1% according to non-official estimates). Considering that agricultural and waste management practices contribute to more than 80% of total NH_3 and CH_4 emissions (Fig. 1), the results reinforce the hypothesis that these activities remained mostly unaffected during the COVID-19 mobility restrictions and lockdowns.

For SO_2, CO and PM2.5, official relative emission changes reported by emep_ceip (-10.8%, -8.2% and -4.1%) are much larger than the ones reported by guevaraetal (-4.6%, -4.7% and -2.1%). For SO_2, discrepancies between results are mainly driven by the differences reported for the public power sector (A_PublicPower), which represent more than 30% of total SO_2 (Fig. 1). For this sector, the three non-official estimates report changes in emissions ranging from -7.2% to -2.7%, which are significantly lower than the official estimates (-19.5%) (see Sect. 3.1.1 for further details). In the case of doumbiaetal and forsteretal, the underestimation in the public power sector is compensated by a significant overestimation of the SO_2 emission reduction in the manufacturing industry sector (B_Industry). While official estimates report a reduction of 7.8%, doumbiaetal and forsteretal indicate reduction of 20.2 and 22.8%, respectively. A similar situation is observed for CO_2, for which only liuetal is in line with the emission changes reported by unfccc for the public power sector (i.e., -14.4% versus -11.8%).

For CO and PM2.5, differences in relative emission changes reported by guevaraetal and official estimates are mainly driven by the discrepancies observed in the residential/commercial stationary combustion activities (C_OtherStaComb), the largest contributor to total emissions for these two species (Fig. 1). Guevaraetal shows an increase in emissions (1.7% for CO and 1.8% for PM2.5), while emep_ceip indicates a reduction of 2.7% for CO and 1.9% for PM2.5. The discrepancies are much larger when looking at the results reported by forsteretal (6.6% for both CO and PM2.5) and doumbiaetal (5.9% for CO and 6.0% for PM2.5). Sect. 3.1.3 goes into detail about the reasons for these discrepancies. As seen for SO_2, the good agreement between CO and PM2.5 total emission changes reported by forsteretal/doumbiaetal and emep_ceip is the result of an error compensation: the aforementioned underestimation in the residential/commercial stationary combustion activities is balanced with an overestimation in the reductions reported by official estimates for the manufacturing industry (e.g., -3% according to emep_ceip versus -21.0% according to doumbiaetal for PM2.5) and road transport (e.g., -19% according to emep_ceip versus -27% according to forsteretal for CO) sectors.

It is worth mentioning the large reduction in SO_2 shipping emissions reported by official estimates (-46.3%), which is mainly caused by the 2020 Global Sulphur Cap, which entered into force on the first of January 2020. The reduction reported by guevaraetal for this sector and pollutant is much lower (-11%), as it only accounts for the impact of COVID-19 restrictions. Nevertheless, when looking at NO_x and CO_2 shipping emissions, a much better agreement is found between the relative changes reported by emep_ceip (-13.5%), unfccc (-11%) and guevaraetal (-11%), confirming that the larger reduction found for SO_2 is mainly linked to a non-COVID-19 effect. For the shipping sector, important discrepancies are observed between the official estimates and the results reported by the other near-real time datasets (doumbiaetal, forsteretal and liuetal), as they report only global emission changes and do not distinguish between European and non-European seas. The relative CO_2 emission reductions reported by liuetal (-3.1%) and doumbiaetal (-9.5%) are lower than the official UNFCCC estimates (-11%), while forsteretal reductions are more than two times larger (-23.5%). The large inconsistency found for forsteretal could be related not only to the differences in terms of spatial coverage, but also to the fact that for this database emission trends for shipping were derived from forecasted activity (see Sect. 2.2) rather than measured statistics. Finally, for NMVOC guevaraetal reports the closest emission reduction value to official estimates, both being quite low (-2.1% and -2.5%, respectively).

Table 3 Relative changes [%] in NO_x, NMVOC, CO, SO_2, PM2.5 and NH_3 emissions per GNFR sector at the EU27+UK as reported by official (emep_ceip) and non-official (guevaraetal, doumbiaetal, forsteretal) estimates

GNFR	NOx				NMVOC			
	emep_ceip	guevaraetal	doumbiaetal	forsteretal	emep_ceip	guevaraetal	doumbiaetal	forsteretal
A_PublicPower	-12.2	-3.3	-3.3	-7.1	-4.5	-3.3	-3.2	-8.5
B_Industry	-5.4	-6.7	-21.7	-24.1	-2.9	-2.8	-22.1	-24.6
C_OtherStaComb	-2.2	-3.0	-2.8	-3.5	-3.0	1.1	4.7	5.3
D_Fugitive	-11.1	-10.7	0.0	0.0	-12.7	-10.1	0.0	0.0
E_Solvents	-17.0	0.0	0.0	0.0	2.1	-1.3	0.0	0.0
F_RoadTransport	-18.4	-16.8	-23.9	-28.7	-13.0	-18.8	-22.5	-27.5
G_Shipping	-13.5	-11.0	-9.5	-23.5	-12.2	-11.0	-9.5	-23.5
H_Aviation	-57.4	-55.7	-41.1	-52.9	-55.5	-54.9	-40.9	-52.7
I_Offroad	-7.3	-1.7	0.0	0.0	-5.2	-2.0	0.0	0.0
J_Waste	0.7	0.0	0.0	0.0	-10.3	0.0	0.0	0.0
K_AgriLivestock	-0.3	-	-	-	-0.4	0.0	0.0	0.0
L_AgriOther	1.4	0.0	0.0	0.0	0.3	0.0	0.0	0.0
Total except G_Shipping	-11.3	-10.5	-15.9	-19.3	-2.1	-2.5	-2.8	-3.3
	CO				SO_2			
	emep_ceip	guevaraetal	doumbiaetal	forsteretal	emep_ceip	guevaraetal	doumbiaetal	forsteretal
A_PublicPower	-3.9	-3.2	-3.1	-7.3	-19.5	-2.9	-2.7	-7.2
B_Industry	-12.3	-7.3	-20.9	-23.2	-7.8	-6.4	-20.2	-22.8
C_OtherStaComb	-2.7	1.7	5.9	6.6	-1.2	-0.5	1.5	1.4
D_Fugitive	-8.7	-6.5	0.0	0.0	-11.5	-9.2	0.0	0.0
E_Solvents	-8.5	0.0	0.0	0.0	-19.9	0.0	0.0	0.0
F_RoadTransport	-19.2	-17.8	-22.2	-27.1	-13.0	-17.6	-25.2	-30.4
G_Shipping	-7.4	-11.0	-9.5	-23.5	-46.3	-11.0	-9.5	-23.5
H_Aviation	-48.4	-51.2	-38.4	-50.1	-59.4	-56.1	-42.5	-54.0
I_Offroad	-2.4	-2.7	0.0	0.0	-17.2	-0.3	0.0	0.0
J_Waste	-1.4	0.0	0.0	0.0	-2.6	0.0	0.0	0.0
K_AgriLivestock	-	-	-	-	-	-	-	-
L_AgriOther	-3.8	0.0	0.0	0.0	-3.9	0.0	0.0	0.0
Total except G_Shipping	-8.2	-4.7	-6.4	-7.6	-10.8	-4.6	-9.4	-12.1
	NH_3				PM2.5			
	emep_ceip	guevaraetal	doumbiaetal	forsteretal	emep_ceip	guevaraetal	doumbiaetal	forsteretal
A_PublicPower	7.3	-3.4	-3.1	-9.3	-6.6	-3.0	-2.8	-7.5
B_Industry	0.0	-3.6	-20.2	-22.7	-3.0	-6.6	-21.0	-23.5
C_OtherStaComb	-2.6	1.7	5.8	6.4	-1.9	1.8	6.0	6.6
D_Fugitive	-4.4	-0.7	0.0	0.0	-19.0	-8.5	0.0	0.0
E_Solvents	-6.1	0.0	0.0	0.0	-18.8	0.0	0.0	0.0
F_RoadTransport	-16.3	-17.8	-23.3	-28.4	-16.3	-16.3	-23.5	-28.4
G_Shipping	-6.2	-	-	-	-19.4	-11.0	-9.5	-23.5
H_Aviation	-55.7	-55.9	-49.3	-45.4	-58.1	-54.4	-34.7	-55.4
I_Offroad	-3.5	-1.2	0.0	0.0	-8.2	-1.9	0.0	0.0
J_Waste	-0.4	0.0	0.0	0.0	1.4	0.0	0.0	0.0
K_AgriLivestock	-0.1	0.0	0.0	0.0	-0.5	0.0	0.0	0.0
L_AgriOther	-1.5	0.0	0.0	0.0	-2.6	0.0	0.0	0.0
Total except G_Shipping	-1.1	-0.2	-0.5	-0.5	-4.1	-2.1	-2.8	-3.6

Table 4 Relative changes [%] in CO_2 and CH_4 emissions per GNFR sector at the EU27e+UK as reported by official (unfccc) and non-official (guevaraetal, doumbiaetal, forsteretal, liuetal) estimates

GNFR	CO_2					CH_4			
	unfccc	guevaraetal	doumbiaetal	forsteretal	liuetal	unfccc	guevaraetal	doumbiaetal	forsteretal
A_PublicPower	-14.4	-3.4	-3.2	-7.2	-11.8	0.4	-3.0	-3.1	-6.4
B_Industry	-6.7	-6.6	-20.7	-23.1	-7.7	-6.6	-4.9	-21.0	-23.5
C_OtherStaComb	-1.3	-1.5	0.1	-0.1	-2.0	-1.0	1.2	4.6	5.1
D_Fugitive	-12.5	-4.3	0.0	0.0	-	-5.2	-6.7	0.0	0.0
E_Solvents	-1.5	0.0	0.0	0.0	-	-12.4	0.0	0.0	0.0
F_RoadTransport	-13.8	-16.5	-24.4	-29.3	-5.6	-13.9	-18.7	-23.1	-28.0
G_Shipping	-11.0	-11.0	-9.5	-23.5	-3.1	5.6	-	-	-
H_Aviation	-57.6	-56.0	-41.7	-52.9	-58.2	-57.4	-56.1	-43.4	-53.2
I_Offroad	-12.5	-1.6	0.0	0.0	-	-16.8	-1.9	0.0	0.0
J_Waste	-1.4	0.0	0.0	0.0	-	-2.1	0.0	0.0	0.0
K_AgriLivestock	-	-	-	-	-	-0.1	0.0	0.0	0.0
L_AgriOther	-	-	0.0	-	-	5.6	0.0	0.0	0.0
Total except G_Shipping	-12.2	-7.2	-12.2	-15.2	-11.6	-1.4	-0.9	-0.1	-0.2

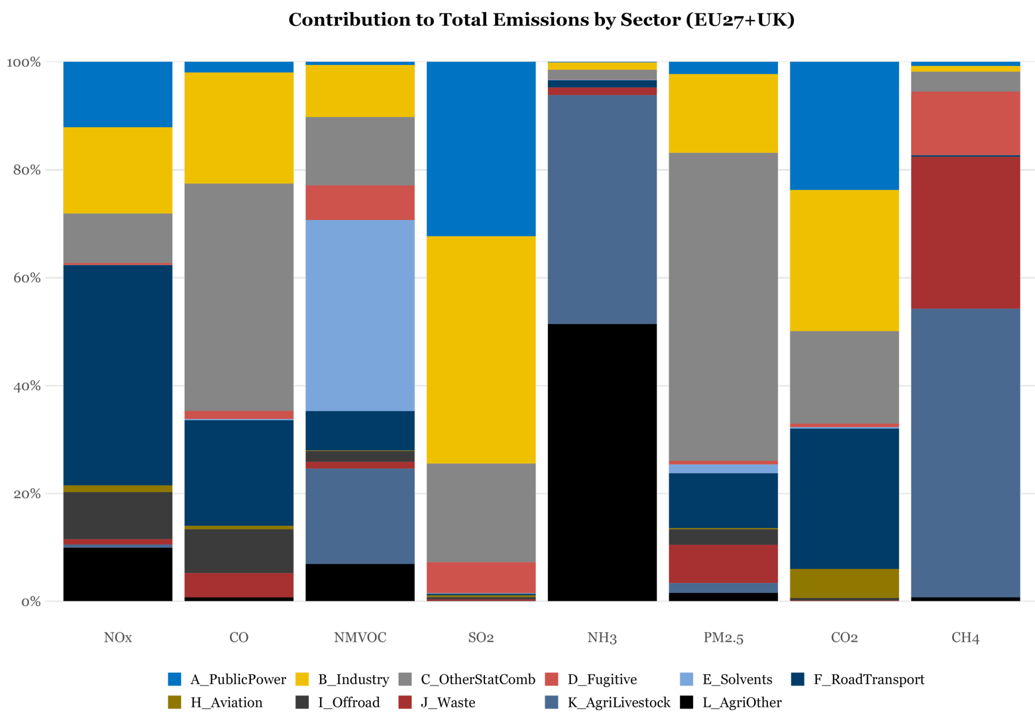


Figure 1: Sectoral contributions [%] to total 2019 emissions at the EU27 + UK level (CEIP, 2022; UNFCCC, 2022). Emissions are reported following the Gridded Nomenclature For Reporting (GNFR) classification system. Shipping emissions (GNFR_G) are excluded from the analysis.

Changes observed at the country level per individual sector are discussed in the following Sect. 3.1.1 to Sect. 3.1.8. For each sector, we focus the analysis on the species to which the sector reports a contribution larger than 20% to the total EU27+UK bloc emissions of the respective species (Fig. 1). For those sectors with contributions lower than 20% for any species (i.e., aviation, fugitive emissions from fossil fuels, off-road mobile sources), we considered the most representative species. Note that sectors GNFR_J (waste management), GNFR_K (agriculture, livestock) and GNFR_L (agriculture, other practices including use of fertilizers and agricultural waste burning) were excluded from the discussion as all the near-real time datasets assumed that emissions from these sources did not change in 2020 due to a lack of specific activity information or because of the nature of the European COVID-19 restrictions policies, which considered these activities to be essential during lockdowns. As shown in Fig. S1, this hypothesis is consistent with the official estimates, which report relative changes in emissions of maximum +/-5% in most countries.

3.1.1 Public power

Figure 2a and 2b shows the relative SO_2 and CO_2 emission changes [%] reported by each dataset per country and at the EU27+UK level for the public power sector (GNFR_A).

For SO_2, the three near-real time datasets consistently report much lower relative changes than official estimates. This discrepancy is partially because guevaraetal and doumbiaetal assume that COVID-19 restrictions had an impact on total electricity demand, but not on the electricity mix, which slightly shifted towards renewables and therefore implied an additional reduction of activity in fossil fuel power plants (IEA, 2021). However, one of the most relevant aspects of these discrepancies is the role that national decarbonization trends played in the drop of emissions between 2019 and 2020. This is illustrated with the examples of Spain and Estonia, which are among the countries showing the largest drop of emissions according to official reports (i.e., -60% and -45%, respectively). For Spain, the reduction is mainly related to the shutdown of seven coal-fired power plants in June 2020 as they were unable to comply with stricter EU air pollution standards (Europe Beyond Coal, 2022, Fig. S2), whereas the reduction in Estonia is due to a drop of 44% in the electricity produced by oil shale (IEA, 2022). In both countries, these reductions are part of commitments to a sustainable transition towards climate neutrality and that were started to be executed before the outbreak of the COVID-19 crisis, e.g., in Estonia, power production from oil shale has already dropped by more than half from 9.5 TWh to 4.3 TWh between 2018 and 2019.

For CO_2, similar discrepancies are observed between official and near-real time estimates, except for liuetal, whose results are much more in line with unfccc because its relative emission changes consider changes in the electricity production by fuel type between 2019 and 2020, and therefore integrate the impact of the decarbonization efforts in the electric power sector, even though emission factors for each fuel type are assumed to be constant (equal to the year) in their methodology. This is clearly observed in Spain and Estonia, where liuetal reproduces the official reported drops well (i.e., -26% according to unfccc and -21% according to liuetal for Spain; -35% according to unfccc and -40% according to liuetal for Estonia).

Changes in official emissions reported by emep_ceip and unfccc are generally consistent across SO_2 and CO_2, except in some countries such as Lithuania and Latvia, where SO_2 remains almost unchanged (4% and -6%) while CO_2 significantly increases (more than 50%) and decreases (-25%), respectively. For these two countries, the reason for this inconsistency is a significant change in the amount of electricity produced from natural gas between 2019 and 2020 (90% for Lithuania and -65% for Latvia; IEA, 2022), which had a significant impact in CO_2 emissions, but was almost negligible in terms of SO_2 changes due to the low Sulphur content associated with this fuel. In other countries, such as Luxemburg and Croatia, the large discrepancies between changes in SO_2 (increases of approximately +50% and +100%, respectively) and CO_2 emissions (changes below 5%) may indicate an issue with the reported data.

3.1.2 Manufacturing industry

As shown in Fig. 2c and 2d, guevaraetal and liuetal are the near-real time estimates that present the closest values to the official NMVOC and CO_2 relative changes reported for the industrial manufacturing sector, respectively. Oppositely, for doumbiaetal and forsteretal large discrepancies are observed with official estimates, especially in the case of NMVOC, where the reductions reported at the EU27+UK level are 4.5 and 8.5 times larger, respectively. Both guevaraetal and liuetal consider the use of industrial production indexes as a proxy for this sector, while doumbiaetal and forsteretal rely on Google mobility data.

It is worth noting how guevaraetal reproduces the heterogenous changes across both pollutants at the EU27+UK level, with NMVOC presenting an approximately 2 times lower reduction (-2.9%) than CO_2 (-6.7%). This result can be partially explained by the fact that during the lockdowns the food and chemical industries (both of which contribute significantly to total NMVOC industrial emissions) were considered to be essential; as a consequence, their activity was less reduced than that of other energy-intensive industrial branches such as iron and steel manufacturing or non-metallic mineral products, which present larger contributions to total industrial CO_2 emissions.

Inconsistencies between emep_ceip and unfccc official emission changes are observed for Cyprus and Malta, with NMVOC emissions remaining almost unchanged while CO_2 show increases by 20% to 30%. In the case of a small countries like these two, the national emissions are rather sensitive to dynamics at the single facility level, resulting in large relative year to year changes.

3.1.3 Residential/commercial stationary combustion activities

For this sector, relative PM2.5 emission changes reported by all the near-real time datasets are inconsistent with official estimates (Fig. 2e and 2f). While the first group indicates a general increase of emissions, the former reports a decrease in almost all European countries. The differences between official and non-official estimates are in general much larger for doumbiaetal and forsteretal than for guevaraetal. This could be explained by the fact that, while all three datasets use Google mobility reports as a data proxy for this sector, guevaraetal is the only one that adjusted the original values considering energy consumption statistics from the residential and commercial sectors (Guevara et al., 2022). All in all, the message from the three near-real time estimates is the same: during 2020 people spent more time at home due to confinement measures and therefore the consumption of residential wood combustion, which represents more than 90% of total PM2.5 from this sector, increased when compared to a 2020 business-as-usual situation. Nevertheless, and as explained in Sect. 2.3, relative changes reported by emep_ceip use 2019 as a baseline, and therefore they include the effect not only of COVID-19, but also the impact of meteorological changes. As reported by the Copernicus Climate Change Service (C3S), Europe experienced its warmest winter on record in 2020, with temperatures up to 5°C warmer than the 1981–2010 seasonal average in north-eastern Europe (C3S, 2020a). The impact of the exceptionally mild winter temperatures in 2020 is illustrated in Fig. 4a, which shows the relative changes in number of Heating Degree Days (HDD) per European country between 2019 and 2020 (Eurostat, 2022). Overall, HDD was -5% lower in 2020 when compared to 2019, with values up to -20% in Malta and approximately -10% in Finland, France or Estonia. However, the increase of temperatures was not uniform and some countries such as Bulgaria and Hungary presented increases in the HDD of approximately +5%. Because HDD is an indicator designed to describe the energy requirements of buildings, a decrease (increase) in its value implies a decrease (increase) in the combustion of fuels and associated emissions needed for space heating. Figure 4.b shows a scatterplot of relative changes in PM2.5 emissions as reported by emep_ceip and in HDD per country. It is observed in several countries that a clear relationship is identified, with emissions decreasing when the HDD decreases (e.g., Finland) and the other way around (e.g., Bulgaria). These findings are consistent with those reported by Ciais et al., (2022) using ENSTO-G daily gas consumption data in buildings, who also showed that climate variations played a larger role in residential energy consumption across Europe in 2020 than COVID-19 induced stay-home orders, except in Italy and France. Nevertheless, the relationship is not always consistent. For instance, in Estonia PM2.5 emissions and HDD present relative changes of similar magnitude but of opposite sign (+ 10% and -10%, respectively), indicating that other factors, such as fuel-switching or inconsistencies in the officially reported emission time series, among others, could play a role.

For CO_2, it is observed that liuetal is the near-real time estimate that is generally more in line with the official unfccc emission changes. This result is consistent with the fact that of the near-real time datasets only liuetal accounts for the impact of meteorology, which at the same time reinforces the hypothesis that changes in this sector are mainly driven by changes in the meteorology. As a matter of fact, liuetal assumes that changes in emissions are only driven by changes in population weighted 2m temperature for this sector, and no impact from COVID-19 is included in the 2020 emissions. This can be illustrated by the fact that both liuetal and the relative changes in the HDD point out Malta as the country experiencing the largest decrease (around -20% in both cases). This result, however, contrasts with the relative changes reported by unfccc, which indicate a nearly +10% increase in CO_2 emissions in this country.

3.1.4 Fugitive emissions from fossil fuels

Fig. 5a and 5b shows the relative changes in CH_4 emissions from activities related to the extraction, processing and delivery of fossil fuels to the point of final use. Guevaraetal is the only near-real time dataset that reports information for this sector while all the other estimates assume no changes in emissions during 2020. Results are fairly in line with official estimates at the EU27+UK level (-5.2% versus -7.2% for CH_4). It is also interesting to see how guevaraetal can reproduce the large drop in emissions occurred in Greece (close to -40%), which is related to a significant decrease in coal mining activities (Guevara et al., 2022).

The official reported drop in European CH_4 emissions (not only for this sector but also for total emissions as stated in Table 4) contrasts with recent observational-based studies that claimed increases in CH_4 emissions during 2020 using TROPOMI observations and inverse-modelling techniques (McNorton et al., 2022). As reported by Stevenson et al. (2022), the increased CH_4 atmospheric growth captured by TROPOMI is probably due to the net effect of NOx, CO, and NMVOC emission changes on CH_4 atmospheric lifetime rather than on changes in primary emission sources.

3.1.5 Solvents

For the sector solvent use, only guevaraetal reports changes in emissions in 2020, as the other near-real time datasets do not report information for this sector. However, the changes estimated by guevaraetal only focus on a few industrial activities (i.e., metal degreasing and printing) and do not cover the domestic use of solvents, which results in a very limited change of the total NMVOCs at the EU27+UK level (-1.3%). Interestingly, large inconsistencies are observed in the official relative changes reported between European countries. While most of them indicate changes in total emissions between -5% and +5%, significant increases (e.g., +50% in the Netherlands, +33% in Finland, +25% in Portugal) and decreases (e.g., -25% in Lithuania) are observed in certain countries. This inconsistency is mainly driven by the heterogeneous estimation of changes in NMVOC emissions from the use of the so-called pandemic products (e.g., hand sanitizer gels). This hypothesis is illustrated in Fig. 3, which shows official relative NMVOC emission changes for the domestic solvent use sector (NFR2D3a). Similarly to what is observed at the GNFR level, NMVOC emission changes from this activity are very heterogeneous across countries, with Portugal, the Netherlands and Finland presenting increases larger than 100%, and many other presenting changes ranging from -5% to 5%. The COVID-19 recommendation on the use of hand sanitizers as a safety measure was a measure consistently implemented across European governments during 2020 and, therefore, its impact on NMVOC emissions from this activity should be, in theory, also consistent across national reported inventories. However, several countries use a very basic emission estimation method (tier 1) for this activity, which uses population data as activity data and thus does not reflect the increased use of hand sanitizers.

3.1.6 Road transport

For the traffic sector, guevaraetal is the dataset more in line with the NOx (Fig. 5c) and CO_2 (Fig. 5d) relative changes reported by official estimates at EU27+UK level and in those countries that were most affected by COVID-19 restrictions (e.g., Spain, Italy, UK, France). Doumbiaetal and forsteretal present the largest discrepancies with official NOx estimates, with relative changes between 1.5 and 2 times larger on average (Fig. 5c). When compared to unfccc, results by liuetal tend to present lower CO_2 emission changes (2.5 times lower at the EU27+UK level, Fig. 5d). Differences are particularly relevant in those countries where liuetal suggests almost no changes in CO_2 emissions (e.g., Austria, Germany) or even slight increases (e.g., Estonia, Lithuania) (Fig. 5d). In fact, official estimates do not report any country with increasing NOx or CO_2 road-transport emissions in 2020, Romania being the country closest to a negligible change (-2.3% for CO_2). Out of all the near-real time estimates, guevaraetal and liuetal are the only ones that combined the use of new mobility metrics (Google reports and Tomtom congestion statistics, respectively) with traditional statistics (measured traffic counts) to derive the impact of COVID-19 restrictions on this sector. Contrary to what is shown for the public power or the residential sectors, the good agreement observed between guevaraetal and ceip_emep/unfccc suggests that the changes in emissions from this sector where almost exclusively related to the COVID-19 mobility restrictions.

3.1.7 Aviation

The aviation sector reports the largest drops in emissions according to all official and non-official estimates (Fig. 5.e). At the same time, it is also the sector with the fewest differences in estimates at the EU27+UK level, with overall CO_2 reductions ranging from -53% to -58%, except for doumbiaetal, which report much lower reductions (-41.7%). The analysis at the country level though suggests that liuetal is the dataset that is more in line with the official results reported by unfccc. The reduction of emissions is quite consistent across countries, except for Bulgaria and Luxemburg, where reductions are significantly below the average (-30% and -10%, respectively) and only liuetal is capable of partially reproducing them (-40% and -20%, respectively). Results by doumbiaetal tend to underestimate the reductions reported by unfccc by a factor of 1.6 on average (e.g., -66% versus -54% for Italy and -57% versus -37% for Poland). While unfccc and liuetal reports changes in emissions from landing and take-off (LTO) and cruise domestic operations, doumbiaetal, guevaraetal and forstersetal only reflect changes from LTO from both domestic and international air traffic, which could explain why the discrepancies are larger.

3.1.8 Off-road mobile sources

As for the case of the fugitive emissions from fossil fuels (Sect. 3.1.4), for off-road mobile source emissions only guevaraetal considers the impact of COVID-19 restrictions. However, and as shown in Fig. 5.f, significant discrepancies exist between this dataset and the official emep_ceip estimates, with the former reporting larger NO_x emission reductions (-7.3% versus -1.7%). The methodology of guevaraetal considered the impact of the mobility restrictions only in industrial machinery, assuming that other types of machinery included in this sector (i.e., agricultural, gardening, recreational boats) were not affected by the pandemic. Interestingly, all official estimates report a decrease in emissions, except for the cases of Portugal and Greece, where increases of +6% and +38% are observed, respectively.

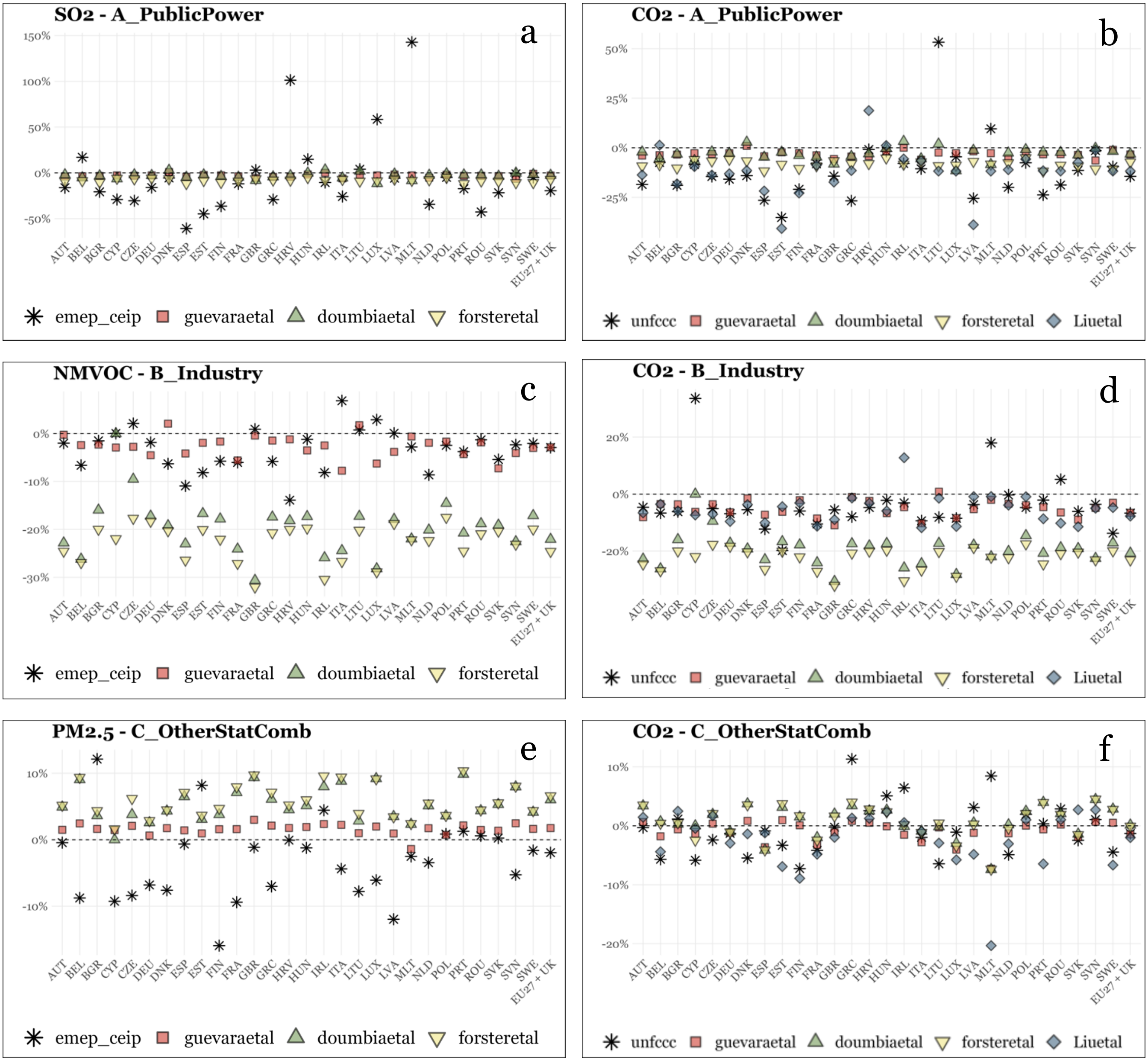


Figure 2 Relative emission changes [%] reported by official (emep_ceip, unfccc) and non-official datasets (guevaraetal, forsteretal, doumbiaetal, liuetal) per country and at the EU27+UK level for the public power sector (a,b), manufacturing industry sector (c, d) and other stationary combustion activities (e, f)

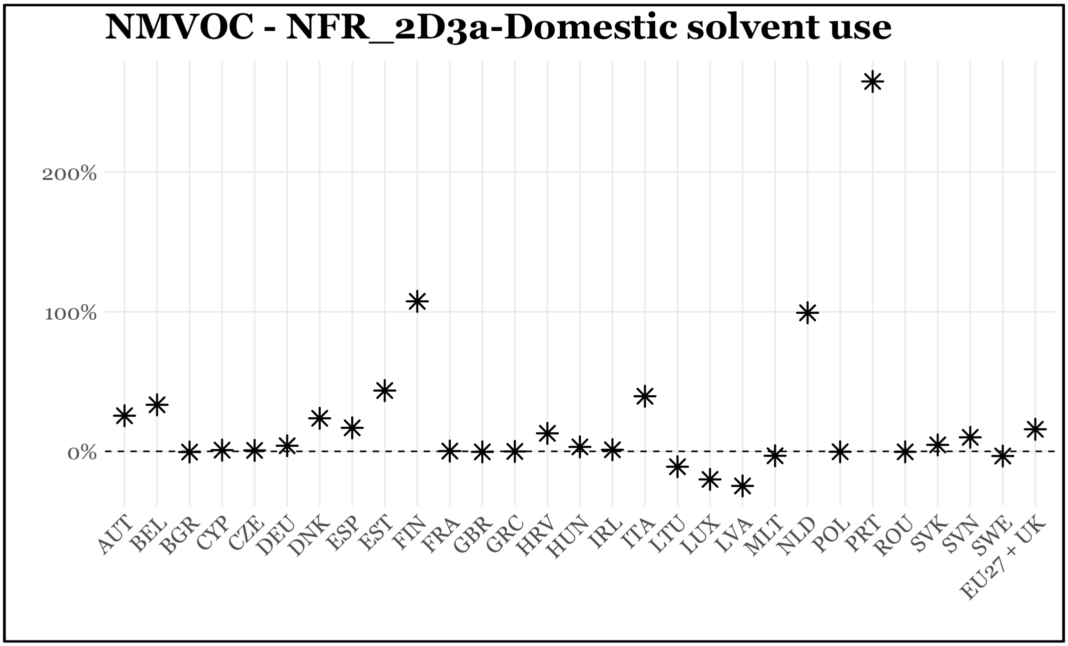


Figure 3 Relative NMVOC emission changes [%] reported by official estimates (emep_ceip) per country and at the EU27+UK level for the domestic use of solvent activity (NFR 2D3a) (CEIP, 2022)

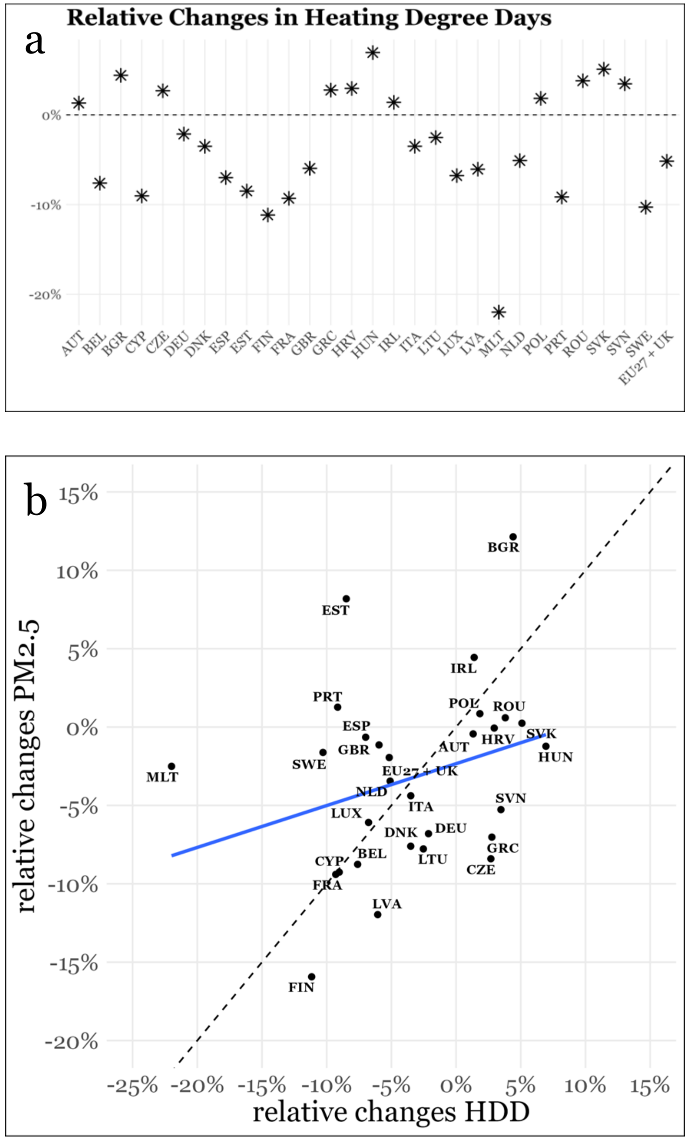


Figure 4 Relative changes [%] in the number of Heating Degree Days (HDD) per country and at the EU27+UK level between 2019 and 2020 (Eurostat, 2022) (a) and scatter plot showing the relative changes in the HDD and in PM2.5 emissions from the residential/commercial sector per country and at the EU27+UK level (b).

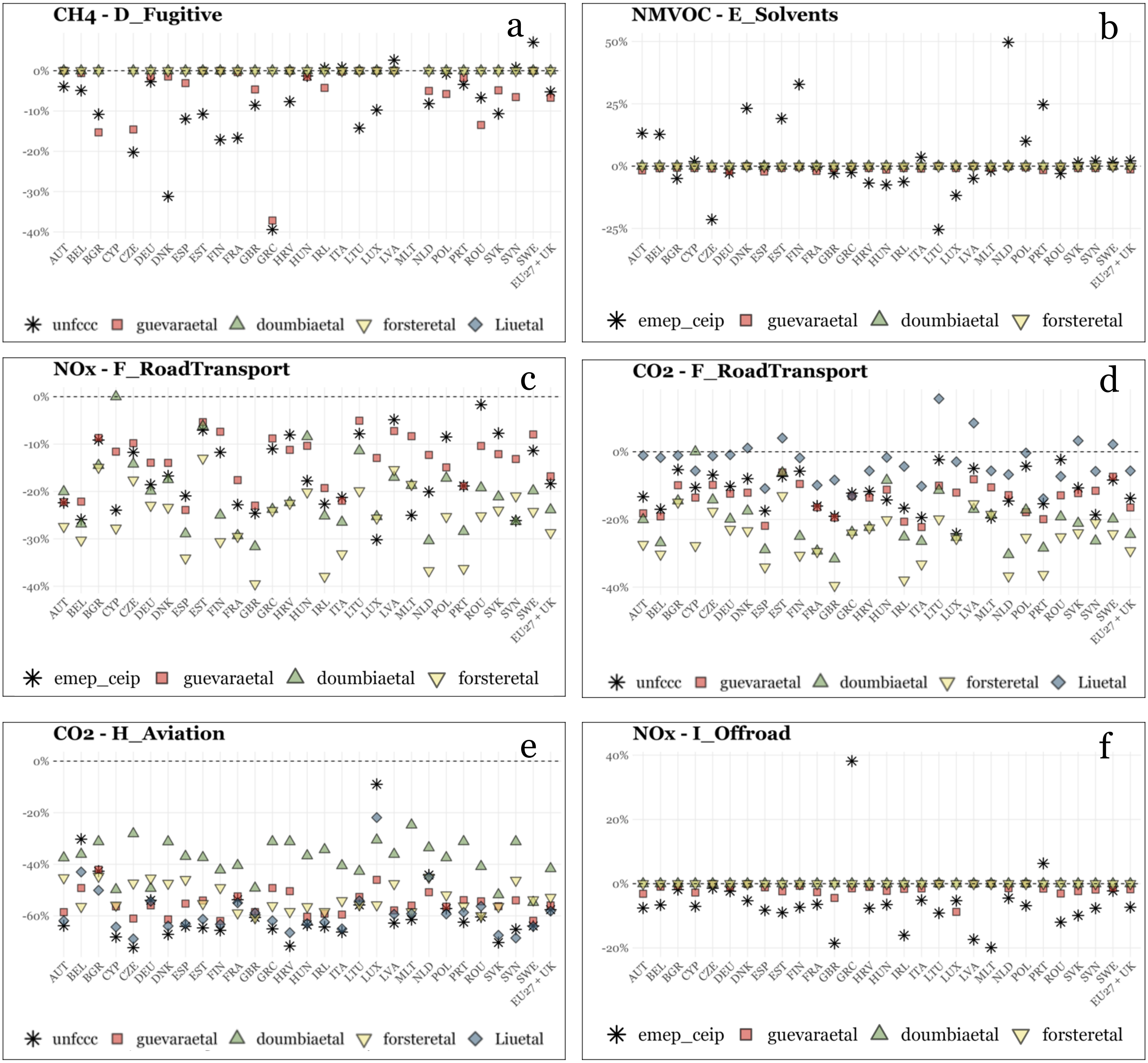


Figure 5 Relative emission changes [%] reported by official (emep_ceip, unfccc) and non-official datasets (guevaraetal, forsteretal, doumbiaetal, liuetal) per country and at the EU27+UK level for the fugitive fossil fuel sector (a), use of solvents sector (b) road transport (c, d), aviation (e) and the off-road mobile sources (f)

3.2 Monthly and quarterly emission changes

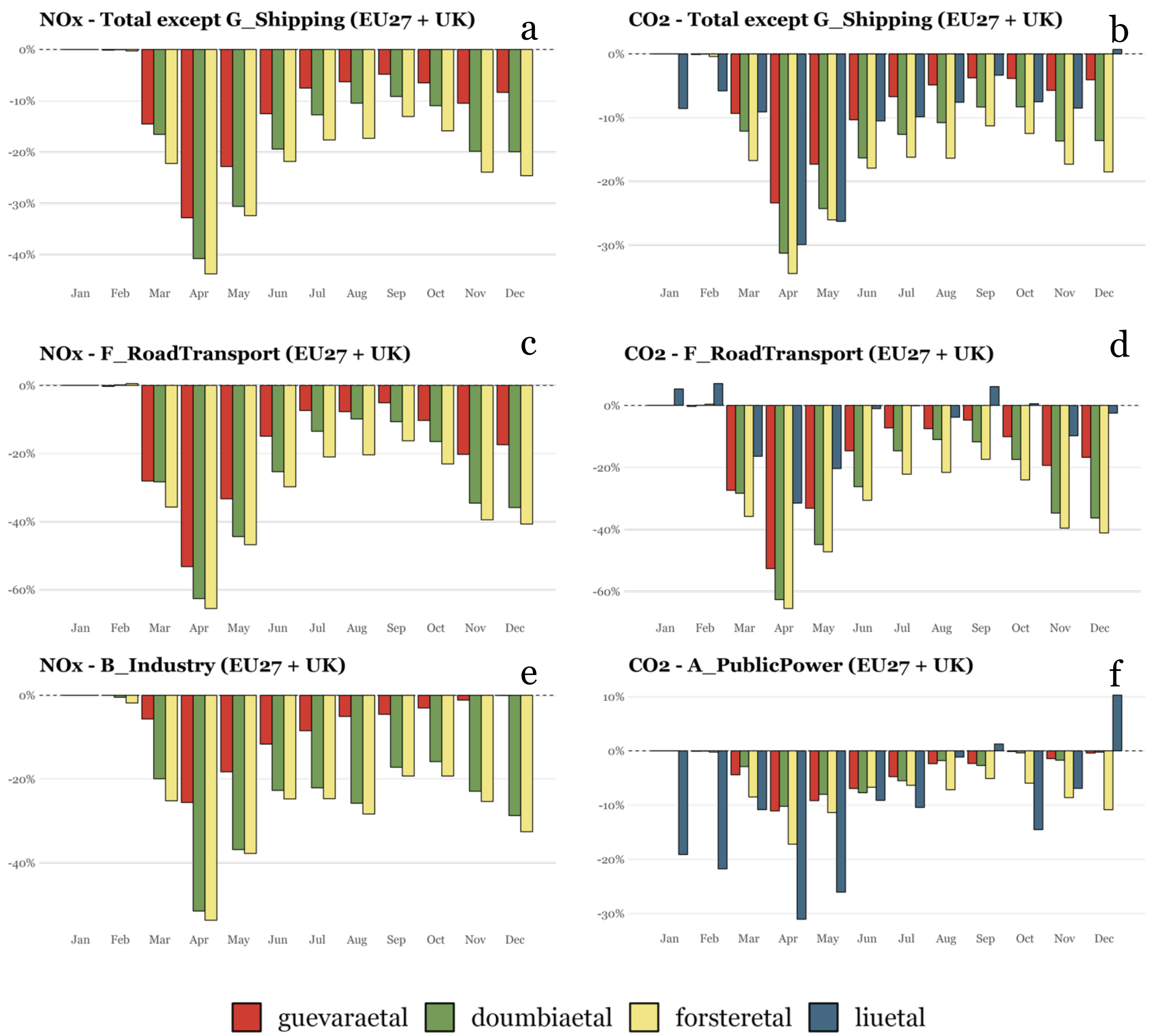
Figure 6 shows the relative changes in monthly NO_x and CO_2 emissions occurred in the EU27 + UK as reported by each of the near-real time datasets described in Sect. 2.2. Official reported data could not be included in this comparison as emissions are available only at the annual level for most of the countries, and just a few of them publicly disclose information at a finer resolution (i.e., monthly, quarterly), as discussed later in this section.

For total NO_x and CO_2, a similar temporal pattern is reported by the four datasets, with: (i) the largest drops occurring during the first round of lockdowns (March to May), (ii) emissions getting closer to pre-pandemic levels when national governments rolled back COVID-19 measures (June to September) and (iii) a new round of lower intensity drops associated with the second pandemic wave in Europe (October to December). However, discrepancies exist regarding the magnitude of the changes reported by each dataset over the three periods.

For NO_x, the drops reported by guevaraetal during March-May and October-December are 1.3 to 2.3 times lower than those provided by forsteretal and doumbiaetal. Significant differences of a similar magnitude are also observed during summertime, when doumbiaetal and forsteretal report much larger reductions when compared to guevaraetal. These discrepancies are mainly driven by the different NO_x emission changes estimated for road transport during the same periods (Fig. 6c). When looking at the NO_x emissions changes in the manufacturing industry sector (Fig. 6d), discrepancies between datasets occur both in terms of the magnitude and timing of the drops. Concerning the temporal aspect, both doumbiaetal and forsteretal reproduce a pattern similar to that of road transport emissions, with a first drop occurring during March-May (reductions up to -53% and -55% in April), a recovery period during the summer and a second drop between November and December (reductions up to between -29% and -32% in December). Oppositely, guevaraetal results suggest a pronounced recovery from May onwards, with emission reductions reaching levels very close to business-as-usual by the end of the year (-0.05% in December). These results are in line with the fact that most restrictions imposed in October, November and December were generally slower and softer than those implemented in March-April (e.g., curfews, limited social gatherings, early closing times for restaurants and bars), and had no effect on the manufacturing industry. The differences between doumbiaetal/forsteretal and guevaraetal results can be directly linked to the activity proxies considered for the manufacturing industrial sector. The first two datasets considered Google mobility data to estimate changes in industrial emissions, whereas guevaraetal results are based on changes in industrial production indices.

For road transport CO_2 emissions (Fig. 6d), the drops reported by liuetal in April (around -28%) are almost 2 times lower than those estimated by the other three datasets (between -50% and -60%). For this sector, the consistency observed between guevaraetal, doumbiaetal and forsteretal during the first wave of the COVID-19 epidemic (i.e., March, April and May) is dissipated in summer, specially during July and August, when forsteretal suggests important decreases in emissions (close to

-20%), doumbiaetal indicates reductions around -10% and guevaraetal reports moderate decreases (approximately -5%). The drops reported for traffic CO_2 emissions by forsteretal and doumbiaetal are back in line during the second wave of contamination (i.e., November and December, close to -40%), with the results estimated by guevaraetal and liuetal being much lower once again (between 2 and 5 times). For CO_2 emissions from the public power sector (Fig. 6f), liuetal already reports significant drops in January and February (approximately -20%), before the beginning of the pandemic. This result reinforces the hypothesis discussed in Sect. 3.1.1, which indicates that changes in 2020 emissions from this sector were mainly driven by national coal phase out commitments that have been continuously implemented since the UN Paris Agreement was adopted during the COP21 in December 2015. For this sector, results reported by guevaraetal and doumbiaetal are generally in line, since in both cases the electricity demand data from ENTSO-E is used as the main proxy to derive the emission adjustment factors (Table 2).



480 **Figure 6 Relative NO_x and CO_2 monthly emission changes [%] reported by each near-real time dataset at the EU27+UK level for total emissions except shipping (a, b) and selected sectors including road transport (c, d), manufacturing industry (e) and public power (f).**

Figures 7 and 8 present a comparison of the near-real time estimates against publicly disclosed national monthly (France, CITEPA, 2022) and quarterly (UK, BEIS, 2022; the Netherlands, CBS, 2022) estimates reported by national inventory agencies. For UK and the Netherlands, official results are only provided for GHGs and 5 general sectors, whereas for France information is available for both AP and GHGs at a detailed activity level (75 subsectors), allowing a more extended comparison (i.e., NO_x and CO_2 for total emissions and selected sectors).

The guevaraetal results are the ones closer to the French NO_x official estimates (i.e., CITEPA) during the periods corresponding to the two main waves of pandemic prevention and control policies (i.e., March-May and October-December). This consistency is observed for total emissions (Fig. 7.a) as well as for the road transport (Fig. 7.c) and industrial manufacturing (Fig. 7.e) sectors. The largest discrepancy between the two datasets is observed in April (-49% versus -38%) and is mainly driven by differences in the manufacturing industry sector (-38% versus -26%), the results reported for road transport being the same (-64%). The doumbiaetal and forsteretal datasets tend to overestimate the official NO_x emission reductions during the two lockdown periods, the largest discrepancy occurring for the manufacturing industry sector in November and December, when the two near-real time datasets indicate reductions of around -30% while CITEPA reports values above BAU levels (up to 9%). This inconsistency is in line with the results from Fig. 6.e previously discussed. The drops of total NO_x emissions occurred during April and May (-38% and -27%) are also overestimated by both doumbiaetal (-59% and -47%) and forsteretal (-60% and -45%). Regarding total CO_2 emissions (Fig. 7.b), guevaraetal and liuetal are in general the datasets more in line with official estimates. The same conclusion is obtained when looking at the results for the road transport sector (Fig. 7.d). The drops reported by CITEPA during April and May (-63% and -37%) are well reproduced by guevaraetal (-61% and -33%), slightly underestimated by liuetal (-50% and -26%) and significantly overestimated by doumbiaetal (-80% and -59%) and forsteretal (-79% and -57%). As shown before (Sect. 3.1.1), liuetal is the dataset that generally reproduces better the official changes reported for the public power sector (Fig. 7.f), being able to capture the increases occurred during summertime, which are partially linked to the record temperatures experienced in France (C3S, 2020b) and the associated increase in the energy demand for the use of air conditioning systems. Despite the good agreement between liuetal and CITEPA for this sector, some important discrepancies are still observed mainly in April, when the near-real time dataset significantly overestimates the reported drop (-44% versus -71%).

The official relative CO_2 quarterly emission changes estimated by BEIS for the UK are in good agreement with the results reported by guevaraetal and liuetal, while a general overestimation is observed for doumbiaetal and forsteretal (Fig. 8.a). All datasets report the largest drop in the second quarter of the year, i.e., -24% according to BEIS and guevaraetal, -30% according to liuetal, -33% according to doumbiaetal and -35% according to forsteretal. For the Netherlands, liuetal is the one closer to the CBS official estimates for all quarters (e.g., -15% in both cases during the second quarter), the results by forsteretal and doumbiaetal being again the ones that present the largest discrepancy (Fig. 8.b). Interestingly, the drop of CO_2 emissions reported during the first quarter of the year (-11%) is of the same magnitude as the ones reported during the second (-15%)

and fourth (-10%) quarters, when national lockdowns were implemented. This drop is only partially reproduced by liuetal and it is mainly related to a drop in the CO_2 emissions from the power sector (not shown), which was triggered by the retirement of hard coal-fired power plants by the end of 2019.

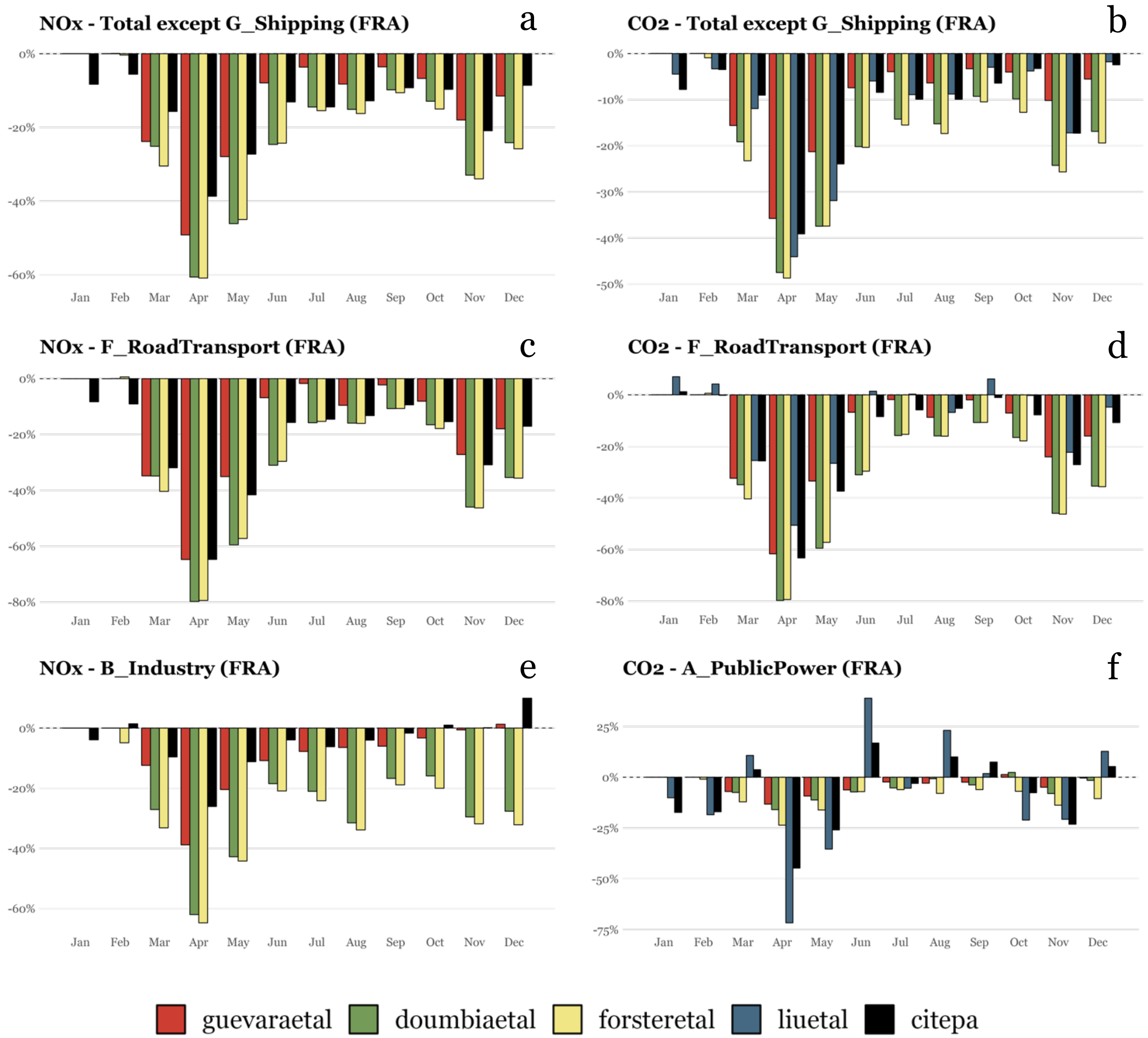


Figure 7 Relative NO_x and CO_2 monthly emission changes [%] reported by each near-real time dataset and CITEPA (2022) for France for total emissions except shipping (a, b) and selected sectors including road transport (c, d), manufacturing industry (e) and public power (f).

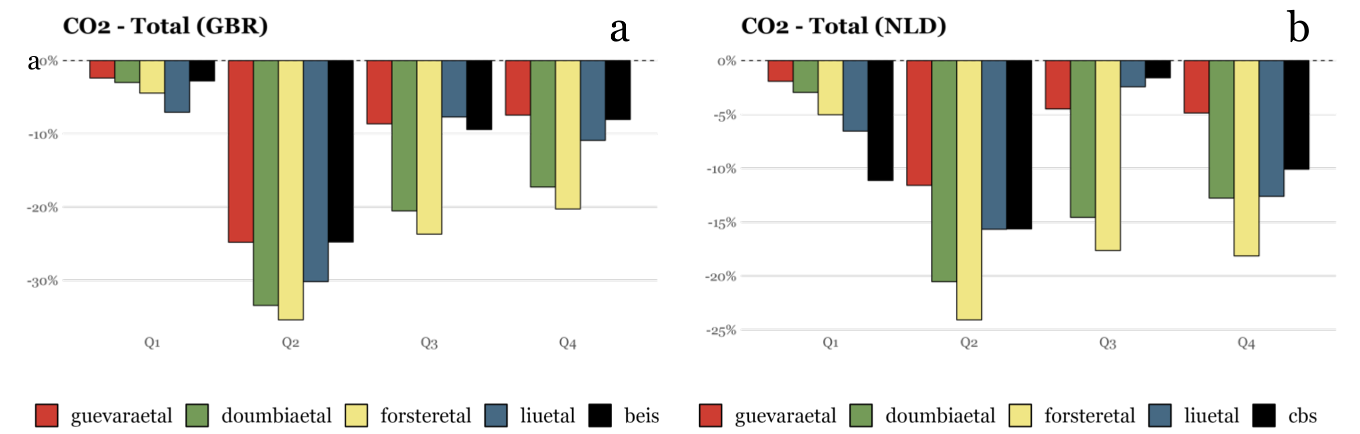


Figure 8 Relative total CO_2 quarterly emission changes [%] reported by each near-real time dataset and official estimates from BEIS (2022) and CBS (2022) for UK (a) and the Netherlands (b), respectively.

4 Conclusions

This work presents the results of an intercomparison of relative European anthropogenic emission changes in 2020 reported by official and non-official estimates. Official estimates include the national inventories of air pollutants (AP; NO_x, NMVOC, SO_2, NH_3, PM2.5) and greenhouse gases (GHG; CO_2 and CH_4) reported under the CLRTAP and the UNFCCC, respectively. The selection of near-real time emission estimates includes the CAMS COVID-19 European emission adjustment factors (guevaraetal), the global CONFORM dataset (doumbiaetal), the COVID-19 estimates developed by Forster et al. (2020) (forsteretal) and the CO_2 emission estimates reported by the Carbon Monitor initiative (liuetal). The comparison focusses on the EU27 + UK and is performed on an annual, quarterly and monthly basis. The following conclusions were obtained from the intercomparison work:

- NOx and CO_2 are consistently being reported by official and non-official estimates as the pollutants that experienced the largest reductions in Europe in 2020 (-11.3% and -12.2% according to official estimates). Similarly, NH_3 and CH_4 are reported by official and the near-real time datasets as the species with the lowest reductions (i.e., -1.1% and -1.4% according to official estimates and between -0.9% and 0.1% according to non-official estimates).
- Despite this agreement, large discrepancies arise between the official and non-official datasets when comparing results for specific sectors and countries.
- The guevaraetal dataset tends to be more in line with official AP relative emission change estimates, while the results reported by forsteretal and doumbiaetal, which are largely derived from Google mobility data, present larger discrepancies.
- Results reported by liuetal are generally in a good agreement with official CO_2 estimates, except for the road transport sector, where they tend to report relative emission reductions much lower than those provided by the UNFCCC official inventories.
- For the residential combustion, public energy industry and shipping sectors, changes in emissions occurred between 2019 and 2020 were mainly dominated by non-COVID-19 factors, such as meteorology (i.e., warmer winter), the implementation of national decarbonization plans in the electricity sector, and the introduction of the Global Sulphur Cap rule, respectively.
- The increase in NMVOC emissions from the use of pandemic products (e.g., hand sanitizer gels) is heterogeneously considered in official CLRTAP inventories, as several countries use a very basic emission estimation method (tier 1) that uses population data as activity data and thus does not reflect the increased use of these products.
- Relative changes in AP and GHG emissions reported by the CLRTAP and UNFCCC official estimates are in general consistent. However, some discrepancies were detected in some cases (e.g., changes in SO_2 versus CO_2 emissions from public power), which could be attributed to issues with the reported data or the coordination between AP and GHG inventory development efforts.

- Regarding monthly relative changes in total NO_x and CO_2, similar patterns are observed in the different near-real time estimates, with the largest drops occurring during first round of lockdowns (March to May), emissions getting closer to business-as-usual levels between June and September, coinciding with the ease of restrictions, and a new round of lower intensity drops occurring between October to December, when a second pandemic wave affected Europe. However, important discrepancies exist regarding the magnitude of the changes reported by each dataset during the three periods, which are again related to the different activity proxies used to estimate the drops in emissions.
- When compared to official quarterly and monthly estimates reported by national inventory agencies, guevaraetal and liuetal are again the datasets that are in a better agreement, both for total emissions and specific sectors, including road transport, manufacturing industry and public power.
- The present intercomparison work does not allow checking the quality of the near-real time estimates in an absolute way since, even being based on local data and detailed estimation methodologies, official national emission inventories have also uncertainties associated to them and cannot be considered as the ground truth. Nonetheless, the cases where datasets converge on similar trends could be interpreted as providing an encouraging cross-verification of the official and independent emission inventories.
- Linked to the previous point, official emission inventory estimates are subject to continuous revisions as the underlying data (e.g., energy statistic, emission factors) and estimation methodologies are updated or improved every year. These revisions may occasionally incur significant changes to emissions from specific countries/sectors/species (e.g., Kuenen et al., 2022), and subsequently to the corresponding comparison results presented in this work

The COVID-19 outbreak has remarkably contributed to a crucial change in how we quantify and understand emissions of AP and GHG. New datasets and proxies based on inter alia mobility and congestion data derived from smartphones or GPS systems have emerged that did not exist before or were not extensively being considered by the emission modelling community. The near-real time estimates presented in this work demonstrate how emission compilation methodologies can take advantage from the emergence of big data from remote sensing technologies and smart devices. The irruption of these technologies and associated datasets, which are expected to continue growing, provides the opportunity for a change of paradigm in the production of emission estimates for monitoring and modelling applications, mainly air quality forecasting. As proposed by Tong et al. (2012), improved predictions of air quality require bringing emission science to a new level and moving from inventory-based data processing approaches (i.e., generation of hourly model ready emission data by processing existing and pre-calculated annual emission estimates) to modelling approaches that use and integrate near-real time data collected from multiple networks and monitors. The need for near-real time emission information has grown not only because of the COVID-19 pandemic, but also as a result of an increased interest from the general public in climate mitigation and environmental protection, as well as subsequent events that are causing disruptions to the business-as-usual emission levels, most notably the war in Ukraine and the associated energy crisis.

Despite the new opportunities created by the aforementioned technological advancements, estimating emissions in near-real time still presents several challenges. Firstly, the results of this intercomparison work highlight that caution is required when using new mobility data to estimate changes in emissions, and that these proxies should be combined with traditional statistics such as measured traffic counts or energy consumption statistics. However, traditional information is still difficult to be acquired in a consistent way, particularly when working at the global level, as the number of global repositories giving access to near-real time and high-resolution emission proxy information is very scarce. As previously highlighted, the results reported by the guevaraetal dataset, which covers only Europe, are generally more in line with official estimates. This demonstrates how difficult is to obtain accurate and consistent local information when working at the global level. At the same time, differences between guevaraetal and official reported emissions for specific sectors and countries indicate that uncertainties are large, even in case of large disturbances such as the COVID-19 pandemic, and that current approaches might miss normal interannual variations. Secondly, digitized near-real time information arising from new smart technologies covering key sectors such as electricity production, aviation or road transport is emerging; however, for some other relevant activities, such as use of solvents, residential and commercial combustion (particularly residential wood combustion) and agricultural activities, it is likely that near-real time activity monitoring will remain scarce. Observations from satellite-based sensors are key to partially overcome this limitation, as exemplified by the Global Fire Assimilation System (GFAS; Kaiser et al., 2021) for monitoring biomass burning emissions or the use of very high-resolution satellites (e.g., WorldView3, WV3) to detect and quantify CH_4 emitters (Irakulis-Loitxate et al., 2022), among others.

5 Data availability

Officially AP (i.e., NO_x, NMVOC, SO_2, CO, NH_3 and PM2.5) and GHGs (i.e., CO_2 and CH_4) reported emissions for 2019 and 2020 (reporting year 2022) were obtained from https://www.ceip.at/webdab-emission-database/reported-emissiondata and https://unfccc.int/ghg-inventories-annex-i-parties/2022, respectively. The collection of the CAMS COVID-19 emission adjustment factors reported by Guevara et al. (2022) are available from https://doi.org/10.24380/k966-3957. The CONFORM emission adjustment factors reported by Doumbia et al. (2021) are available from https://permalink.aeris-data.fr/CONFORM. The emission adjustment factors reported by Forster et al. (2020) are available from https://github.com/Priestley-Centre/COVID19_emissions. The CO_2 European emissions reported by Carbon Monitor (Liu et al., 2020) are available from https://eu.carbonmonitor.org/. Copernicus CAMS-REG_v5.1 2020 business-as-usual (BAU) emission inventory (Kuenen et al., 2022b) is distributed from the Emissions of atmospheric Compounds and Compilation on Ancillary Data (ECCAD) system (https://doi.org/10.24380/eptm-kn40).

A numeric file containing annual and monthly processed emissions per country, GNFR sector and pollutant is provided as part of the supplementary material of the paper. For the official inventories (EMEP-CEIP and UNFCCC) and Liu et al. (2020) we provide the corresponding emissions reported for the years 2019 and 2020. For Guevara et al., (2022), Doumbia et al., (2021) and Forster et al., (2020) we provide the CAMS-REG_v5.1 business-as-usual (BAU) 2020 emissions and the result of combining this inventory with the COVID-19 emission adjustment factors reported by each one of the three databases. The file is provided in Excel format and includes a README sheet describing each one of the information fields.

6 Authors contributions

MG conceived and coordinated the study. MG, HP, OJ and CPGP prepared the comparison plots and contribute to the interpretation and discussion of the results. HACDvdG, JK, IS, CG, TD, PC, ZL, SS, MB and RL contributed to the interpretation and discussion of the results. OJ and CPGP supervised the work. MG prepared the manuscript with contributions from all co-authors.

7 Competing interests

The authors declare that they have no conflict of interest.

8 Acknowledgments

The research leading to these results has received funding from the Copernicus Atmosphere Monitoring Service (CAMS), which is implemented by the European Centre for Medium-Range Weather Forecasts (ECMWF) on behalf of the European Commission. We acknowledge support from the VITALISE project (PID2019-108086RA-I00) funded by MCIN/AEI/10.13039/501100011033; from the MITIGATE project (PID2020-116324RA695 I00/AEI/10.13039/501100011033) from the Agencia Estatal de Investigación (AEI); from the BROWNING project (RTI2018-099894-BI00) from the Ministerio de Ciencia, Innovación y Universidades; from the AXA Research Fund; and from the European Research Council (grant no. 773051, FRAGMENT). Authors also thank the two anonymous reviewers for their constructive feedback, which helped improve the quality of the paper.

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