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Did Germany reach its 2020 climate targets thanks to COVID-19?

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Abstract

In this paper, we estimate the effects of COVID-19 on greenhouse gas emissions (GHG) in Germany in 2020 at the sectoral and national level. Counterfactual emissions are estimated based on autoregressive econometric models and distinguish between different factors of emissions based on decomposition analysis. Our findings at the national level suggest that COVID-19 lowered GHG emissions in 2020 in Germany by about 45 Mt CO_2-eq (6.1%). Accordingly, about two-thirds of the reduction in emissions between 2019 and 2020 in Germany may be attributed to COVID-19. Our findings at the sectoral level imply that all sectors, with the exception of the transport sector, would have met their emissions target in 2020 without COVID-19. Thus, for the buildings sector and the transport sector, our results suggest policy responses that differ from those pursued by the German government to comply with the provisions of the Federal Climate Change Act.

Key policy insights:

- COVID-19 lowered greenhouse gas emissions (GHG) in Germany in 2020 by 6.1% compared to counterfactual emissions.
- Without COVID-19, all sectors but the transport sector would have met their emissions targets.
- Climate policy response should take into account the effects of extraordinary events like COVID-19 on GHG emissions based on counterfactual emissions.
- Counterfactual emissions should be considered prior to crediting emissions surplus or deficit to subsequent years.

Key words: COVID-19, climate targets, climate policy, greenhouse gas emissions.

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List of abbreviations

AR	Autoregressive
bn.	Billion
CO_2-eq.	Carbon dioxide equivalent
CRF	Common reporting framework
EU ETS	EU emissions trading system
F-gases	Fluorinated greenhouse gases
GDP	Gross domestic product
GHG	Greenhouse gases
GVA	Gross value added
HDT	Heavy-duty trucks
ind.	Industry
IPCC	Intergovernmental Panel on Climate Change
kJ	Kilojoule
m^2	Square meter
Mt	Million metric tonne
NIR	National Inventory Report
nº	Number of
PEC	Primary energy consumption
pop	Population
tot	Total
UNFCCC	United Nations Framework Convention on Climate Change

1 Introduction

In December 2019, the German parliament passed the Federal Climate Change Act (Bundes-Klimaschutzgesetz) which envisions climate neutrality from 2050 on, sets a national target of reducing greenhouse gas (GHG) emissions by at least 55% in 2030 compared to 1990 levels, and includes binding annual targets for the economic sectors energy, industry, buildings, transport, agriculture, and waste. In addition, the act includes a crediting mechanism for these sectoral targets: should GHG emissions in a sector exceed or fall short of the target, the difference will be credited equally to the remaining years until 2030. For 2020, the Council of Experts on Climate Change, which is responsible for an evaluation of the GHG emissions data published by the Federal Environment Agency (Umweltbundesamt 2021a), found that all sectors apart from the buildings sector had met their targets in 2020 (Expertenrat für Klimafragen 2021). As required by the Federal Climate Change Act, the federal ministry responsible for the buildings sector subsequently had to present an immediate action programme, which is to ensure the sector's compliance with its emission targets in the future.

The measures implemented to curb the spread of the COVID-19 virus and repercussions from the global international interdependence of economies, however, had substantial effects on economic activity and GHG emissions in 2020 (see e.g. Andreoni 2021; IEA 2021; Liu et al. 2020a; Shan et al. 2021). In Germany, for example, real gross domestic product (GDP) in 2020 was about 5% lower than in 2019 (Destatis 2021a), primarily because of lower industry output. Lower economic activity led to a drop in the demand for electricity and natural gas thus reducing GHG emissions in the industry and energy sectors. Furthermore, because employees were encouraged to work from home or were on short-time work schemes, the pandemic altered their working and commuting patterns, which impact emissions in residential and commercial buildings and in transport. Because of these changes in energy consumption patterns in most sectors, it is important to quantify the contribution of COVID-19 to emissions in 2020 at the level of economic sectors. Some sectors may only have achieved their 2020 targets thanks to COVID-19, while others may have missed their targets because of COVID-19. Thus, immediate action programmes may be implemented which are driven by extraordinary events, but which may be costly in terms of meeting medium and long-term emissions targets.

In this paper, we analyse the effect of COVID-19 on sectoral and national GHG emissions in Germany. To this end, we compare factual emissions as reported in Umweltbundesamt (2021a) with counterfactual emissions. To estimate the counterfactual emissions, we first employ Kaya identities (adapted to the specificities of each sector or sub-sector) to decompose sectoral emissions into the main factors. Then, we estimate autoregressive econometric models for each of these factors to predict their values in 2020. Multiplying the predicted values then yields our estimate of the counterfactual emissions in 2020 for the sub-sectors and sectors.

Our findings suggest that all sectors apart from the transport sector would have met their emission target in 2020 had there been no COVID-19. Thus, for the buildings sector and the transport sector, our results suggest policy responses that differ from those pursued by the German government to comply with the provisions of the Federal Climate Change Act. At the national level, our findings suggest that COVID-19 has lowered the factual GHG emissions in Germany in 2020 by about 6.1% compared to the counterfactual development. This means that about two-thirds of the observed reductions in GHG emissions in Germany compared to 2019 levels may be attributed to the effects of COVID-19.

Only a few studies have previously attempted to quantify the impact of COVID-19 on GHG emissions in Germany. In an early analysis Agora Energiewende (2020) estimates that COVID-19 lowered GHG emissions by about 20 Mt CO_2-eq. This estimate, however, is based on qualitative reasoning rather than on quantitative modelling. Other studies investigated the impact of COVID-19 by analysing the effects of measures implemented to contain the pandemic on the actual emissions. For example, relying on the methodology developed by Le Quéré et al. (2020), Creutzig et al. (2021, 2020) employ high temporal resolution data for the first half of 2020 to analyse the impact of COVID-19 on total CO_2-eq emissions and on the transport sector. Other studies estimated GHG emissions for Germany in 2020 and compared those with 2019 levels (e.g. Liu et al. 2020b; Umweltbundesamt 2021b), but they did not try to identify the effect of COVID-19. In comparison, related studies have explored the effects of COVID-19 recovery programmes (Chiappinelli et al. 2021; Hepburn et al. 2020; Lahcen et al. 2020; Obergassel et al. 2020), the impact of COVID-19 on the acceptance of such programmes by the general public (Engler et al. 2021), and opportunities to pursue more stringent climate targets in the wake of the COVID-19 crisis (Meles et al. 2020).

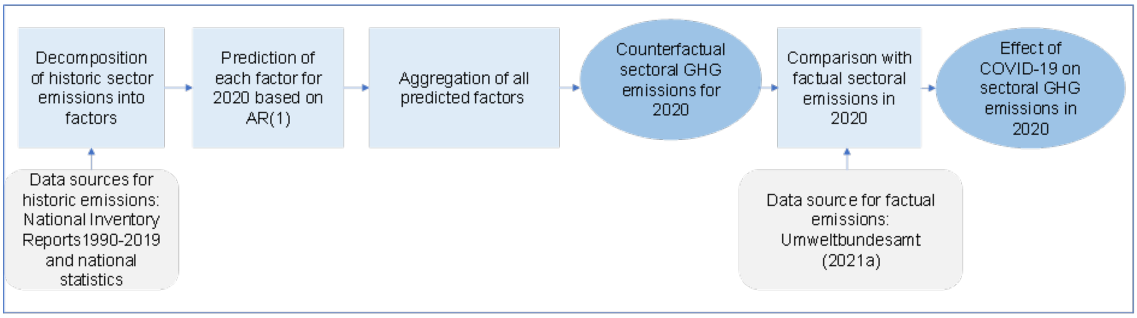
To the best of our knowledge, no study has yet quantified the effects of COVID-19 on GHG emissions in Germany employing quantitative methods to estimate the counterfactual emissions in 2020. In particular, our study is the first to empirically identify the effects of COVID-19 at the levels of individual sectors. Our findings provide insights for the making of climate policy, particularly whether adjustments are needed to ensure the compliance of individual sectors in Germany to meet their targets. The methodology employed to estimate the effects of COVID-19 on GHG emissions in Germany may be adapted for other countries. Likewise, it may be used to study the effects of other extraordinary events on GHG emissions such as economic crises, migration, and technological breakthroughs.

We organise the remainder of our manuscript as follows. In Section 2 we describe the methodology. In Section 3 we report and discuss results. In Section 4, we summarise the main findings and provide insights for policymaking.

2 Methodology and data

To estimate the effect of the COVID-19 pandemic on GHG emissions, we compare our estimate of the counterfactual emissions in 2020 with the factual emissions reported by the Federal Environment Agency of Germany (Umweltbundesamt 2021a). The difference in emission levels is assumed to be attributable to the effects of the COVID-19.[1] Figure 1 provides an overview of the methodology employed to estimate the effects of the COVID-19 pandemic on GHG emissions.

Figure 1: Overview of methodology and data sources analysis at sectoral levels



2.1 Kaya identity

First, we used the Kaya identity (Kaya 1989) to define the main factors driving emissions in each sector. The Kaya identity has frequently been applied in the energy and climate policy literature to decompose GHG emissions at the sectoral or national levels (see Oshiro et al. 2016 and Sharmina et al. 2021). Based on the Kaya identity, the GHG emissions of a sector may be presented as the product of the following factors: population, activity, energy intensity and carbon intensity. We adapted the standard Kaya identity to each economic sector thereby taking into account sector specificities and data availability (Ang and Zhang 2000; Förster et al. 2018; Mavromatidis et al. 2016). For most sectors, data availability allowed decompositions at the level of sub-sectors. For example, in the transport sector, we distinguish emissions caused by passenger transport (i.e. cars) and by freight transport (i.e. heavy-duty trucks (HDTs)). To

1 Since the German Federal Climate Change Act defines targets for the economic sectors in Germany, our analysis pertains to GHG emissions for economic sectors. Table A1 in Appendix A provides an overview of the linkage between these sectors and the sectors as defined in the UNFCCC common reporting framework (CRF) (IPCC 2019).

illustrate, we employ the following identity to decompose GHG emissions in the sub-sector passenger transport:

$$\underbrace{GHG_{(cars)}}_{Emissions} = \underbrace{pop}_{Population} * \underbrace{\frac{distance\ travelled_{total}}{pop}}_{Activity} * \underbrace{\frac{distance\ travelled_{cars}}{distance\ travelled_{total}}}_{Modal\ shift} * \underbrace{\frac{PEC_{cars}}{distance\ travelled_{cars}}}_{Energy\ intensity} * \underbrace{\frac{GHG_{cars}}{PEC_{cars}}}_{Carbon\ intensity} \quad (1)$$

In addition to the standard Kaya identity, equation (1) includes the factor “modal shift”, which denotes the share of distance travelled by car compared to all transportation modes. In other words, "modal shift" reflects structural change in the sector. In Table 1 and Appendix B, we describe in detail the decompositions employed in our analyses for all sectors and sub-sectors.

Table 1: Factors used based on Kaya identity for each sector

Sector/sub-sector	Factor	Details
Energy		
-	Population	pop
	Activity	$\frac{GDP}{pop}$
	Energy intensity	$\frac{PEC}{GDP}$
	Carbon intensity	$\frac{GHG_{energy}}{PEC}$
Industry		
Fuel-related	GVA	GVA_{tot}
	Structural change	$\frac{GVA_{industry}}{GVA_{tot}}$
	Energy Intensity	$\frac{PEC_{fuel}}{GVA_{industry}}$
	Carbon intensity	$\frac{GHG_{fuel}}{PEC_{fuel}}$
Process-related	GVA	GVA_{tot}
	Structural change	$\frac{GVA_{industry}}{GVA_{tot}}$
	Carbon intensity	$\frac{GHG_{industry}}{GVA_{industry}}$

Sector/sub-sector	Factor	Details
Transport		
Passenger	Population	pop
	Transport intensity	$\frac{distance\ travelled_{total}}{pop}$
	Share of private cars	$\frac{distance\ travelled_{cars}}{distance\ travelled_{total}}$
	Energy intensity of cars	$\frac{PEC_{cars}}{distance\ travelled_{cars}}$
	Carbon intensity of cars	$\frac{GHG_{cars}}{PEC_{cars}}$
Road freight	Total economic activity	GDP
	Transport intensity	$\frac{distance\ travelled_{total}}{GDP}$
	Share of HDT	$\frac{distance\ travelled_{HDT}}{distance\ travelled_{total}}$
	Energy intensity of HDT	$\frac{GHG_{HDT}}{PEC_{HDT}}$
	Carbon intensity of HDT	$\frac{PEC_{HDT}}{distance\ travelled_{HDT}}$
Buildings		
Residential	Population	pop
	Buildings per capita	$\frac{n°\ buildings}{pop}$
	Size intensity	$\frac{m^2_{tot}}{n°buildings}$
	Energy intensity	$\frac{PEC_{residential}}{m^2_{tot}}$
	Carbon intensity	$\frac{GHG_{residential}}{PEC_{residential}}$
Commercial	Population	pop
	Activity	$\frac{GDP}{pop}$
	Energy intensity	$\frac{PEC_{commercial}}{GDP}$
	Carbon intensity	$\frac{GHG_{residential}}{PEC_{residential}}$

Sector/sub-sector	Factor	Details
Agriculture		
Livestock	Population	pop
	Livestock per capita	$\frac{n° \, livestock_{tot}}{pop}$
	Share of livestock (j)	$\frac{n° \, livestock_j}{n° \, livestock_{tot}}$
	Carbon intensity of livestock (j)	$\frac{GHG \, livestock_j}{n° \, livestock_j}$
Crops	Population	pop
	Carbon intensity	$\frac{GHG_{crops}}{pop}$
Waste		
Solid waste	Population	pop
	Waste per capita	$\frac{solid \, waste_{total}}{pop}$
	Share of disposal mode (j)	$\frac{solid \, waste_j}{solid \, waste_{total}}$
	Carbon intensity of disposal mode (j)	$\frac{GHG_j}{solid \, waste_j}$
Wastewater	Population	pop
	Wastewater per capita	$\frac{waste \, water_{tot}}{pop}$
	Carbon intensity	$\frac{GHG_{waste \, water}}{waste \, water_{tot}}$

2.2 Econometric analysis

We estimate the counterfactual emissions for 2020 via time series econometric methods. To this end, we employ first-order autoregressive models AR(1) which explain the evolution of a factor at time *t* based on the value of the same factor in the previous year (*t-1*). AR models are particularly suitable for capturing processes that are based on capital-intensive structures such as GHG emissions. For example, ARs have previously been used to forecast CO_2 emissions by Hosseini et al. (2019), Liu and Raftery (2021), and Nyoni and Mutongi (2019).

In general, an AR(1) model can be expressed as:

$$y_t = \delta + \varphi y_{t-1} + \varepsilon_t \tag{2}$$

Where δ and φ are parameters and ε_t is a non-systematic error term. To estimate the parameters, we employ ordinary least squares (OLS). Historic data on the factors is typically available from 1995 to 2019. Because our time series are relatively short, we use a bias correction according to Kendall (1954). Meaning, we use the following transformation:[2]

$$\varphi_K = \varphi + \frac{1+3\varphi}{T} \quad (3)$$

where T is the length of the time series in years (i.e. typically 15). To ensure stationarity of the time series we estimate equation (3) in first differences. All final specifications pass the Kwiatkowski-Phillips-Schmidt-Shin (KPSS) test (Kwiatkowski et al. 1992) for stationarity at a level of significance of 1%.

For each factor, we use our estimates of δ and of φ_K to predict its value for 2020. As is common practice, we assume that the structural relationships obtained from historic data are valid for the prediction period 2020. To achieve our estimate of counterfactual emissions in 2020, we multiply the values predicted for 2020 for each factor. In Figure A1 of Appendix A we illustrate this approach for emissions from passenger transport akin to equation (1).[3] Identification requires that only effects related to COVID-19 are responsible for deviations of these counterfactual emissions from factual emissions in 2020. For example, we abstract from effects of policies implemented in 2020. In our context, households may have stockpiled heating oil in 2020 because the German government temporarily reduced the value-added taxes in 2020 to ease the burden of COVID-19 on the economy. Similarly, we ignore effects on emissions in 2020 brought forward in time by future policies. For example, subsequent to the Fuel Emissions Trading Act (Brennstoffemissionshandelsgesetz) a national carbon price for heating fuels in Germany came into force in January 2021. Therefore, households and organizations belonging to the commerce sectors had an incentive to bring the purchase of heating oil forward in time.

We use AR models for all sectors except waste, because the time series of the factors in the waste sector showed structural breaks which would lead to biased parameter estimates. For the waste sector we therefore use the average growth

2 In addition, we checked the robustness of our results using the bias correction method developed by Phillips and Yu (2005) which leads to similar results. The findings of these specification checks are available upon request.

3 Due to space constraints, we cannot show a similar graph for all sectors and sub-sectors.

rate in emissions between 2015 and 2019 to estimate the counterfactual emissions in 2020.

Sub-sectoral estimates of counterfactual emissions are added up to obtain an estimate of counterfactual emissions at the sectoral level. In a later step we also calculate counterfactual emissions at the national level by adding up the estimates of counterfactual emissions of all sectors. Because data on factors was lacking for some sub-sectors (mostly in the transport and agricultural sector) our decomposition approach covers only about 95% of total GHG emissions in Germany (see Table A2 in Appendix A). For the sub-sectors with missing data on factors, we regressed AR(1) models on the level of emissions (rather than factors) using data from National Inventory Reports (NIRs) (Umweltbundesamt 2021c). We include these additional estimates to obtain our final estimate of counterfactual emissions at the sectoral levels.

2.3 Data

For the sectoral analysis, we retrieved data on the time series of the factors from the NIR 2021 (Umweltbundesamt 2021c) and various subject-matter-series from the Federal Statistical Office of Germany (Destatis 2020a, 2021a, 2021b, 2021c, 2021d). Information on the distances travelled by passenger cars (in passenger*km) and freight vehicles (in tonnes*km) data is obtained from Allekotte et al. (2020). As for the national level, historical data for GHG emissions were taken from NIR 2021 (Umweltbundesamt 2021c), while data on past levels of GDP were obtained from Destatis (2021c). Table A3 in Appendix A provides an overview of the data sources used. Descriptive statistics are reported in Table A4 for all factors by sectors and sub-sectors.

3 Results and discussion

We first present and discuss our findings at the level of the economic sectors in Germany, and then at the national level. We document the results of all econometric models in detail in Appendix A, Table A5.

3.1 Sectoral level

In the following sub-sections, we present our estimates of the counterfactual emissions in relation to factual emissions for 2020 at the levels of economic sectors and sub-sectors. To relate our findings to pre-pandemic periods, we also report factual emissions for 2019. Table 2 summarises our key findings.

Table 2: Counterfactual and factual emissions

	Factual emissions in 2019†	**Factual emissions in 2020†**	**Counter-factual emissions in 2020**	**COVID-19 effect: Difference between factual and counterfactual emissions in 2020**	
	[Mt CO_2-eq]	[Mt CO_2-eq]	[Mt CO_2-eq]	[Mt CO_2-eq]	%
Energy	258.0	220.5	244.9	-24.4	-11.1%
Industry	186.8	178.1	182.5	-4.4	-2.5%
Buildings	123.5	120.0	115.8	+4.2	+3.5%
Transport	164.3	145.6	165.4	-19.8	-13.6%
Agriculture	67.9	66.4	67.0	-0.6	-0.9%
Waste (and others)	9.2	8.9	8.8	+0.1	+1.1%
Total	809.8	739.5	784.4	-44.9	-6.1%

Sources: Umweltbundesamt (2021a, 2021c), own calculations.

3.1.1 Energy

For the energy sector, our methodology yields a point estimate for the counterfactual emissions for 2020 of 244.9 Mt CO_2-eq. Thus, in this sector, counterfactual emissions are substantially higher than factual emissions. This difference is higher than in all other sectors in absolute terms (24.4 Mt CO_2-eq) and second only to the transport sector in relative terms (11.1%). Compared to the factual emissions in 2019, the counterfactual (factual) emissions in 2020 correspond to a reduction of 5.1% (14.5%).

The energy sector has been affected by the COVID-19 pandemic in multiple ways. Gross electricity consumption in 2020 was 552.2 TWh which is 4.1% lower than in 2019 (AGEB, 2021). This development may be explained by the macroeconomic impact of the Corona pandemic, particularly the drop in electricity and heat demand in the industrial sector, which indirectly reduces the primary energy demand and the energy intensity (primary energy per capita) in the energy sector. In addition, the price of natural gas had dropped in 2020 which led to the substitution of coal-fired power plants by combined cycle gas turbines (CCGT) fuelled by natural gas. The price of EU allowances in the EU emissions trading system (EU ETS) was at around 25 Euro/tCO_2-eq in 2020, thus providing similar financial incentives to substitute coal-fired power by gas-fuelled CCGT as in 2019. In addition, the share of renewable energy in the electricity mix in Germany grew from 45.8% (238 TWh) to 50.7% (249 TWh) in 2020, partly due to the increase in capacity of PV installations and favourable weather conditions for wind and PV (AGEB 2021). In conclusion, the difference in emissions between actual and counterfactual emissions in the energy sector may be explained by a lower level of activity, a drop in energy intensity, and a lower emission intensity compared to the predicted values of these factors. Our results for the energy sector align with findings by Creutzig et al. (2020), who estimate that about one third of the reductions in the energy sector in the first half of 2020 compared to 2019 levels was due to lower economic activity, while about two thirds were caused by other factors including weather conditions, a higher share of renewable energies and price effects.

3.1.2 Industry

Our decomposition of emissions in the industry sector distinguishes between energy-related emissions stemming from fuel combustion and process-related emissions resulting from industrial processes (e.g. in the production of cement clinker or steel). Our estimates for the counterfactual GHG emissions amount to 123.8 Mt CO_2-eq for fuel-related emissions and 44.9 Mt CO_2-eq, for process-related emissions. Together with the predicted emissions of fluorinated greenhouse gases (F-gases) (13.8 Mt CO_2-eq), these figures form our estimate of the counterfactual emissions for the entire industry sector in 2020 of approximately 182.5 Mt CO_2-eq. This means that counterfactual emissions in the industry sector are estimated to be 4.4 Mt CO_2-eq (2.5%) higher than the factual emissions. Compared to 2019 emission levels, the counterfactual (factual) emissions in 2020 are 2.3% (4.7%) lower.

COVID-19 affected companies in the industry sector through a drop in domestic and export demand and interruptions in supply (e.g. due to short-time work and logistical bottlenecks in the supply chain). As a result, gross value added (GVA) in the manufacturing sector in 2020 was about 10% lower than in 2019 (Destatis 2021c). In Germany, the automotive sector (including component suppliers) was particularly affected. Sales in this sector were estimated to have declined by 73% in 2020 compared to 2019 (DIHK, 2020). In conclusion, the difference between actual and counterfactual emissions in the industry sector may primarily be explained by a lower level of activity.

3.1.3 Buildings

Our point estimate for the counterfactual emissions of 115.8 Mt CO_2-eq implies that the buildings sector is the only economic sector in Germany for which COVID-19 has led to an increase in GHG emissions. The difference between factual and counterfactual emissions amounts to 4.2 Mt CO_2-eq (3.5%). Compared to 2019 emission levels, 2020 counterfactual (factual) emission levels in the buildings sector are 6.2% (2.8%) lower.[4]

More specifically, our estimates for the counterfactual GHG emissions are 86.1 Mt CO_2-eq for residential buildings, which is 5.3% lower than factual emissions in 2020 (90.9 Mt CO_2-eq), and 4.1% higher than emissions in 2019 (89.8 Mt CO_2-eq) (Umweltbundesamt, 2021a). Clearly, the increase in teleworking and short-time work to contain the pandemic resulted in higher heating demands and GHG emissions in residential buildings. In comparison, counterfactual GHG emissions in buildings in the commercial sector (commerce, trade, services and public) in 2020 are estimated at 28.8 Mt CO_2-eq. Thus, estimated counterfactual GHG emissions in commercial buildings in 2020 are slightly lower (0.7 Mt CO_2-eq; 2%) than factual emissions and 8.8% lower than in 2019. Lockdown measures such as curfews and business restrictions for restaurants, bars and hotels lowered GHG emissions in commercial buildings, which were not offset by measures taken to limit the spreading of the virus such as additional ventilation of office buildings, schools and other public buildings (UfU 2021).

In conclusion the difference between actual and counterfactual emissions in the buildings sector in 2020 may primarily be explained by a higher than predicted energy intensity in residential buildings, which outweigh a lower than predicted energy intensity in the commercial sector. In addition, factual emissions in the buildings sector may also have been driven by stockpiling of heating oil. This behaviour could be due to the temporarily reduced value added tax rates in

4 These figures are adjusted for differences in heating degree days between years.

2020, as well as the knowledge that as of January 2021 a carbon price for heating fuels was to come into force. This stockpiling effect has been estimated to correspond to 1.7 Mt CO_2-eq (AGEB 2021). Thus, counterfactual emissions in the buildings sector in 2020 would have been below the factual emissions even if the entire stockpiling effect had been subtracted from the factual emissions.

3.1.4 Transport

We estimate the counterfactual GHG emissions for the entire transport sector in 2020 at approximately 165.4 Mt CO_2-eq, which is 13.6% higher than the factual emissions. Compared to the emissions in the transport sector in 2019, the counterfactual (factual) emissions in 2020 correspond to a reduction of 0.7% (11.4%). These findings are in line with Creutzig et al. (2021) who - relying among others on GPS data for passenger distances travelled - estimate 'hypothetical' emissions for the transport sector in 2020 at about 161 Mt CO_2-eq. The road transport sub-sector (i.e. passenger and freight transport combined), which makes up almost 90% of GHG emissions in the transport sector (Umweltbundesamt, 2021a), accounted by far for the bulk of these reductions. Relying on the methodology outlined in Figure 1, we estimate counterfactual GHG emissions for road transport at 160.6 Mt CO_2-eq, which is in the range of the emission levels observed in 2018 (157.8 Mt CO_2-eq) and 2019 (159.7 Mt CO_2-eq) but 18.6 Mt CO_2-eq (9.1%) higher than the factual emissions in 2020.[5]

Because data on the decomposition factors was lacking, we estimated the counterfactual emissions for the other sub-sectors such as domestic aviation, railways and domestic shipping based on the development of past emissions as documented in the NIRs. In relative terms, domestic aviation experienced the highest impact due to the pandemic: the factual emissions (0.9 Mt CO_2-eq) are estimated to be about 60% lower than the counterfactual emissions (2.3 Mt CO_2-eq) in 2020. This finding is in line with Umweltbundesamt (2021b), which concludes that emissions from domestic aviation in 2020 had dropped by around 60% compared to 2019. Finally, we estimate that the pandemic lowered emissions in the sub-sectors railways and domestic shipping by only 3% each.

Apparently, the extraordinary reduction in GHG emissions observed in road transport are due to the increase in teleworking and short-time work due to the pandemic. In particular, Creutzig et al. (2020) find that total passenger kilome-

5 Because data on actual emissions is only available for road transport, we cannot estimate the effects of COVID-19 separately for passenger and freight transport.

tres travelled in 2020 were 12.4% lower than in 2020. Similarly, according to the Federal Highway Research Institute, passenger kilometres travelled in 2020 on federal highways were about 10.8% below 2019 levels (Schönebeck et al. 2020). This decrease in emissions from road transport more than offset any increase in emissions from passenger transport which resulted from people shifting from public transport modes to private cars because they did not want to expose themselves to the risk of infection with COVID-19 in trains, trams, and busses.[6]

Thus, for the sub-sector passenger transport, the difference in emissions between actual and counterfactual emissions may be explained by a lower than predicted activity, which more than offset the effects of structural change (i.e. modal shift). Additionally, the drop in industrial demand slightly depressed needs for commercial transport services. Hence, for emissions related to freight transport, the difference between counterfactual and factual emissions may be explained by the factor activity which turned out to be somewhat lower than predicted (Umweltbundesamt 2021b).

3.1.5 Agriculture

We estimate the counterfactual GHG emissions in 2020 in the agriculture sector at 66 Mt CO_2-eq of which 30.8 Mt CO_2-eq pertain to livestock and 35.2 Mt CO_2-eq to crops. While COVID-19 caused shifts and delays in the food supply chain in Germany, the impact on the total emissions in agriculture appears to be minimal. Our findings suggest that factual emissions in 2020 are 0.6 Mt CO_2-eq (0.9%) lower than counterfactual emissions. Compared to 2019 emission levels, 2020 counterfactual (factual) emission levels in the agricultural sector are 6.2% (2.8%) lower. Because of constraints imposed by COVID-19-measures, demand for domestic agricultural products (such as meat, vegetables, fruits and milk products) from restaurants and hotels was generally lower, but higher demand in supermarkets, for example, appears to have compensated for these effects.

6 For example, total long-distance passenger numbers (train and long-distance buses) in 2020 were 46% lower in the first half of 2020 and 75% lower in the second half of 2020 than in 2019 (Destatis 2020b).

3.1.6 Waste

For the waste sector, we predict counterfactual GHG emissions in 2020 to range around 8 Mt CO_2-eq. The majority of these emissions are estimated to relate to the solid waste 7.8 Mt CO_2-eq and only 1 Mt CO_2-eq to wastewater. Thus, we find virtually no difference between factual and counterfactual emissions for the sector overall, which is in line with Gosten and Henkel (2020). Teleworking and short-time work may have led to an increase in waste in the residential sector and to a decrease in waste in industrial, commerce and services sectors of about equal magnitudes.

3.2 National level

Adding up the projected emissions of the individual sectors results in counterfactual emissions at the national level of 784.4 Mt CO_2-eq, which is about 45 Mt CO_2-eq (6.1%) higher than the actual emissions reported for 2020 by the Federal Environment Agency (Umweltbundesamt 2021a). Because factual emissions in 2020 were 70.2 Mt CO_2-eq lower than in 2019, COVID-19 effects are estimated to account for about two thirds (64%) of these emission reductions.

To corroborate these findings, we also estimated counterfactual emissions employing AR(1) estimations of the national emissions intensity (GHG/GDP). Based on this approach, we predict the counterfactual carbon intensity for 2020 to be at 7.58 CO_2-eq /GDP. This factor is 5.8% lower than it was in 2019. To estimate the counterfactual emissions at the national level, we multiply the counterfactual carbon intensity for 2020 with an estimate of counterfactual GDP for 2020. For the latter, we use a projection of the GDP growth rate for 2020 (1.1%) published by the Ministry of Economics and Energy (BMWi, 2020) in January of 2020, i.e. just before any impact of COVID-19 in Germany was foreseeable. We interpret this value as the likeliest economic growth in GDP that would have occurred in the absence of COVID-19. This method yields an estimate of the counterfactual GHG emissions at the national level for 2020 of 787.4 Mt CO_2-eq, which is very close to the figure we obtained by adding up the counterfactual emissions of the individual sectors (784.4 Mt CO_2-eq).

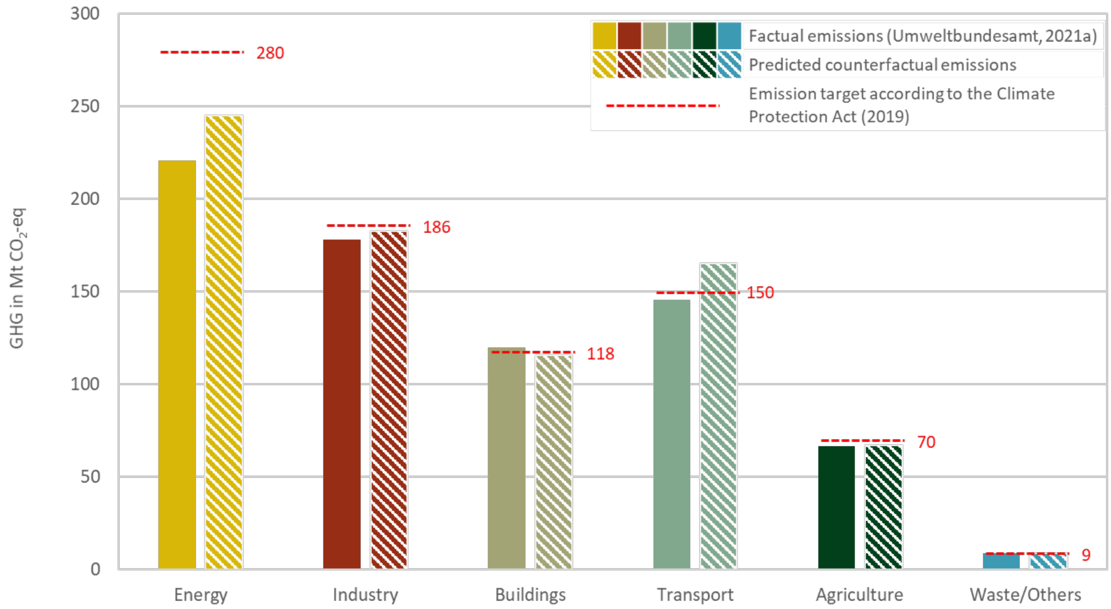
Thus, our findings on the impact of COVID-19 on GHG emissions in Germany at the national level appear to be robust to alternative methods of constructing the counterfactual emissions. We further note that our result is consistent with the finding by the Germany Climate Council (Expertenrat für Klimafragen 2021). Based on a decomposition analysis, the Council attributes a decrease in GHG emissions of 40 Mt CO_2-eq to the decline of economic activity effect in 2020. Our estimate of the COVID-19 effect is about twice as high as the early estimate by Agora Energiewende (2020). Likewise, according to our findings, COVID-19 contributed about twice as much to the observed drop in GHG emissions in Germany between 2019 and 2020 than suggested by the Federal Environment Agency (Umweltbundesamt 2021b). Thus, the aggregate contribution of other factors (including policy measures) to this reduction in GHG emissions may have been smaller than implied by the agency's report.

4 Conclusion

In this paper we quantify the effects of COVID-19 on GHG emissions at the sectoral and national levels, to quantify the effects of COVID-19 in 2020 in Germany. Counterfactual emissions are estimated based on autoregressive econometric models, and typically distinguish between different factors driving emissions. Our findings at the national level suggest that COVID-19 lowered GHG emissions in 2020 by about 45 Mt CO_2-eq (6.1%). Thus, about two-thirds of the drop in emissions between 2019 and 2020 in Germany may be attributed to COVID-19. Our findings at the sectoral level suggest that COVID-19 lead to a reduction in GHG emissions in the energy sector (24.4 Mt CO_2-eq; 11.1%), the industry sector (4.4 Mt CO_2-eq; 2.5%), and the transport sector (19.8 Mt CO_2-eq; 2.5%). In contrast, we find COVID-19 to have increased GHG emissions in the buildings sector by 4.2 Mt CO_2-eq (3.5%). In comparison, we find virtually no effect of COVID-19 on GHG emissions in the agricultural sector and in the waste sector.

These findings have important implications for policymaking. In particular, as we illustrate in Figure 2, all sectors but the buildings sector met their individual GHG emissions targets for 2020 set in the Federal Climate Change Act of 2019. Our results, however, suggest that without COVID-19 the transport sector would not have met its target, while the buildings sector would have met its target. Yet, as provided by the act, the Federal Ministry of the Interior, Building and Community (BMI) and the Federal Ministry for Economic Affairs and Energy (BMWI) need to rapidly present an immediate action programme for the buildings sector which is to lead to additional cumulative savings of 2 Mt CO_2-eq in the subsequent years and thereby ensure compliance with the annual sectoral emissions budget.

Figure 2: Comparison of counterfactual GHG emissions with factual emissions and targets for economic sectors in Germany in 2020



Our findings further suggest that in the absence of COVID-19, the Federal Ministry of Transport and Digital Infrastructure (BMVI) would have had to propose an immediate action programme to lower emissions in the transport sector. Notably, studies conducted before COVID-19 emerged had typically called for more ambitious measures to be implemented because they expected sectors to miss their GHG emission targets - especially the transport sector (see e.g. Öko-Institut et al. 2020). The findings of our study support these requests, thereby exemplifying a shortcoming of the Federal Climate Change Act. When there are extraordinary events with far-reaching effects on GHG emissions such as the COVID-19 pandemic, counterfactual emissions should be considered in the measurement, reporting and verification (MRV) process before deciding which sectors need to rapidly implement immediate action plans. Similarly, counterfactual emissions should also be considered before crediting emissions to subsequent years, which may further delay measures necessary to achieve future climate targets.[7] Likewise, the German Council of Experts on Climate Change (Expertenrat für Klimafragen 2021), suggests that the need for an immediate action programme should be assessed regardless of whether the sectoral emis-

7 From 2021 onwards surplus emissions of sectors with respect to their emissions limits will be credited to future years, thus making it easier for these sectors to meet future targets.

sions targets for a particular year are met or not. Such a comprehensive assessment should also consider data uncertainties (e.g. related to 'factual' emissions), the effects of extraordinary events such as COVID-19, the interactions between sectors (e.g. energy and transport in light of increases in e-mobility), as well as effects of new climate policy measures prior to deciding on an immediate action programme.

Failure to implement additional measures may turn out to be costly in the medium term once the transitory emissions reductions induced by COVID-19 no longer occur. Such additional measures have become even more urgent following the revision of the Climate Change Act of June 2021, which now foresees climate neutrality for 2045 rather than 2050 (BMU 2021). This revision was necessary after the German Federal Constitutional Court (BVerfG 2021) had ruled the original Act violated the fundamental rights of the younger generation.

Finally, the methodology employed to quantify the effect of COVID-19 on GHG emissions in Germany could readily be applied to other countries, if data on GHG decomposition were available. Similarly, the methodology could be used to study the effects of other extraordinary events on greenhouse gas emissions such as economic crisis (affecting primarily the factor 'activity'), migration (affecting primarily the factor 'population'), or technological breakthroughs (affecting primarily the factors 'energy intensity' and 'carbon intensity').

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Appendix A: Supplementary data and methodology

Table A1: Matching of economic sectors in Germany with UNFCCC common reporting framework (CRF)

CRF categories	Economic sectors/ sub-sectors	Included in de-composition?	Comments
1 – Energy	**Energy**		
1.A.1	Energy industries	Yes	-
1.A.3.e	Natural gas compressor	Yes	-
1.B	Diffuse emission from fuel	Yes	-
2 – Industry	**Industry**		
1.A.2	Manufacturing industries and construction	Yes	Fuel-related emissions
2.A	Mineral industry	Yes	Process-related emis-sions
2.B	Chemical industry	Yes	Process-related emis-sions
2.C	Metal industry	Yes	Process-related emis-sions
2.D-H	Other processes and product uses	Yes	Process-related emis-sions
	Sum of F-gases†	No	Regression based on NIR
3 – Buildings	**Buildings**		
1.A.4.a	Commercial/institutional	Yes	-
1.A.4.b	Residential	Yes	-
1.A.5	Military	No	Regression based on NIR
4 – Transport	**Transport**		
1.A.3.a	Domestic aviation	No	Regression based on NIR
1.A.3.b	Road transport	Yes	Passenger and freight
1.A.3.c	Railways	No	Regression based on NIR
1.A.3.d	Domestic shipping	No	Regression based on NIR

CRF categories	Economic sectors/ sub-sectors	Included in de-composition?	Comments
5 – Agriculture	**Agriculture**		
1.A.5	Stationary and mobile furnace	No	Regression based on NIR
3.A	Enteric fermentation	Yes	-
3.B	Manure management	Yes	-
3.D	Agricultural soils	Yes	-
3.G	Liming	No	Regression based on NIR
3.H	Urea application	No	Regression based on NIR
3.I	Other carbon containing fertilizers	No	Regression based on NIR
3.J	Others	No	Regression based on NIR
6 – Waste and others	**Waste and others**		
5.A	Solid waste disposal	Yes	-
5.B	Biological treatment of solid waste	Yes	-
5.D	Wastewater treatment and discharge	Yes	-
5.E	Others	No	Regression based on NIR

† F-gases comprise of hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF6). Emissions of F-gases arise from various CRF categories such as CRF 2.B, 2.C, 2.E, 2.F and 2.G (Eurostat 2017).

Table A2: Comparison of GHG emissions covered in decomposition analysis with NIR

Sectors based on the Federal Climate Change Act (2019)	GHG emissions covered in decomposition analysis	GHG emissions in 2019 based on NIR	Coverage rate
Energy	257.7	258.0	99.9%
Industry	172.8	186.8	92.5%
Buildings	122.5	123.5	99.3%
Transport	146.4	164.3	89.1%
Agriculture	56.5	67.9	83.2%
Waste and others	9.2	9.2	99.6%
Total	765.2	809.8	94.5%

Table A3: Overview of variables, units and data sources

Variable	Unit	Data source
GHG (all sectors)	kt CO_2-eq	(Umweltbundesamt, 2021c)
Population	Mio.	(Destatis, 2021c)
PEC (all sectors)	TJ	(Umweltbundesamt, 2021c)
GDP	EUR bn.	(Destatis, 2021c)
GVA	EUR bn.	(Destatis, 2021c)
Distance travelled (cars)	Passenger*km	(Allekotte et al., 2020)
Distance travelled (HDT)	Tonnes*km	(Allekotte et al., 2020)
N° of residential buildings	-	(Destatis, 2021d)
m^2 of residential buildings	km^2	(Destatis, 2021d)
N° of livestock (total and by type)	Thousands	(Umweltbundesamt, 2021a)
Solid waste	kt	(Umweltbundesamt, 2021a)
Waste water	kt degradable organic component	(Umweltbundesamt, 2021a)

Figure A1: Historic development and predicted values decomposition factors in passenger transport

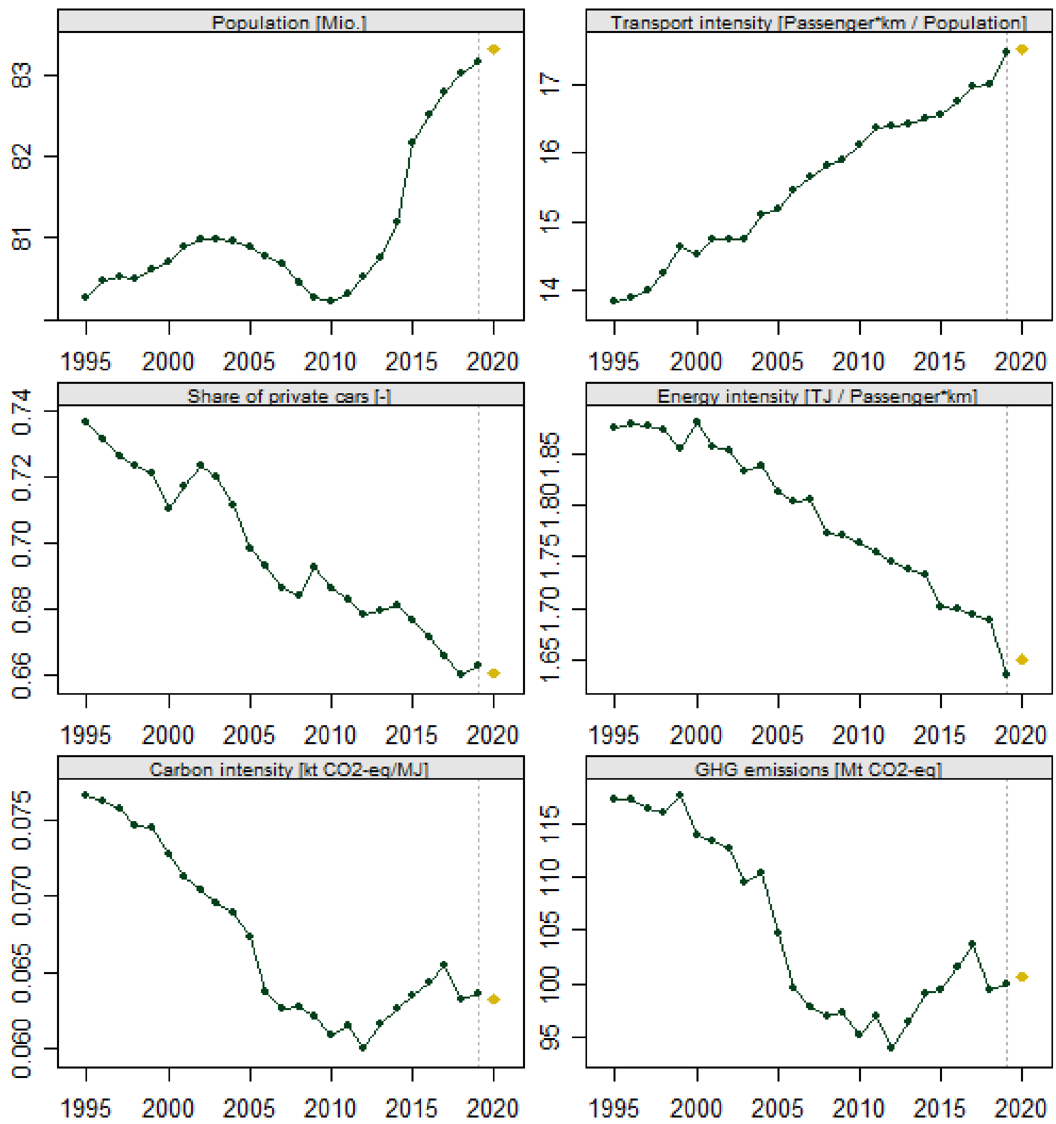

Table A4: Descriptive statistics of factors by sectors and sub-sectors

Sector/ subsector	Factor	Min.	Max.	Median	Mean	Std. dev.
Energy	Population	80.22	83.17	80.77	81.07	0.90
	Activity	0.96	1.28	1.11	1.12	0.10
	Energy Intensity	44666.11	74927.18	66749.17	63924.37	8575.60
	Carbon intensity	0.05	0.07	0.07	0.06	0.00
Industry: Fuel-related	GVA	1716.52	3092.49	2192.83	2268.08	414.06
	Structural Change	0.28	0.33	0.30	0.30	0.01
	Energy Intensity	1952.44	3324.87	2624.30	2637.35	419.15
	Carbon intensity	0.07	0.08	0.07	0.07	0.00
Industry: Process-related	GVA	1716.52	3092.49	2192.83	2268.08	414.06
	Structural change	0.28	0.33	0.30	0.30	0.01
	Carbon intensity	51.43	145.20	92.22	89.55	29.83
Buildings: Residential	Population	80.22	83.17	80.77	81.07	0.90
	Buildings per capita	0.46	0.72	0.58	0.58	0.09
	Size intensity	0.08	0.09	0.09	0.09	0.00
	Energy intensity	439.28	494.19	485.04	477.40	15.92
	Carbon intensity	0.05	0.06	0.06	0.06	0.00
Buildings: Commercial	Population	2328.34	3232.26	2724.77	2751.72	270.63
	Activity	0.96	1.28	1.11	1.12	0.10
	Energy intensity	197.23	356.55	251.56	268.27	53.94
	Carbon intensity	0.05	0.07	0.06	0.06	0.00
Transport Passenger	Population	80.22	83.17	80.77	81.07	0.90
	Transport intensity	13835.35	17458.07	15647.21	15566.63	1074.95
	Share of private cars	0.66	0.74	0.69	0.70	0.02
	Energy intensity of cars	1.63	1.88	1.80	1.79	0.07
	Carbon intensity of cars	0.060	0.077	0.064	0.067	0.00
Transport: Road freight	Total economic activity	80.22	83.17	80.77	81.07	0.90
	Transport intensity	0.66	0.74	0.69	0.70	0.02
	Share of heavy-duty trucks (HDT)	13835.35	17458.07	15647.21	15566.63	1074.95

Sector/ subsector	Factor	Min.	Max.	Median	Mean	Std. dev.
	Energy intensity of HDT	1.63	1.88	1.80	1.79	0.07
	Carbon intensity of HDT	0.061	0.084	0.074	0.073	0.00
Agriculture: Livestock	Population	80.22	83.17	80.77	81.07	0.90
	Livestock per capita	1883.73	2672.86	2075.00	2191.72	280.64
	Diet shift for cattle	0.06	0.11	0.08	0.08	0.02
	Diet shift for sheep	0.01	0.02	0.02	0.01	0.00
	Diet shift for swine	0.10	0.14	0.14	0.13	0.01
	Diet shift for other livestock	0.74	0.83	0.77	0.78	0.03
	Carbon intensity for cattle	2.10	2.35	2.24	2.22	0.06
	Carbon intensity for sheep	0.17	0.18	0.17	0.18	0.00
	Carbon intensity for swine	0.15	0.16	0.15	0.16	0.00
	Carbon intensity for other livestock	0.00	0.00	0.00	0.00	0.00
Agriculture: Crops	Population	80.22	83.17	80.77	81.07	0.90
	Carbon intensity	0.00	0.00	0.00	0.00	0.00
	Fertilizer per capita	56201.89	65475.51	60394.08	60661.43	2150.03
Waste: Solid waste	Population	80.22	83.17	80.77	81.07	0.90
	Waste per capita	165.91	385.73	190.84	238.99	73.05
	Disposal mode for biological treatment	0.17	0.94	0.86	0.67	0.28
	Disposal mode for incineration and open burning	0.01	0.03	0.02	0.02	0.01
	Disposal mode for solid waste disposal	0.03	0.82	0.11	0.30	0.28
	Carbon intensity for biological treatment	0.06	0.07	0.07	0.06	0.00
	Carbon intensity for solid waste disposal	1.41	13.80	9.94	7.09	4.80

Sector/ subsector	Factor	Min.	Max.	Median	Mean	Std. dev.
Waste: Waste water	Population	80.22	83.17	80.77	81.07	0.90
	Waste water per capita	43.61	56.71	47.23	48.54	4.32
	Carbon intensity	0.28	0.48	0.30	0.32	0.05

Table A5: Results of AR(1) estimations

Sector/sub-sector	Factor	KPSS test statistic	φ	φ_K	Predicted value
Energy	Population	0.306	0.653***	0.776***	83.310
	Activity	0.045	-0.088***	-0.057***	1.298
	Energy Intensity	0.435*	-0.042***	-0.006***	43494.580
	Carbon intensity	0.1811	0.189***	0.254***	0.052
Industry: Fuel-related	GVA	0.5323*	0.122*	0.179*	3153.824
	Structural change	0.251	-0.185***	-0.166***	0.298
	Energy intensity	0.046	0.018*	0.062*	1898.316
	Carbon intensity	0.233	-0.300***	-0.296***	0.070
Industry: Process-related	GVA	0.532**	0.122***	0.179***	3153.820
	Structural change	0.250	-0.185*	-0.166*	0.298
	Carbon intensity	0.137	0.068***	0.118***	47.850
Buildings: Residential	Population	0.306	0.653***	0.776***	83.310
	Buildings per capita	0.636**	0.623***	0.743***	0.497
	Size intensity	0.096	-0.059[a]	-0.025	0.090
	Energy intensity	0.129	-0.403***	-0.412***	0.480
	Carbon intensity	0.351	-0.206*	-0.190*	0.050
Buildings: Commercial	Population	0.306	0.653***	0.776***	83.310
	Activity	0.180	-0.437***	-0.450***	0.050
	Energy intensity	0.069	-0.584***	-0.615***	164.690
	Carbon intensity	0.081	-0.044***	-0.008***	3270.180
Transport: Passenger	Population	0.306	0.653***	0.776***	83.310
	Transport intensity	0.082	-0.327***	-0.326***	1.751
	Share of private cars	0.058	0.103**	0.158**	0.661
	Energy intensity of cars	0.439	-0.552***	-0.579***	1.650
	Carbon intensity	0.368	0.189*	0.255*	0.063

Sector/sub-sector	Factor	KPSS test statistic	φ	φ_K	Predicted value
Transport: Road freight	Total economic activity	0.081	-0.044***	-0.008***	3270.182
	Transport intensity	0.271	-0.013[b]	0.028	2.190
	Share of HDT	0.187	-0.276**	-0.269**	0.726
	Energy intensity of HDT	0.241	0.099***	0.1525***	1.244
	Carbon intensity	0.177	0.272*	0.348*	0.072
Agriculture: Livestock	Population	0.306	0.653***	0.776***	83.310
	Livestock per capita	0.090	0.530***	0.640***	2541.880
	Diet shift for cattle	0.100	0.281***	0.358***	0.053
	Diet shift for sheep	0.101	0.298***	0.376***	0.008
	Diet shift for swine	0.302	0.118***	0.174***	0.101
	Diet shift for other livestock	0.122	0.242***	0.314***	0.838
	Carbon intensity for cattle	0.161	0.042***	0.089***	2.364
	Carbon intensity for sheep	0.145	-0.530***	-0.554***	0.175
	Carbon intensity for swine	0.233	0.1723	0.236	0.155
	Carbon intensity for other livestock	0.076	0.486***	0.589***	0.003
Agriculture: Crops†	Population	0.306	0.653***	0.776***	83.310
	Carbon intensity	0.201	0.134***	0.193***	0.005
	Fertilizer per capita	0.216	0.183	0.248	55970
Waste: Solid waste†	Population	0.306	0.653***	0.776***	83.310
	Waste per capita	-	-	-	182.898
	Disposal mode for biological treatment	-	-	-	0.962
	Disposal mode for incineration and open burning	-	-	-	0.024
	Disposal mode for solid waste disposal	-	-	-	0.031
	Carbon intensity for biological treatment	-	-	-	0.070
	Carbon intensity for solid waste disposal	-	-	-	14.302
Waste: Wastewater	Population	0.306	0.653***	0.776***	83.310
	Wastewater per capita	0.540	-0.348***	-0.350***	42.980
	Carbon intensity	0.200**	0.613***	0.731***	0.274

† Prediction is based on 5-year average due to structural breaks in the time series.
***p<0.01, **p<0.05, *p<0.1.
[a] p-value = 0.767; [b] p-value = 0.961.

Appendix B: Factor decomposition at sectoral level

Energy

In the energy sector, the drivers of emissions correspond to the standard Kaya identity. Emissions in the energy sector are calculated as the product of population, activity (gross domestic product (GDP) per capita), energy intensity (primary energy consumption per unit of GDP) and emission intensity (emissions per unit of PEC).

$$GHG_{energy} = pop * \frac{GDP}{pop} * \frac{PEC}{GDP} * \frac{GHG_{energy}}{PEC} \quad \text{(B1)}$$

Industry

We distinguish emissions in the industry sector depending on whether they originate from the combustion of fuels or from industrial processes (e.g. in the production of cement clinker and steel). Because industrial output is less sensitive to demographic changes, we excluded population as a factor and use the absolute value of gross value added (GVA) instead. Furthermore, we included the share of the industrial sector in the total economic activity to reflect structural change. Because direct emissions related to energy use are accounted for in equation (B2), the sub-sector industrial processes does not include a term reflecting energy intensity.

$$GHG_{Ind.\ fuel} = GVA_{tot} * \frac{GVA_{industry}}{GVA_{tot}} * \frac{PEC_{Ind.\ fuel}}{GVA_{industry}} * \frac{GHG_{Ind.\ fuel}}{PEC_{Ind.\ fuel}} \quad \text{(B2)}$$

$$GHG_{Ind.processes} = GVA_{tot} * \frac{GVA_{industry}}{GVA_{tot}} * \frac{GHG_{Ind.\ processes}}{GVA_{industry}} \quad \text{(B3)}$$

Buildings

In the buildings sector, we differentiate GHG emissions stemming from private residential buildings and commercial buildings. For the residential sector, the 'activity factor' is captured by the number of flats per capita and the average flat size in m^2. We used heating degree days provided by BDEW (BDEW, 2020) to account for the effects of weather on heating demand.

$$GHG_{residential} = pop * \frac{n° \, buildings}{pop} * \frac{m^2_{tot}}{n° buildings} * \frac{PEC_{residential}}{m^2_{tot}} * \frac{GHG_{residential}}{PEC_{residential}} \tag{B4}$$

$$GHG_{commercial} = pop * \frac{GDP}{pop} * \frac{PEC_{commercial}}{GDP} * \frac{GHG_{residential}}{PEC_{residential}} \tag{B5}$$

Transport

In the transport sector, we distinguish between GHG emissions pertaining to passenger transport (cars) or freight transport (heavy duty trucks (HDT)). Eq. 1 in the main text shows the factors included in the passenger transport decomposition. Total passenger-kilometre per capita and total tonnes-km per unit of GDP correspond to the factor 'activity' in the standard Kaya identity. For both sub-sectors, we include change in the mode of transportation (i.e. distance travelled by car and HDT as a share of total distance travelled) to reflect structural change. The fourth term in (1) and (B6) represents fuel efficiency and correspond to the factor 'energy intensity'.

$$GHG_{freight(HDT)} = GDP * \frac{distance \; travelled_{total}}{GDP} * \frac{distance \; traveledd_{HDT}}{distance \; travelled_{total}} * \frac{PEC_{HDT}}{distance \; travelled_{HDT}} * \frac{GHG_{HDT}}{PEC_{HDT}} \tag{B6}$$

Agriculture

In the agriculture sector, GHG emissions are differentiated between emissions stemming from livestock and from crops. The third factor in equation (B7) captures structural effects, i.e. changes in diets and reflects the share of different kinds of livestock *j* (i.e., pigs, cows, sheep and others) in the total number of livestock.

$$GHG_{livestock} = \sum_j GHG \; livestock_j = pop * \frac{n° \; livestock_{tot}}{pop} * \frac{n° \; livestock_j}{n° \; livestock_{tot}} * \frac{GHG \; livestock_j}{n° \; livestock_j} \tag{B7}$$

$$GHG_{crops} = pop * \frac{GHG_{crops}}{pop} \tag{B8}$$

Waste

For the waste sector, we distinguish between wastewater and solid waste. The second term of Eq. (B9) and (B10) capture total waste per capita and indicates the activity effect. The third term in Eq. (B9) indicate the "mode shift" between different types (j) of waste management (i.e. waste landfilling, biological waste treatment, waste incineration).

$$GHG_{Solid\ waste} = \sum_{j} GHG_j = pop * \frac{solid\ waste_{total}}{pop} * \frac{solid\ waste_j}{solid\ waste_{total}} * \frac{GHG_j}{solid\ waste_j} \quad \text{(B9)}$$

$$GHG_{waste\ water} = pop * \frac{waste\ water_{tot}}{pop} * \frac{GHG_{waste\ water}}{waste\ water_{tot}} \quad \text{(B10)}$$

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