Supplementary Information of

A technology-based global non-methane volatile organic compounds (NMVOC) emission inventory under the MEIC framework

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Supplementary Text S1. Calculation of emission factors.

S1.1. Road transport

The fleet-based model for on-road transport provides NMVOC emission factors under three emission modes: running, evaporation, and start as illustrated below.

Running emissions

As the cumulative mileage increases, the running emission factor increases in comparison to the emission factor of a new vehicle, due to wear and tear, component failure, and poor maintenance etc. Therefore, the "deterioration factor" was introduced to represent the impacts of vehicle aging on running emission factor. For running emissions, annual average emission factors at country level was calculated as follows:

$$EF_{c,y,v,f,s,p,running} = BEF_{c,v,f,s,p} \times D_{v,f,s,y,p} \quad (S1.1)$$

where c, y, v, f, s, and p represent country, year, vehicle category, fuel type, emission standard, and species (i.e., NMVOC here), respectively; BEF represent the baseline emission factor based on fuel consumption; D represents the vehicle deterioration factor. The larger the cumulative mileage of the fleet in the year y, the larger the deterioration factor.

To estimate the deterioration factor, we referred to the approach in the International Vehicle Emission (IVE) model (Davis et al., 2005), and divided the cumulative mileage of passenger cars and trucks into three stages: less than 80,000 kilometers, greater than 160,000 kilometers, and between 80,000 and 160,000 kilometers. We first calculated the cumulative mileage of vehicles with different ages year by year, determined their deterioration factors based on the mileage division, and finally estimated the emission-standard-specific deterioration factors in each year, incorporating age distribution and emission standard implementation.

As previous studies have shown that the baseline emission factors that correspond to the same emission standard are somewhat different across countries and regions, the application of emission factors from local field measurements is important for accurately estimating running emissions. In this study, global default emission factors for each emission standard were obtained from the EMEP Guidebook (EEA, 2019; 2023). We then extensively reviewed the literatures on emission factor measurements and estimates of on-road transport emissions, and used local emission factors to replace the global default values in large economies (e.g., Zheng et al., 2014), improving the accuracy of emission estimates at regional and country level.

Evaporation emissions

For gasoline-fueled vehicles, the fuels in the vehicle engine and tank evaporate and dissipate into the atmosphere. This emission process is affected by ambient temperature. We relied on the Tier 1 approach recommended in the EMEP Guidebook to obtain global default values, as shown in equation $S1.2$ (EEA, 2019), and further integrated local emission factors at regional or country level (e.g., Zheng et al., 2014).

$$EF_{c,y,v,f,evap} = Stock_{c,y,f,v} \times \sum_{m=1}^{m=12} EF\_evap_{y,m,v,f,temp} \times Day_{y,m} / Fuel_{c,y,v,f} \quad (S1.2)$$

where m represents month; $Stock$, Day, and $Fuel$ represent vehicle ownership, number of the days in month m of year y, and fuel consumption, respectively; $temp$ represents temperature

interval. Following the division in the EMEP Guidebook, the monthly average temperature was divided into four temperature intervals: < 0°C, 0-10°C, 10-20°C, and > 20°C (EEA, 2019). EF_evap represents the daily NMVOC emissions per vehicle in different temperature intervals. Fuel consumption in each month was assumed to be equal within a year. The monthly average temperature in each country was calculated from the ERA5 0.25°×0.25° reanalysis data (Hersbach et al., 2020).

Start emissions

During the start process, incomplete fuel combustion produces NMVOC emissions (called start emissions here). Start emissions are also affected by ambient environment. When ambient temperature is low, the time required for the catalyst to reach the operating temperature becomes longer, and thus start-mode emission factors increase. We relied on the Tier 2 approach recommended in the EMEP Guidebook to obtain global default values, as shown in equation $S1.3$ (EEA, 2019), and further integrated local emission factors at regional or country level (e.g., Zheng et al., 2014).

$$EF_{c,y,v,f,s,p,cold} = EF\_rnning_{c,y,v,f,s,p} \times \alpha_{v,f,s,p,m} \times \beta_{v,f,s,p,m} \quad (S1.3)$$

where EF_rnning represents running emission factor in equation $S1.1$; α represents the cold start factor that is a function of temperatures, and β is a factor related to temperatures and vehicle types. The values of α and β were obtained from the EMEP Guidebook (EEA, 2019).

S1.2. Off-road transport

For off-road vehicles used in agriculture, forestry, and fishing, emission-standard-specific emission factors were obtained from the MOtor Vehicle Emission Simulator (MOVES) for North America and the EMEP Guidebook for other regions with emission standards (US EPA, 2021; EEA, 2023; the emission standards in each country were mapped to the EU standards according to emission limits). For countries without emission standards, EU pre-1981 emission factors were used.

The NMVOC emissions from international and domestic aviation were estimated by flight based the detailed flight information provided by OAG, including flight time, flight route, and aircraft type (OAG). The flight process was divided into landing and take-off (LTO) and cruise phases. The aircraft-type- and engine-type-specific emission factors (i.e., the NMVOC emissions per unit LTO time and per unit cruise distance) were obtained from the EMEP database (EEA, 2023). For the aircraft and engine types that were not included in the EMEP database, we used the average emission factors of aircrafts with similar seat number and aircraft size. For navigation emissions, we referred to previous studies that estimated emissions based on navigation routes and vessel types (Wang et al., 2021; Liu et al., 2016; Luo et al., 2024).

S1.3. Industrial process

Tyre production

For tyre production, since the unit of activity rates is thousand units and the unit of unabated emission factors in the EMEP Guidebook is g/kg tyres (EEA, 2023), the weight of tyres needs to be known to transfer the emission factor unit to kg/unit. The weight of tyres depends on vehicle category, and thus the average weight of tyres produced in a country were assumed to be determined by the vehicle-category-specific fleet structure. Here, it was assumed that the weight of tyres of different vehicle categories was between 8.6 kg to 49.9 kg based on literatures and market surveys.

Then we estimated the average weight of tyres produced in each country, using the assumed weight and the ownership of different vehicle categories in the fleet-based model (Yan et al., 2024; Zheng et al., 2014). The unabated emission factors in kg/unit were then calculated by multiplying the average weight and the default unabated emission factor in the EMEP Guidebook (EEA, 2023). This resulted in unabated emission factors ranging from 0.09 kg/unit to 0.46 kg/unit in 1970 and from 0.09 kg/unit to 0.25 kg/unit in 2020.

S1.4. Solvent use

Vehicle resealing

The unabated emission factor of vehicle resealing was provided in unit of kg/capita, heavily depending on income level and economic development level (e.g., 0.01-0.2 kg/capita; EEA, 2023). Here, we used a power function to fit the lower and upper values in the EMEP Guidebook, representing the increase in unabated emission factor as GDP per capita increases as below:

$$EF_{vehicle\ resealing} = 0.0016 \times (GDP\ per\ capita)^{0.4016} \quad (S1.4)$$

Dry cleaning

The unabated emission factor of dry cleaning was also provided in unit of kg/capita (e.g., 0.2-0.6 kg/capita; US EPA, 1995), which is tightly related to the access of residents to dry cleaning machines. Here, it was assumed that 0.6 kg/capita and 0.2 kg/capita represented the emission level of urban and rural population, respectively. The emission unabated factors in each country were calculated as below:

$$EF_{dry\ cleaning} = 0.6 \times urbanization\ rate + 0.2 \times (1 - urbanization\ rate) \quad (S1.5)$$

Domestic solvent use

The emissions from domestic solvent use were estimated by a population-based method (EEA, 2023). We first collected emission factors (emissions per capita) from literatures (Pearson, 2019; Zhang et al., 2009; Klimont et al., 2002; French National Emission Inventory Agency, 2021; Brussels Instituut voor Milieubeheer, 2010; Rijksinstituut voor Volksgezondheid en Milieu, 2022), which ranged from 0.1 kg/capita to 2.4 kg/capita. Several parameters, including GDP per capita, urbanization rate, latitude, and temperature were used to check if they had good correlation with the collected emission factors, and finally GDP per capita and annual average temperature were selected as independent variables in the fitting model. A power function was used to fit the model as shown below:

$$EF_{domestic\ solvent\ use} = 0.08 \times GDP^{0.39} \times Temp^{3.62}\ (R = 0.72, RMSE = -0.01) \quad (S1.6)$$

It represents the increase in emission factors driven by economic growth, which boosts personal VCPs consumption, and rising temperatures, which enhance evaporation.

Supplementary Text S2. Technology turnover model for residential stoves.

Here, we distinguished traditional and advanced stoves for residential coal and biomass combustion. First, we collected data on the proportions of traditional and advanced stoves from literatures, and obtained 86 data points in 29 countries that accounted for approximately 74% of global residential energy consumption in 2020.

Next, we investigated the relationships between the collected data and socioeconomic parameters. It was shown that country-level GDP per capita and urbanization rate both had good correlation with the collected data (R^2 = ~0.80): the higher the GDP per capita and urbanization rates, the higher the proportions of advanced stoves. Therefore, GDP per capita and urbanization rate were selected as independent variables in the fitting model.

We then tested different functional forms for the fitting model, including linear function, combined linear and quadratic function, combined linear and square root function, and combined linear and indeterminate power function. We selected the one with highest R^2 and smallest RMSE. The final fitting model is shown as below:

$$f(GDP\ per\ capita, urbanization\ rate) = 6.719 \times GDP\ per\ caipta^{0.241} + 0.3325 \times urbanization\ rate - 29.06 \quad (S2.1)$$

The model was then validated by a 10-fold cross-validation approach. 90% of the original collected data points were randomly selected to fit the model, and the remaining 10% of data points were used for validation. The results showed that the fitting model was reliable (R^2 = 0.85, RMSE = 5.14).

The model was finally used to estimate the full time series of stove type evolution for all countries. To separate the technology distributions for rural and urban areas, it was assumed that the proportions of advanced stoves were 0% for rural residential combustion, and then the proportions of advanced stoves for urban residential combustion could be calculated. The model represented the increased proportions of advanced stove as economy and urbanization develop, with constraint from collected data.

Supplementary Text S3. Driving factor decomposition.

To illustrate the effects of different emission parameters on global and regional emission changes, we performed a driving factor decomposition analysis in this study. Three factors were considered, i.e., activity rate, technology distribution and unabated emission factor, and emission control. Following our previous studies (Liu et al., 2015; Liu et al., 2021), for a given period, we developed three hypothetical scenarios to estimate the contributions from each factor incrementally. For example, for the period of 1970-1990, we built the baseline scenario by changing the activity rate from the amount in 1990 to the amount in 1970, and then changed the other two factors incrementally to the levels in 1970. The differences between every consecutive step was an estimate of the contributions from each factor.

Supplementary Text S4. Uncertainty analysis.

Emission estimates are subject to uncertainty because of incomplete information of activity rates, emission factors, and other parameters (Gurney et al., 2016). In order to more completely assess the uncertainties of our NMVOC emission estimates, uncertainty analysis was performed at country level by source category, following the methodology demonstrated by previous studies (Zhao et al., 2011; Tong et al., 2018; Chen et al., 2022). The term "uncertainty" here refers to the lower and upper bounds of the 95% confidential interval (CI) around the central estimate. Input parameters of activity rates, technology distributions, unabated emission factors, and penetration ratios of control technologies, as well as corresponding statistical distributions (see Table S11), were placed in a Monte Carlo framework, and 1,000 simulations were performed to analyze the uncertainties of NMVOC emissions.

For activity rates, normal distribution was used for simulation; for other parameters, lognormal and uniform distribution were mainly used for simulation. If negative numbers were generated, the value was set to 0. It should be noted that for activity rates and unabated emission factors, the simulations were independent among the source categories, but for technology distributions and penetration ratios of control technologies, the simulations were not independent when two or more technologies were applied, because they represented the "proportions" of technologies applied that should always summed up to 100%. In this case, the simulations of a group of correlated technologies were performed as below, using a modified approach based on previous work (Lu et al., 2011).

In a simulation with n technologies (of which proportions were X_1, X_2, …, X_n), we first randomly selected a technology (i.e., randomly selected i from 1, 2, …, n, and obtained technology i with X_i), and uniform distribution was used to calculate the proportion in random sampling (so called X_i'); then the sum of proportions of remaining $n-1$ technologies were normalized to $(100 - X_i')$. Next, another technology was randomly selected from the remaining technologies (i.e., randomly selected j from 1, 2, …, n, excluding i, and obtained technology j with X_j), and random sampling was performed for X_j to obtain X_j'; the sum of proportions of remaining $n-2$ technologies were again normalized to $(100 - X_i' - X_j')$… The sampling was performed iteratively until there was only one technology left and a simulation was finished. By performing 1,000 simulations, we can quantify the uncertainties of technology distributions or penetration ratios of control technologies with the constraint that proportions summed up to 100% in each step.

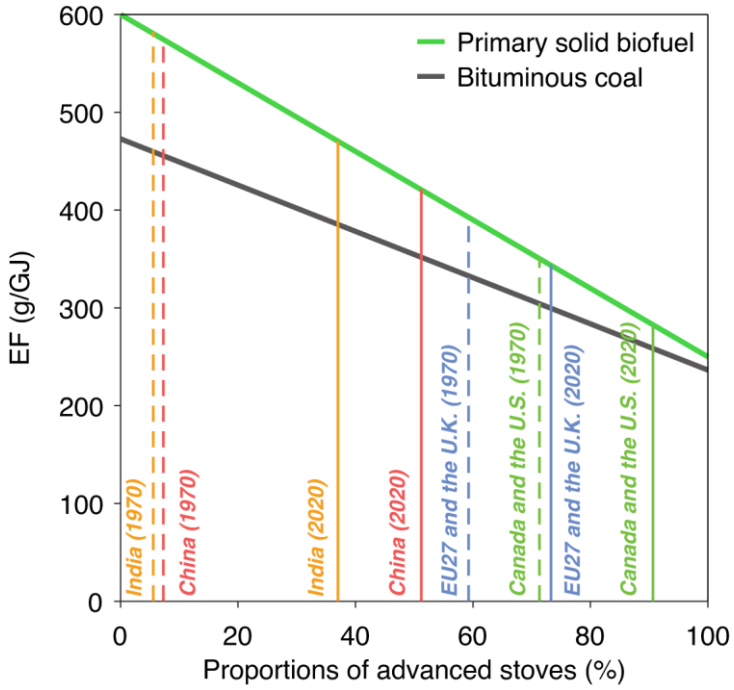

Figure S1. Decreases of unabated emission factors for residential biomass and coal combustion as proportions of advanced stoves increase. The dashed and solid lines represent the regional proportions of advanced stoves and corresponding unabated emission factors in 1970 and 2020, respectively.

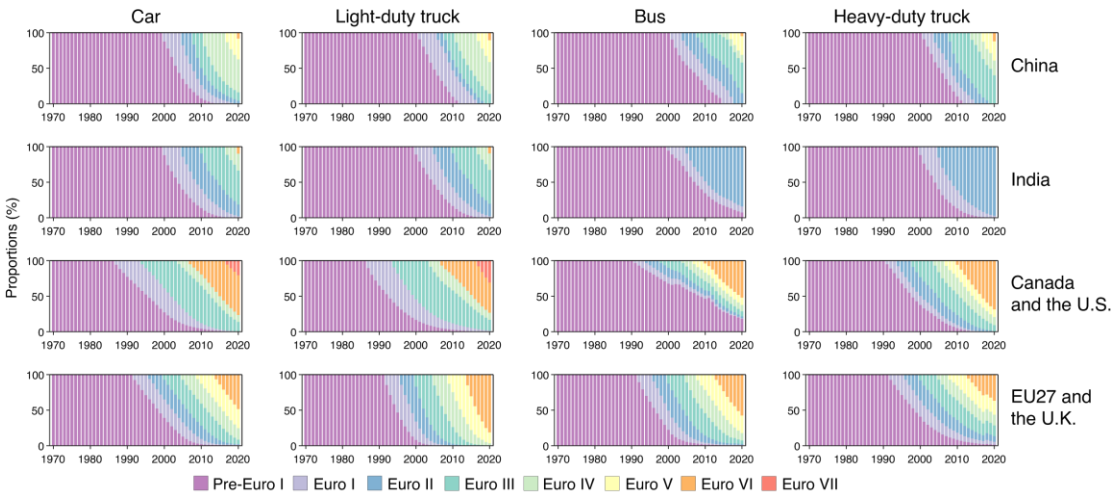

Figure S2. Proportions of emission-standard-specific cars, light-duty trucks, buses, and heavy-duty trucks in China, India, Canada and the U.S., and EU27 and the U.K. from 1970 to 2020.

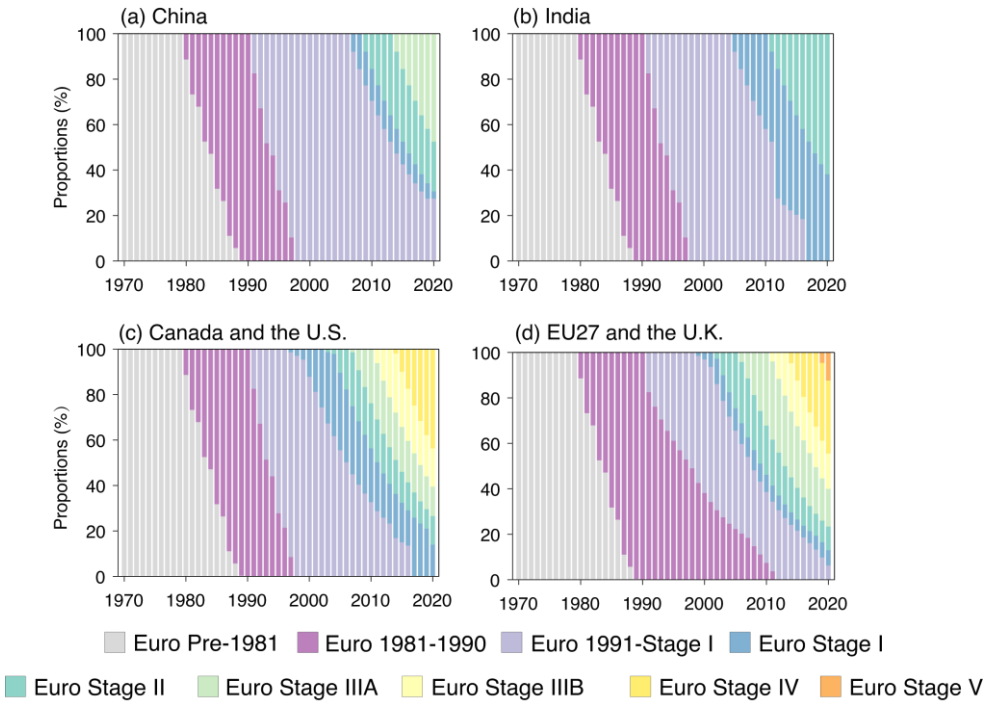

Figure S3. Proportions of emission-standard-specific off-road vehicles in China, India, Canada and the U.S., and EU27 and the U.K. from 1970 to 2020.

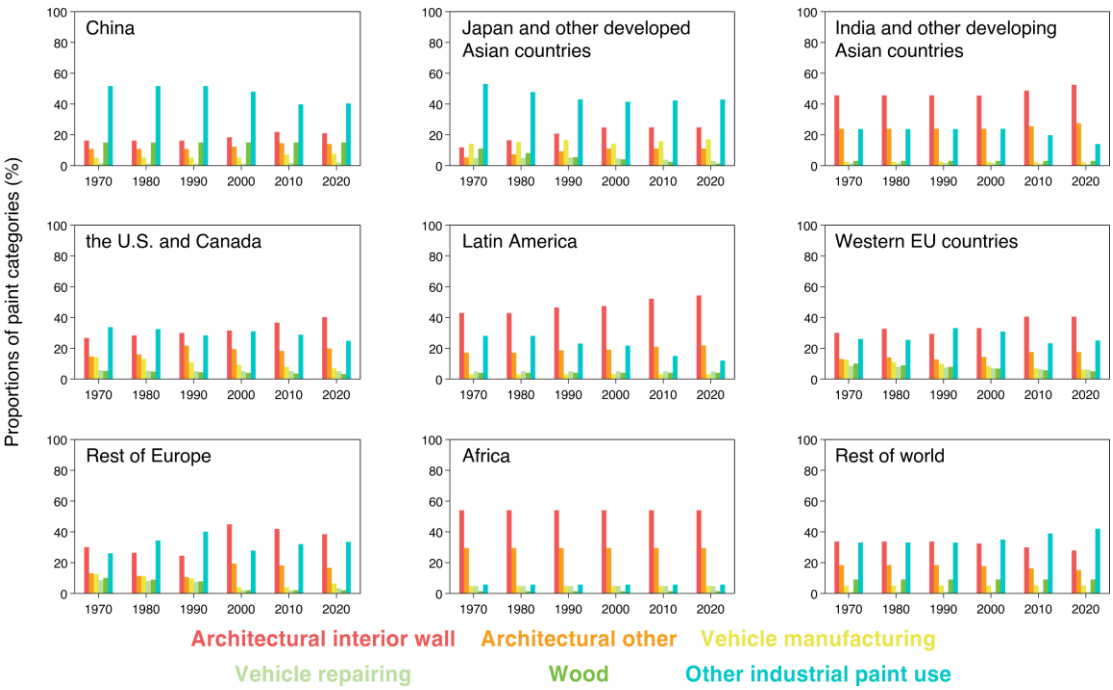

Figure S4. Proportions of six application purposes for paint consumption in the selected regions in 1970, 1980, 1990, 2000, 2010, and 2020.

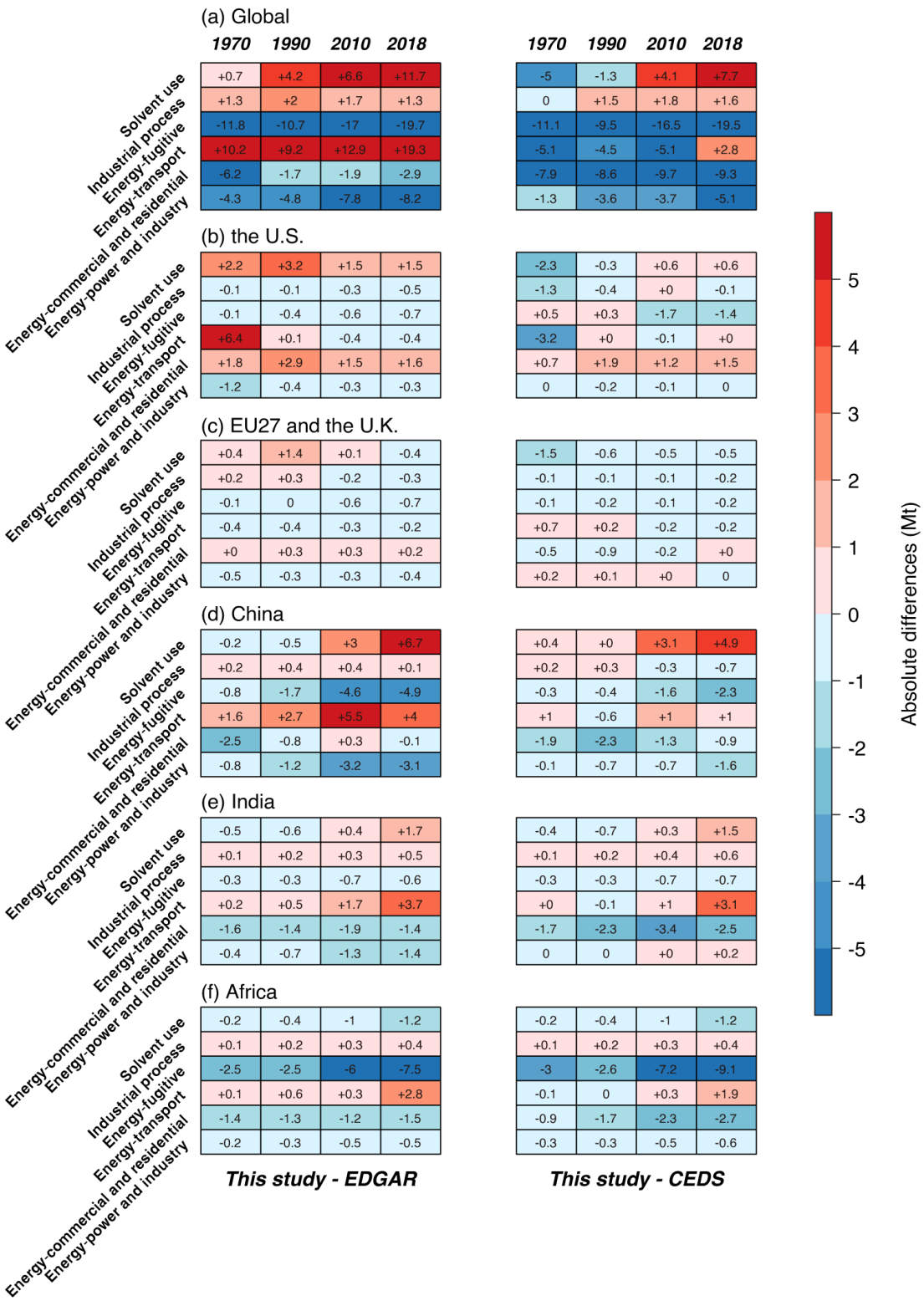

Figure S5. The same as Figure 11 but for absolute differences.

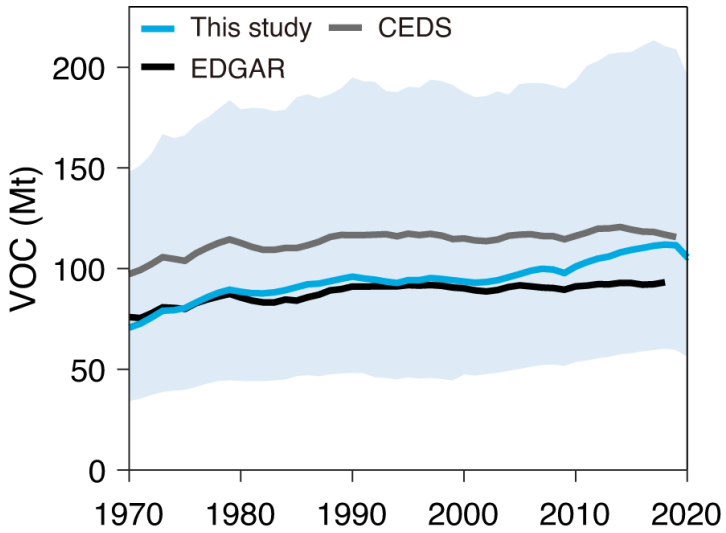

Figure S6. The same as Figure 10a but excluding all fugitive emissions from solid fuel production.

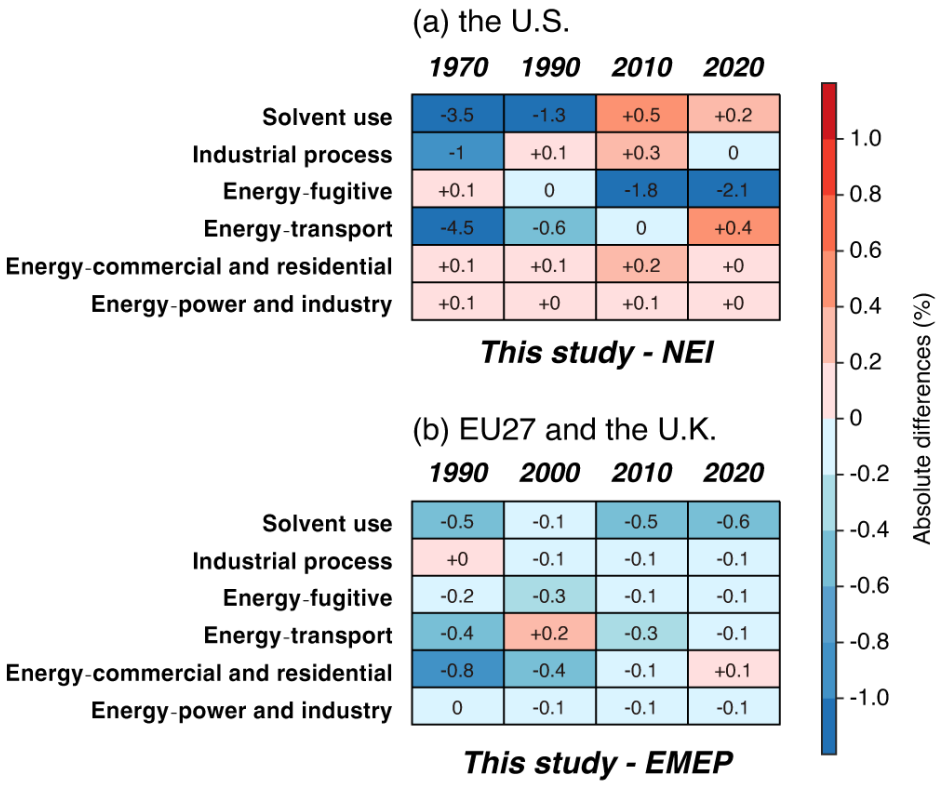

Figure S7. The same as Figure 12 but for absolute differences.

Table S1. The source categories, their IPCC GL code categories, and mapping to the major and detailed sources in the analysis.

1st level (Major sectors)	2nd level	3rd level	4th level	5th level	IPCC GL code category	Mapping to detailed sources
Energy-power and industry	Power generation	Coal (Anthracite, Coking coal, Other bituminous coal, Sub-bituminous coal, Lignite, Patent fuel, Coke oven coke, Gas coke, Coal tar, BKB, Gas works gas, Coke oven gas, Blast furnace gas, Other recovered gases, Peat, Peat products)	None	None	1A1a	Distinguished by fuel type (Coal, Oil, Gas, and Biomass in 2nd level)
	Heat (auto producer)					
	Heat (public)					
	Coal mines					
	Oil and gas extraction					
	Blast furnaces					
	Gas works					
	Gasification plants for biogases					
	Coke ovens					
	Patent fuel plants					
	BKB/peat briquette plants	Oil (Crude oil, Natural gas liquids, Refinery feedstocks, Additives/blending components, Other hydrocarbons, Refinery gas, Ethane, Liquefied petroleum gases (LPG), Motor gasoline excluding biofuels, Aviation gasoline, Gasoline type jet fuel, Kerosene type jet fuel excluding biofuels, Other kerosene, Gas/diesel oil excluding biofuels, Fuel oil, Naphtha, White spirit and SBP, Lubricants, Bitumen, Paraffin waxes, Petroleum			1A1b and 1A1c	
	Oil refineries					
	Coal liquefaction plants					
	Liquefaction (LNG) / regasification plants					
	Gas-to-liquids (GTL) plants					
	Own use in electricity, CHP and heat plants					
	Charcoal production plants					
	Non-specified transformation industries					
	Iron and steel				1A2a	
	Non-ferrous metals				1A2b	
	Chemicals				1A2c	
	Pulp and paper				1A2d	

	Food and tobacco	coke, Other oil products, Oil shale and oil sands)			1A2e	
	Cement				1A2f	
	Other non-metallic minerals				1A2f	
	Transport equipment	Natural gas (Natural gas)			1A2g	
	Machinery				1A2h	
	Mining and quarrying	Biomass (Renewable municipal waste, Primary solid biofuels, Biogases, Bio gasoline, Biodiesels, Bio jet kerosene, Other liquid biofuels, Non-specified primary biofuels/waste, Charcoal)			1A2i	
	Wood products				1A2j	
	Construction				1A2k	
	Textile and leather				1A2l	
	Other non-specified industries				1A2m	
Energy-transport	International aviation		LTO and cruise		1A3a	Other transport
	Domestic aviation					
	Rail		None		1A3c	
	International navigation				1A3d	
	Domestic navigation					
	Pipeline transport					
	Other non-specified transport				1A3e	
	Agriculture and forestry		Emission standards	Implied in emission factors	1A4c	Off road AFF
	Fishing					
	Cars		Running, start, evaporation (Stage 0, Stage 1, Stage 2, Stage 3, Stage 4, Stage 5, Stage 6, Stage 7)	Implied in emission factors	1A3b	Cars
	Light duty trucks					Light duty trucks
	Buses					Buses
	Heavy duty trucks					Heavy duty trucks
	Motorcycles					Motorcycles
	Other fleet totals					Other transport
Energy-commercial and residential	Commercial and institutional		Traditional stoves and advanced stoves	None	1A4a	Distinguished by fuel type (Coal, Oil, Gas, and Biomass in 2nd level)
	Residential (rural)				1A4b	
	Residential (urban)					
	Non-specified		None	None	1A5	

	sectors					
Energy-fugitive	Fugitive (solid fuel production)	Coke oven coke production	None	None	1B1c	Solid fuel production
	Fugitive (oil and gas)	Oil production	None	Abatement	1B2a	Oil production, storage, transport, and refining
		Oil storage and transport				
		Oil refining				
		Gasoline storage				Gasoline/Diesel storage and distribution
		Gasoline distribution				
		Diesel storage				
		Venting and flaring				Venting and flaring
		Flaring in oil refinery				
		Natural gas production, processing, storage, and distribution			1B2b	Natural gas production, storage, transport, and distribution
		Gas venting and flaring				Venting and flaring
Industrial process	Mineral industry	Cement production	None	None	2A1	Other industries
		Clicker production			2A1	
		Glass production			2A3	
	Chemical industry (inorganic)	Ammonia	None	Abatement	2B1	Chemical industry (inorganic)
		Carbon black			2B8	
	Chemical industry (organic)	Adipic acid	None	Abatement	2B3	Chemical industry (organic)
		Ethylene			2B8	
		Vinyl chloride			2B8	
		Styrene			2B11	
		Low density polyethylene (LDPE)			2B11	
		High density polyethylene (HDPE)			2B11	
		Polyvinyl chloride (PVC)			2B11	
		Polypropylene (PP)			2B11	
		Polystyrene (PS)			2B11	
		SAN & ABS resins			2B11	
		Other synthetic resins			2B11	
		Ethylene oxide			2B8	
		Methanol			2B8	
		Acrylonitrile			2B8	
		Glyoxylic acid			2B4	

	Chemical industry (manufacturing)	Synthetic rubber	None	Abatement	2D3	Chemical industry (manufacturing)
		Tyre production				
		Pharmaceutical production				
		Asphalt				
		Paint production				
		Printing ink production				
		Glues production				
		Shoes production				
		Leather tanning				
		Synthetic fibre				
		Wool				
		Silk				
		Cloth				
		Artificial fibre				
	Metal industry	Sinter production	None	None	2C1	Other industries
		Pellet production				
		Pig iron production				
		DRI production				
		Steel production	EAF/BOF/OHF			
	Pulp, paper, and food industry	Paper pulp	None	Abatement	2H1	Paper and pulp industry
		Paper				
		Plywood				
		Bread			2H2	Food industry
		Biscuit				
		Sugar				
		Flour				
		Oilseed			2D	
		Beer			2H2	
		Wine				
		Spirit				
Solvent use	Paint use	Architectural interior wall	Waterborne and solvent-based paints	Abatement	2D3	Architecture paint
		Architecture other				
		Vehicle manufacturing				Vehicle paint
		Vehicle repairing				
		Wood				Other industry paint
		Other industrial paint				
	Other industrial use	Vehicle dewax	None	Abatement		Other solvent use
		Vehicle reseal				
		Printing ink use				Printing

		Glues and adhesives use			Other solvent use
		Preservation of wood			
		Degreasing			
		Dry cleaning			Dry cleaning
Domestic use	Domestic use	Domestic use	None	Abatement	Domestic solvent use
		Pesticide			Other solvent use

Table S2. The countries/territories, their ISO-3166 codes, and mapping to the regions in the analysis.

Country/territory	ISO-3166 code	Region
Afghanistan	AFG	Rest of Asia
Albania	ALB	Rest of Europe
Algeria	DZA	Rest of world
American Samoa	ASM	Rest of world
Angola	AGO	Rest of world
Anguilla	AIA	Latin America
Antigua and Barbuda	ATG	Latin America
Argentina	ARG	Latin America
Armenia	ARM	Rest of Asia
Aruba	ABW	Latin America
Australia	AUS	Rest of world
Austria	AUT	EU27 & the U.K.
Azerbaijan	AZE	Rest of Asia
Bahamas	BHS	Latin America
Bahrain	BHR	the Middle East
Bangladesh	BGD	Rest of Asia
Barbados	BRB	Latin America
Belarus	BLR	Rest of Europe
Belgium	BEL	EU27 & the U.K.
Belize	BLZ	Latin America
Benin	BEN	Rest of world
Bermuda	BMU	Latin America
Bhutan	BTN	Rest of Asia
Bolivia	BOL	Latin America
Bonaire, Sint Eustatius and Saba	BES	Latin America
Bosnia and Herzegovina	BIH	Rest of Europe
Botswana	BWA	Rest of world
Brazil	BRA	Latin America
Brunei Darussalam	BRN	Rest of Asia
Bulgaria	BGR	EU27 & the U.K.
Burkina Faso	BFA	Rest of world
Burundi	BDI	Rest of world
Cape Verde	CPV	Rest of world
Cambodia	KHM	Rest of Asia
Cameroon	CMR	Rest of world
Canada	CAN	Canada and the U.S.
Cayman Islands	CYM	Latin America
Central African Republic	CAF	Rest of world
Chad	TCD	Rest of world
Chile	CHL	Latin America

China (including Hong Kong, Macao, and Taiwan)	CHN	China
Colombia	COL	Latin America
Comoros	COM	Rest of world
Democratic Republic of Congo	COD	Rest of world
Congo	COG	Rest of world
Cook Islands	COK	Rest of world
Costa Rica	CRI	Latin America
Croatia	HRV	EU27 & the U.K.
Cuba	CUB	Latin America
Curacao	CUW	Latin America
Cyprus	CYP	EU27 & the U.K.
Czech Republic	CZE	EU27 & the U.K.
Cote d'Ivoire	CIV	Rest of world
Denmark	DNK	EU27 & the U.K.
Djibouti	DJI	Rest of world
Dominica	DMA	Latin America
Dominican Republic	DOM	Latin America
Ecuador	ECU	Latin America
Egypt	EGY	Rest of world
El Salvador	SLV	Latin America
Equatorial Guinea	GNQ	Rest of world
Eritrea	ERI	Rest of world
Estonia	EST	EU27 & the U.K.
Swaziland	SWZ	Rest of world
Ethiopia	ETH	Rest of world
Falkland Islands	FLK	Latin America
Faeroe Islands	FRO	Rest of Europe
Fiji	FJI	Rest of world
Finland	FIN	EU27 & the U.K.
France	FRA	EU27 & the U.K.
French Guiana	GUF	Latin America
French Polynesia	PYF	Rest of world
Gabon	GAB	Rest of world
Gambia	GMB	Rest of world
Georgia	GEO	Rest of Asia
Germany	DEU	EU27 & the U.K.
Ghana	GHA	Rest of world
Gibraltar	GIB	Rest of Europe
Greece	GRC	EU27 & the U.K.
Greenland	GRL	Rest of Europe
Grenada	GRD	Latin America
Guadeloupe	GLP	Latin America
Guam	GUM	Rest of world

Guatemala	GTM	Latin America
Guinea	GIN	Rest of world
Guinea-Bissau	GNB	Rest of world
Guyana	GUY	Latin America
Haiti	HTI	Latin America
Honduras	HND	Latin America
Hungary	HUN	EU27 & the U.K.
Iceland	ISL	Rest of Europe
India	IND	India
Indonesia	IDN	Rest of Asia
Islamic Republic of Iran	IRN	the Middle East
Iraq	IRQ	the Middle East
Ireland	IRL	EU27 & the U.K.
Isle of Man	IMN	Rest of Europe
Israel	ISR	the Middle East
Italy	ITA	EU27 & the U.K.
Jamaica	JAM	Latin America
Japan	JPN	Rest of Asia
Jersey	JEY	Rest of Europe
Jordan	JOR	the Middle East
Kazakhstan	KAZ	Rest of Asia
Kenya	KEN	Rest of world
Kiribati	KIR	Rest of world
Democratic People's Republic of Korea	PRK	Rest of Asia
Republic of Korea	KOR	Rest of Asia
Kuwait	KWT	the Middle East
Kyrgyzstan	KGZ	Rest of Asia
Laos	LAO	Rest of Asia
Latvia	LVA	EU27 & the U.K.
Lebanon	LBN	the Middle East
Lesotho	LSO	Rest of world
Liberia	LBR	Rest of world
Libya	LBY	Rest of world
Liechtenstein	LIE	Rest of Europe
Lithuania	LTU	EU27 & the U.K.
Luxembourg	LUX	EU27 & the U.K.
Madagascar	MDG	Rest of world
Malawi	MWI	Rest of world
Malaysia	MYS	Rest of Asia
Maldives	MDV	Rest of Asia
Mali	MLI	Rest of world
Malta	MLT	EU27 & the U.K.
Marshall Islands	MHL	Rest of world

Martinique	MTQ	Latin America
Mauritania	MRT	Rest of world
Mauritius	MUS	Rest of world
Mayotte	MYT	Rest of world
Mexico	MEX	Latin America
Federated States of Micronesia	FSM	Rest of world
Moldova	MDA	Rest of Europe
Mongolia	MNG	Rest of Asia
Montenegro	MNE	Rest of Europe
Montserrat	MSR	Latin America
Morocco	MAR	Rest of world
Mozambique	MOZ	Rest of world
Myanmar	MMR	Rest of Asia
Namibia	NAM	Rest of world
Nauru	NRU	Rest of world
Nepal	NPL	Rest of Asia
Netherlands	NLD	EU27 & the U.K.
New Caledonia	NCL	Rest of world
New Zealand	NZL	Rest of world
Nicaragua	NIC	Latin America
Niger	NER	Rest of world
Nigeria	NGA	Rest of world
Niue	NIU	Rest of world
Norfolk Island	NFK	Rest of world
North Macedonia	MKD	Rest of Europe
Northern Mariana Islands	MNP	Rest of world
Norway	NOR	Rest of Europe
Oman	OMN	the Middle East
Pakistan	PAK	Rest of Asia
Palau	PLW	Rest of world
Palestine	PSE	the Middle East
Panama	PAN	Latin America
Papua New Guinea	PNG	Rest of world
Paraguay	PRY	Latin America
Peru	PER	Latin America
Philippines	PHL	Rest of Asia
Pitcairn	PCN	Rest of world
Poland	POL	EU27 & the U.K.
Portugal	PRT	EU27 & the U.K.
Puerto Rico	PRI	Latin America
Qatar	QAT	the Middle East
Romania	ROU	EU27 & the U.K.
Russia	RUS	Rest of Europe

Rwanda	RWA	Rest of world
Reunion	REU	Rest of world
Saint Helena	SHN	Rest of world
Saint Kitts and Nevis	KNA	Latin America
Saint Lucia	LCA	Latin America
Saint Pierre and Miquelon	SPM	Latin America
Saint Vincent and Grenadines	VCT	Latin America
Samoa	WSM	Rest of world
Sao Tome and Principe	STP	Rest of world
Saudi Arabia	SAU	the Middle East
Senegal	SEN	Rest of world
Serbia	SRB	Rest of Europe
Seychelles	SYC	Rest of world
Sierra Leone	SLE	Rest of world
Singapore	SGP	Rest of Asia
Sint Maarten	SXM	Latin America
Slovakia	SVK	EU27 & the U.K.
Slovenia	SVN	EU27 & the U.K.
Solomon Islands	SLB	Rest of world
Somalia	SOM	Rest of world
South Africa	ZAF	Rest of world
South Sudan	SSD	Rest of world
Spain	ESP	EU27 & the U.K.
Sri Lanka	LKA	Rest of Asia
Sudan	SDN	Rest of world
Suriname	SUR	Latin America
Sweden	SWE	EU27 & the U.K.
Switzerland	CHE	Rest of Europe
Syria	SYR	the Middle East
Tajikistan	TJK	Rest of Asia
Tanzania	TZA	Rest of world
Thailand	THA	Rest of Asia
Timor-Leste	TLS	Rest of Asia
Togo	TGO	Rest of world
Tokelau	TKL	Rest of world
Tonga	TON	Rest of world
Trinidad and Tobago	TTO	Latin America
Tunisia	TUN	Rest of world
Turkey	TUR	the Middle East
Turkmenistan	TKM	Rest of Asia
Turks and Caicos Islands	TCA	Latin America
Tuvalu	TUV	Rest of world
Uganda	UGA	Rest of world

Ukraine	UKR	Rest of Europe
United Arab Emirates	ARE	the Middle East
United Kingdom	GBR	EU27 & the U.K.
United States	USA	Canada and the U.S.
Uruguay	URY	Latin America
Uzbekistan	UZB	Rest of Asia
Vanuatu	VUT	Rest of world
Venezuela	VEN	Latin America
Vietnam	VNM	Rest of Asia
British Virgin Islands	VGB	Latin America
United States Virgin Islands	VIR	Latin America
Wallis and Futuna Islands	WLF	Rest of world
Western Sahara	ESH	Rest of world
Yemen	YEM	the Middle East
Zambia	ZMB	Rest of world
Zimbabwe	ZWE	Rest of world

Table S3. The types and data sources of activity rates for the source categories.

1st level	2nd level	Activity rate type	Activity rate data source
Power generation	Coal (Anthracite, Coking coal, Other bituminous coal, Sub-bituminous coal, Lignite, Patent fuel, Coke oven coke, Gas coke, Coal tar, BKB, Gas works gas, Coke oven gas, Blast furnace gas, Other recovered gases, Peat, Peat products)	Fuel consumption	IEA World Energy Statistics
Heat (auto producer)			
Heat (public)			
Coal mines			
Oil and gas extraction			
Blast furnaces			
Gas works			
Gasification plants for biogases			
Coke ovens			
Patent fuel plants			
BKB/peat briquette plants			
Oil refineries	Oil (Crude oil, Natural gas liquids, Refinery feedstocks, Additives/blending components, Other hydrocarbons, Refinery gas, Ethane, Liquefied petroleum gases (LPG), Motor gasoline excluding biofuels, Aviation gasoline, Gasoline type jet fuel, Kerosene type jet fuel excluding biofuels, Other kerosene, Gas/diesel oil excluding biofuels, Fuel oil, Naphtha, White spirit and SBP, Lubricants, Bitumen, Paraffin waxes, Petroleum coke, Other oil products, Oil shale and oil sands)		
Coal liquefaction plants			
Liquefaction (LNG) / regasification plants			
Gas-to-liquids (GTL) plants			
Own use in electricity, CHP and heat plants			
Charcoal production plants			
Non-specified transformation industries			
Iron and steel			
Non-ferrous metals			
Chemicals			
Pulp and paper			
Food and tobacco			
Cement			
Other non-metallic minerals			
Transport equipment			
Machinery			
Mining and quarrying	Natural gas (Natural gas)		
Wood products			
Construction			
Textile and leather	Biomass (Renewable municipal waste, Primary solid biofuels, Biogases, Bio gasoline, Biodiesels, Bio jet kerosene, Other liquid biofuels, Non-specified primary		
Other non-specified industries			
International aviation			
Domestic aviation			
Rail			
International navigation			
Domestic navigation			

Pipeline transport	biofuels/waste, Charcoal)		
Other non-specified transport			
Agriculture and forestry			
Fishing			
Cars			
Light duty trucks			
Buses			
Heavy duty trucks			
Motorcycles			
Other fleet totals			
Commercial and institutional			
Residential (rural)			
Residential (urban)			
Non-specified sectors			
Fugitive (solid fuel production)	Coke oven coke production	Production	UNdata
Fugitive (oil and gas)	Oil production	Crude oil production	IEA World Oil Statistics
	Oil storage and transport	Crude oil production	
	Oil refining	Refinery gross output	
	Gasoline storage	Motor gasoline demand	
	Gasoline distribution	Motor gasoline demand	
	Diesel storage	Gas/diesel oil demand	
	Venting and flaring	Crude oil production	
	Flaring in oil refinery	Refinery gross output	
	Natural gas production, processing, storage, and distribution	Indigenous production	IEA World Natural Gas Statistics
	Gas venting and flaring	Indigenous production	
Mineral industry	Cement production	Production	USGS
	Clicker production		
	Glass production		UN Data, UNFCCC dataset, and official websites of National Bureau of Statistics in large economies
Chemical industry (inorganic)	Ammonia	Production	USGS
	Carbon black		UNdata, UN statistics, and UNFCCC
Chemical industry (organic)	Adipic acid	Production	UNdata, UN statistics, and UNFCCC
	Ethylene		
	Vinyl chloride		
	Styrene		
	Low density polyethylene (LDPE)		
	High density polyethylene		

	(HDPE)		
	Polyvinyl chloride (PVC)		
	Polypropylene (PP)		
	Polystyrene (PS)		
	SAN & ABS resins		
	Other synthetic resins		
	Ethylene oxide		
	Methanol		
	Acrylonitrile		
	Glyoxylic acid		
Chemical industry (manufacturing)	Synthetic rubber	Production	UNdata, UN statistics, and UNFCCC
	Tyre production		
	Pharmaceutical production		
	Asphalt		
	Paint production		
	Printing ink production		
	Glues production		
	Shoes production		
	Leather tanning		FAOSTAT
	Synthetic fibre		UNdata, UN statistics, and UNFCCC
	Wool		
	Silk		
	Cloth		
	Artificial fibre		
Metal industry	Sinter production	Production	Global Iron and Steel Emission Database (GISD) (Xu et al., 2023), World Steel Association
	Pellet production		
	Pig iron production		
	DRI production		
	Steel production		
Pulp, paper, and food industry	Paper pulp	Production	FAOSTAT
	Paper		
	Plywood		
	Bread		UNdata, UN statistics, and UNFCCC
	Biscuit		
	Sugar		FAOSTAT
	Flour		UNdata, UN statistics, and UNFCCC
	Oilseed		
	Beer		FAOSTAT
	Wine		
	Spirit		UNdata, UN statistics, and UNFCCC
Paint use	Architectural interior wall	Paint apparent consumption	UNdata, UN statistics, UNFCCC, and UN Comtrade
	Architecture other		

	Vehicle manufacturing		
	Vehicle repairing		
	Wood		
	Other industrial paint		
Other industrial use	Vehicle dewax	Vehicle ownership	On-road vehicle model (Yan et al., 2024)
	Vehicle reseal	Population	UN
	Printing ink use	Printing ink apparent consumption	UNdata, UN statistics, UNFCCC, and UN Comtrade
	Glues and adhesives use	Glues apparent consumption	
	Preservation of wood	Amount of wood preserved	UNdata, UN statistics, and UNFCCC
	Degreasing	Amount of degreasing solvent	Estimated from printing ink consumption (Li et al., 2017; Li et al., 2019)
	Dry cleaning	Population	UN
Domestic use	Domestic use	Population	UN
	Pesticide	Pesticide consumption	FAOSTAT

Table S4. Unabated emission factors.

1st level	2nd level	3rd level	Unit	Reference	Emission factor
Power generation Heat (auto producer) Heat (public) Coal mines Oil and gas extraction Blast furnaces Gas works Gasification plants for biogases Coke ovens Patent fuel plants BKB/peat briquette plants Oil refineries Coal liquefaction plants Liquefaction (LNG) / regasification plants Gas-to-liquids (GTL) plants Own use in electricity, CHP and heat plants Charcoal production plants Non-specified transformation industries Iron and steel Non-ferrous metals Chemicals Pulp and paper Food and tobacco Cement Other non-metallic minerals Transport equipment Machinery Mining and quarrying Wood products Construction	Coal (Anthracite, Coking coal, Other bituminous coal, Sub-bituminous coal, Lignite, Patent fuel, Coke oven coke, Gas coke, Coal tar, BKB, Gas works gas, Coke oven gas, Blast furnace gas, Other recovered gases, Peat, Peat products) Oil (Crude oil, Natural gas liquids, Refinery feedstocks, Additives/blending components, Other hydrocarbons, Refinery gas, Ethane, Liquefied petroleum gases (LPG), Motor gasoline excluding biofuels, Aviation gasoline, Gasoline type jet fuel, Kerosene type jet fuel excluding biofuels, Other kerosene, Gas/diesel oil excluding biofuels, Fuel oil, Naphtha, White spirit and SBP, Lubricants, Bitumen, Paraffin	None	g/kg (solid and liquid) g/m^3 (gas)	US EPA, 1995; EEA, 2023	Bituminous coal: 0.025 Sub-bituminous coal: 0.025 Lignite: 0.015 Other coal: 0.02 Oil: 0.10 Gas: 0.088 Biomass: 0.11
			g/kg (solid and liquid) g/m^3 (gas)	EEA, 2023; Li et al., 2019; Klimont et al., 2002	Coal: 1.78 Oil: 0.11 Natural gas: 0.14 Other gases: 0.012-0.08 Biomass: 0.75

Textile and leather	waxes, Petroleum coke, Other oil products, Oil shale and oil sands)				
Other non-specified industries					
International aviation		LTO and cruise	Engine-, flight-condition-, and fuel-dependent; See Supplementary Text S2		
Domestic aviation					
Rail	Natural gas (Natural gas)	None	g/kg	EEA, 2023	Coal: 3.48 Oil: 4.65
International navigation	Biomass (Renewable municipal waste, Primary solid biofuels, Biogases, Bio gasoline, Biodiesels, Bio jet kerosene, Other liquid biofuels, Non-specified primary biofuels/waste, Charcoal)		Shipping-route-dependent; See Supplementary Text S2		
Domestic navigation					
Pipeline transport			g/kg (solid and liquid) g/m^3 (gas)	EEA, 2023	Oil: 0.22 Gas: 0.06
Other non-specified transport				EEA, 2023	Gasoline: 150.18 Diesel: 8.08
Agriculture and forestry		Emission standards	Emission-standard-dependent; See Supplementary Text S2		
Fishing					
Cars		Running, start, evaporation (Stage 0, Stage 1, Stage 2, Stage 3, Stage 4, Stage 5, Stage 6, Stage 7)	Mode- and emission-standard-dependent; See Supplementary Text S2		
Light duty trucks					
Buses					
Heavy duty trucks					
Motorcycles					
Other fleet totals					
Commercial and institutional		Traditional	g/kg (solid and liquid) g/m^3 (gas)	EEA, 2023	Coal: 2 Oil: 0.66 Natural gas: 0.04 Other gases: 0.02-0.03 Biomass: 4.68
		Advanced			Coal: 0.46 Biomass: 0.19 Other fuels are the same as traditional stove.
Residential (rural)		Traditional	g/kg (solid and liquid) g/m^3 (gas)	EEA, 2023; Keita et al., 2021	Coal: 12 Oil: 0.05 Natural gas: 0.07 Other gases: 0.005-0.04 Biomass: 9.36 EFs in Keita et al., 2021 are used for Africa
Residential (urban)		Advanced			Coal: 6 Biomass: 3.9

					Other fuels are the same as traditional stove
Non-specified sectors		None	The same as residential		
Fugitive (solid fuel production)	Coke oven coke production	None	g/kg	Klimont et al., 2002; Bo et al., 2008	1.345
Fugitive (oil and gas)	Oil production	None	g/kg	EEA, 2023; Li et al., 2019	0.2
	Oil storage and transport				0.2
	Oil refining				1.11
	Gasoline storage				1.97
	Gasoline distribution				4.26
	Diesel storage			US EPA, 1995	0.002
	Venting and flaring			EEA, 2023	1.25
	Flaring in oil refinery				0.002
	Natural gas production, processing, storage, and distribution		g/m^3	EEA, 2023	0.1
	Gas venting and flaring			EEA, 2023	0.243
Mineral industry	Cement production	None	To avoid double counting, emissions are only calculated in combustion sources.		
	Clicker production				
	Glass production		g/kg	US EPA, 1995	0.1
Chemical industry (inorganic)	Ammonia	None	g/kg	US EPA, 1995, 2001	4.72
	Carbon black				53.57
Chemical industry (organic)	Adipic acid	None	g/kg	US EPA, 1995, 2001	4.79
	Ethylene			EEA, 2023	0.6
	Vinyl chloride				2.5
	Styrene				1
	Low density polyethylene (LDPE)				2.4
	High density polyethylene (HDPE)				2.3
	Polyvinyl chloride			US EPA,	8.5

	(PVC)			1995, 2001	
	Polypropylene (PP)			EEA, 2023	4
	Polystyrene (PS)			US EPA, 1995, 2001; Li et al., 2019	21.15
	SAN & ABS resins			EEA, 2023	3
	Other synthetic resins				8
	Ethylene oxide				2
	Methanol			US EPA, 1995, 2001	1.5
	Acrylonitrile			EEA, 2023	1
	Glyoxylic acid				8
Chemical industry (manufacturing)	Synthetic rubber	None	g/kg	EEA, 2023	8
	Tyre production		Related to average type weight of the fleets; See Supplementary Text S2		
	Pharmaceutical production		g/kg	EEA, 2023	300
	Asphalt			US EPA, 1995, 2001	2.516
	Paint production				15
	Printing ink production			US EPA, 1995, 2001; Li et al., 2019	60
	Glues production			EEA, 2023	11
	Shoes production		t/pair		0.000045
	Leather tanning		g/kg	He, 2015	0. 18
	Synthetic fibre			EEA, 2023; Li et al., 2019	10
	Wool				10
	Silk				10
	Cloth				23
	Artificial fibre			US EPA, 1995, 2001	103.7
Metal industry	Sinter production	None	g/kg	EEA, 2023	0.138
	Pellet production				0.014
	Pig iron production				0
	DRI production				0
	Steel production	EAF			0.046
		BOF			0.027
		OHF			0.027
Pulp, paper, and food industry	Paper pulp	None	g/kg	EEA, 2023	2
	Paper			US EPA,	0.1

				1995, 2001	
	Plywood		g/m^3	US EPA, 1995, 2001; Li et al., 2019	500
	Bread		g/kg	EEA, 2023	6.25
	Biscuit				1
	Sugar				10
	Flour				2
	Oilseed				1.57
	Beer				0.35
	Wine			US EPA, 1995, 2001	0.7
	Spirit		g/hL		1560
Paint use	Architectural interior wall	Waterborne	g/kg	Li et al., 2019	180
		Solvent-based			620
	Architecture other	Waterborne			300
		Solvent-based			620
	Vehicle manufacturing	Waterborne			50
		Solvent-based			730
	Vehicle repairing	Waterborne			150
		Solvent-based			750
	Wood	Waterborne			225
		Solvent-based			660
	Other industrial paint	Waterborne			150
		Solvent-based			440
Other industrial use	Vehicle dewax	None	kg/vehicle	EEA, 2023	1
	Vehicle reseal			Population-based See Supplementary Text S2	
	Printing ink use		g/kg -	US EPA, 1995, 2001; Li et al., 2019	575
	Glues and adhesives use			EEA, 2023	66
	Preservation of wood		kg/m^3	EEA, 2023	30.55
	Degreasing		g/kg	US EPA, 1995, 2001	1000
	Dry cleaning			Population-based See Supplementary Text S2	
Domestic use	Domestic use	None		Population-based See Supplementary Text S2	

Pesticide	g/kg	US EPA, 1995, 2001; Li et al., 2019	356.16

Table S5. Regional proportions of advanced stove for residential coal and biomass combustion.

Region	1970	1990	2010	2020
China	7.3%	9.7%	38.4%	51.2%
India	5.6%	10.3%	23.8%	37.0%
Middle East	33.7%	46.7%	56.9%	64.5%
Rest of Asia	8.2%	15.0%	23.6%	25.1%
Canada and the U.S.	71.3%	80.3%	88.3%	90.6%
Latin America	33.1%	42.7%	52.6%	57.9%
EU27 and the U.K.	59.2%	67.0%	71.7%	73.3%
Rest of Europe	46.2%	53.5%	55.5%	53.1%
Rest of world	13.2%	15.5%	20.8%	24.4%

Table S6. Region mapping to typical regions for NMVOC emission control policies/legislation.

Region	Mapping to
Canada	the U.S.
Norway and Switzerland	EU
South Korea	Japan
Australia, New Zealand, and other developing countries	EU

Table S7. Control technologies and removal efficiencies (EEA, 2023; EU-BRITE, 2006, 2007a, 2007b, 2007c, 2015, 2017, 2019; US EPA, 2001; US EPA, 2007; Li et al., 2019).

Source category	Control technology	Removal efficiency
Oil production	Leak detection and repair (LDAR)	43%-81%
Oil storage and transport	Vapor recovery (absorption and adsorption)	90%-95%
	Vapor recovery (cooling/condensation and membrane separation)	90%-98%
Oil refining	LDAR + exhaust absorption and adsorption	70%-75%
	LDAR + partial burn with CO boiler or full burn regeneration	90%
Gasoline storage	Stage I control (vapor balance and vapor recovery unit)	95%-98%
Gasoline distribution	Stage II control (passive and active systems)	70%-85%
Diesel storage	-	-
Venting and flaring	The same as oil production	
Flaring in oil refinery	The same as oil refinery	
Natural-gas-related sources	-	-
Chemical industry (organic) (adipic acid, ethylene, vinyl chloride, styrene, ethylene oxide, methanol, ethyl alcohol, acrylonitrile, glyoxylic acid)	LDAR + exhaust absorption and adsorption	79%
	LDAR + exhaust incineration	90%
Chemical industry (organic) (PE, PS, PVC, PP, resins, fibres)	LDAR + exhaust absorption and adsorption	47%
	LDAR + exhaust incineration	66%-80%
Chemical industry (manufacturing) (rubber, tyre)	LDAR + exhaust absorption and adsorption	48%
	LDAR + exhaust incineration	75%
Chemical industry (manufacturing) (paint, printing ink, glue and adhesive)	LDAR + exhaust absorption and adsorption	70%
	LDAR + exhaust incineration + use of good practices + solvent recovery	80%-85%
Chemical industry (others); Paper industry; Food industry	Referred to chemical industry above	60%-90%
Paint use (architectural)	Improved application technology + High-efficiency spraying equipment	20%-40%
Paint use (vehicle manufacturing)	Activated carbon adsorption/absorption	40%
	Thermal incineration + electrostatic spraying	60%

Paint use (wood)	Activated carbon adsorption/absorption	76%
	Thermal incineration + electrostatic spraying	90%
Paint (others)	Referred to the technologies above	50%-81%
Vehicle dewax; Vehicle reseal	Improved application technology	20%
Printing ink use	Activated carbon adsorption/absorption	48%
	Reduced consumption of isopropanol and of cleaning agents with high flash points + thermal incineration	76%
Glues and adhesives use	Activated carbon adsorption or condensation	70%
	Thermal incineration	80%
Preservation of wood	Activated carbon adsorption or condensation	67%
	Enclosure of drying and other areas and venting through end-of-pipe controls such as condensation or incineration	90%
Degreasing	Open-top degreaser with activated carbon filter	80%
	Closed degreaser using A3 solvents or fluoro solvents (HFC and HFE) with activated carbon filter	97%
Dry cleaning	Open-circuit machine with activated carbon filter	70%
	New generation closed-circuit PER machine	95%
Other solvent use	Referred to paint use (architectural)	20%-40%

Table S8. The values of parameters used in S-shaped curves ($X(t) = (X_0 - X_f)e^{\left(-\frac{(t-t_0)^2}{2s^2}\right)} + X_f$).

Parameter	Value
X_0	0
X_f	100
t_0	Start year of the policy/legislaiton
s	5

Table S9. Data sources of supplementary regional and global activity rates for chemical industry.

Region	Data sources
United States and Canada	Morikis, 2019; Qu, 2000; Chew et al., 1985; IFSC, 1972; Greiner and Veleva, 2004; Croll, 2009; Shi, 1984; Timetric, 2011; Liu, 2007; Zheng, 1996; Guo, 1999; Bo, 2012
EU countries (Germany, France, Italy, the U.K., Netherlands, Belgium, Sweden, Austria, Denmark, Portugal; Spain, Croatia, Poland, Hungary, Czech)	Behm and Schlachta, 2019; Qu, 2000; Chew et al., 1985; IFSC, 1972; van Broekhuizen et al., 2000; ICI Paints, 1989; Kougoulis et al., 2012; Shi, 1984; Timetric, 2011; Gagro, 2021; Liu, 2007; Zheng, 1996; Guo, 1999; Bo, 2012
Non-EU European countries (Switzerland, Norway, Russia, CIS countries)	Chew et al., 1985; IFSC, 1972; van Broekhuizen et al., 2000; Woodex, 2020; Xu, 2002; Timetric, 2011; Liu, 2007; Zheng, 1996; Zhuang, 1996; Bo, 2012
China	Li et al., 2017; Li et al., 2019
Other Asia (Japan, India, South Korea, Indonesia, Malaysia, Phillippines, Thailand, Vietnam)	Qu, 2000; Chew et al., 1985; IFSC, 1972; CBC, 2017; Liu, 2018; Zhong, 2019; Punmiya, 2020; KAISAI Paint, 2019; Shi, 1984; Timetric, 2011; Liu, 2007; Zheng, 1996; Zhuang, 1996; Guo, 1999; Bo, 2012
Latin America (Brazil, Argentina, Colombia, Mexico)	Coating Express, 2014; Zhu, 1982; Yang, 2004; Timetric, 2011; Liu, 2007; Zhuang, 1996; Guo, 1999; Bo, 2012
Other countries (Australia, New Zealand, Saudi Arabia, United Arab Emirates, Qatar, Bahrain, Turkey, Iran)	IFSC, 1972; Timetric, 2011; Liu, 2007; Sun, 1998, 1999; Bo, 2012
World	Morikis, 2019; Qu, 2000; von Dungen and Maier, 2015; CBC, 2017; Liu, 2018; Zhong, 2019; Growney, 2018; ICI Paints, 1989; Shi, 1984; Timetric, 2011; Gagro, 2021, 2018; Liu, 1984; Oullette, 2004; Menukhin, 2018, 2020; Liu, 2007; Zheng, 1996; Zhuang, 1996; Guo, 1999; Bo, 2012

Table S10. Region and income groups of countries/territories used in the mixed effects models (World Bank, 2022).

Country/territory	Region group 1	Region group 2	Income group
Afghanistan	Central and Western Asia	Other Asia	Low income
Albania	Eastern Europe	Europe	Upper middle income
Algeria	Middle East and North Africa	Africa	Lower middle income
American Samoa	Oceania and Pacific	Oceania and Pacific	Upper middle income
Angola	Sub-Saharan Africa	Africa	Lower middle income
Anguilla	Latin America	Latin America	High income
Antigua and Barbuda	Latin America	Latin America	High income
Argentina	Latin America	Latin America	Upper middle income
Armenia	Central and Western Asia	Other Asia	Upper middle income
Aruba	Latin America	Latin America	High income
Australia	Oceania and Pacific	Oceania and Pacific	High income
Austria	Western Europe	Europe	High income
Azerbaijan	Central and Western Asia	Other Asia	Upper middle income
Bahamas	Latin America	Latin America	High income
Bahrain	Middle East and North Africa	Other Asia	High income
Bangladesh	South and Southeast Asia	Other Asia	Lower middle income
Barbados	Latin America	Latin America	High income
Belarus	Eastern Europe	Europe	Upper middle income
Belgium	Western Europe	Europe	High income
Belize	Latin America	Latin America	Lower middle income
Benin	Sub-Saharan Africa	Africa	Lower middle income
Bermuda	Latin America	Latin America	High income

Bhutan	South and Southeast Asia	Other Asia	Lower middle income
Bolivia	Latin America	Latin America	Lower middle income
Bonaire, Sint Eustatius and Saba	Latin America	Latin America	High income
Bosnia and Herzegovina	Eastern Europe	Europe	Upper middle income
Botswana	Sub-Saharan Africa	Africa	Upper middle income
Brazil	Latin America	Latin America	Upper middle income
Brunei Darussalam	South and Southeast Asia	Other Asia	High income
Bulgaria	Eastern Europe	Europe	Upper middle income
Burkina Faso	Sub-Saharan Africa	Africa	Low income
Burundi	Sub-Saharan Africa	Africa	Low income
Cape Verde	Sub-Saharan Africa	Africa	Lower middle income
Cambodia	South and Southeast Asia	Other Asia	Lower middle income
Cameroon	Sub-Saharan Africa	Africa	Lower middle income
Canada	Canada	Canada and USA	High income
Cayman Islands	Latin America	Latin America	High income
Central African Republic	Sub-Saharan Africa	Africa	Low income
Chad	Sub-Saharan Africa	Africa	Low income
Chile	Latin America	Latin America	High income
China (including Hong Kong, Macao, and Taiwan)	China	China	Upper middle income
Colombia	Latin America	Latin America	Upper middle income
Comoros	Sub-Saharan Africa	Africa	Lower middle income
Democratic Republic of Congo	Sub-Saharan Africa	Africa	Low income
Congo	Sub-Saharan Africa	Africa	Lower middle income
Cook Islands	Oceania and Pacific	Oceania and Pacific	High income

Costa Rica	Latin America	Latin America	Upper middle income
Croatia	Eastern Europe	Europe	High income
Cuba	Latin America	Latin America	Upper middle income
Curacao	Latin America	Latin America	High income
Cyprus	Eastern Europe	Europe	High income
Czech Republic	Eastern Europe	Europe	High income
Côte d'Ivoire	Sub-Saharan Africa	Africa	Lower middle income
Denmark	Western Europe	Europe	High income
Djibouti	Sub-Saharan Africa	Africa	Lower middle income
Dominica	Latin America	Latin America	Upper middle income
Dominican Republic	Latin America	Latin America	Upper middle income
Ecuador	Latin America	Latin America	Upper middle income
Egypt	Middle East and North Africa	Africa	Lower middle income
El Salvador	Latin America	Latin America	Lower middle income
Equatorial Guinea	Sub-Saharan Africa	Africa	Upper middle income
Eritrea	Sub-Saharan Africa	Africa	Low income
Estonia	Eastern Europe	Europe	High income
Swaziland	Sub-Saharan Africa	Africa	Lower middle income
Ethiopia	Sub-Saharan Africa	Africa	Low income
Falkland Islands	Latin America	Latin America	High income
Faeroe Islands	Western Europe	Europe	High income
Fiji	Oceania and Pacific	Oceania and Pacific	Upper middle income
Finland	Western Europe	Europe	High income
France	Western Europe	Europe	High income

French Guiana	Latin America	Latin America	High income
French Polynesia	Oceania and Pacific	Oceania and Pacific	High income
Gabon	Sub-Saharan Africa	Africa	Upper middle income
Gambia	Sub-Saharan Africa	Africa	Low income
Georgia	Central and Western Asia	Other Asia	Upper middle income
Germany	Western Europe	Europe	High income
Ghana	Sub-Saharan Africa	Africa	Lower middle income
Gibraltar	Western Europe	Europe	High income
Greece	Western Europe	Europe	High income
Greenland	Western Europe	Europe	High income
Grenada	Latin America	Latin America	Upper middle income
Guadeloupe	Latin America	Latin America	High income
Guam	Oceania and Pacific	Oceania and Pacific	High income
Guatemala	Latin America	Latin America	Upper middle income
Guinea	Sub-Saharan Africa	Africa	Low income
Guinea-Bissau	Sub-Saharan Africa	Africa	Low income
Guyana	Latin America	Latin America	Upper middle income
Haiti	Latin America	Latin America	Lower middle income
Honduras	Latin America	Latin America	Lower middle income
Hungary	Eastern Europe	Europe	High income
Iceland	Western Europe	Europe	High income
India	India	India	Lower middle income
Indonesia	South and Southeast Asia	Other Asia	Lower middle income
Islamic Republic of Iran	Middle East and North Africa	Other Asia	Lower middle income

Iraq	Middle East and North Africa	Other Asia	Upper middle income
Ireland	Western Europe	Europe	High income
Isle of Man	Western Europe	Europe	High income
Israel	Middle East and North Africa	Other Asia	High income
Italy	Western Europe	Europe	High income
Jamaica	Latin America	Latin America	Upper middle income
Japan	East Asia	Other Asia	High income
Jersey	Western Europe	Europe	High income
Jordan	Middle East and North Africa	Other Asia	Upper middle income
Kazakhstan	Central and Western Asia	Other Asia	Upper middle income
Kenya	Sub-Saharan Africa	Africa	Lower middle income
Kiribati	Oceania and Pacific	Oceania and Pacific	Lower middle income
Democratic People's Republic of Korea	East Asia	Other Asia	Low income
Republic of Korea	East Asia	Other Asia	High income
Kuwait	Middle East and North Africa	Other Asia	High income
Kyrgyzstan	Central and Western Asia	Other Asia	Lower middle income
Laos	South and Southeast Asia	Other Asia	Lower middle income
Latvia	Eastern Europe	Europe	High income
Lebanon	Middle East and North Africa	Other Asia	Upper middle income
Lesotho	Sub-Saharan Africa	Africa	Lower middle income
Liberia	Sub-Saharan Africa	Africa	Low income
Libya	Middle East and North Africa	Africa	Upper middle income
Liechtenstein	Western Europe	Europe	High income
Lithuania	Eastern Europe	Europe	High income

Luxembourg	Western Europe	Europe	High income
Madagascar	Sub-Saharan Africa	Africa	Low income
Malawi	Sub-Saharan Africa	Africa	Low income
Malaysia	South and Southeast Asia	Other Asia	Upper middle income
Maldives	South and Southeast Asia	Other Asia	Upper middle income
Mali	Sub-Saharan Africa	Africa	Low income
Malta	Western Europe	Europe	High income
Marshall Islands	Oceania and Pacific	Oceania and Pacific	Upper middle income
Martinique	Latin America	Latin America	High income
Mauritania	Sub-Saharan Africa	Africa	Lower middle income
Mauritius	Sub-Saharan Africa	Africa	Upper middle income
Mayotte	Sub-Saharan Africa	Africa	Upper middle income
Mexico	Latin America	Latin America	Upper middle income
Federated States of Micronesia	Oceania and Pacific	Oceania and Pacific	Lower middle income
Moldova	Eastern Europe	Europe	Upper middle income
Mongolia	Central and Western Asia	Other Asia	Lower middle income
Montenegro	Eastern Europe	Europe	Upper middle income
Montserrat	Latin America	Latin America	Upper middle income
Morocco	Middle East and North Africa	Africa	Lower middle income
Mozambique	Sub-Saharan Africa	Africa	Low income
Myanmar	South and Southeast Asia	Other Asia	Lower middle income
Namibia	Sub-Saharan Africa	Africa	Upper middle income
Nauru	Oceania and Pacific	Oceania and Pacific	High income
Nepal	South and Southeast Asia	Other Asia	Lower middle income

Netherlands	Western Europe	Europe	High income
New Caledonia	Oceania and Pacific	Oceania and Pacific	High income
New Zealand	Oceania and Pacific	Oceania and Pacific	High income
Nicaragua	Latin America	Latin America	Lower middle income
Niger	Sub-Saharan Africa	Africa	Low income
Nigeria	Sub-Saharan Africa	Africa	Lower middle income
Niue	Oceania and Pacific	Oceania and Pacific	Upper middle income
Norfolk Island	Oceania and Pacific	Oceania and Pacific	High income
North Macedonia	Eastern Europe	Europe	Upper middle income
Northern Mariana Islands	Oceania and Pacific	Oceania and Pacific	High income
Norway	Western Europe	Europe	High income
Oman	Middle East and North Africa	Other Asia	High income
Pakistan	South and Southeast Asia	Other Asia	Lower middle income
Palau	Oceania and Pacific	Oceania and Pacific	High income
Palestine	Middle East and North Africa	Other Asia	Lower middle income
Panama	Latin America	Latin America	Upper middle income
Papua New Guinea	Oceania and Pacific	Oceania and Pacific	Lower middle income
Paraguay	Latin America	Latin America	Upper middle income
Peru	Latin America	Latin America	Upper middle income
Philippines	South and Southeast Asia	Other Asia	Lower middle income
Pitcairn	Oceania and Pacific	Oceania and Pacific	Lower middle income
Poland	Eastern Europe	Europe	High income
Portugal	Western Europe	Europe	High income
Puerto Rico	Latin America	Latin America	High income

Qatar	Middle East and North Africa	Other Asia	High income
Romania	Eastern Europe	Europe	Upper middle income
Russia	Russia	Russia	Upper middle income
Rwanda	Sub-Saharan Africa	Africa	Low income
Reunion	Sub-Saharan Africa	Africa	High income
Saint Helena	Sub-Saharan Africa	Africa	Upper middle income
Saint Kitts and Nevis	Latin America	Latin America	High income
Saint Lucia	Latin America	Latin America	Upper middle income
Saint Pierre and Miquelon	Latin America	Latin America	High income
Saint Vincent and Grenadines	Latin America	Latin America	Upper middle income
Samoa	Oceania and Pacific	Oceania and Pacific	Lower middle income
Sao Tome and Principe	Sub-Saharan Africa	Africa	Lower middle income
Saudi Arabia	Middle East and North Africa	Other Asia	High income
Senegal	Sub-Saharan Africa	Africa	Lower middle income
Serbia	Eastern Europe	Europe	Upper middle income
Seychelles	Sub-Saharan Africa	Africa	High income
Sierra Leone	Sub-Saharan Africa	Africa	Low income
Singapore	South and Southeast Asia	Other Asia	High income
Sint Maarten	Latin America	Latin America	High income
Slovakia	Eastern Europe	Europe	High income
Slovenia	Eastern Europe	Europe	High income
Solomon Islands	Oceania and Pacific	Oceania and Pacific	Lower middle income
Somalia	Sub-Saharan Africa	Africa	Low income
South Africa	Sub-Saharan Africa	Africa	Upper middle income

South Sudan	Sub-Saharan Africa	Africa	Low income
Spain	Western Europe	Europe	High income
Sri Lanka	South and Southeast Asia	Other Asia	Lower middle income
Sudan	Middle East and North Africa	Africa	Low income
Suriname	Latin America	Latin America	Upper middle income
Sweden	Western Europe	Europe	High income
Switzerland	Western Europe	Europe	High income
Syria	Middle East and North Africa	Other Asia	Low income
Tajikistan	Central and Western Asia	Other Asia	Lower middle income
Tanzania	Sub-Saharan Africa	Africa	Lower middle income
Thailand	South and Southeast Asia	Other Asia	Upper middle income
Timor-Leste	South and Southeast Asia	Other Asia	Lower middle income
Togo	Sub-Saharan Africa	Africa	Low income
Tokelau	Oceania and Pacific	Oceania and Pacific	Upper middle income
Tonga	Oceania and Pacific	Oceania and Pacific	Upper middle income
Trinidad and Tobago	Latin America	Latin America	High income
Tunisia	Middle East and North Africa	Africa	Lower middle income
Turkey	Middle East and North Africa	Europe	Upper middle income
Turkmenistan	Central and Western Asia	Other Asia	Upper middle income
Turks and Caicos Islands	Latin America	Latin America	High income
Tuvalu	Oceania and Pacific	Oceania and Pacific	Upper middle income
Uganda	Sub-Saharan Africa	Africa	Low income
Ukraine	Eastern Europe	Europe	Lower middle income
United Arab Emirates	Middle East and North Africa	Other Asia	High income

United Kingdom	Western Europe	Europe	High income
United States	United States	Canada and USA	High income
Uruguay	Latin America	Latin America	High income
Uzbekistan	Central and Western Asia	Other Asia	Lower middle income
Vanuatu	Oceania and Pacific	Oceania and Pacific	Lower middle income
Venezuela	Latin America	Latin America	Lower middle income
Vietnam	South and Southeast Asia	Other Asia	Lower middle income
British Virgin Islands	Latin America	Latin America	High income
United States Virgin Islands	Latin America	Latin America	High income
Wallis and Futuna Islands	Oceania and Pacific	Oceania and Pacific	High income
Western Sahara	Middle East and North Africa	Africa	Lower middle income
Yemen	Middle East and North Africa	Other Asia	Low income
Zambia	Sub-Saharan Africa	Africa	Lower middle income
Zimbabwe	Sub-Saharan Africa	Africa	Lower middle income

Table S11. Data sources of compiled regional data for paint application purposes and waterborne paint proportions.

Region	Major data sources
China	Wei et al. 2008; Li et al., 2017; Li et al., 2019; Zhiyan Consulting, 2017
United States and Canada	Combustion Department, 1970; Zhao et al., 1998; Greiner and Veleva, 2004; American Coatings Association, 2022
Western Europe	Combustion Department, 1970; Wang, 1989; Zhou, 1997; Harries et al., 2002; Gagro, 2021; Broekhuizen et al., 2000;
Eastern Europe and Russia	Combustion Department, 1970; Fang, 1983; Xu, 2002; IRL, 2012; KDM International Ltd, 2019
Japan	Combustion Department, 1970; Sun, 1998; Timetric, 2011, Menukhin, 2020
India	Zhou, 1998; Devaraj et al., 2007; Timetric, 2011; Mordor Intelligence, 2021
Other Asia	Refer to Japan or India
Latin America	Zhu, 1982; Zhou, 1997; Timetric, 2011; Rácz and Yamaga, 2017
Middle East and Africa	Galbraith, 2005; IRL, 2015; Pollard et al., 2018
Other region	Zhou, 1997, 2000; Timetric, 2011

Table S12. The probability distributions of emission parameters (Bond et al., 2004; Lu et al., 2011; Zhao et al., 2011; Tong et al., 2018; EEA, 2023).

1st level	2nd level	Activity rate	Technology distribution	Emission factor	Penetration ratios of control technology
Power generation	Coal (Anthracite, Coking coal, Other bituminous coal, Sub-bituminous coal, Lignite, Patent fuel, Coke oven coke, Gas coke, Coal tar, BKB, Gas works gas, Coke oven gas, Blast furnace gas, Other recovered gases, Peat, Peat products)	Normal Fossil fuel: 1970-1999 OECD countries CV=15%; non-OECD countries with local data fusion CV=20%; other countries CV=25% 2000-2020 OECD countries CV=10%; non-OECD countries with local data fusion CV=15%; other countries CV=20%'; Biomass: 1970-1999 OECD countries CV=40%; non-OECD countries with local data fusion CV=45%; other countries CV=50% 2000-2020 OECD countries CV=30%; non-OECD countries with local data fusion CV=35%; other countries CV=40%	None	Lognormal CV=10%	None
Heat (auto producer)					
Heat (public)					
Coal mines					
Oil and gas extraction					
Blast furnaces					
Gas works					
Gasification plants for biogases					
Coke ovens					
Patent fuel plants					
BKB/peat briquette plants					
Oil refineries	Oil (Crude oil, Natural gas liquids, Refinery feedstocks, Additives/blending components, Other hydrocarbons, Refinery gas, Ethane, Liquefied petroleum gases (LPG), Motor gasoline excluding biofuels, Aviation gasoline, Gasoline type jet fuel, Kerosene type jet fuel excluding biofuels, Other kerosene, Gas/diesel oil excluding biofuels, Fuel oil, Naphtha, White spirit and SBP,				
Coal liquefaction plants					
Liquefaction (LNG) / regasification plants					
Gas-to-liquids (GTL) plants					
Own use in electricity, CHP and heat plants					
Charcoal production plants					
Non-specified transformation industries					
Iron and steel					
Non-ferrous metals					
Chemicals					
Pulp and paper					
Food and tobacco					
Cement					
Other non-metallic minerals					
Transport equipment					
Machinery					
Mining and quarrying					
Wood products					

Construction	Lubricants, Bitumen, Paraffin waxes, Petroleum coke, Other oil products, Oil shale and oil sands)				
Textile and leather					
Other non-specified industries					
International aviation					
Domestic aviation					
Rail					
International navigation	Natural gas (Natural gas)				
Domestic navigation					
Pipeline transport	Biomass (Renewable municipal waste, Primary solid biofuels, Biogases, Bio gasoline, Biodiesels, Bio jet kerosene, Other liquid biofuels, Non-specified primary biofuels/waste, Charcoal)		None	Lognormal CV=15%	None
Other non-specified transport					
Agriculture and forestry					
Fishing					
Cars			Uniform ±30%	Lognormal CV=10%	None
Light duty trucks					
Buses					
Heavy duty trucks					
Motorcycles					
Other fleet totals			None		
Commercial and institutional			Uniform ±30%	Lognormal CV=20%	None
Residential (rural)					
Residential (urban)					
Non-specified sectors			None		
Fugitive (solid fuel production)	Coke oven coke production	Normal 1970-1999 OECD countries CV=15%; non-OECD countries with local data fusion CV=20%; other countries CV=25% 2000-2020 OECD countries CV=10%; non-OECD countries with local data fusion CV=15%; other countries	None	Uniform ±90%	None
Fugitive (oil and gas)	Oil production			Uniform ±90%	Uniform ±30%
	Oil storage and transport				
	Oil refining				
	Gasoline storage				
	Gasoline distribution				
	Diesel storage				
	Venting and flaring				
	Flaring in oil refinery				
	Natural gas production, processing, storage, and distribution				

	Gas venting and flaring	CV=20%			
Mineral industry	Cement production		None	Uniform ±80%	None
	Clicker production				
	Glass production				
Chemical industry (inorganic)	Ammonia		None		
	Carbon black				
Chemical industry (organic)	Adipic acid	Normal 1970-1999 Developed countries CV=15% Other countries CV=20% 2000-2020 Developed countries CV=10% Other countries CV=15%	None	Uniform ±95%	Uniform ±30%
	Ethylene				
	Vinyl chloride				
	Styrene				
	Low density polyethylene (LDPE)				
	High density polyethylene (HDPE)				
	Polyvinyl chloride (PVC)				
	Polypropylene (PP)				
	Polystyrene (PS)				
	SAN & ABS resins				
	Other synthetic resins				
	Ethylene oxide				
	Methanol				
	Acrylonitrile				
	Glyoxylic acid				
Chemical industry (manufacturing)	Synthetic rubber		None		
	Tyre production				
	Pharmaceutical production				
	Asphalt				
	Paint production				
	Printing ink production				
	Glues production				
	Shoes production				
	Leather tanning				
	Synthetic fibre				
	Wool				
	Silk				
	Cloth				

	Artificial fibre				
Metal industry	Sinter production		None	Uniform ±60%	None
	Pellet production				
	Pig iron production				
	DRI production				
	Steel production		Uniform ±30%		
Pulp, paper, and food industry	Paper pulp		None	Uniform ±95%	Uniform ±30%
	Paper				
	Plywood				
	Bread				
	Biscuit				
	Sugar				
	Flour				
	Oilseed				
	Beer				
	Wine				
	Spirit				
Paint use	Architectural interior wall	Normal 1970-1999 Developed countries CV=25% Other countries CV=30% 2000-2020 Developed countries CV=15% Other countries CV=20%	Uniform ±30%		Uniform ±30%
	Architecture other				
	Vehicle manufacturing				
	Vehicle repairing				
	Wood				
	Other industrial paint				
Other industrial use	Vehicle dewax		None	Uniform ±95%	Uniform ±30%
	Vehicle reseal				
	Printing ink use				
	Glues and adhesives use				
	Preservation of wood				
	Degreasing				
	Dry cleaning				
Domestic use	Domestic use		None		Uniform ±30%
	Pesticide				

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