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Development of Renewable Energy and its Impact on Air Quality

Co-benefits and Trade-Offs

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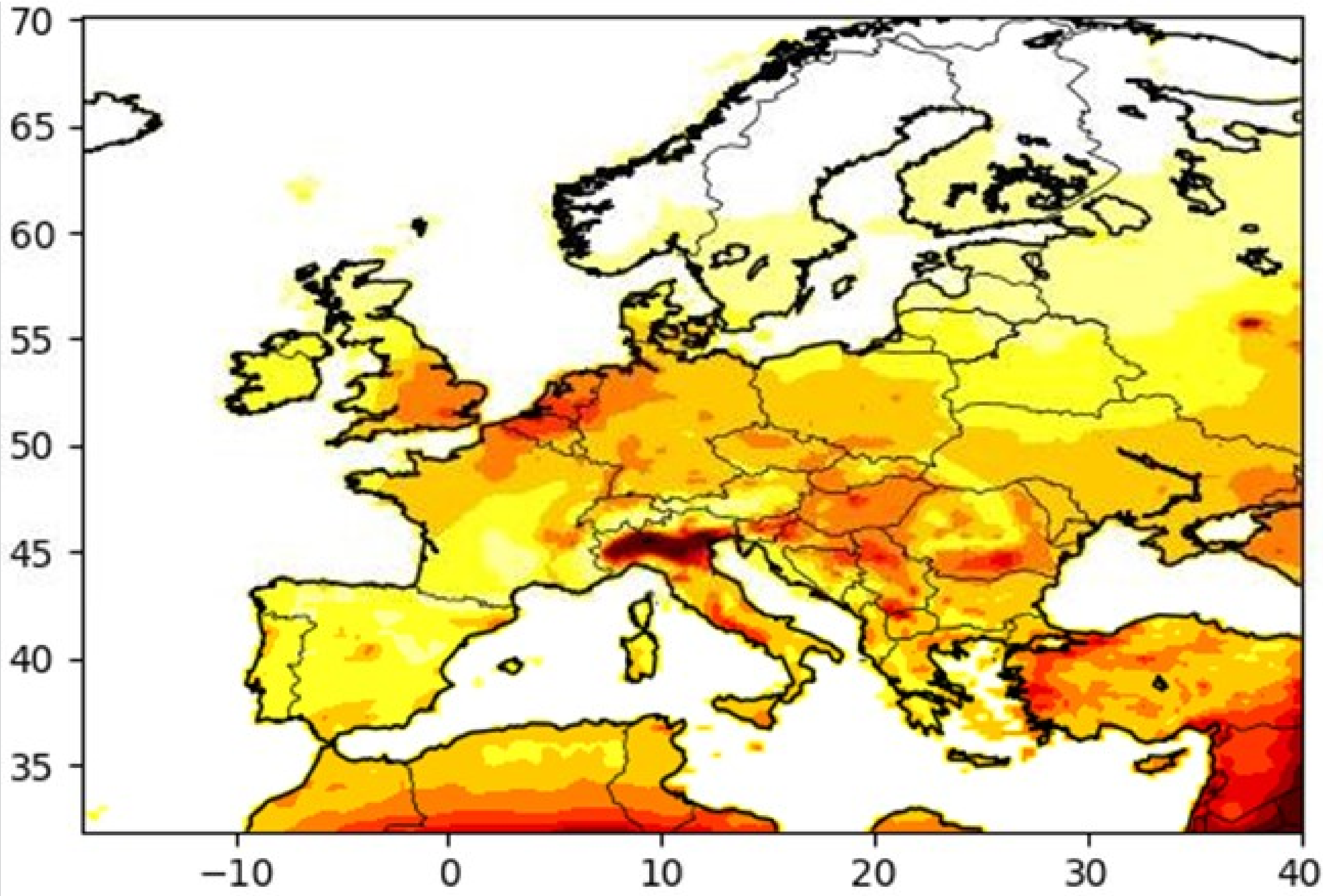

Authors:
Florian Couvidat (INERIS), Susana Lopez-Aparicio (NILU), Simone Schucht (INERIS), Elsa Real (INERIS), Henrik Grythe (NILU)

ETC/ATNI consortium partners:
NILU – Norwegian Institute for Air Research, Aether Limited, Czech Hydrometeorological Institute (CHMI), EMISIA SA, Institut National de l'Environnement Industriel et des risques (INERIS), Universitat Autònoma de Barcelona (UAB), Umweltbundesamt GmbH (UBA-V), 4sfera Innova, Transport & Mobility Leuven NV (TML)

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Cover photo: Annual concentrations of PM2.5 simulated with CHIMERE (see Map 7). © ETC/ATNI
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The withdrawal of the United Kingdom from the European Union did not affect the production of the report. Data reported by the United Kingdom are included in all analyses and assessments contained herein, unless otherwise indicated.

Author(s)
Florian Couvidat (INERIS), Susana Lopez-Aparicio (NILU), Simone Schucht (INERIS), Elsa Real (INERIS), Henrik Grythe (NILU)

ETC/ATNI c/o NILU
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European Topic Centre on Air pollution,
transport, noise and industrial pollution
c/o NILU – Norwegian Institute for Air Research
P.O. Box 100, NO-2027 Kjeller, Norway
Tel.: +47 63 89 80 00
Email: etc.atni@nilu.no
Web : https://www.eionet.europa.eu/etcs/etc-atni

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Summary

This study is an continuation of the work initiated in the European Topic Centre on Climate Change Mitigation and Energy (ETC/CME; report 2019/8) on the effect of the development of renewable energy sources (RES) since 2005 on emissions of anthropogenic air pollutants, which found that RES have led to an estimated increase of primary particulate matter emissions and a decrease of emissions of sulphur oxides and nitrogen oxides. The current study aims at evaluating the impact of these emission changes on air quality and human health by using the air quality model CHIMERE to understand the distribution of emissions. To this end, the emissions corresponding to a reference scenario and to different scenarios of development of renewable energy sources were spatialized over Europe based on the spatialization of emissions used within the Copernicus Atmosphere Monitoring Service (CAMS). The CHIMERE model was applied to calculate, for the year 2016, the impact of the different scenarios on air quality. Finally, the possible impact on human health was assessed. We also include a specific section devoted to residential emission spatialization techniques to review the related uncertainties.

According to the simulation results using emissions based on official data, significant increases of particulate matter concentrations exceeding 1 $\mu g/m^3$ were found for some countries, linked primarily to the increase in residential wood burning when comparing 2005 with 2016. Exceptions were Portugal and Greece (two countries that decreased their use of biomass for heating). At the scale of the EU27+UK, in 2016, the interplay between emission increases due to biomass use and emission decreases due to all other RES growth is estimated to be responsible for around 9 200 premature deaths and 97 000 years of life lost. As such, the increase in solid biomass heating alone, (due particularly by the high emissions of fine particulate matter from domestic stoves), is estimated to be responsible for an increase of around 10 700 premature deaths and 113 000 years of life lost in 2016. These premature deaths could have been prevented by promoting the development of other RES than solid biomass heating.

Similar results were found at the European scale with simulations using emissions based on expert estimates but with strong differences according to the country. The differences are mostly due to differences in emissions that may not account for semi-volatile organic compounds for some countries. Excluding heating with biomass, all other RES use appears to have led to small reductions of particulate matter concentrations across the Union, with air quality benefits estimated at 1 600 avoided premature deaths and 16 000 prevented years of life lost in 2016. This is because the deployment of RES other than heating from solid biomass from 2005 to 2016 only lead to small changes in emissions of pollutants. However, these sources represented only 13% of the heating and electricity production in 2016.

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The Copernicus Atmosphere Monitoring Service is also acknowledged for making publicly available regional emission of pollutants prepared by TNO.

1 Introduction

The deployment of renewable energy sources (RES) is a key component of climate mitigation and for achieving the international commitments of the EU and its Member States under the Paris Agreement (UNFCC, 2015[1]). By developing RES, Europe has substituted part of its energy production from non-renewable sources (especially from fossil fuels). By increasing the share of RES in the production of energy, Europe managed to reduce greenhouse gas (GHG) emissions. In 2016, RES represented 17.0% of the energy consumed in the European Union, having increased from only 9.1% in 2005[2] (these numbers include both Croatia that joined the European Union in 2013 and the United Kingdom). Between 2005 and 2016, RES increased in absolute terms by a factor 2 for the production of electricity (from 42 000 kilotonnes of oil equivalent (ktoe) to 82 561 ktoe) and by a factor 1.5 in heating and cooling services (from 66 444 ktoe to 99 858 ktoe).

This task develops further the assessment work initiated in 2018 by EEA and its ETC/CME (ETC/CME, 2019). That study indicated that the recent development of RES contributes to reduced GHG emissions but also has an impact on the emission of air pollutants, linked to combustible renewables. It estimated the impact of RES development on the emissions of main air pollutants based on implied emission factors collected (i) from the Greenhouse gas - Air pollution Interactions and Synergies (GAINS) model and (ii) from official national portals, where available. Across the European Union, the growth in RES use led to a reduction in emissions of sulphur oxides (SO_x) and nitrogen oxides (NO_x) by decreasing the consumption of fossil fuels; in tandem, primary particulate matter (PM) emissions increased due to higher emissions caused by growing residential wood burning.

The objectives of this study is to assess with the help of the air quality model CHIMERE (Couvidat et al., 2018) the possible impacts of the air pollutant emissions attributable to the development of renewable energy consumption in the European Union since 2005 (including Croatia that joined in 2013 and UK that left in 2020, hereafter referred to as EU27+UK). The resulting annual mean exposure to PM is subsequently translated into premature death for the year 2016.

[1] https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement
[2] EUROSTAT renewable energy statistics (2020).

2 Methodology

Three main steps were followed in order to evaluate the impact of RES development on air quality in 2005 and 2016, the basis for translating exposure into premature deaths and the economic cost of health impact estimates for the year 2016:

- For selected scenarios, the changes in emissions due to RES development were mapped based on the spatial distribution of emissions in the CAMS-REG-AP inventory (CAMS regional inventory for air pollutants), the regional inventory for Europe (including emissions for EU and other European countries) and were evaluated qualitatively regarding their potential impacts.
- The model CHIMERE was used at a resolution of 0.4°x 0.25° (around 25 x 25 km^2) to estimate the impact of the different scenarios on the concentrations of the main pollutants ($PM_{2.5}$, PM_{10}, NO_2, O_3).
- Impacts on human health due to fine PM ($PM_{2.5}$) air pollution were subsequently assessed by computing exposure from the simulation results.
- The year 2016 was selected as the most recent year with a dataset available in the CAMS-REG-AP inventory.

- For renewable energy sources, the SHort Assessment of Renewable Energy Sources (SHARES) tool results published by Eurostat in 2018 were used.

2.1 Scenarios

The inferred emission levels of the main air pollutants (PM, NMVOC[3], SO_x, NO_x) obtained from the ETC/CME Report 2019/8 in the CAMS-REG-AP inventory were used to simulate the impact of pollutant concentrations (O_3, NO_2, PM_{10}, $PM_{2.5}$) with the air quality model CHIMERE for the following scenarios:

1. 2016 reference (with the actual RES development): based on CAMS-REG-AP;
2. 2016 assuming no RES development happened since 2005;
3. 2016 assuming no RES development happened since 2005 for heating from solid biomass energy;
4. 2016 assuming no RES development happened since 2005 for photovoltaic energy;
5. 2016 assuming no RES development happened since 2005 for wind energy (offshore and onshore);
6. 2016 assuming no RES development happened since 2005 for other renewable electricity energy sources (excluding photovoltaic and wind energies). These energy sources are referred as "other renewable electricity" RES and include electricity from biogas, bioliquids, concentration solar power, geothermal, hydropower, solid biomass, tidal, wave and ocean energy;
7. 2016 assuming no RES development happened since 2005 for renewable heating (excluding solid biomass). These energy sources are referred as "other renewable heating" RES and include heating from biogas, bioliquids, geothermal, solar thermal and heat pumps;

These scenarios assumed that the energy produced by RES growth have replaced an equal amount of energy produced by the consumption of fossil fuels. In the case of combustion-based renewables, emissions can increase for some air pollutants. This is because some renewable fuels have higher emission factors than the weighted average fossil fuel emission factor of the fossil fuel they are assumed to substitute. The use of wood for heating (which is the largest source of primary $PM_{2.5}$

[3] Non-methane volatile organic compounds: VOC excluding methane.

emitted to the air in Europe) can for example substitute the use of natural gas, which has relatively low emission factors.

Table 1 shows the increase in energy consumption and the corresponding avoided $PM_{2.5}$ emissions. It shows that, for EU27+UK, a large part of the increase of renewable energy consumption between 2005 and 2016 (30%) is due to solid biomass consumption for heating . This deployment of soil biomass consumption for heating (scenario 3) led to a significant increase of $PM_{2.5}$ emissions of 143 kT (1 300 kT of primary $PM_{2.5}$ where emitted in 2016 in EU27+UK). This increase of $PM_{2.5}$ emissions could have been avoided by replacing fossil fuel consumption for heating by other RES technologies, i.e.if the 22 731 ktoe emitted according to scenario 3 were allocated to scenario 7. For other scenarios, the change in emissions due to the development of RES (relative to the 2016 emissions) are below ±1% (except for avoided SO_2 emissions from the deployment of wind energy) and are therefore expected to have a minor impact on air pollutant emissions. With the deployment of RES other than heating from solid biomass, 0.6%, 1%, -0.1% and 4.5% of the 2016 emissions of $PM_{2.5}$, NO_x, NMVOC and SO_2 would have been avoided. It is important to keep in mind that RES other than heating from solid biomass represent only 13% of heating and electricity energy production.

Table 1: Increase in energy consumption and avoided emissions (relative to 2016 emissions) due to RES deployment between 2005 and 2016 in EU-27+UK for each of the scenarios.

Scenario	increase in energy consumption (in ktoe)	Energy consumption in 2005 (in ktoe)	Energy consumption in 2016 (in ktoe)	Avoided emissions compared to 2016 UE27+UK emissions			
				$PM_{2.5}$	NOx	NMVOC	SO_2
3	22 731	61 700	84 431	**-11%**	-0,50%	**-3,8%**	**2,5%**
4	8 975	126	9 101	0,06%	0,33%	0,03%	0,88%
5	20 810	5 940	26 750	0,14%	0,78%	0,05%	**2,3%**
6	10 938	35 941	46 879	-0,17%	-0,21%	-0,28%	0,81%
7	10 752	4 287	15 039	0,55%	0,13%	0,06%	0,50%

The impact of scenario 2 on emissions by countries and by pollutants is illustrated in Table 2. Comparing 2005 and 2016, Portugal, Croatia and Greece were the only countries that managed to reduce the emissions for all pollutants due to deploying renewable energy sources. In all the other countries, $PM_{2.5}$ and NMVOC emissions increased. Portugal, Croatia and Greece are the only countries that had reduced their residential consumption of biomass while it had increased for the other countries. In the case of Greece, it was reported that the Greek public-debt crisis prompted a rapid increase in the un-regulated combustion of solid fuels in Greece, which led to air quality degradation (ETC/ACM, 2015). In the officially data available via the CEIP website, Greece reported a decrease of biomass consumption of 30% for the 2005-2010 period. This decrease was followed by quick increase of 65% between 2010 and 2012. However, after this period, the consumption of biomass decreased and led to a net decrease of wood consumption of 12% when comparing 2005 and 2016.

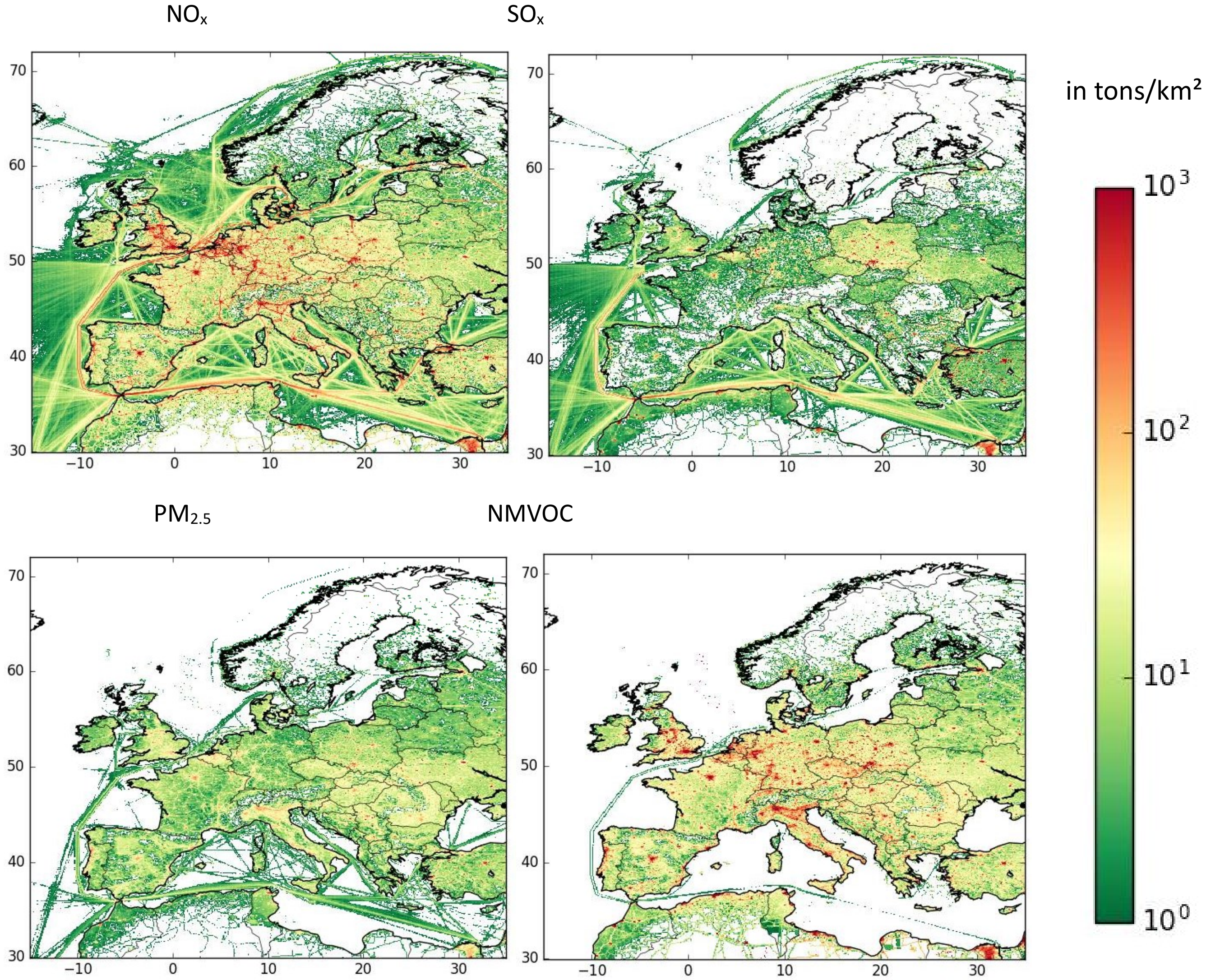
Table 2: Absolute effect (in kilotons) of deploying renewable energy since 2005 on air pollutant emissions, by pollutant and country, in 2016.

	$PM_{2.5}$	PM_{10}	NO_x	SO_2	NMVOC
Austria	2,8	2,9	-1,0	-1,1	12,0
Belgium	14,0	14,5	-0,7	-0,2	19,9
Bulgaria	1,3	1,1	-0,6	-10,7	4,7
Croatia	-0,5	-0,6	-0,6	-0,6	-0,9
Cyprus	0,1	0,1	-0,2	-0,5	0,2
Czech Republic	2,1	2,0	0,9	-6,7	8,7
Denmark	11,2	11,5	0,4	0,3	11,5
Estonia	4,0	4,0	-0,2	-1,1	6,2
Finland	9,9	10,0	2,0	-6,3	17,1
France	12,2	12,6	-8,3	-3,6	23,4
Germany	4,9	4,9	-4,9	-21,7	14,5
Greece	-1,1	-1,3	-5,6	-4,4	-1,6
Hungary	13,3	13,8	1,3	-2,2	25,8
Ireland	0,0	0,0	-1,3	-1,7	0,8
Italy	29,7	30,5	11,3	1,9	56,9
Latvia	0,1	0,1	0,2	0,3	0,6
Lithuania	2,9	2,9	0,4	-6,8	6,1
Luxembourg	0,2	0,2	0,0	0,1	0,5
Malta	0,0	0,0	-0,1	-0,1	0,0
Netherlands	2,1	2,2	-0,1	0,9	5,3
Poland	4,2	4,0	-3,1	-33,1	32,6
Portugal	-7,1	-7,3	-4,4	-0,1	-11,8
Romania	3,1	3,2	-2,5	-10,7	4,3
Slovakia	3,0	3,0	0,4	0,2	3,5
Slovenia	3,3	3,4	0,0	-0,1	4,8
Spain	2,7	2,6	-10,3	-12,3	5,3
Sweden	5,3	5,5	-3,5	-4,3	10,0
United Kingdom	11,7	12,3	-11,3	-31,2	21,4

As mentioned above, the year 2016 was selected as the most recent year with a dataset available in the CAMS-REG-AP inventory. The mapping strategies of scenarios was based on the spatialization of macro-sectors in the CAMS-REG-AP inventory. The mapping methodology is detailed in section 3.2.

Map 1 shows the emission maps of the CAMS-REG-AP inventory for NO_x, SO_x, $PM_{2.5}$ and NMVOC for the year 2016.

Map 1: Emission maps for NO_x, SO_x, $PM_{2.5}$ and NMVOC for the reference scenario, year 2016 (Scenario 1)



However, some studies (for example Dernier van der Gon, 2015) showed that the emissions from residential wood burning over Europe may be significantly underestimated and that emissions should account for the semi-volatile organic aerosols (SVOC), PM that is formed almost instantaneously in the atmosphere by dilution and cooling. SVOC emissions are generally not considered in official emission inventories compiled for example under the EU's National Emission reduction Commitments (NEC) Directive (see e.g. EEA, 2019a). In the CAMS-REG-AP inventory, TNO[4] developed for the year 2015 an additional emission dataset based on expert estimates[5], which takes into account semi-volatile

[4] Netherlands Organisation for Applied Scientific Research.

[5] The national emissions reported by countries for the residential combustion sector (NFR C) are replaced by a bottom-up estimates using emission factors determined by TNO. These emission factors are determined in Denier van der Gon et al. (2015).

compounds for residential wood burning, using a harmonized methology. The scaling factors are also applied to scenario 7 in order to obtain scenario 9: the absolute effect of RWB deployment is also multiplied by the scaling factors.

Map 2 shows the emission maps of PM$2_{.5}$ for the year 2016 based on official reporting (scenario 1) and on expert estimates (scenario 8).

Table 3 presents the differences in national emissions of primary $PM_{2.5}$ for the “Other stationary combustion” sector (which is dominated by residential wood burning (RWB) emissions from domestic stoves). The column “Scaling factor” corresponds to the ratio between expert estimates and official data (except for Lithuania and the Czech Republic, for which explanations are given further below). This scaling factor exceeds a factor 2 for several countries (Austria, Cyprus, Estonia, Finland, France, Germany, the Netherlands, Poland and Sweden), and is close to 1 (from 0,9 to 1,3) for some countries (Belgium, Bulgaria, Croatia, Italy, Luxembourg, Romania, Slovakia).

In order to account for emissions of semi-volatile compounds that may affect the results of this study, two additional scenarios, based on expert estimates, were also investigated:

- Scenario 8: 2016 reference (with the actual RES development) based on expert estimates of wood burning emissions including condensables (equivalent to scenario 1)
- Scenario 9: 2016 assuming no RES development happened since 2005 for solid biomass energy based on expert estimates of wood burning emissions including condensables (equivalent to scenario 3)

As 2016 emissions (version 3.1 of the CAMS-REG-AP inventory) from expert estimates were not available, they were estimated by using a scaling factor based on the year 2015 (version 2.2.1 of the CAMS-REG-AP inventory). This scaling factor corresponds to the ratio for national emissions between expert estimates and official data. This scaling assumes that the underestimation of emissions is the same for the years 2015 and 2016 and implies that the calculation of emissions was based on the same methodology (i.e. that no country switched to another method that takes into account SVOC in their emissions). Only two countries have significant differences in their national emissions for the “Other stationary combustion” sector when comparing 2015 and 2016:

- the Czech Republic, for which emissions increased from 12,8 kT in 2015 to 29 kT in 2016. As the official data for 2016 emissions reported under the Convention on Long-range Transboundary Air Pollution (CLRTAP)[6] is close to the one of 2015 based on expert estimates, the 2016 emissions in the CAMS-REG-AP version 3.1 probably account for SVOC. This hypothesis is supported by the data from the official reporting for the year 2015 (available on the CEIP website), which increased from 12.8 kT (for the data reported in 2017) to 29.7 kT (for the data reported in 2018). A scaling factor of 1,18 was therefore used for Czech Republic (ratio between the expert estimate and the 2018 official reporting for year 2015).
- Lithuania, for which emissions decreased from 13.8 kT in 2015 to 3.2 kT in 2016. This change is due to changes in the reporting between the years 2017 and 2018. One possibility is therefore that Lithuania previously accounted for SVOC in their emission inventory (supported by the low differences in emissions between official data and expert estimates) but switched

[6] EU Member States officially report emissions of main air pollutants (NOX, NMVOCs, SO2, NH3, CO, PM, BC, HMs and POPs) under the EU’s National Emission reduction Commitments (NEC) Directive, which entered into force on 31 December 2016. Reporting under the NEC Directive is largely, i.e. down to minor differences for the Spanish and Portuguese inventories, harmonized with reporting under CLRTAP.

to a method that does not account for SVOC. The scaling factor (5,86) is therefore calculated by the ratio between the expert estimates and the value reported for year 2015 in the 2018 reporting (3.2 kT).

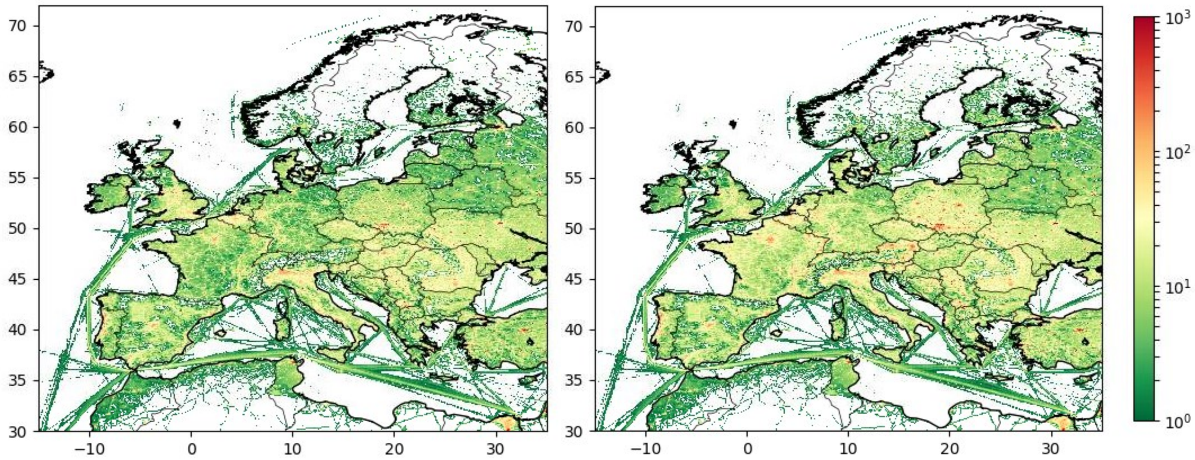
The scaling factors are also applied to scenario 7 in order to obtain scenario 9: the absolute effect of RWB deployment is also multiplied by the scaling factors.

Map 2 shows the emission maps of $PM_{2.5}$ for the year 2016 based on official reporting (scenario 1) and on expert estimates (scenario 8).

Table 3: National emissions of fine particulate matter ($PM_{2.5}$) in the "Other stationary combustion" (in kilotons) in the CAMS-REG-AP inventory for the years 2015 and 2016, according to official data and expert estimates. Expert estimates for 2016 correct official data by using the scaling factors indicated in the table.

	2015 (version 2_2_1)		2016 (version 3_1)		Scaling Factor
	Official data	Expert estimates	Official data	Expert estimates	
Austria	6.4	56.8	8.1	72.4	8.93
Belgium	16.3	16.0	14.7	14.5	0.99
Bulgaria	23.1	25.6	26.0	28.8	1.11
Croatia	15.7	14.7	13.4	12.6	0.94
Cyprus	0.1	0.3	0.1	0.4	3.50
Czech Republic	12.8	35.0	29.0	34.2	1.18
Denmark	13.9	20.6	14.7	21.7	1.47
Estonia	2.6	11.4	2.8	12.3	4.41
Finland	10.0	22.3	11.1	24.7	2.22
France	74.8	218.1	74.7	218.0	2.92
Germany	20.3	71.1	21.7	76.1	3.50
Greece	11.2	19.6	11.2	19.6	1.76
Hungary	46.2	28.0	45.4	27.6	0.61
Ireland	7.5	4.5	7.0	4.2	0.60
Italy	110.5	114.6	107.1	111.1	1.04
Latvia	11.5	22.4	9.4	18.4	1.95
Lithuania	13.8	18.5	3.2	20.5	5.86
Luxembourg	0.6	0.8	0.6	0.8	1.25
Malta	0.0	0.0	0.0	0.0	1.39
Netherlands	2.0	13.2	2.1	13.3	6.45
Poland	66.0	185.3	70.2	197.0	2.81
Portugal	16.1	24.4	16.2	24.4	1.51
Romania	93.6	101.4	90.2	97.6	1.08
Slovakia	25.7	23.5	23.4	21.4	0.91
Slovenia	8.7	14.9	9.0	15.4	1.71
Spain	53.7	68.7	53.7	68.8	1.28
Sweden	5.8	30.8	6.0	31.6	5.30
United Kingdom	45.3	24.3	44.6	24.0	0.54

Map 2: Emission maps of $PM_{2.5}$ for scenario 1 (left) based on official data and for scenario 8 (right) based on expert estimates



2.2 Description of CHIMERE

The air quality model **CHIMERE** (Couvidat et al., 2018) is co-developed by the CNRS (the French National Council for Scientific Research) and INERIS (French National Institute for Industrial Environment and Risks). It is a computer program that gathers a set of equations representing the transport and transformation of chemical species to simulate the temporal evolution of air pollutants over a range of spatial scales, from the regional scale (several thousand kilometers) to the urban scale (spatial resolution of a few kilometers).

Using meteorological and emission data, CHIMERE models tridimensional concentrations for various pollutants (such as O_3, NO_2 or PM) with hourly outputs. The model integrates a chemical mechanism containing more than one hundred chemical reactions. It simulates the formation and evolution of airborne particles with diameters ranging from a few nanometers to 10 µm. Particles in CHIMERE consist of primary PM (anthropic or natural) emitted directly into the air and of secondary PM that are formed by chemical reactions in the atmosphere (nitrate, ammonium, sulfate and secondary organic aerosols).

Primary organic aerosols may represent a large fraction of primary PM, especially for particles emitted from biomass burning. In CHIMERE, these compounds **can be considered either as non-volatile** (all compounds remain in the particle phase) **or as semi-volatile** (they partition between the gas phase and the particle phase according to ambient conditions). The primary semi-volatile compounds present in the gas phase may be further oxidized and form less volatile compounds following the mechanism described by Couvidat et al. (2018).

2.3 CHIMERE configuration

In this study, due to the disparity of methods used by countries that may or may not account for SVOC in RWB emissions when compiling their official emission inventories (see section 2.1), **we assumed that primary organic compounds are non-volatile for scenarios 1 to 7**. This assumption may lead to an overestimation of PM concentrations for countries that account for SVOC in their emissions (as some primary compounds may volatilize from the particle, assuming non-volatility may lead to an excess of SVOC present inside the particle) and to an underestimation for the other countries (as condensables are not taken into account). **For the additional scenarios 8 and 9** (that take into account these compounds in their emissions), **primary organic compounds are assumed to be semi-volatile** in order to produce a more realistic estimate of the impact of RWB emissions.

CHIMERE was run over Europe at a resolution of 0.4°x0.25° by using the Integrated Forecasting System (IFS) meteorological data from the European Centre for Medium-range Weather Forecasts (ECMWF). Boundary conditions of gases and particles were derived from monthly mean climatology based on MACC[7] forecast simulation results.

2.4 Health impact assessment

The quantification of impacts on human health relies on the health impact assessment (HIA) tool Alpha-RiskPoll (ARP; developed by EMRC, and described in Schucht et al., (2015)). This HIA tool is regularly used in European policy analyses, such as the Clean Air For Europe (CAFE) programme or the European Commission's Clean Air Outlook[8] (e.g. IIASA, 2017). ARP uses the methods for benefit assessment that were first developed under the EC funded ExternE project (External cost of Energy[9]) during the 1990s. These methods are extensively documented in several studies (Holland et al., 2005a; Holland et al., 2005b; Holland et al., 2005c; Holland et al., 2011 and Hurley et al., 2005). They have been applied since the end of the 1990s to cost-benefit assessments of EC and UNECE[10] policies and were thoroughly reviewed (Krupnick et al., 2005; WHO, 2013a, b). The current version of the model implements the methods recommended by the World Health Organisation (WHO)/Europe review « Health Risks of Air Pollution in Europe » (HRAPIE) (WHO, 2013b, a), which is described in Holland (2014a, b). Recommendations made in HRAPIE and applied in ARP concern the Concentration-Response Functions, linking levels of pollutant exposure to a set of specific health endpoints (mortality and different morbidity impacts). The same concentration-response functions are used by the EEA (cf. EEA, 2019b; ETC/ATNI, 2019).

In the present study, the use of ARP is **restricted to quantifying one health endpoint, mortality from chronic (long-term) exposure to $PM_{2.5}$**, expressed in two metrics calculated on an annual basis: premature deaths and years of life lost (YOLL).

The health endpoint mortality due to chronic exposure to $PM_{2.5}$ is calculated for the age-group above 30 years based on the recommended Relative Risk of 1.062 for a 10 µg/m^3 increase of $PM_{2.5}$ (95% confidence interval is 1.040-1.083). Mortality effects are calculated for all-cause (natural) mortality, as linear functions and in response to a one-year pulse change without lag, without any threshold for $PM_{2.5}$ concentrations. Following WHO advice, all particulate matter emissions are treated as equally harmful, irrespective of source and chemical composition, since a precise quantification of the health effects of individual PM components is not possible according to current knowledge (Miller et al., 2011; WHO, 2007, 2013a, c; COMEAP, 2015).

Population data (total and age class specific population data) used in ARP relies on the United Nations' World Population Prospects, 2017 Revision[11]. Information on mortality (all-age natural deaths, and 30+ years natural deaths) were extracted (and calculated) from the WHO Mortality Database[12] (International Statistical Classification of Diseases and Related Health Problems, ICD-9 and ICD-10

[7] MACC = Monitoring Atmospheric Composition and Climate, was an EU research project (FP7) and 'precursor' of the operational CAMS.
[8] https://ec.europa.eu/environment/air/clean_air/outlook.htm
[9] http://www.externe.info/externe_d7/.
[10] United Nations Economic Commission for Europe.
[11] https://esa.un.org/unpd/wpp/Download/Standard/Population/
[12] http://www.who.int/healthinfo/mortality_data/en/

classification, March and October 2017 updates, respectively). For a given country, the age distribution is assumed to be the same over all the country.

Whereas we calculate premature mortality in an identical way compared to other EEA publications (e.g. EEA, 2017; EEA, 2019b; ETC/ATNI 2019), the CHIMERE model uses a simplified approach for the estimation of YOLL. ETC/ATNI (2019) calculates YOLL from premature deaths. Premature deaths are calculated for 5-year age groups, the number of years of life lost due to premature mortality is then calculated by summing over all age classes the product of the number of deaths in age class *i* attributable to air pollution and the life expectancy at age of death in age class *i*. In the current study, premature deaths are calculated for the whole population over 30 years, and an estimated relative risk for YOLL, calculated based on numerous life table runs for Europe by the UK Institute of Occupational Medicine (IOM), is used to calculate YOLL for the total population.

In earlier work by the European Topic Centre (ETC/ACM, 2017), results of this methodology were compared with those presented in EEA (2017). While estimates of premature deaths based on ARP and those presented in EEA (2017) were almost identical for the EU-27+UK countries (difference of about 1.1 % for the year 2014), the YOLL results showed a slightly higher difference (5.7 % higher in ARP compared to EEA for the year 2014). The outcome of that work is that the YOLL results from the two methodologies are sufficiently close and do not require an adaptation of approach. Moreover, the present analysis focuses more on **relative changes of results over time** and between different exposure data sets (or scenarios; all calculated with an identical methodological approach), than on absolute numbers for a specific year.

As a further difference compared to ETC/ATNI (2019), we calculate mortality impacts using only the central value of the confidence interval for the recommended Concentration Response Function . For the present work we do not estimate the uncertainties of the calculations with help of the minimum and maximum values of the confidence interval. Also, we account for total $PM_{2.5}$, whereas other EEA work uses an alternative baseline concentrations of 2.5 $\mu g/m^3$ for $PM_{2.5}$.

Note further that ARP population and mortality data are set up in 5 year steps. In the present study we, therefore, use population data for 2015, while pollution exposure is calculated for 2016. The impact of this on changes in mortality impacts between the different scenarios is expected to be negligible.

3 RES emission mapping and its uncertainties

3.1 Assessment of the reference emissions to estimate avoided concentrations from RES development With a focus on the “Other Stationary Combustion” sector

3.1.1 Background

In this chapter, we describe the emissions used as reference for the assessment of avoided emissions and concentrations associated with the growth of RES since 2005. In addition, we assess the emissions with a special focus on their spatial distribution, as this distribution will determine to a large extent the final outcomes of the chemical transport model (CHIMERE) and, hence, the calculated population exposure to pollutant concentrations.

Due to short atmospheric residence time for most compounds, air pollution levels are to a large extent determined by the local sources. However, for most emissions, accurate spatial distribution relies on the availability of suitable ancillary data that allows the proper representation of the emission processes. Data to distribute emissions over the grid are frequently available at national or sub-national level but are often inconsistent between countries and stored locally. Consistent data at European level is scarce, which limits the possibilities of developing consistent methods across the model domain.

In regional inventories, emissions are often spatially distributed by using spatial proxies. For the national gridded data of emissions (using the Gridded Nomenclature For Reporting GNFR) from sector C (Other Stationary Combustion), which is dominated by residential heating, a widely used proxy is population density. This proxy has been intensively discussed in the literature, as emissions may be overallocated on populated areas. Subsequently, it would increase the uncertainties over population exposure estimates. Moreover, years of policy interventions and local air quality plans, heating infrastructure, cultural and climatic differences make the relationship between population distribution and residential heating different between cities and countries. Across different emission modelling teams, a variety of spatial proxies are used along with population density to describe these differences in emissions from the residential sector.

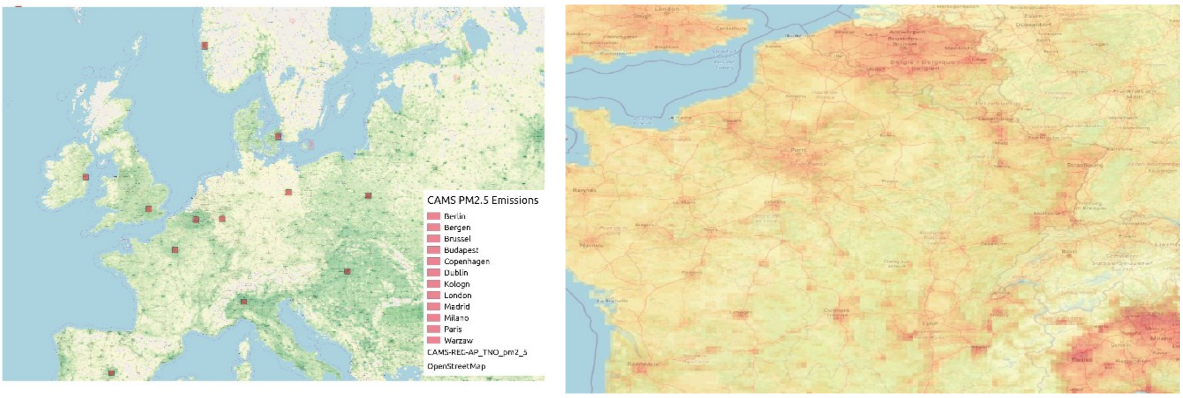
The spatial pattern of emissions is an important aspect since how emission reductions influence population exposure will ultimately be determined by where the reductions take place. The spatial distribution of aggregated emission data by proxies are stand-ins for underlying differences in spatial emission patterns; thus, a comparison between the commonly used regional emission inventories, i.e., CAMS, EMEP (European Monitoring and Evaluation Programme) and ECLIPSE (Evaluating the Climate and Air Quality Impacts of Short-Lived Pollutants), will reveal how national proxies differ and how they influence calculated emission patterns, concentration of air pollutants and exposure to air pollution. In addition, the comparison will shed light on the potential implication of choosing to use CAMS emissions as reference for the assessment of avoided concentrations related to RES growth.

3.1.2 Emission description - CAMS-REG-AP

The emission inventory used for Europe is the CAMS-REG-AP version 4.2 for the year 2016 (Granier et al., 2019). CAMS-REG-AP emissions are based on emissions reported by European countries to the CLRTAP and are developed following the sector aggregation basis of TNO_MACC-II and TNO_MACC-III emission inventories (Kuenen et al., 2014). From the point of view of the spatial distribution, CAMS-REG-AP is based on a consistent methodology across the whole of the European continent, in contrary to the gridded emissions submitted to the CLRTAP (i.e., the EMEP inventory) where each reporting country applies its own gridding methodology and proxies. So, at a national scale, the reported amount of emissions are identical in these two inventories whereas their precise location within each country may differ.

Emissions from residential combustion in CAM-REG-AP (subsector 1A4bi) are included in the NFR sector “C Other Stationary Combustion” (Figure 1). In addition, the sector “C Other Stationary Combustion” includes emissions from stationary combustion in Commercial/institutional (subsector 1A4ai), in Agriculture/Forestry/Fishing (1A4ci) and in Other (including military). Residential combustion in Europe relies on different fuels, such as coal, liquid fuels, gas and solid biomass. In CAM-REG-AP, the spatial distribution of emissions from residential combustion based on light or medium fuels is done using total population, whereas emissions from coal and heavy liquid fuel-based combustion are distributed based solely on rural population (Kuenen et al., 2014). In the case of solid biomass, the spatial distribution is based on a dedicated wood use map (Kuenen et al., 2014) based on the principle that wood combustion appliances are not uniformly distributed, neither their use. The wood use map is developed based on population density, a wood demand function and a wood supply function based on local wood production rates. This spatial distribution considers both population density and proximity to wood. This approach constitutes an improvement compared to the use of population density as unique proxy; however, it still involves an overallocation of emissions from residential wood combustion to cities (Kuenen et al., 2014; Timmermans et al., 2013).

Figure 1: CAMS-REG-AP $PM_{2.5}$ emissions from “C Other Stationary Combustion” sector in Europe (left) and in a zoom on France (right).



3.1.3 Assessment of different spatial distribution approaches

We have compared the spatial distribution of $PM_{2.5}$ emissions from “C Other Stationary Combustion” in CAMS-REG-AP[13] with EMEP[14] and ECLIPSE-GAINS[15] inventories. With this exercise, we aim at contributing to the understanding of how the proxies behind the spatial distribution influence emissions, and the relationship with population density, one of the most used proxies. We then assessed the potential implications of the modelling results to evaluate the avoided concentration levels associated with the development of RES (i.e. the comparison of 2005 and 2016 results).

EMEP emission inventory

The EMEP emission inventory represents the reported spatial emission data submitted by parties to the Convention on Long-range Transboundary Air Pollution (CLRTAP), and it is used as input for modelling atmospheric concentration and deposition fields. Since 2017, gridded emissions have to be officially reported with the resolution of 0.1x0.1 longitude - latitude for the 14 GNFR (Nomenclature

[13] The Copernicus Atmosphere Monitoring Service regional emissions.
[14] European Monitoring and Evaluation Programme.
[15] Air pollution Interactions and Synergies (GAINS) model.

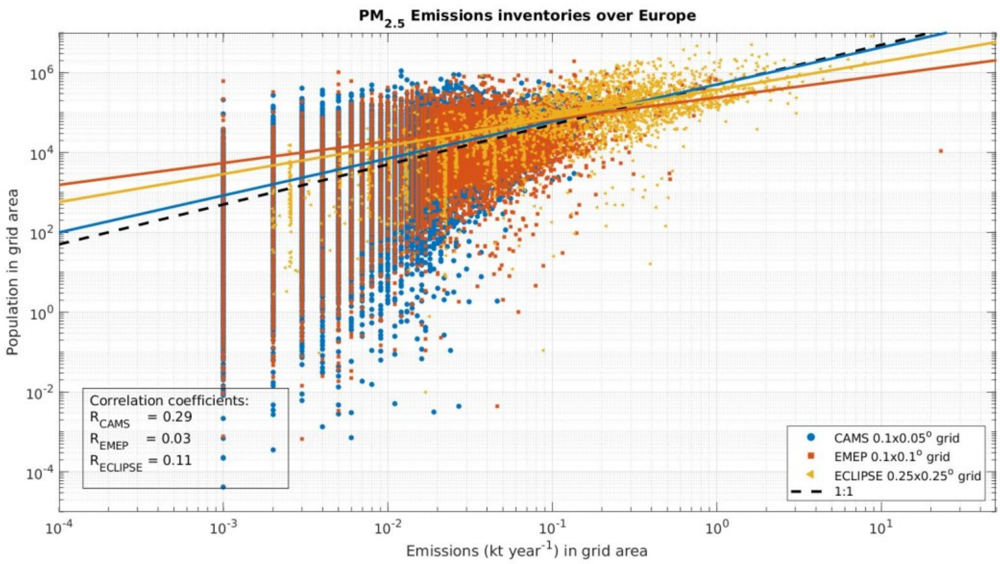
for reporting gridded emissions) sectors every four years. Countries are free to report emissions more frequently. The EMEP emission inventory contains reported gridded sectorial emissions and large point source data. In the case sectors are missing from the reporting, sectoral proxy data from CAMS-REG-AP (Granier et al., 2019), JRC/EDGAR and large point source data from The European Pollutant Release and Transfer Register (E-PRTR, 2020) are used. The parties to the CLRTAP developed their own methodologies to grid national emissions following the recommendations in the EMEP/EEA Guidebook (2019). The description of each gridding method should be included in the countries' Informative Inventory Report (IIR) submitted to the CLRTAP. However, in many cases the IIRs lack detailed description of the proxies used for each sector/subsector.

A few examples of methods reported by countries: **Sweden** (Swedish Environmental Protection Agency, 2018), gridded emissions reported in 2017 (for year 2015) for the residential sector were calculated based on activity data at municipality level (i.e., number of boilers/stoves) and energy demand estimated at county level. Within each municipality, the emissions were distributed over the total small house areas [m^2] per grid cell, also taking into account the availability of other heating technologies, e.g., district heating, in every grid cell. In **Germany** (German Informative Inventory Report, 2020), emissions from the residential heating sector are gridded based on the distribution of the emissions among the energy carriers (i.e., oil, gases, wood and other solid fuels), then the emissions per energy source are distributed within the district, or municipalities in the case of wood fuel, based on the land use classes 'continuous urban fabric', 'discontinuous urban fabric' and 'industrial and commercial units'. In **Norway**, the Informative Inventory Report does not provide detailed information on the method used to grid emissions submitted to the CLRTAP. A visualization of the emissions from residential combustion seems to indicate that emissions are distributed uniformly over all 19 county administrative levels, the resolution at which wood consumption data is available, and it is not constrained to residential neither urban/rural areas.

ECLIPSE-GAINS emission inventory

The ECLIPSE-GAINS emission inventory (version 5a) is a global emission data set at 0.5x0.5 degree spatial resolution developed with the GAINS model (Klimont at al 2017). The emission inventory includes sectorial emissions from energy, industry, solvent use, transport, domestic combustion, agriculture, open burning of agricultural waste and waste treatment. The ECLIPSE-GAINS emission inventory is built up following a consistent methodology based on essential information about key sources of emissions, environmental policies and mitigation opportunities. The model relies on national and international statistics on activity data for energy use, industrial production and agricultural activities, the International Energy Agency being, however, the primary source for activity data. The calculated emissions are then distributed using spatial proxies, which in the case of emissions from domestic combustion are built on the use of total, urban and rural population (Lamarque et al., 2010).

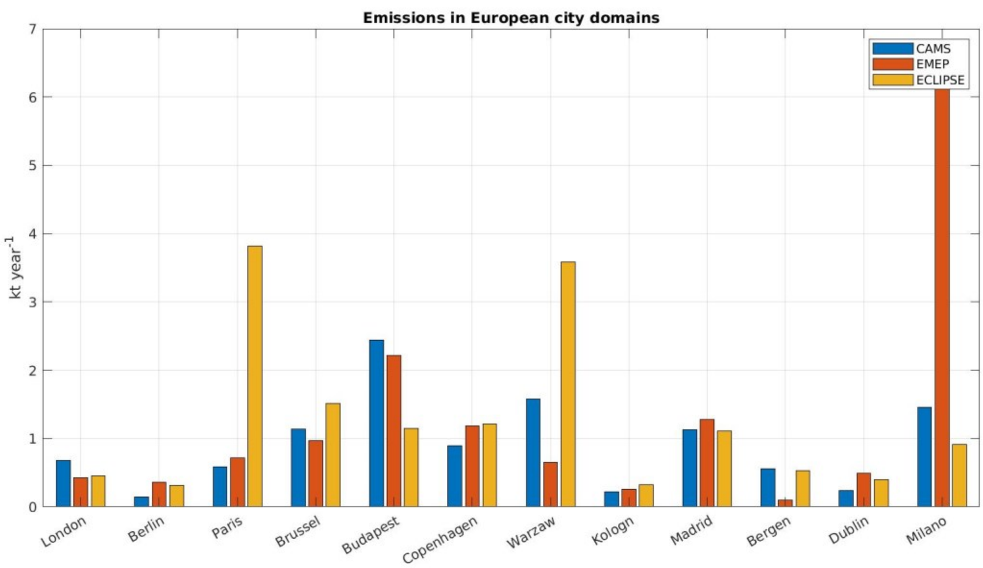
Figure 2: Population at the grid versus $PM_{2.5}$ emissions from C_OtherStationaryComb at the same grid based on CAMS, EMEP and ECLIPSE. Dashed line indicates 1:1 relationship.



Improving information on emissions from fuel burning in residential homes

Based on existing external documentation it is not easy to fully grasp in detail the spatial distribution of any of the emission models (please see Box 1). All documentations clearly indicate the use of different spatial proxies, which clearly have large impact on emissions attributed to any given city-area (Fig. 3.3). Proxy data such as population or fuel availability can have unintended consequences when applied over a variety of regions.

Figure 3: CAMS (2016), EMEP (2016) and ECLIPSE (2015) $PM_{2.5}$ emissions from the residential combustion sector in domains that include an urban area.



Source: Author's compilation based on data from ECCAD: Emissions of atmospheric Compounds and Compilation of Ancillary Data; https://eccad.aeris-data.fr.

Recent work from Denmark (Plejdrup et al., 2016), Norway (Grythe et al. 2019) and Sweden (Andersson et al., 2015) indicates that suitable data exists at the house scale level (e.g., Lopez-Aparicio et al., 2018) regarding the distribution of residential heating emissions. Fire departments, chimney sweepers and city planning authorities have data on the location and nature of combustion heating appliances. The heating fuel dependency can again be associated to building types and age. To our knowledge, there is no geospatial database available at European scale on, for instance, number and types of building distributed at high spatial resolution. This type of databases is commonly available at the country level based on the information from the country property registry. This information would be highly relevant for the improvement of European regional emission inventories and, especially, for the residential heating sector.

Highly resolved heating technology data have proven to be superior to other proxies (Grythe et al., 2019; Plejdrup et al., 2016) and have the added advantage that they are more uniformly applicable across countries. When applied, these data strongly indicate that when the relation between $PM_{2.5}$ emission and population is below 1:1, the distribution of emissions is a function of the distribution of heating appliances rather than of behavioural aspects. Input data and spatial distribution methods such as these could be established in other countries based on collection of European open databases containing this information. Kuenen et al., (2014) highlighted that the use of wood maps, basis of CAMS emissions and the reference emissions for the assessment of RES development, will improve the spatial distribution compared to a distribution based only on population data.

Box 1: Uncertainties when using population data

A simple exercise has been performed to evaluate the effective weight of population on gridded emissions by CAMS, ECLIPSE and EMEP (Figure 2). Population is a key parameter to spatially distribute emissions, as in ECLIPSE, or used in combination with others such as wood proximity in CAMS. The slope of the linear fit shows how strongly the average increase in emissions is with increasing population. ECLIPSE and CAMS emissions strongly increase with population density in comparison to EMEP that is based on country specific methods (Figure 2). EMEP emissions also increase markedly with population density but with a very low correlation. At European scale, the low correlation of especially EMEP indicates that the country specific distribution method influence emissions aside from population.

As a good evaluation emissions over cities is critical to assess the exposure of population to air pollutant concentrations, a selection of city areas was done to examine the differences between the emission inventories at local level (Domains in Figure 1, left) in order to evaluate the uncertainties of residential emissions over urban areas. Each city domain has the same size, about $40x40km^2$, covering the city centre and most suburban areas. $PM_{2.5}$ emissions from “C Other Stationary Combustion” within the city domains based on CAMS , EMEP and ECLIPSE are shown in Figure 3. There are large differences between the three sets of $PM_{2.5}$ emissions within most of the domains and total emissions vary by up to a factor 3-4. Whereas each emission inventory is based on different spatial distribution proxies, there is no systematic difference between the emissions across the domains. For instance, ECLIPSE $PM_{2.5}$ emissions from the residential combustion sector are higher in Paris, Brussel, Copenhagen, Warsaw and Dublin than $PM_{2.5}$ emissions from CAMS, whereas the opposite sign or similar levels are observed in Bergen, Berlin, Budapest, London, Madrid and Milano. In addition, it seems like the resolution of the inventory does not seem to be a large factor in determining the emission fluxes in the different city domains, as the sum total emissions of each model is roughly the same for all the model.

3.2 Mapping emission scenarios using the CAMS-REG-AP inventory

To simulate the impact of RES development on air quality, a necessary first step is to distribute spatially the changes in emissions. Therefore, avoided emissions for each RES source are allocated to a single nomenclature for reporting (NFR) sector and are spatially distributed according to the spatial distribution of this sector in the CAMS-REG-AP inventory. The "Other stationary combustion" sector (NFR C) is used to distribute spatially emissions from heating sources while the "Energy" sector (NFR A) is used to distribute emissions from electricity sources. However, for a few countries, the avoided emissions of NMVOC due to RES development could exceed the emissions of the sector onto which they are allocated (because of low emissions of NMVOC of the NFR sector in the CAMS-REG-AP inventory), resulting in "negative" emissions. To prevent this issue, the «excess avoided emissions» are allocated to NFR sector B "Industry".

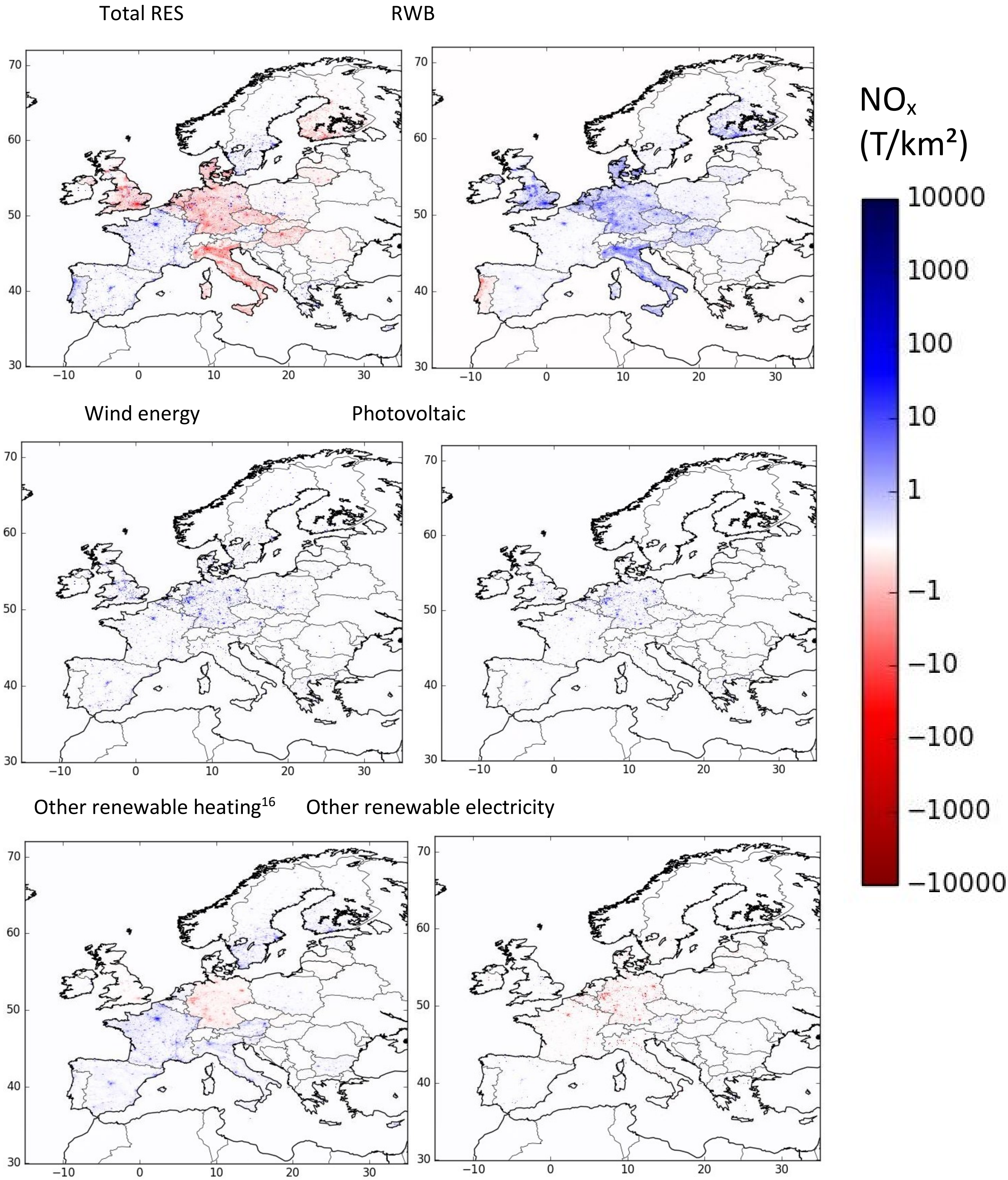
Maps 3 to 6 show the maps of avoided SO_x, NO_x, $PM_{2.5}$ (maps of avoided emissions for PM_{10} are very close to those for $PM_{2.5}$ emissions and are therefore not shown). The NMVOC emissions for the different scenarios studied at the native resolution of the inventory (resolution at which the CAMS-REG-AP data are provided: 0.1°x0.05°). It should be noted that for all pollutants, the changes in emissions due to RES development are dominated by the increase in RWB. An increase of PM and NMVOC emissions is found over most countries, except for Portugal, Croatia and Greece (countries that decreased their residential consumption of biomass while it increased for the other countries). For the other scenarios, low changes in emissions are shown for NO_x and SO_x, while the changes for PM and NMVOC are almost negligible.

The mapping strategy used in this study may affect the results of the simulation. First, because of a lack of certain details. It was for example not possible to distribute the changes in emissions as a function of the technology (some technologies like wind and solar energy production are probably localized in specific areas of countries), or as a function of wood usage. Moreover, the spatialization relies entirely on the spatialization of the NFR sectors C (Other stationary combustion) and A (Energy). Section 3.1 shows that the spatialization of NFR C is quite uncertain with methodologies that may be very different between countries. The spatialization may rely too much on population density for some countries. Even by using wood maps, too much emissions are probably allocated to highly populated areas.

The emissions at the resolution of 0.1°x0.05° are spatially aggregated at 0.4°x0.25° to launch the CHIMERE model. This resolution is too coarse to distinguish cities from suburbs. This lack of resolution will therefore affect the exposure calculation. However, Figure 3 shows that even at a resolution of 40x40km, the spatialization is very uncertain with significant differences for all the cities between several different inventories (CAMS, EMEP and ECLIPSE inventories).

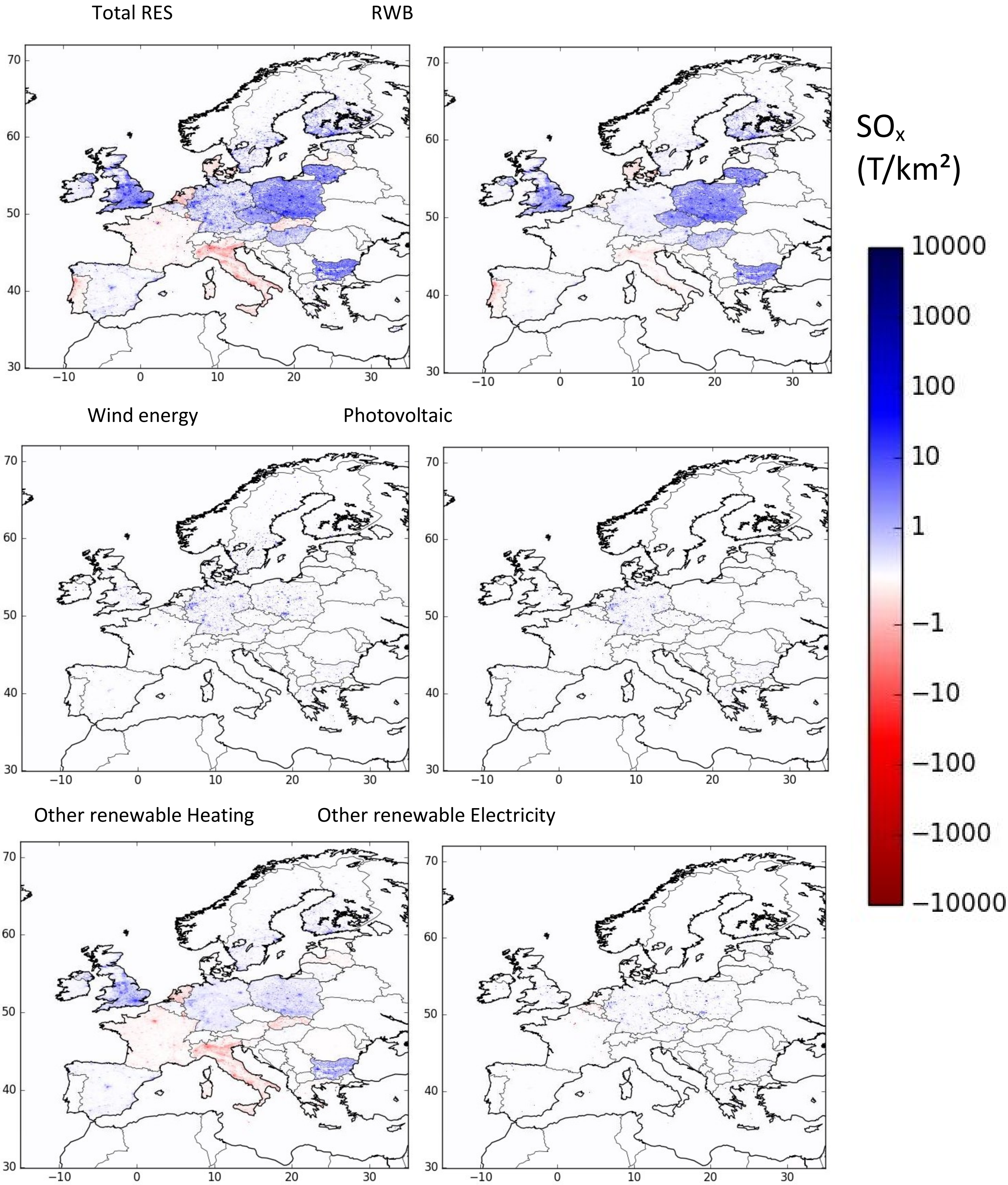
Based on this information, it can be assumed that the exposure to wood burning pollution is probably overestimated for most of the highly populated urban areas.

Map 3: Maps of avoided NO_x emissions by RES development for the different scenarios (All RES, RWB, Wind Energy, Photovoltaic, Other heating sources, Other electricity sources). In red: negative avoided emissions correspond to emission increases due to RES growth since 2005.

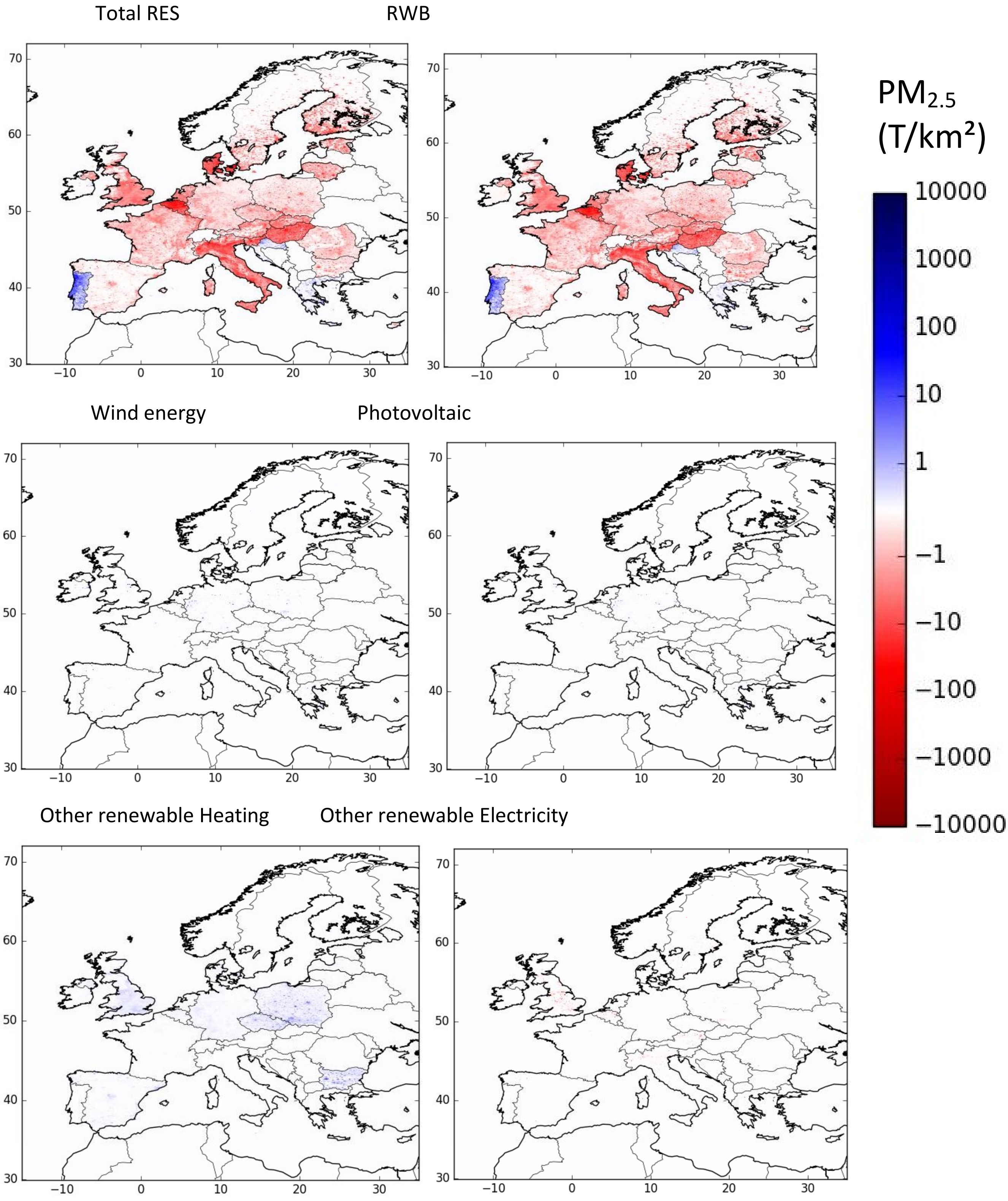


[16] Including electricity from biogas, bioliquid, concentrated solar power, geothermal, hydropower, tidal, wave and ocean energy.

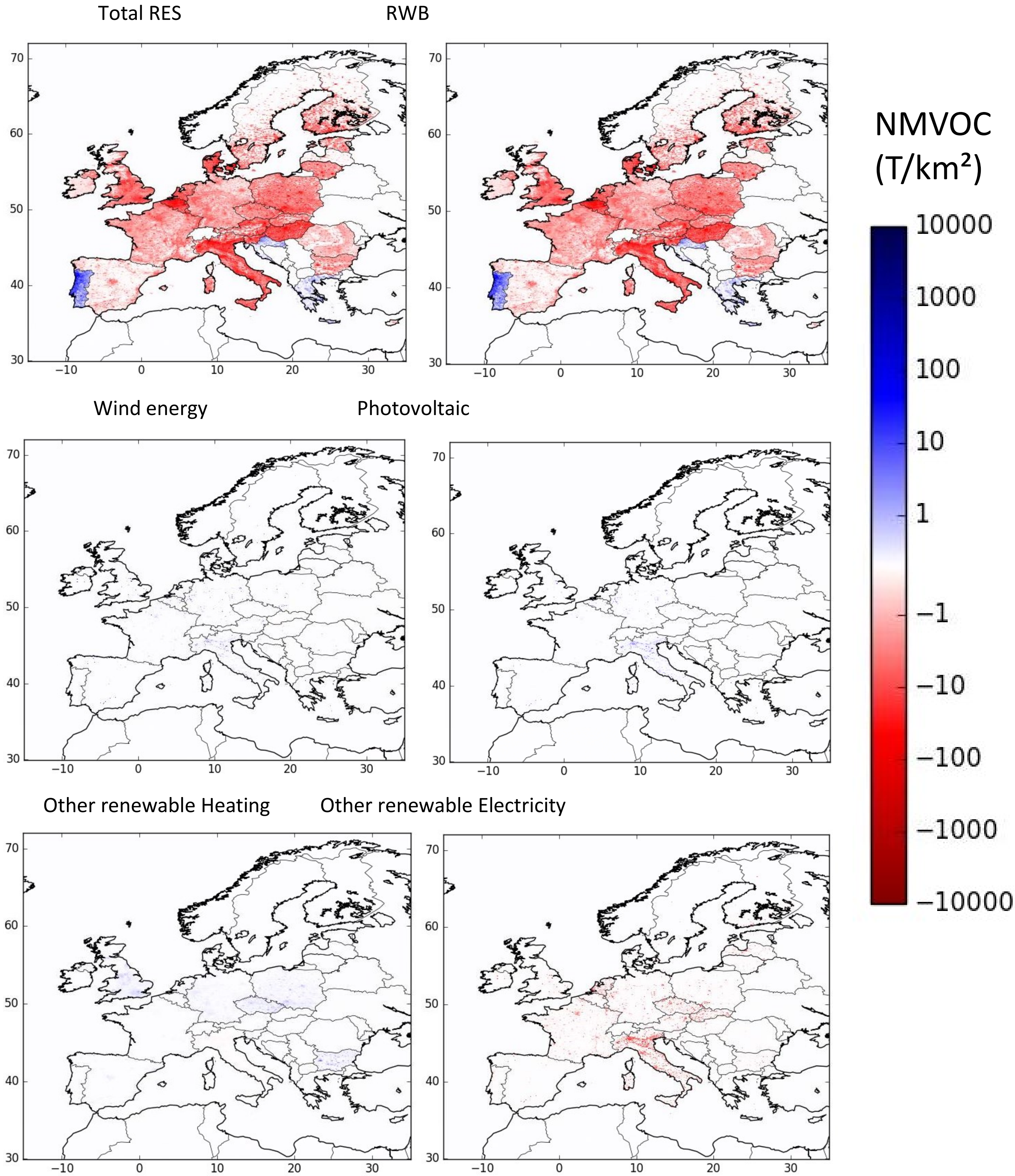
Map 4: Maps of avoided SO_x emissions by RES development for the different scenarios (All RES, RWB, Wind Energy, Photovoltaic, Other heating sources, Other electricity sources). In red: negative avoided emissions correspond to emission increases due to RES growth since 2005.



Map 5: Maps of avoided $PM_{2.5}$ emissions by RES development for the different scenarios (All RES, RWB, Wind Energy, Photovoltaic, Other heating sources, Other electricity sources). In red : negative avoided emissions correspond to emission increases due to RES growth since 2005.



Map 6: Maps of avoided NMVOC emissions by RES development for the different scenarios (All RES, RWB, Wind Energy, Photovoltaic, Other heating sources, Other electricity sources). In red: negative avoided emissions correspond to emission increases due to RES growth since 2005.



4 Impact of RES development on air quality

As illustrated by the Tables in Annex 1, the effects of higher RES use in 2016 compared to 2005 on NO_2 and ground level ozone (O_3) concentrations in the scenario runs are rather low, due to low changes in emissions of the O_3 precursors NO_x and NMVOC. RES development leads to avoided population-weighted NO_2 exposure ranging from -0.18 to 0.08 µg/m^3 for NO_2 and from -0.16 to 0.08 for O_3 (negative avoided concentrations represent increases of concentrations). For SOMO35[17], RES development leads to an increase in population-weighted SOMO35 of up to 1.15%, except for Portugal where SOMO35 decreases by 0.8%. For all the countries, the impact is obviously dominated by the development of RWB since 2005, which leads to an increase of concentrations of NO_2 and O_3 in most countries.

The development of only solar photovoltaic (PV) power, only wind power (both onshore and offshore), only renewable electricity (but excluding solar PV and wind power) and of only other heating sources (but excluding RWB) individually, leads to very low avoided concentrations (below 0,07 µg/m^3 for annual NO_2 concentrations, below ±0.06 µg/m^3 for annual O_3 concentrations and below ± 0.4% for SOMO35).. The development of these technologies leads to a minor decrease of NO_2. For SOMO35, the development of wind power leads to a stronger decrease of concentrations (modest decrease up to 0.4% for Sweden) than photovoltaic power and renewable heating (excluding RWB), while the development of other electricity (excluding solar PV and wind power) leads to a modest increase of SOMO35 (up to 0.35% in Italy). On this basis, the increase in concentrations are attributed principally to the increase of NOx emissions (cf Map 3).

Due to the high increase of primary PM emissions caused by solid biomass combustion (as illustrated in section 2), the impact of **RES development on PM concentrations is significant** with an increase of population weighted concentrations (avoided population weighted concentrations below 0) of $PM_{2.5}$ for most countries (up to 1.5 µg/m3 for Slovenia as shown in Table 4). The median of avoided concentrations due to RWB development is -0,14 µg/m3 for $PM_{2.5}$ for a few countries where RES development has led to a decrease of concentrations (Portugal: 0.5 µg/m^3, Ireland: 0.01 µg/m^3 and Greece:0.07 µg/m^3). Four countries (Belgium, Hungary, Italy and Slovenia) have avoided population weighted concentrations below -1 µg/m^3 and four more countries (Austria, Denmark, Netherlands and Slovakia) have avoided population weighted concentrations below -0.3 µg/m^3.

Map 8 shows that the effect of RES development on air quality is mostly due to the development in RWB. It shows that the increase in RES use when comparing 2005 with 2016 has led to an estimated increase in avoided population weighted annual PM concentrations of up to -1.5 µg/m^3 (i.e. an increase of concentrations due to RES development). However, with the RWB scenario based on expert estimates, an even stronger impact is found, except for a few countries where the impact was already large and that presumably already accounted for SVOC emissions when reporting their official emission inventories (Belgium, Hungary and Italy). Based on expert estimates:

- RWB development led to negative avoided population weighted concentrations (increase in concentrations) except for Portugal and Greece.
- For two countries, these increases in population weighted concentrations exceed 1 µg/m^3 (Slovenia: 1.99 µg/m^3 and Austria: 1.85 µg/m^3)

[17] SOMO35 is the Sum of Ozone Means Over 35 ppb. It is an indicator for health impact. It is defined as the yearly sum of the daily maximum of 8-hour running average over 35 ppb. For each day the maximum of the running 8-hours average for O_3 is selected and the values over 35 ppb are summed over the whole year.

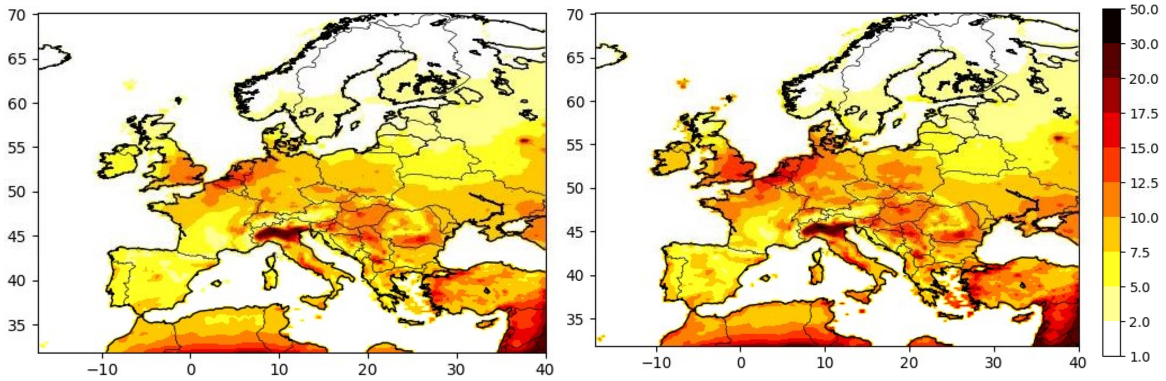
- For thirteen more countries, these increases exceed 0.3 µg/m^3 (Belgium, Czech Republic, Denmark, Estonia, Finland, France, Germany, Hungary, Italy, Luxembourg, Netherlands, Slovakia, Sweden).

In the following analysis and discussion, the focus will be on PM, which is also the air pollutant regulated in the EU's Air Quality Directive with the most harmful impacts on human health (EEA, 2020). Map 7 shows the simulated annual concentrations of $PM_{2.5}$ and PM_{10} for the reference scenario. The highest concentrations are simulated for Northern Italy, Belgium, the Netherlands, North-western Germany, Southern England and several areas in Eastern Europe. $PM_{2.5}$ concentrations similar to those of scenario 1 (differences in concentrations mostly below 0.1 µg/m^3) are simulated for scenarios 4 to 7 (solar PV power, wind power, electricity but excluding solar PV and wind power, and heating excluding RWB). For these scenarios, the population weighted avoided concentrations were between -0,05 µg/m3 to 0,04 µg/m^3. Put together, the development of these technologies could have led to modest benefits on air quality (avoided population weighted concentrations up to 0.09 µg/m^3), except for Italy for which a modest increase of concentrations is simulated (avoided population weighted concentrations of -0.05 µg/m3). For PM_{10}, very similar avoided concentrations to those for $PM_{2.5}$ can be found in Annex 1 (that most of the effects of RES development are on the $PM_{2.5}$ fraction of emissions).

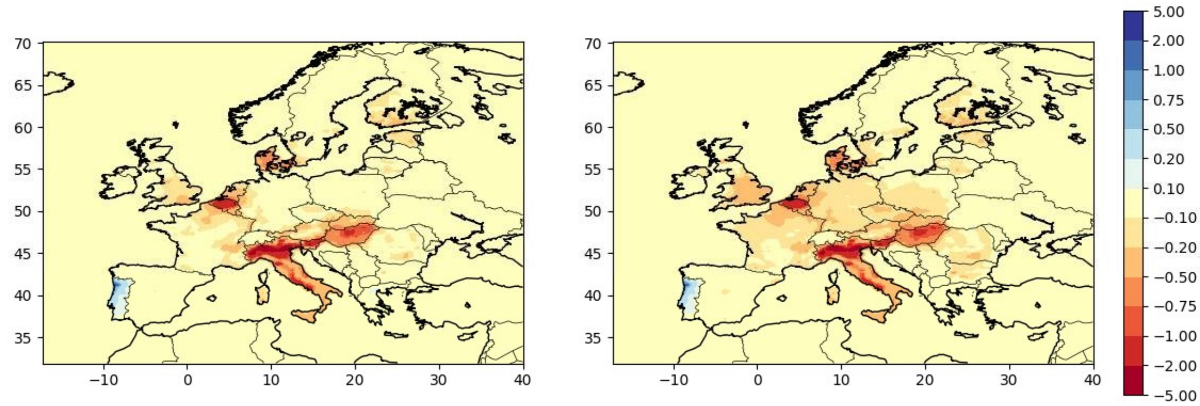
Table 4: Avoided annual $PM_{2.5}$ concentrations (population weighted) in µg/m^3 simulated with the different scenarios per European country.

Technology	all RES Official data	RWB Official data	Solar PV	Wind energy	Other renewable Electricity (least solar PV and wind power)	Other Renewable Heating (least RWB)	RWB Expert estimates
Scenarios	S1-S2	S1-S3	S1-S4	S1-S5	S1-S6	S1-S7	S8-S9
Austria	-0,34	-0,38	0,01	0,02	0,00	0,01	-1,86
Belgium	-1,35	-1,42	0,02	0,04	-0,01	0,02	-0,95
Bulgaria	-0,08	-0,22	0,01	0,01	0,00	0,12	-0,17
Croatia	-0,08	-0,11	0,01	0,02	0,00	0,01	-0,18
Cyprus	-0,03	-0,05	0,00	0,00	0,00	0,00	-0,07
Czech Republic	-0,14	-0,23	0,02	0,03	0,00	0,04	-0,44
Denmark	-0,58	-0,63	0,01	0,02	0,00	0,01	-0,57
Estonia	-0,21	-0,22	0,00	0,01	0,00	0,00	-0,53
Finland	-0,28	-0,30	0,00	0,01	0,00	0,01	-0,41
France	-0,18	-0,22	0,01	0,03	0,00	0,01	-0,35
Germany	-0,11	-0,19	0,02	0,04	0,00	0,02	-0,36
Greece	0,07	0,04	0,01	0,01	0,00	0,00	0,04
Hungary	-1,03	-1,08	0,01	0,02	0,00	0,01	-0,56
Ireland	0,01	-0,03	0,00	0,02	0,00	0,01	-0,02
Italy	-1,33	-1,28	0,01	0,01	-0,02	-0,05	-0,95
Latvia	-0,04	-0,05	0,00	0,01	0,00	0,01	-0,10
Lithuania	-0,14	-0,16	0,00	0,01	0,00	0,01	-0,15
Luxembourg	-0,26	-0,32	0,02	0,04	-0,01	0,01	-0,36
Malta	-0,02	-0,03	0,00	0,00	0,00	0,00	-0,02
Netherlands	-0,38	-0,44	0,02	0,04	-0,01	0,01	-0,75
Poland	-0,07	-0,15	0,01	0,02	0,00	0,04	-0,28
Portugal	0,50	0,48	0,00	0,01	0,00	0,00	0,42
Romania	-0,11	-0,16	0,01	0,03	0,01	0,01	-0,14
Slovakia	-0,39	-0,43	0,01	0,02	0,00	0,01	-0,37
Slovenia	-1,48	-1,50	0,01	0,02	0,00	0,00	-2,00
Spain	-0,04	-0,08	0,00	0,02	0,00	0,03	-0,07
Sweden	-0,14	-0,17	0,00	0,01	0,00	0,01	-0,40
United Kingdom	-0,17	-0,26	0,01	0,04	0,00	0,04	-0,10

Map 7: Simulated annual atmospheric concentrations (in µg/m³) of $PM_{2.5}$ (left) and PM_{10} (right) for the reference scenario (Scenario 1).



Map 8: Simulated avoided concentrations (in µg/m³) of $PM_{2.5}$ due to RES development (left, corresponds to the difference between scenarios 1 and 2) and due to RWB development (right, corresponds to the difference between scenarios 1 and 3). The red color corresponds to negative avoided concentrations (i.e. an increase of concentrations due to RES development since 2005)



5 Health impact assessment

The two following tables present the results of the different scenarios in terms of premature mortality from air pollution. The impacts of the renewable energy development scenarios are most significant concerning PM concentrations. The health effects presented here are premature deaths (Table 5) and years of life lost (Table 6) from chronic exposure to $PM_{2.5}$.

In these tables, absolute numbers of premature mortality are indicated for the two baseline scenarios (scenario 1, based on emissions from official reporting, and scenario 8, based on emissions from expert estimates), while the contribution of the individual renewable energy sources to the overall estimates is indicated for the other scenarios.

The overall number of premature deaths given by the reference simulation (Table 5), approximately 300 thousand for the two reference scenarios, appears lower than other estimates. The Air quality in Europe — 2019 report (EEA, 2019b), for example, indicates 374 thousand premature deaths during the year 2016 due to $PM_{2.5}$ exposure for the EU27+UK. These differences can be explained by the low resolution in the CHIMERE simulation (around 25 km x 25 km) that is too coarse to represent adequately the exposure in dense urban areas (a low resolution is not adequate for dense urban areas with strong local emissions, for example due to road traffic) and by the difficulty of air quality models to simulate PM concentrations due to the complexity of the phenomena involved (such as secondary organic aerosol formation, deposition, size distribution, aerosol microphysics and thermodynamics). The two estimations are however in the same order of magnitude.

Based on emissions from the official reporting, Table 5 indicates that without any further increase in RES use since 2005, approximately 9.2 thousand premature deaths – essentially related to primary PM emissions from the combustion of solid biomass in homes – could have been prevented in the EU27+UK in 2016. By maintaining RWB use at the level of 2005 between 10.7 thousand and 11.2 thousand premature deaths could have been avoided. .

On the other hand, the growth since 2005 in RES use excluding heating from solid biomass is estimated to have reduced premature deaths by approximately 1 500. Excluding "other renewable electricity sources" (all RES except wind and solar energy sources), which have contributed to an increase in premature mortality, the number would have been 1 600 avoided premature deaths. The respective numbers at EU27+UK level are 373, 783 and 445 avoided premature deaths for solar PV, wind energy and other heating (except solid biomass), and 89 additional premature deaths for other electricity. While these numbers may seem low, renewables (excluding heating from solid biomass) only represent 13% of the energetic share for heating and electricity production.

In the scenarios based on official reporting of emissions, the effects caused by RWB development are most prominent for Italy, followed by Germany, the UK, Belgium and France. The only country where the use of these renewables has reduced premature mortality is Portugal.

In the scenarios based on expert estimates of emissions, the estimated number of premature deaths is slightly higher (by 5%). Effects of RWB are again the most important driver of impacts for Italy, Germany and France. For some countries, premature deaths linked to the growth in RWB since 2005 – as calculated with the expert estimates – are significantly higher than those estimated with emissions from official reporting (probably because SVOCs are missing from the emissions in the official reporting for these countries): Austria (885 instead of 183), France (1042 instead of 661), Germany (1 892 instead of 1 012), the Netherlands (630 instead of 370), Poland (641 instead of 342) and Sweden (208 instead of 85). However, for some countries, the estimated number of premature deaths is significantly lower for the simulation results based on expert estimates: Belgium (558 instead of 831), United Kingdom (333 instead of 870), Hungary (396 instead of 777) and Italy (3 307 instead of 4 446).

Table 5: Premature deaths from chronic exposure to $PM_{2.5}$ over EU-27+UK avoided per RES scenario relative to the reference scenario

	Using emission scenarios that are based on official reporting							Using emission scenarios that are based on expert estimates	
	Premature deaths	Avoided premature deaths due to RES development						Premature deaths	Avoided premature deaths
	Reference	RES	RWB	Photolvoltaic	Wind	Other Electricity	Other Heating	Reference	RWB
Austria	4 207	-161	-183	6	10	0	7	6 002	-885
Belgium	7 904	-789	-831	12	25	-4	9	7 491	-558
Bulgaria	6 601	-52	-144	4	9	3	78	6 022	-110
Cyprus	371	-1	-2	0	0	0	0	367	-3
Czech Republic	6 405	-87	-144	11	19	1	27	6 181	-169
Germany	54 358	-565	-1 012	128	227	-22	119	55 860	-1 892
Denmark	2 301	-177	-190	3	7	0	4	2 247	-175
Estonia	346	-18	-19	0	1	0	0	370	-48
Spain	20 609	-88	-204	11	38	5	61	19 244	-166
Finland	952	-83	-88	0	2	0	3	969	-120
France	27 402	-530	-661	35	80	-13	28	28 696	-1 042
United Kingdom	35 491	-564	-870	41	130	1	145	32 343	-333
Greece	6 393	45	28	5	6	2	3	6 153	27
Croatia	3 412	-24	-34	2	5	0	2	3 095	-56
Hungary	8 916	-741	-777	7	17	3	9	7 323	-396
Ireland	1 080	2	-5	1	4	0	2	1 024	-3
Italy	53 011	-4 613	-4 446	44	44	-74	-183	46 881	-3 307
Lithuania	1 269	-34	-38	1	2	0	2	1 386	-154
Luxembourg	205	-5	-7	0	1	0	0	207	-8
Latvia	809	-6	-8	0	1	0	1	841	-24
Malta	194	0	-1	0	0	0	0	190	0
Netherlands	10 675	-316	-370	18	37	-5	4	10 740	-630
Poland	20 642	-166	-342	21	54	3	99	22 483	-641
Portugal	4 941	300	286	2	8	1	2	4 678	250
Romania	17 181	-168	-242	13	41	10	10	15 489	-207
Sweden	2 053	-71	-85	2	6	0	7	2 150	-208
Slovenia	1 451	-168	-171	1	2	0	0	1 538	-227
Slovakia	2 844	-113	-124	3	6	1	3	2 587	-103
Total	**302 024**	**-9 194**	**-10 684**	**373**	**783**	**-89**	**445**	**294 193**	**-11 187**

Table 6: Years of life lost (YOLL)from chronic exposure to $PM_{2.5}$ over EU-27+UK avoided per RES scenario relative to the reference scenario

	Using emission scenarios that are based on official reporting							Using emission scenarios that are based on expert estimates	
	YOLL	Avoided YOLL due to RES development						YOLL	Avoided YOLL
	Reference	RES	RWB	Photolvoltaic	Wind	Other Electricity	Other Heating	Reference	RWB
Austria	46 198	-1 771	-2 015	61	110	2	74	65 909	-9 716
Belgium	93 845	-9 365	-9 863	141	301	-51	111	88 950	-6 621
Bulgaria	58 861	-460	-1 284	39	81	26	698	53 699	-984
Cyprus	7 926	-23	-33	2	3	1	3	7 850	-54
Czech Republic	72 770	-984	-1 639	126	212	12	310	70 229	-1 921
Germany	512 379	-5 328	-9 539	1 207	2 140	-210	1 122	526 530	-17 835
Denmark	27 038	-2 079	-2 230	33	86	-5	43	26 397	-2 055
Estonia	3 709	-197	-208	1	6	1	3	3 967	-512
Spain	221 556	-949	-2 198	119	413	58	661	206 876	-1 783
Finland	10 870	-951	-1 005	3	17	2	35	11 063	-1 370
France	345 665	-6 682	-8 337	447	1 009	-168	355	361 989	-13 146
United Kingdom	411 673	-6 541	-10 092	476	1 511	9	1 679	375 158	-3 862
Greece	68 470	480	301	55	69	25	31	65 896	287
Croatia	33 226	-233	-328	23	47	4	20	30 136	-541
Hungary	92 761	-7 706	-8 080	77	180	27	97	76 184	-4 123
Ireland	18 698	34	-81	13	65	2	31	17 723	-49
Italy	519 708	-45 224	-43 590	433	431	-727	-1 790	459 611	-32 421
Lithuania	12 898	-344	-390	7	22	0	19	14 093	-1 566
Luxembourg	3 262	-87	-109	8	15	-3	2	3 294	-122
Latvia	8 232	-58	-83	3	12	0	10	8 561	-246
Malta	2 696	-5	-7	1	1	0	0	2 635	-7
Netherlands	128 392	-3 805	-4 446	214	447	-55	54	129 174	-7 577
Poland	247 502	-1 986	-4 102	251	651	34	1 193	269 573	-7 689
Portugal	53 035	3 216	3 069	22	87	14	25	50 204	2 686
Romania	175 002	-1 712	-2 469	137	415	105	106	157 767	-2 104
Sweden	22 678	-790	-941	18	67	-4	74	23 751	-2 295
Slovenia	16 454	-1 907	-1 939	15	22	-4	-2	17 448	-2 578
Slovakia	39 586	-1 567	-1 725	36	78	9	36	36 001	-1 434
Total	**3 255 088**	**-97 023**	**-113 365**	**3 969**	**8 499**	**-896**	**5 002**	**3 179 186**	**-119 638**

Table 6 presents the results in terms of Years of Life Lost (YOLL), an indicator that accounts additionally for the age at which premature death occurs. It indicates that with all RES (including RWB, Photovoltaic, wind and other energy sources) contributions frozen at levels reached in 2005, almost 100 thousand life years could have been saved across the EU27+UK in 2016. This result is mainly due to the development of RWB. With RWB use frozen at the levels reached in 2005 between 113 thousand and 120 thousand life years could have been saved. Almost 1000 life years are lost due to the use of “other renewable electricity sources” (i.e. renewable power excluding wind and solar PV power).

Photovoltaic, wind and “other renewable heating sources” (excluding heating from solid biomass), on the other hand, have prevented 17.5 thousand life years. At EU27+UK level, almost 4 thousand life years have been saved due to the growth in energy use from solar PV since 2005, 8.5 thousand due to the increase in wind power use and 5 thousand due to other renewable heating sources (excluding heating from solid biomass).

6 Discussion and conclusions

This study estimates the impact of renewable energy sources (RES) on air quality and human health in 2016 compared to 2005, based on avoided emissions calculations performed within an ETC/CME study (ETC/CME, 2019). Reference were two emission inventories developed within the Copernicus Atmosphere Monitoring Service (CAMS) based (1) on emissions reported by European countries to the CLRTAP and (2) official emission inventories refined by expert estimations, particularly addressing particulate matter emissions. The spatial distribution of emissions was based on a consistent CAMS methodology applied across the whole of the European continent.

The gridded emissions were input to the regional chemical dispersion model CHIMERE, which was used to calculate concentration fields for different RES scenarios, comparing the years 2005 and 2016. The CHIMERE results served as basis for calculating (avoided) impacts on human health (premature deaths, years of life lost).

The results of the presented analysis are highly dependent on the quality of the energy statistics (i.e. the activity data that is voluntarily reported by countries to Eurostat in the context of the annual SHARES exercise) and of the emission inventories. Moreover, the spatialization of the emissions based on the CAMS inventory remains uncertain. An analysis of the spatialization methods of emissions from residential wood burning shows that these methods may rely too much on population density and might lead to an overestimation of emissions over dense urban areas. However, this may be more or less compensated by the low resolution of the CHIMERE runs (approximately 25x25 km^2) that probably lead to an underestimation of PM exposure in urban areas.

Recognising uncertainties, the present analysis focuses more on relative differences in results than on absolute numbers for a specific year, i.e. the analysis compares the years 2005 and 2016 for selected scenarios or exposure data sets, all calculated with the same methodological approach for the whole of Europe.

According to the scenario analyses, the development of RES except the combustion of biomass is reflected in small reductions in $PM_{2.5}$ concentrations, which translates into 1 500 premature deaths avoided in 2016. At EU27+UK level, the results indicate that almost 4 000 life years were saved due to the growth in energy use from solar photovoltaic, 8.500 due to the increase in wind power use and 5 000 due to other renewable heating sources but combustion of biomass.

However, considering the development for all RES sources, except for Portugal, Croatia and Greece, significant increases of PM concentrations (2016 compared with 2005) were found, exceeding 1 µg/m^3 for some countries for $PM_{2.5}$. At the scale of the EU-27+UK, this increase is estimated to be responsible for around 9 200 premature deaths or 97 000 years of life lost for the year 2016, compared with 2005. The reason is that the increase in solid biomass heating alone was estimated to be responsible for an increase of around 10 700 premature deaths and 113 000 years of life lost in 2016 due to a significant increase of PM emissions, an increase that could, however, been prevented by promoting other RES technologies.

To put the increase of 10 700 premature deaths due to the development in residential wood combustion from 2005 compared with 2016 into perspective: In general, measures taken in Europe to improve air quality, such as mitigating emissions and setting up air quality plans in cities, have been successful. According to EEA (2020) around 60 000 fewer people died prematurely due to $PM_{2.5}$ pollution in 2018, compared with 2009.

7 Glossary

ARP	Alpha-RiskPoll: an health impact assessment tool (described in Schucht et al., (2015)).
CAMS	Copernicus Atmosphere Monitoring Service
CAMS-REG-AP	CAMS regional inventory of atmospheric pollutants
CEIP	Centre on Emission Inventories and Projections
CLRTAP	Convention on Long-range Transboundary Air Pollution
CNRS	French National Council for Scientific Research
ECMWF	European Centre for Medium-range Weather Forecasts
ECLIPSE	Evaluating the Climate and Air Quality Impacts of Short-Lived Pollutants
EMEP	European Monitoring and Evaluation Programme
E-PRTR	European Pollutant Release and Transfer Register
EU-27+UK	Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovenia, Slovakia, Spain, Sweden, United Kingdom
GAINS	Greenhouse gas - Air pollution Interactions and Synergies model
HIA	Health Impact Assessment
HRAPIE	Health Risks of Air Pollution in Europe
IFS	Integrated Forecasting System
INERIS	French National Institute for Industrial Environment and Risks
NFR	Nomenclature for reporting
NMVOC	Non-methanic volatile organic compounds
NEC	National Emission reduction Commitments
NO_x	Nitogen oxides
$PM_{2.5}$	Atmospheric particulate matter with an aerodynamic diameter below 2.5 µm
PM_{10}	Atmospheric particulate matter with an aerodynamic diameter below 10 µm
PV	Photovoltaic
RES	Renewable energy sources
RWB	Residential wood burning
SHARES	SHort Assessment of Renewable Energy Sources
SOMO35	Sum of Ozone Means Over 35 ppb. It is an indicator for health impact
SO_x	Oxydized sulphur
SVOC	Semi-volatile organic compounds
WHO	World Health Organisation
YOLL	Years of life lost

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Annex 1
Avoided concentrations of NO_2, Ozone and PM_{10} by country

Table 7: Avoided NO_2 annual concentrations (population averaged) in µg/m3 simulated with the different scenarios.

Technology	all RES Official data	RWB Official data	Solar PV	Wind energy	Other renewable Electricity (least solar PV and wind power)	Other Renewable Heating (least RWB)	RWB Expert estimates
Scenarios	S1-S2	S1-S3	S1-S4	S1-S5	S1-S6	S1-S7	S8-S9
Austria	0,01	-0,06	0,00	0,01	0,00	0,06	-0,05
Belgium	-0,01	-0,04	0,01	0,02	-0,01	0,01	-0,04
Bulgaria	0,01	-0,02	0,00	0,00	0,00	0,02	-0,02
Croatia	0,02	0,00	0,00	0,00	0,00	0,01	0,00
Cyprus	0,03	0,00	0,00	0,00	0,00	0,03	0,00
Czech Republic	-0,08	-0,09	0,01	0,01	0,00	0,00	-0,09
Denmark	-0,07	-0,09	0,00	0,01	0,00	0,01	-0,09
Estonia	0,00	-0,01	0,00	0,00	0,00	0,01	-0,01
Finland	-0,12	-0,16	0,00	0,00	0,00	0,04	-0,16
France	0,06	-0,02	0,00	0,01	0,00	0,07	-0,02
Germany	-0,11	-0,12	0,02	0,02	-0,01	-0,03	-0,11
Greece	0,05	0,02	0,00	0,00	0,00	0,02	0,02
Hungary	-0,13	-0,14	0,00	0,00	0,00	0,01	-0,14
Ireland	0,01	-0,01	0,00	0,01	0,00	0,01	-0,01
Italy	-0,18	-0,22	0,00	0,00	-0,01	0,04	-0,22
Latvia	-0,01	0,00	0,00	0,00	0,00	-0,01	0,00
Lithuania	-0,03	-0,03	0,00	0,00	0,00	0,00	-0,03
Luxembourg	0,00	-0,03	0,01	0,02	-0,01	0,00	-0,03
Malta	0,01	0,00	0,00	0,00	0,00	0,00	0,00
Netherlands	-0,03	-0,06	0,01	0,02	-0,01	0,01	-0,06
Poland	0,00	-0,02	0,00	0,01	0,00	0,00	-0,02
Portugal	0,08	0,06	0,00	0,01	0,00	0,01	0,06
Romania	-0,01	-0,01	0,00	0,00	0,00	0,00	-0,01
Slovakia	-0,02	-0,03	0,00	0,00	0,00	0,00	-0,03
Slovenia	-0,03	-0,09	0,00	0,00	0,00	0,05	-0,08
Spain	0,01	-0,02	0,00	0,01	0,00	0,03	-0,02
Sweden	0,03	-0,02	0,00	0,01	0,00	0,05	-0,02
United Kingdom	-0,10	-0,13	0,01	0,03	0,00	-0,01	-0,13

Table 8: Percentage of avoided SOMO35 annual concentrations (population averaged) simulated with the different scenarios.

Technology	all RES Official data	RWB Official data	Solar PV	Wind energy	Other renewable Electricity (least solar PV and wind power)	Other Renewable Heating (least RWB)	RWB Expert estimates
Scenarios	S1-S2	S1-S3	S1-S4	S1-S5	S1-S6	S1-S7	S8-S9
Austria	-0,73%	-0,85%	0,08%	0,14%	-0,11%	0,00%	-0,72%
Belgium	-1,15%	-1,08%	-0,02%	-0,01%	-0,06%	0,01%	-1,02%
Bulgaria	-0,14%	-0,34%	0,07%	0,12%	-0,04%	0,04%	-0,31%
Croatia	-0,32%	-0,50%	0,10%	0,19%	-0,14%	0,03%	-0,45%
Cyprus	0,08%	-0,09%	0,07%	0,08%	-0,01%	0,04%	-0,08%
Czech Republic	-0,41%	-0,55%	0,11%	0,17%	-0,17%	0,03%	-0,49%
Denmark	-0,23%	-0,45%	0,05%	0,22%	-0,07%	0,02%	-0,39%
Estonia	-0,24%	-0,62%	0,06%	0,33%	-0,08%	0,07%	-0,51%
Finland	-0,24%	-0,67%	0,06%	0,38%	-0,08%	0,07%	-0,54%
France	-0,44%	-0,47%	0,04%	0,10%	-0,08%	-0,03%	-0,42%
Germany	-0,36%	-0,46%	0,05%	0,10%	-0,09%	0,04%	-0,41%
Greece	-0,01%	-0,14%	0,09%	0,10%	-0,04%	-0,02%	-0,13%
Hungary	-0,65%	-0,82%	0,08%	0,16%	-0,09%	0,02%	-0,78%
Ireland	-0,17%	-0,25%	0,01%	0,11%	-0,04%	-0,01%	-0,24%
Italy	-0,89%	-0,79%	0,12%	0,12%	-0,35%	0,00%	-0,75%
Latvia	-0,23%	-0,48%	0,06%	0,26%	-0,14%	0,06%	-0,40%
Lithuania	-0,30%	-0,56%	0,06%	0,26%	-0,11%	0,04%	-0,49%
Luxembourg	-0,56%	-0,65%	0,05%	0,10%	-0,10%	0,04%	-0,60%
Malta	-0,25%	-0,27%	0,07%	0,08%	-0,15%	0,01%	-0,25%
Netherlands	-0,79%	-0,70%	-0,01%	-0,01%	-0,08%	0,01%	-0,65%
Poland	-0,39%	-0,58%	0,07%	0,21%	-0,12%	0,02%	-0,53%
Portugal	0,85%	0,46%	0,05%	0,29%	0,03%	0,02%	0,44%
Romania	0,01%	-0,32%	0,09%	0,24%	-0,01%	0,02%	-0,30%
Slovakia	-0,60%	-0,74%	0,10%	0,16%	-0,16%	0,03%	-0,68%
Slovenia	-0,72%	-0,84%	0,15%	0,17%	-0,21%	0,01%	-0,74%
Spain	0,20%	-0,11%	0,06%	0,24%	0,00%	0,01%	-0,10%
Sweden	-0,13%	-0,54%	0,05%	0,40%	-0,09%	0,04%	-0,45%
United Kingdom	-0,51%	-0,25%	-0,05%	-0,16%	-0,09%	0,04%	-0,24%

Table 9: Avoided O_3 annual concentrations (population averaged) in µg/m3 simulated with the different scenarios.

Technology	all RES Official data	RWB Official data	Solar PV	Wind energy	Other renewable Electricity (least solar PV and wind power)	Other Renewable Heating (least RWB)	RWB Expert estimates
Scenarios	S1-S2	S1-S3	S1-S4	S1-S5	S1-S6	S1-S7	S8-S9
Austria	-0,16	-0,10	0,00	0,01	-0,02	-0,05	-0,09
Belgium	-0,10	-0,05	-0,01	-0,03	0,00	-0,01	-0,05
Bulgaria	-0,05	-0,05	0,01	0,01	-0,01	-0,01	-0,05
Croatia	-0,10	-0,10	0,01	0,02	-0,02	-0,01	-0,09
Cyprus	-0,01	-0,02	0,02	0,02	0,00	-0,02	-0,02
Czech Republic	-0,03	-0,01	0,00	0,00	-0,02	0,01	0,00
Denmark	0,02	0,03	0,00	0,00	0,00	0,00	0,04
Estonia	-0,03	-0,02	0,00	0,01	0,00	-0,01	-0,01
Finland	0,08	0,11	0,00	0,01	0,00	-0,03	0,12
France	-0,11	-0,04	0,00	0,00	-0,01	-0,05	-0,04
Germany	0,01	0,03	-0,01	-0,02	0,00	0,02	0,03
Greece	-0,04	-0,05	0,02	0,02	-0,01	-0,01	-0,04
Hungary	-0,05	-0,05	0,01	0,01	-0,02	0,00	-0,04
Ireland	-0,03	-0,01	0,00	0,00	0,00	-0,01	-0,01
Italy	-0,10	-0,06	0,02	0,02	-0,06	-0,02	-0,05
Latvia	-0,02	-0,03	0,00	0,01	-0,01	0,01	-0,02
Lithuania	-0,02	-0,02	0,00	0,01	-0,01	0,00	-0,02
Luxembourg	-0,08	-0,05	-0,01	-0,02	0,00	0,00	-0,04
Malta	-0,06	-0,06	0,02	0,02	-0,04	0,00	-0,06
Netherlands	-0,06	-0,02	-0,01	-0,03	0,00	0,00	-0,01
Poland	-0,08	-0,06	0,00	0,00	-0,01	0,00	-0,05
Portugal	0,05	0,01	0,01	0,04	0,00	-0,01	0,01
Romania	-0,03	-0,05	0,01	0,02	0,00	0,00	-0,04
Slovakia	-0,10	-0,09	0,00	0,01	-0,02	0,00	-0,08
Slovenia	-0,16	-0,12	0,01	0,02	-0,03	-0,04	-0,10
Spain	0,02	0,00	0,01	0,03	0,00	-0,02	0,00
Sweden	-0,05	-0,02	0,00	0,01	0,00	-0,04	-0,01
United Kingdom	0,02	0,07	-0,01	-0,03	-0,01	0,00	0,07

Table 10: Avoided PM_{10} annual concentrations (population averaged) in µg/m3 simulated with the different scenarios.

Technology	all RES Official data	RWB Official data	Solar PV	Wind energy	Other renewable Electricity (least solar PV and wind power)	Other Renewable Heating (least RWB)	RWB Expert estimates
Scenarios	S1-S2	S1-S3	S1-S4	S1-S5	S1-S6	S1-S7	S8-S9
Austria	-0,34	-0,39	0,01	0,02	0,00	0,02	-1,86
Belgium	-1,37	-1,44	0,02	0,04	-0,01	0,02	-0,97
Bulgaria	-0,07	-0,22	0,01	0,01	0,00	0,13	-0,17
Croatia	-0,08	-0,11	0,01	0,02	0,00	0,01	-0,18
Cyprus	-0,03	-0,05	0,00	0,00	0,00	0,00	-0,07
Czech Republic	-0,13	-0,23	0,02	0,03	0,00	0,05	-0,44
Denmark	-0,59	-0,64	0,01	0,03	0,00	0,01	-0,59
Estonia	-0,21	-0,22	0,00	0,01	0,00	0,00	-0,54
Finland	-0,28	-0,30	0,00	0,01	0,00	0,01	-0,41
France	-0,18	-0,22	0,01	0,03	0,00	0,01	-0,35
Germany	-0,10	-0,19	0,02	0,04	0,00	0,02	-0,36
Greece	0,07	0,04	0,01	0,01	0,00	0,00	0,04
Hungary	-1,05	-1,10	0,01	0,02	0,00	0,01	-0,58
Ireland	0,02	-0,03	0,00	0,03	0,00	0,01	-0,02
Italy	-1,35	-1,30	0,01	0,01	-0,02	-0,05	-0,97
Latvia	-0,03	-0,05	0,00	0,01	0,00	0,01	-0,09
Lithuania	-0,14	-0,16	0,00	0,01	0,00	0,01	-0,14
Luxembourg	-0,26	-0,33	0,02	0,04	-0,01	0,01	-0,36
Malta	-0,02	-0,03	0,00	0,01	0,00	0,00	-0,02
Netherlands	-0,38	-0,44	0,02	0,05	-0,01	0,00	-0,75
Poland	-0,07	-0,15	0,01	0,02	0,00	0,04	-0,28
Portugal	0,51	0,49	0,00	0,01	0,00	0,00	0,43
Romania	-0,11	-0,16	0,01	0,03	0,01	0,01	-0,14
Slovakia	-0,40	-0,44	0,01	0,02	0,00	0,01	-0,38
Slovenia	-1,50	-1,53	0,01	0,02	0,00	0,00	-2,03
Spain	-0,03	-0,08	0,00	0,02	0,00	0,03	-0,07
Sweden	-0,14	-0,16	0,00	0,01	0,00	0,01	-0,40
United Kingdom	-0,16	-0,26	0,01	0,04	0,00	0,05	-0,10

European Topic Centre on Air pollution,
transport, noise and industrial pollution
c/o NILU – Norwegian Institute for Air Research
P.O. Box 100, NO-2027 Kjeller, Norway
Tel.: +47 63 89 80 00
Email: etc.atni@nilu.no
Web : https://www.eionet.europa.eu/etcs/etc-atni

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