Forty years of improvements in European air quality: regional policy-1 industry interactions with global impacts 2

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Abstract 14

The EDGARv4.3 (Emissions Database for Global Atmospheric Research) global anthropogenic 15

emissions inventory of gaseous (SO₂, NO_x, CO, non-methane volatile organic compounds and 16

NH₃) and particulate (PM₁₀, PM_{2.5}, black and organic carbon) air pollutants for the period 1970-17

2010 is used to develop retrospective air pollution emissions scenarios to quantify the roles and 18 contributions of changes in energy consumption and efficiency, technology progress and end-of-19

20 pipe emission reduction measures and their resulting impact on health and crop yields at 21 European and global scale. The reference EDGARv4.3 emissions include observed and reported

changes in activity data, fuel consumption and air pollution abatement technologies over the past 22 4 decades, combined with Tier 1 and region-specific Tier 2 emission factors. Two further 23

retrospective scenarios assess the interplay of policy and industry. The highest emission 24 STAG TECH scenario assesses the impact of the technology and end-of-pipe reduction 25

measures in the European Union, by considering historical fuel consumption, along with a 26 stagnation of technology with constant emission factors since 1970, and assuming no further 27

28 abatement measures and improvement imposed by European emission standards. The lowest

emission STAG ENERGY scenario evaluates the impact of increased fuel consumption by 29 considering unchanged energy consumption since the year 1970, but assuming the technological 30

development, end-of-pipe reductions, fuel mix and energy efficiency of 2010. Our scenario 31

analysis focuses on the three most important and most regulated sectors (power generation, 32

manufacturing industry and road transport), which are subject to multi-pollutant European Union 33

Air Quality regulations. Stagnation of technology and air pollution reduction measures at 1970 34

35 levels would have led to 129 % (or factor 2.3) higher SO₂, 71 % higher NOx and 69 % higher

36 PM_{2.5} emissions in Europe (EU27), demonstrating the large role that technology has played in

reducing emissions in 2010. However, stagnation of energy consumption at 1970 levels, but with 37 2010 fuel mix and energy efficiency, and assuming current (year 2010) technology and emission 38

control standards, would have lowered todays NO_x emissions by ca 38 %, SO_2 by 50 % and PM_{2.5} by 12 % in Europe. A reduced-form chemical transport model is applied to calculate regional and global levels of aerosol and ozone concentrations and to assess the associated impact of air quality improvements on human health and crop yield loss, showing substantial impacts of EU technologies and standards inside as well as outside Europe. We assess that the interplay of policy and technological advance in Europe had substantial benefits in Europe, but also led to important improvement of particulate matter air quality in other parts of the world.

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9 1 Introduction

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In the last few decades, air quality issues have gained worldwide importance due to the fast pace 11 of industrialization in many countries (Fenger, 2009). Air pollution negatively affects human 12 health (Pope and Dockery, 2006; Anderson et al., 2012; Lelieveld et al., 2015), influences 13 climate, visibility and ecosystems (Monks et al., 2009; IPCC, 2013), and therefore has significant 14 15 impacts on human life and the environment. It is crucial to understand the impacts of 16 anthropogenic air pollutants which are released into the atmosphere by large and small-scale combustion, industrial processes, transportation, waste disposal, agriculture and forest and land-17 18 use change. Emission inventories have been developed in order to quantify total and sectorspecific emissions at the country, regional and global levels (e.g. EMEP (European Monitoring 19 and Evaluation Programme, http://www.emep.int/), EPA (Environmental Protection Agency, 20 http://www.epa.gov/ttn/chief/eiinformation.html) or HTAP (Hemispheric Transport of Air 21 Pollution, http://htap.org). For some industrialized countries, legislation has been introduced 22 since the mid-1980s for the power generation sector, and since mid-1990s for road transport. In 23 24 many developing regions, e.g. in China, only recently regulations have been implemented for these two sectors (CSC, 2013). Therefore, we focus here on European air quality legislation, 25 having a much longer history and affecting not only Europe, but several other countries 26 elsewhere in the world (e.g. vehicle emission reduction standards in Japan and other Asian 27 countries; refer to Crippa et al., 2016). Figure 1 and Table S5.1 summarize European regulations 28 for air quality and air pollutant emissions since 1970, when the first air quality directive was 29 30 introduced. In our work we make use of the EDGARv4.3 emission data (http://edgar.jrc.ec.europa.eu/index.php) to compare the recent (year 2010) situation with 31 32 retrospective scenarios (years 1970-2010) that assess the importance of changes in fuel use and 33 air pollution abatement technology in determining the trends of air pollutant emissions in Europe and around the world, and their impact on air quality, health and crops. Most literature on 34 emission scenarios focuses on projecting actual emissions into the future to assess possible 35 pathways of air quality and climate in view of new policies. So far, limited attention has been 36 given to assess the role of the policy-industry interplay in avoiding emissions. Some publications 37 have analyzed past emissions trends for the most important air pollutants, but mainly focused on 38 selected substances or specific regions (e.g., Klimont et al. (2013) for global SO₂, or Kurokawa 39

et al. (2013) for Asia). Historical global emissions data sets for the past decades or century have 1 2 been compiled by combining several emission inventories, e.g., Lamarque et al. (2010) for 1850-2000 and Granier et al. (2011) for 1980–2010. However, an analysis of the factors driving these 3 emissions trends is difficult because of the heterogeneity and regional differences of the original 4 data that might show inconsistencies over the full time period and in global coverage and cause 5 6 artificial variability. Amann et al. (2013) report the evolution of anthropogenic emissions of key air pollutants between 1990 and 2010 for several world regions using the GAINS (Greenhouse 7 Gas Air Pollution Interactions and Synergies) model. GAINS is also used to provide scenarios of 8 future emissions (up to the year 2050) including specific assumptions of air quality and climate 9 policies (e.g., Cofala et al., 2007). Few studies have been devoted to understand the drivers of 10 11 historical emissions trends. Paruolo et al. (2015) performed a statistical causality analysis of income and SO₂ and CO₂ historic emission time series using EDGARv4.2, challenging the often 12 assumed causal relationship between increasing GDP and decreasing emissions assumed in the 13 environmental Kuznetz curve. Rafaj et al. (2014) aimed to identify the driving factors (historical 14 energy balances, population and economic growth, fuel mix, etc.) of air pollutants emissions in 15 Europe from 1960 to 2010, using the RAINS (Regional Air Pollution and Simulation) and 16 17 GAINS (Greenhouse Gas and Air Pollution Interactions and Synergies) (http://gains.iiasa.ac.at/models/) modelling frameworks. They decomposed the emissions into 18 19 determinant factors (energy intensity, conversion efficiency, fuel mix and pollution control) to understand the evolution for SO₂, NO_x and CO₂ in Europe. They found that in Europe SO₂ 20 emissions declined due to the combined effect of reduced energy intensity and shift to cleaner 21 fuels, while abatement measures mainly reduced NO_x emissions. In this work, we do not seek to 22 23 analyze and decompose the emission determinant factors in view of assessing further potential of optimized reduction policies, but rather want to demonstrate the cumulative effect on emission 24 25 levels in 2010 of two major factors influencing air pollution: increasing energy use and the 26 combined technology-policy achievements to reduce emissions. To this end we develop two retrospective scenarios for 1970-2010 from a European industry-air policy perspective (Fig. 2), 27 28 and representing a range of emissions that would have been reached in 2010 under different scenario assumptions. The first and highest emission scenario, STAG TECH, assumes after 29 1970 no further improvements in technologies and abatement measures. The second 30 retrospective and lowest emission scenario (STAG ENERGY) assumes stagnation of energy 31 consumption since 1970, while the fuel mix, energy efficiency, emission factors and abatements 32 are assumed as in the reference 2010 data. The change in global energy consumption over the 33 34 last decades for the energy sector amounted to a factor 3.6, and 2.6 for the transport sector; i.e. much more than the global population increase (1.8-fold). In addition, historical fuel 35 consumption showed shifts in the energy mix. The latter is country-specific and depends, among 36 others on policy choices, as well as on accessible natural reserves, the fuel price and stability, 37 and the energy stored per unit of fuel volume. Compared to future scenarios analysis, 38 retrospective scenarios have the advantage of using the well-known activity data time series. 39 Obviously, no new policies can be proposed retrospectively, but compared to decomposition 40

2 technology choices, and energy developments in arriving at 2010 emission levels. The data-3 driven analysis focuses both on European and global historical (1970-2010) emissions for a relatively complete set of gaseous air pollutants, SO₂, NO_x, CO, non-methane volatile organic 4 compounds (NMVOCs) and NH₃ and particulate matter, i.e. PM₁₀, PM_{2.5}, black carbon (BC) and 5 organic carbon (OC). Finally, deploying the TM5-FASST (Fast Screening Scenario Tool based 6 on the global chemical Transport Model 5) source-receptor model, (Tavoni et al., 2014), we also 7 demonstrate in this work the impacts of the two scenarios on health and crops, protection of 8 which being primary objectives of environmental policies. 9

analysis (e.g. Rafaj et al. 2014), our results more explicitly show the impact of policy and

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11 2 Methodology

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In Sect. 2.1 an overview of the data and assumptions used to develop the two emission scenarios is provided, addressing the EDGAR v4.3 bottom up emissions data set for the REF (reference), STAG_TECH and STAG_ENERGY emissions. This is followed by a short description of the TM5-FASST model used here to screen the impact of the considered emission scenarios on pollutant concentrations, human health and crop yields in Sect. 2.2.

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19 2.1 EDGAR v4.3 emission data and scenarios

EDGARv4.3 (Emissions Database for Global Atmospheric Research version v4.3; 20 21 http://edgar.jrc.ec.europa.eu/index.php) is used as the reference inventory of anthropogenic emissions, providing global grid maps of sector-specific historical emission data from 1970 to 22 23 2010 for SO₂, NO_x, CO, total non-methane volatile organic components NMVOCs, NH₃, as well as particulate matter components, namely PM10, PM2.5, BC, OC. EDGARv4.3 relies on 24 international energy balances of IEA (2014) and agricultural statistics of FAO (2012) and 25 regional or national information and assumptions on technology use and emission control 26 standards. EDGARv4.3 is one of the few global emission inventories with consistent 27 methodologies to calculate emission time series covering 4 decades for air pollutants with high 28 spatial resolution of 0.1°×0.1° and consistent sector-specific breakdowns. Moreover, recent 29 comparisons show the reliability of this emission inventory based on the good agreement 30 between the EDGARv4.3 2008 and 2010 emission data and the best estimates provided by 31 32 official national data merged in the HTAP v2.2 data set (Janssens-Maenhout et al., 2015). A more detailed comparison between EDGARv4.3 and the MACCity data at the country level is 33 documented in Sect. S3 in the Supplement, showing regional differences from a few percent up 34 to 50 %, which is within the range of uncertainties for specific components. The EDGAR data 35 sets are calculated using a consistent bottom-up approach with full time series of the activity data 36 and allow straightforward implementation of scenario assumptions. We start from the calculation 37

of the reference emissions of a specific pollutant x at time t due to activity data (AD) of sector i1 2 with technologies *j* and end-of-pipe measures *k* and fuel type *f* in a country *C* as follows:

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$$EM_{REF,C,i}(t,x) = \sum_{j,k,f} [AD_{C,i,f}(t) * TECH_{C,i,j,f}(t) * EOP_{C,i,j,k,f}(t) * EF_{C,j,f,i}(t,x) * (1 - RED_{C,i,j,f,k}(x))]$$

4 (eq. 1)

with TECH representing the penetration fraction of a specific technology in a sector, EOP the 5 installed fraction of end-of-pipe measures (EOP), EF the uncontrolled emission factors and RED 6 7 the emission reduction associated with the end-of-pipe control measures. We treat all 12 sectors of Table 1 separately and for each sector we provide a global grid map per pollutant and per 8 9 month in 2010 for the three scenarios on http://edgar.jrc.ec.europa.eu/pegasos/; in addition time series (1970-2010) of the reference data are reported as annual emissions by sector for each 10 11 country on the same website. An overview of 2010 pollutant emissions is also reported in Sect. 12 S2 for the three scenarios for 24 world regions. For the STAG TECH and STAG ENERGY scenarios we focus on the main sectors that were effectively targeted by air quality measures 13 imposed by EU policies¹. Firstly, the European power industry represents large national point 14 sources, which continuously emit over a long period and have since the 1980s been equipped 15 with additional end-of-pipe control measures, which is modeled at the Tier 2 level. The industrial 16 combustion processes that are most suitable to be regulated are the power industry and non-17 power generating industry and the manufacturing industry (cement, steel and nonferrous metal 18 industry, chemicals² production, paper/food/textiles/wood and machinery production). This 19 sector was subject to a much faster change in technology and market globalization, with a strong 20 combined change in emission factors and (end-of-pipe) control measures, modeled at the Tier 1 21 level. Road transport is the third sector that has been effectively regulated in Europe since the 22 1990s, with standards for the automobile industry modeled at the Tier 2 level. Detailed 23 24 information about processes, technologies and abatement measures adopted for the three sectors 25 of interest are summarized in Sect. S4.

STAG TECH: We modeled the STAG TECH scenario by assuming for the three sectors of 26 27 interest constant 1970 emission factors to all technologies present in the emission database for 28 the EU (specified mainly regionally, but few also globally). We further assumed in the STAG TECH scenario no implementation of end-of-pipe (EOP) control measures in Europe. 29 Other regional standards regulating end-of-pipe control, e.g. US power plant standards were not 30 changed, because they fell outside the European scope of this study. Thus in STAG TECH, 31 European energy production is generated by the power plants of 1970 without additional end-of-32 pipe measures as shown in eq. 2 (in other words the emission reduction RED equals the lower 33 limit³).

¹ In 2010, the EU had 27 member states and is therefore defined as such in this study.

² Not including the petrochemical industry with oil production and refining.

³ This is the technological default of fly ash not passing through the stack.

$$1 \qquad EM_{STAG_TECH,C,i}(2010,x) = \sum_{j,k,f} [AD_{C,i,f}(2010) * TECH_{C,i,j,f}(2010) * EOP_{C,i,j,k,f}(1970) * EF_{C,j,f,i}(1970,x) * (1 - RED_{C,i,j,f,k}(x))]$$

3 (eq.2)

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In the 1970s and 1980s there was a relatively large turnover of power plants (Platts database, 5 2007, http://www.platts.com/), resulting in a high share of power plants which reached 30-40 6 years of operational time in 2010, which is weighing strongly in the STAG TECH scenario 7 results. However, in other world regions, while 1970 EF's were kept constant, the emission 8 reduction factors (RED) were changing over time. Here STAG TECH results leads to even 9 larger emissions. For the manufacturing industry, the effect of technology stagnation could only 10 be reflected by keeping the emission factors, modeled at regional or global levels, constant. For 11 12 road transport, the technology stagnation was mainly reflected by not considering the emission reductions from particle filters and catalysts of all the vehicles under EURO standards, mainly 13 present in the fleet inside Europe but also outside⁴ (under this scenario EURO standards 1 to 5 14 equal the pre-EURO standards). The EURO standard penetration is shown in Table S5.2 for 15 diesel and petrol passenger cars, light and heavy-duty vehicles and busses. The change over time 16 in technology and the implementation of the air pollutant abatement measures is assumed in 17 EDGARv4.3 to start in the year the directive came into force, but the actual timing of the 18 implementation is subject to large uncertainty as it could be pre-empted by, e.g., striving towards 19 newer technologies in the case of the manufacturing industry. It could also be delayed by, e.g., 20 the slow penetration of vehicles with new standards in the national fleet. In this work we do not 21 22 aim to analyze when exactly the emission reductions effectively took place, but instead we take stock of the achievements by 2010, by comparing the reference with STAG TECH emissions in 23 24 2010.

25 STAG ENERGY: The STAG ENERGY scenario was modeled by assuming that the three sectors of interest consumed the same amount of energy (TJ) as in 1970, but with the 2010 fuel 26 mix, energy efficiency (EFF), technologies, and end-of-pipe abatements, as shown in eq. 3. Since 27 28 the fuel market is to a large extent global, this scenario was implemented in all countries for the three selected sectors. All power plants, vehicles and industries with the reference 2010 29 emissions standards consume coal, gas and oil with the 2010 share but at 1970 energy level (in 30 TJ). In addition to the calibration per sector of the energy consumption level (in TJ), we 31 evaluated the change in energy efficiency by fuel type, sector and region. For the power 32 generation sector we we scaled for each country the "main activity producer electricity plants 33 (TJ)" with the 1970 over 2010 ratio of the "electricity output of main activity producer electricity 34

⁴ Aside of the American continent (North, Central, South), which implements mainly US Tier standards, other countries show a considerable share of EURO standards even outside Europe, in particular but not only Japan, Korea, etc.

plants (GWh)" from IEA (2014). For the road transport sector we scaled the "fuel consumption for road transport" with a factor composed of the 1970 over 2010 road transport fuel consumption ratio multiplied with the 1970 over 2010 fuel efficiency ratio. The latter was calculated with the macro-regional averaged values of petrol and diesel economies (l/100km) in 2010 and 1975 (because of missing 1970 data) for different type of vehicles (passenger cars, light duty vehicles, heavy duty vehicles, busses, mopeds and motorcycles) distinguishing the fuel consumption for petrol and diesel based on the EPA Trends report (EPA, 2013).

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$$EM_{STAG_{ENERGY,C,i}}(2010, x) = \frac{\left[\sum_{f} AD_{C,i,f}(1970)\right] / EFF_{C,i,f}(1970)}{\left[\sum_{f} AD_{C,i,f}(2010)\right] / EFF_{C,i,f}(2010)} * EM_{REF,C,i}(2010, x)$$
 (eq.3)

The comparison of the STAG ENERGY emissions scenario with the reference emissions REF in 9 2010 highlights the emission reductions that were not realized because of increased energy 10 consumption (e.g. to generate extra kWh electricity or to drive more distance per vehicle) with 11 the 2010 technology and 2010 end-of-pipe abatement. Compared to the 1970 reference 12 emissions, STAG ENERGY demonstrates the benefit of all industrial developments towards less 13 energy-intensive and less polluting technologies. It includes not only the technological progress 14 with end-of-pipe measures but also the shifts towards less carbon-intensive fuels (e.g. natural gas 15 16 instead of coal) and increase of fuel economy and energy efficiency. On the other hand, 17 compared to the REF(2010) data, STAG ENERGY assess to what extent emission increases by consumption growth. It should be noted that pre-combustion treatment (cleaning) of fuels, such 18 as coal washing or desulfurization of diesel and heavy residual fuel oil is not part of the 19 STAG ENERGY scenario but is addressed as a technology effect in the STAG TECH scenario. 20 Therefore, the fuel quality directives show their emissions savings (mainly on sulfur) in the 21 STAG TECH scenario while the fuel taxation policies (e.g. preferring diesel over petrol) are 22 present in the STAG ENERGY scenario. 23

24 In the ACPD version of this paper (Crippa et al., 2015, ACPD), another scenario called 25 STAG FUEL discussed the combined impact of stagnation of fuel-mix and fuel amount. However, in revising the manuscript we decided to focus on the consumption of energy (TJ) 26 instead of fuel because we consider the fuel mix and efficiency choices as exogenous variables 27 just as the technology progress and end-of-pipe measures. When considering a stagnation of fuel 28 with constant fuel mix and energy since 1970, due to the remaining contributions of relatively 29 dirty fuel, this scenario results in higher emissions than STAG ENERGY. This scenario is here 30 not further discussed, since the interpretation of results is not adding much to the 31 STAG ENERGY scenario. The interested reader is referred to the corresponding ACPD paper. 32

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34 2.2 Reduced-form air quality model TM5-FASST

2 The TM5-FASST model (Fast Scenario Screening Tool, version v4.2.0 2014) is a linearized source-receptor model derived at a receptor resolution of 1°×1° from the global chemical 3 transport model TM5-CTM (Tracer model 5, chemistry transport model, Krol et al., 2005) for 4 gaseous and particulate matter atmospheric pollutants. It considers 56 world regions (both as 5 source and receptor regions), with a higher detail over Europe which is represented by 16 6 regions. Detailed information on the FASST model can be found in dedicated works (Van 7 Dingenen et al., 2009, 2015), while here we summarize its basic working principle and 8 assumptions. The concentration of a substance x at time t, caused by the emission of a precursor l9 with source strength EM (emission) in source region S1, ... 56 and received in receptor region 10 11 $R1, \ldots 56$ is calculated by the addition of a base concentration (BASE) and the contribution of the linearized matrix function for each precursor (Eq. 4): 12

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$$\begin{bmatrix} CONC_{R1} \\ ... \\ CONC_{R56} \end{bmatrix} (t,x) = \begin{bmatrix} BASE_{R1} \\ ... \\ BASE_{R56} \end{bmatrix} (t,x) + \sum_{l} \begin{bmatrix} \alpha_{R1S1}(t,x,l) & ... & \alpha_{R1S56}(t,x,l) \\ ... & ... \\ \alpha_{R56S1}(t,x,l) & ... & \alpha_{R56S56}(t,x,l) \end{bmatrix} \cdot \begin{bmatrix} \Delta EM_{S1}(t,l) \\ ... \\ \Delta EM_{S56}(t,l) \end{bmatrix}$$
(eq.4)

where $\alpha_{R1S1}, ..., \alpha_{R56S56}$ are the source receptor coefficients for precursors *l* emission reduction of substance *x* and Δ EM the difference between the reference emission and the actual data. They have been derived from precursor emission perturbation model runs with TM5 using a reference emission dataset for the year 2000 and meteorology fields for the year 2001.

For each source region, the TM5-FASST model requires as input the annual emissions of 18 primary PM_{2.5}, to be specified as BC, primary organic matter (assumed to be 1.3*OC), and of the 19 precursors (SO₂, NO_x, NMVOCs and NH₃) in order to estimate the corresponding PM_{2.5} and 20 ozone concentrations in the receptor regions. Making use of source-receptor relationships, it 21 converts the emissions from any source region to pollutant concentrations at any receptor region, 22 emulating underlying meteorological and chemical processes. Only anthropogenic emissions are 23 24 input to this model and the considered chemical reactions include the formation of secondary inorganic aerosol species (ammonium nitrate and sulfate) from gaseous precursors (SO₂, NO_x 25 and NH₃), while no estimation of anthropogenic SOA (secondary organic aerosols) is performed. 26 We note that natural emissions, e.g. secondary organic aerosol from biogenic sources, lightning 27 NOx, and biogenic sources of VOCs (etc.), are included in the reference simulation following 28 the AEROCOM recommendations in Dentener et al. (2006), however without accompanying 29 30 source-receptor relationship calculations. Ozone formation is simulated through the reactions involving VOCs and NOx. FASST evaluates the impacts of O₃ and PM_{2.5} concentrations on 31 32 health and crops and vegetation. Tropospheric ozone and particulate matter negatively affect 33 human health, increasing respiratory and cardiovascular diseases, lung cancer, etc. (WHO, 2013). Through parameterizations relating pollutant concentrations and exposed population 34 (Anenberg et al., 2009; Jerrett et al., 2009; Burnett, 2014), TM5-FASST estimates the premature 35 mortality for a population older than 30 years of age, exposed to O₃ and PM_{2.5} concentrations. 36 Moreover, ozone is a toxic compound for plants, reducing crop productivity (especially for 37

wheat) and affecting plant diversity (UNEP/WMO, 2011). Following the procedure developed 1

- 2 by Van Dingenen et al. (2009), the TM5-FASST model can quantify the loss yield due to crop
- exposure to O₃ for four types of crops (wheat, maize, rice and soy) at global and regional levels. 3
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5 **3** Emission scenarios results

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7 In Fig. 3, we first compare the global reference emission levels in 1970 (REF(1970)) and 2010 8 (REF(2010)), and then the two retrospective scenarios (STAG TECH and STAG ENERGY) to 9 the REF(2010). With the scenarios we focus on the three selected sectors: power industry (labeled "power"), non-power industrial combustion of the manufacturing industry ("industry") 10 and road transport ("road"). We then evaluate the changes at the EU level in Fig. 4. Note that in 11 our evaluations we consider the year 2010 as the reference year. 12

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3.1 Global emission trends 14

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Global SO₂ emissions from power, industry and road transport sectors (Fig. 3) do not show a 16 significant trend from 1970 (at 68 Tg) to 2010 (75 Tg), because the emission reductions by pre-17 18 combustion preparation of fuel (e.g., coal sulfur wash) and the post combustion exhaust treatment of SO₂ (e.g., by flue gas desulfurization (FGD) units) were counterbalanced by the 19 increased use of fuel (in particular of coal) worldwide. In both 1970 and 2010 the power sector 20 contributed strongest to total sulfur emissions, and for the STAG TECH scenario, when no 21 technological progress for sulfur emission reduction would have taken place in the EU, global 22 power SO_2 emissions would have been 1.3 times higher than REF. However, for 23 STAG ENERGY, assuming constant energy consumption as in 1970 for the power, industry and 24 25 road transport sectors, but with current technology and end-of-pipe measures and 2010 fuel mix and efficiency, global SO₂ emissions would be only 24 % of the 2010 emissions. For the other 26 pollutants, like NO_x, CO and NMVOCs, we see a significant increase in REF from 1970 to 2010, 27 which reflects mainly the increase in energy consumption in the power, sector (e.g., NO_x) 28 29 emissions from power generation tripled globally, from 10.5 to 31.4 Tg). Depending on the pollutant, the STAG ENERGY emissions are lower by 40 to 75 % in 2010 (Fig. 3). The largest 30 impact of STAG ENERGY in 2010 is seen in the power generation sector emissions (more than 31 80 % as global average for all pollutants), ranging from ca 20 % reduction in developing and 32 33 emerging regions (e.g. Asia, Latin America, etc.) to more than 95 % reduction in industrialized regions (USA, EU, Japan, etc.). 34

- When comparing the STAG TECH to the REF(2010) case, we find a global reduction of road 35 emissions by 8.5 times for SO₂, ca 1.5 times for NO_x, CO and NMVOCs and 2 times for PM, 36
- which clearly illustrates the phasing-in of less emitting vehicles due to stricter EURO standards. 37
- A shift from diesel to petrol could have caused a further reduction of PM emissions but the 38 opposite took place: diesel vehicles represented only ca. 20 % of the global fleet in 1970
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compared to ca. 75 % in 2010. Therefore the PM emission reductions shown in the 1 STAG ENERGY scenario compared to the REF(2010) is less strong for transport emissions and 2 mainly driven by the power sector. Other sectors, such as residential combustion, also contribute 3 significantly to the total emissions, but are not so easily controlled and moreover there was no 4 5 comprehensive legislation in place. For the aerosols (PM_{10} , PM_{25} and BC) the increase in REF emission levels from 1970 to 2010 is stronger than for other pollutants (ca 40 %), although we 6 7 remark here that the major contribution comes from residential combustion, which was not 8 evaluated in our scenarios. More information on the ratios between each retrospective scenario and the reference case are given in Tables S1.1 and S1.2. In the sections below, we focus on the 9 three sectors separately for the historical trend in Europe with REF(1970) and REF(2010), and 10 then the STAG TECH and STAG ENERGY scenario cases. 11

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13 **3.2** European emission trends

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15 **3.2.1** EU power industry ("power")

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17 Figure 5 presents the evolution over the years 1970-2010 of SO₂ and PM₁₀ power plant emissions in Europe, highlighting the role played over time in actual emission levels (blue area) 18 19 by the introduction of abatement measures (EOP, red area), and by the change in emission factors and technology (green area, STAG TECH). The concurrent effects due to the change in 20 fuel quality (directive 98/70/EC, 1998, as well as international conventions like CLRTAP and 21 Gothenburg Protocol) leading to the introduction of abatement measures (non-regenerative 22 dry/semidry and wet flue gas desulfurisation), following the directive regulating emissions from 23 large combustion plants (2001/80/EC), determined the actual (REF) 2010 emission levels. 24 Concerning particulate matter (here represented by PM10, but similar results are obtained for 25 PM_{2.5} and its carbonaceous components), in 1970 power plants were already equipped with some 26 abatement measures (e.g., cyclones), which were more and more installed in the nineties (using 27 finer filters) not only due to legislative restrictions. In particular pre-combustion treatment of fuel 28 and an engine design optimizing the combustion process helped not only to reduce the emissions 29 but also to increase the fuel efficiency (decreasing the variable cost of fuel input) and robustness 30 (protecting delicate components from corrosive air pollutant gases and to shorten outages). 31 Therefore, the major reduction in REF PM₁₀ emissions between 1970 and 2010 is due to the 32 33 application of abatement measures. The impact of European legislation on emissions from the power generation sector, evaluated by STAG TECH, can strictly be interpreted only in the 34 European context. As we explained earlier, STAG TECH took into account a stagnation of 35 technologies at the global level and in addition for Europe alone, regulations on air pollution 36 reduction equipment. The effect of additional policies outside of Europe has not been taken into 37 account here as discussed in the introduction and methodology sections. Figure 4 shows that in 38 Europe the REF emissions decreased from 1970 to 2010 for all air pollutants and aerosols. This 39 reduction was primarily obtained through the introduction of end-of-pipe measures. 40

For the STAG ENERGY scenario, we observe the lowest emissions both at global and European 1 scales. With this scenario, in 2010 pollutant emissions would vary between 10 % and 30 % of the 2 REF(2010) emission values both at the European and global scales (refer to Figs. 3b and 4b as 3 well to Table S1.2). Compared to REF(1970), the STAG ENERGY scenario shows around 95 % 4 lower SO₂ and PM emissions, 76 % lower NO_x and ca 30 % lower CO and NMVOC due to all 5 technological progress, enhanced energy efficiency and an important shift to less carbon-6 intensive fuel use. In 2010, coal-related fuels represented ca. 49 % of EU fuel consumption, a 7 8 decrease of 16 % compared to the 65 % in 1970, while the EU phased out the use of heavy residual fuel oil in the power sector, leading contribution of oil decreasing from 25.5 % to 9 %. 9 The EU power sector increased its fuel consumption by adding natural gas, in particular in UK, 10 Sweden, and Spain (IEA, 2014). Moreover, Poland and Germany increased the share of lignite 11 over bituminous coal in their power industry (IEA, 2014), leading to lower BC emissions. The 12 balance is made by a higher share of clean, low-sulphur fuels, such as natural gas and wood, (35 13 vs. 9 % and 7 vs. 0.5%, in 2010 and 1970, respectively). Therefore, SO₂ emissions from power 14 plants were drastically reduced in Europe from 1970 to 2010 due to the shift to cleaner fuels and 15 due to technological treatments of both fuels (to lower sulfur content) and flue gas (to lower SO₂ 16 emission) following EU policies, confirming the analysis of Rafaj et al. (2014). At the European 17 level, in 2010 the STAG TECH scenario produced 1.7 times higher NO_x emissions than REF, 18 when assuming technology stagnation and less optimized combustion processes (lower 19 efficiency, lower air-fuel mix) (see Table S1.1 and Fig. 4b). Interestingly, also NH₃ emissions 20 are higher in STAG TECH compared to REF due to the fuel shift from oil to gas which emits 21 much less NH₃ than oil. European legislation has been also successful in effectively abating 22 23 PM₁₀ emissions from power plants, reducing them by a factor of 6.3 compared to the STAG TECH scenario. Similar results are found for PM2.5 emissions and its components (BC 24 and OC). 25

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27 **3.2.2** EU manufacturing industry ("industry")

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The primary emissions of industrial activities, including all manufacturing activities, are SO₂, 29 NO_x, CO and PM, while NMVOC emissions are to a large extent due to the use of solvents and 30 31 specific chemical processes. As shown in Table S1.2, the ratio of STAG ENERGY to REF(2010) for the industrial sector is larger than 1 for EU27 due to the presence of heavy 32 industry in European countries in the seventies (the ratio of STAG ENERGY to REF(2010) for 33 Central Europe is 2.1, while for OECD Europe is 1.6). Ratios higher than 1 are also observed for 34 other world regions such as USA, Japan, Asia-Stan, Russia, Turkey and Ukraine due to the shift 35 of the heavy industry to emerging countries like China and India having a STAG ENERGY to 36 REF(2010) ratios equal to 0.2-0.3. We note that the ratio STAG ENERGY to REF(2010) does 37 38 not vary for the different substances since the change in energy efficiency and its fuel dependence were not considered for the industrial sector. The emissions from the manufacturing 39 industry were affected by the shift to cleaner fuels from 1970 to 2010 and, in particular, there 40 was a considerable reduction in the use of heavy residual fuel oil. From 1970 to 2010 the relative 41

fuel usage in manufacturing industries changed from 26.9 to 16.9 % for coal, from 18.8 to 52.4 1 2 % for gas, from 53.6 to 18.9 % for oil and from 0.7 to 11.9 % for wood. The impact of technological development and deployment of pollutant abatement measures on the industrial 3 sector is depicted in Fig. 4b. When comparing the STAG TECH and REF(2010), we find that 4 only the emissions from SO₂, CO, NH₃ and PM components are moderately affected in Europe 5 with ratios ranging from 1.2 to 2.6, except for NH₃ where, as mentioned before, the ratio is 3.9 6 due to higher emissions from oil combustion than from gas. Therefore, even in Europe, REF 7 emissions from the manufacturing industry sector are generally higher in absolute terms than 8 those from the power sector (see Fig. 4), because of the deployment of less clean fuels and less 9 efficient technologies, as well as the lack of stringent effective abatement measures. The recent 10 European directive 2010/75/EU will further regulate emissions from industrial activities, with 11 emission reductions expected to materialize after 2010. 12

13 **3.2.3** EU road transport ("road")

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The largest effects of technology changes and end-of-pipe control measures are observed in the 15 road sector in the EU. The fuel quality directive reduced SO₂ emissions by 2 orders of magnitude 16 (a factor 160, see Fig. 4b). Lower SO₂ emissions in 2010 are mainly associated with the 17 implementation of EU fuel quality directives (in accordance with international conventions), the 18 shift to cleaner fuels, and less by the presence of EOP measures. With the optimization of 19 combustion technology (motor inside flow and combustion, common rail fuel injection, 20 preheating) CO and NMVOC emissions have also been reduced. With the adoption of EURO 21 standards, particulate filters have increasingly been introduced in the car fleets, and exhaust PM 22 levels were reduced by more than a factor of 4. However, real-world emissions become more 23 determined by a relatively small fraction of vehicles with lower emissions standards or defect 24 equipment, such as the so-called super-emitting cars. Moreover, particulate filters do not work 25 properly when the S content in the fuel is larger than 50 ppm, an issue when cars are exported to 26 developing countries (such as Africa) with less clean fuel on the market. Furthermore, EURO 27 standards reduced NO_x emissions by 2.5 times, at the expense of a 5.5 times increasing NH₃ 28 29 emissions because of the catalysts (NH₃ is the only substance that is decreased in emissions 30 under the STAG TECH scenario, refer to Fig. 4b and Table S1.1). REF(2010) CO emissions are reduced by 6 times in 2010 compared to STAG TECH. Figure 4 highlights the impact of the 31 increased energy consumption in the road transport sector from 1970 to 2010, resulting in the 32 lowest emissions for all pollutants as observed for the STAG ENERGY scenario. At European 33 scale pollutants are reduced from 1.4 to 2.5 times of the actual REF(2010) values if the energy 34 consumption remained at 1970 levels (STAG ENERGY). Similar values are observed for USA 35 and other industrialized countries, while lower impact is seen for developing regions (from few 36 37 percent up to 20% reduction). European NO_x and BC emissions in EU increased in 2010 by a factor of ca 2.3, compared to the STAG ENERGY scenario (see Fig. 4a), not only due to the 38 increased fuel consumption, but also to the shift from petrol to diesel, thus emitting more NO_x 39 40 and particulate matter, for passenger cars in the EU (Fig. 6). Figure 7 shows the change in road transport emissions over time for SO₂ and PM_{2.5} in Europe. Already in the 1970s, Europe was 41

moving towards the use of cleaner fuels, strengthened by the agreements made in the 1 international CLRTAP and Gothenburg Protocol, thus reducing SO₂ road emissions. In 1999 the 2 European Union directive 1999/32/EC required the improvement of petrol and diesel fuel 3 quality, lowering their S content. On the other hand, the deployment of cleaner fuels did not 4 reduce primary particulate matter emissions (e.g., PM_{2.5} as shown in Fig. 7). Only with the 5 gradual introduction of particle filters in the 1990s, requested by EURO standards for vehicles 6 from EURO1 in 1992 to EURO5 in 2009 (Table S5.2), PM road transport emissions reduced by 7 8 a factor 4-5. This exemplifies the policy response to different type of pollutants and sources through the implementation of new policies. Figure 8 reports road transport PM2.5 emissions for 9 the year 2010 and for the two scenarios (STAG TECH and STAG ENERGY) for world regions 10 (details about region classifications can be found in Sect. S4.4). The comparison of 11 STAG TECH and REF(2010) PM_{2.5} data represents the emissions reductions due to the 12 implementation of 2010 technologies and EURO standard abatements, while the difference 13 between the STAG ENERGY scenario and the REF(2010) data represents the enhanced 14 emissions (60 %) due to the increased energy consumption from 1970 to 2010. A decrease of ca 15 50 % of PM_{2.5} road emissions (0.91 Tg) is observed globally due to the implementation of the 16 EURO standards on vehicles. This reduction is almost equally attributed to the impact of EU 17 standards in Europe (0.47 Tg) as well as outside of the EU (0.44 Tg). Major impact of EURO 18 standards outside Europe is found in China, Southeast Asia, India, the Middle East, Indonesia, 19 Japan, Oceania, etc., while a smaller impact is seen in North America due to the deployment of 20 standards not affected by the STAG TECH scenario (i.e. the North America UT1, UT2, UT3, 21 PH1 and PH2 standards). Further analysis about the spillover of the EURO standards outside 22 23 Europe are presented in Crippa et al. (2016, submitted).

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25 **3.3 European hotspots: avoided emissions for the year 2010**

Figure 9 shows the spatial $(0.1^{\circ} \times 0.1^{\circ} \text{ lat-lon})$ distribution in Europe of the difference in 26 emissions of the STAG TECH and REF(2010) scenarios for selected pollutants (SO₂, NO_x, CO, 27 PM_{10} and BC). These maps can be interpreted as the emissions reduction in Europe due to the 28 implementation of European air quality legislation on the power generation industry and road 29 transport, together with the change in emission factors and technologies, which also affected the 30 industrial sector. The avoided SO₂ emissions are mainly located in western European urban areas 31 (e.g., Paris, Madrid, London, Rome, Berlin and the Benelux region) due to the co-location of 32 several major emitting activities, while many point sources (power plants and industries) are 33 spread over Europe, leading to the reduction in SO₂ emissions due to the switch to cleaner fuels 34 (shifting of fuel types and lower sulfur content). A different spatial distribution of emission 35 reductions is found for NO_x and CO, where in addition to urban areas, a large reduction is 36 observed for road transport (road tracks are visible for both pollutants). Interestingly, Italy, 37 Germany, the United Kingdom and the Benelux region display strong and more uniform CO 38 emission reductions compared to other European regions (e.g., France and Spain) because of the 39 contributions of the manufacturing industry. PM₁₀ and BC grid maps highlight the effectiveness 40 of EURO standards on road vehicles especially in western European countries, representing a 41

successful example to be followed by eastern European regions. Finally, the implementation of particulate filters on power plants and industries was highly effective in very industrialized areas

- 3 (e.g., Benelux) and other major conurbations.
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5 4 Corresponding impacts on air quality, health and crops

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7 4.1 Concentration and composition changes

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9 Power, industry and road emissions data from the considered scenarios have been used in the TM5-FASST model to derive the corresponding population weighted-average PM_{2.5} and O₃ 10 11 concentrations for main world regions. Figure 10 shows the global impact of the historical change in emissions of 1970 compared to 2010 (REF(1970) vs. REF(2010)) on PM_{2.5} and O₃ 12 concentrations, and those of STAG_ENERGY and STAG TECH relative to the REF(2010) data. 13 Note that delta emissions are calculated as the difference between each scenario and the 14 REF(2010) data. PM_{2.5} REF concentrations decreased from 1970 to 2010 by 4.7 and 5 μ gm⁻³ in 15 the USA and Europe, respectively, while increased concentrations in 2010 are especially 16 observed for Asian countries (15 and 12.5 µgm⁻³ for China and India respectively), Africa (0.7 17 μ gm⁻³) and Latin America (0.5 μ gm⁻³). A similar pattern is also observed for O₃ where 18 19 industrialized countries had higher computed concentrations in 1970 compared to 2010 (delta O₃) equal to 3.1 ppb for USA and to 0.4 ppb for Europe), while developing countries increased their 20 concentrations in 2010 by 12.8, 5, 2.7 and 0.9 ppb for Asia, Latin America, Africa and Russia, 21 respectively. Similarly to the change observed from 1970 to 2010, comparing the 22 STAG ENERGY scenario to the REF(2010) case, PM2.5 and O3 concentrations show the 23 expected opposite patterns for industrialized and emerging countries; however, the largest impact 24 is observed for Asia where the stagnation of energy consumption at 1970 levels would have 25 produced much lower concentrations (annual population-weighted average delta $PM_{2.5} = 11.9$ 26 μ gm⁻³ and delta O₃ = 13.7 ppb) compared to the reference 2010 levels. A markedly different 27 impact pattern is observed for the STAG TECH scenario versus the REF(2010), since the 28 stagnation of technologies at 1970 levels applied to present-day consumption would have 29 produced enhanced emissions for all world regions, especially for Europe (delta $PM_{2.5} = 4.9$ 30 μ gm⁻³ and delta O₃ = 2.5 ppb), Asia (delta PM_{2.5} = 1.7 μ gm⁻³ and delta O₃ = 1.8 ppb) and Russia 31 (delta $PM_{2.5} = 0.8 \ \mu gm^{-3}$ and delta $O_3 = 2 \text{ ppb}$). As shown in more detail in Fig. S6.1, the 32 33 implementation of EU air quality legislation for industrial facilities, in particular power plants, and of the EURO standards for road vehicles, coupled with the change in technology and fuel 34 quality, led to on average $4-5 \ \mu gm^{-3}$ lower concentrations in Europe as PM_{2.5} (including both the 35 primary and secondary particulate components simulated by TM5-FASST). Power plant PM_{2.5} 36 concentrations decreased by 1.9 and 2.9 µgm⁻³ in western and central Europe (with a more coal-37 fired power industry). However, effects of power plant emission reductions (STAG TECH 38 scenario) in other regions (Japan, China, USA, India, etc. with delta PM_{2.5} values between 1.5 39 and 3.7 µgm⁻³) are significant. For Japan and China, large contribution in concentration 40 reduction is seen from the road sector (1.3 and 1.1 µgm⁻³ respectively), and are related to an 41

export of EURO standards via market globalization. The market impacts of this specific sector 1 are studied in more detail separately in Crippa et al. (2016, submitted). For the USA, the large 2 reduction in PM_{2.5} concentration is due to the power generation sector. Although the end-of-pipe 3 measure implementation in US power plants is ascribed to US air quality legislation (and thus 4 not analyzed in the STAG TECH scenario), both Europe and the USA profited equally from fuel 5 quality improvement. Looking into the detailed chemical composition of the PM2.5 changes for 6 the power, road transport and industrial sectors (Fig. S6.2), we gain further insights into the 7 8 sectors and processes that contributed to the concentration reductions. Power plant emissions typically consist of aerosol precursor gases and particulate matter (also including fly ash); 9 therefore, its delta PM_{2.5} chemical composition is mainly formed by secondary inorganic 10 components (nitrates, sulfates and ammonium) as well as other PM_{2.5}. Similar aerosol chemical 11 composition changes are found for industrial sources with less secondary particulate sulfates as 12 heavy residual fuel oil is phased out. A different PM2.5 chemical composition response is found 13 for road transport, which consists of primary organic matter, BC, as well as ammonium nitrate 14 15 particles formed by the chemical reaction of NO_x and NH₃ emitted by this sector. The delta particulate SO₄ mainly represents the impact of the change in the sulfur fuel content in 16 worldwide regions due to the implementation of EU fuel quality directives as well as 17 international conventions and globally it corresponds to ca. 0.5 μ gm⁻³ less for the year 2010 on 18 average (1.5 µgm⁻³ for USA, 1.3 µgm⁻³ for China, 1.1 µgm⁻³ for central Europe and 0.9 µgm⁻³ 19 for western Europe). While the impact on PM2.5 concentrations due to technology and emission 20 reductions (STAG TECH scenario) are mostly found within the source region with emissions 21 change (Europe, Japan, China), longer-range effects are found for ozone. This is an important 22 23 result because it represents the need of having intercontinental policies for some pollutants. O₃ formation is driven by the reaction of the precursors NO_x, CO and NMVOCs, derived mostly 24 from the road sector and strongly abated over the past two decades with the EURO standards. 25 26 The avoided annual and regional average O₃ concentrations range between 0.5 and 6 ppb, which significantly affects the current O₃ levels ranging from 30 to 50 ppb and which are most present 27 in the hot arid regions of North Africa, the Middle East and Turkey. 28

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4.2 Health and crop impacts of improved air quality

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Modeled surface delta PM_{2.5} and O₃ concentrations are used in TM5-FASST to estimate the 32 impact of the specific scenario assumptions on human health (using the life expectancy standard 33 of GBD (2010)) and crop yield (expressed in tons of crops extra produced or not lost) (see Fig. 34 10). An increase of PM_{2.5} is reflected by a reduction of the average life expectancy, since 35 enhanced PM concentrations are the main harmful components impacting human health. So, 36 comparing the reference 1970 situation with the 2010 one, globally a loss in average life 37 expectancy is observed mainly for North America (4.7 months for USA and 1.4 months for 38 Canada) and Europe (4.2 and 5 months for Central and Western Europe, respectively), while 39 increased life expectancy is found for developing countries (4.8 months for Asia) (see Fig. 10a). 40 Considering the STAG ENERGY case, life expectancy increases in most of the world's regions 41

(4.2 and 7.2 months for China and India, 1-2 months for African countries and 0.8 months for 1 Latin America), while a loss in life expectancy is observed for the STAG TECH scenario versus 2 the REF(2010). As expected, in STAG TECH a significant negative impact on life expectancy is 3 found for western and central European countries (4-5 months, see also Fig. S6.3), where the 4 impact of emission reduction measures is largest. Coherently, life expectancy decreases also for 5 other industrialized countries, like Japan and USA (3.3 and 2 months) and to a lesser extent in 6 developing and emerging countries. Major health benefits from emission reduction measures are 7 observed in highly populated areas where PM and ozone changes are large. It is obvious that the 8 road transport sector, important in densely populated (urban) areas is contributing significantly to 9 the health impact. O₃ concentrations negatively influence crop growth, so the reduction in O₃ 10 concentrations observed for the REF(1970) vs. REF(2010) and STAG ENERGY vs. REF(2010) 11 is reflected in a net positive crop yield (global gain equal to 15.5 and 28 million Mt for the two 12 scenarios, respectively). Conversely, as shown in Fig. 10b and more in detail in Fig. S6.3, also 13 here, the emission control measures on vehicles are mostly responsible for mitigating impacts on 14 15 crop yields. The introduction of vehicle EURO standards led to reduction of worldwide ozone levels due to its atmospheric transport, corresponding to a crop yield benefit up to 8.3 million Mt 16 of avoided crop loss, representing 0.3 % of world production of maize, wheat, rice and soy. 17 Specifically, the reduction of road transport emissions allowed the production of an additional 2 18 Mt of crops in China in 2010, 1.4 in Western Europe, 1 in India, etc. 19

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21 5 Conclusions

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23 The interplay of European air quality policies and technological advancement to reduce anthropogenic emissions in Europe and the world over the last 40 years has been investigated. 24 25 Our analysis looks back to 1970, when the first European air quality directive was introduced and compares with 2010, the last year with reliable statistical data availability. In addition to our 26 reference EDGARv4.3 reference emissions, we introduced two retrospective scenarios in order 27 to analyze separately the impact of concurrent factors on 2010 emission levels. Specifically, the 28 STAG ENERGY scenario evaluates the change in energy consumption, energy efficiency and 29 fuel shift, and the STAG_TECH scenario the change in technologies with implementation of 30 abatement measures. The two scenarios present a range of emissions, lower and higher than the 31 32 reference case for the year 2010, which assess the specific role and impact of EU legislation on air quality, of technology development and of fuel use. The story told by these scenarios can be 33 informative for designing multi-pollutant abatement policies in emerging economies. Here we 34 focus on the emissions of the most relevant pollutants (SO₂, NOx, CO, NMVOCs and NH₃) and 35 of particulate matter (PM₁₀, PM_{2.5}, BC, OC) affecting air quality at global and European levels. 36 Global REF emissions of most components stabilized or increased, due to the increased growth 37 of activities in particular of countries with emerging economies, despite emission control 38 measures such as implemented in industrialized countries. For example, European SO₂ emissions 39 40 were reduced by 80 % from 1970 to 2010, while there was almost no change at the global level. Looking at the European situation, we assess the progress leading to the 2010 emission levels for 41

3 key sectors. For the power and manufacturing industry sectors, the increased fuel consumption 1 was coupled with a shift towards cleaner fuels (from coal-related fuels to gas), and supported by 2 the implementation of fuel quality directives, regulating the sulfur fuel content as well as end-of-3 pipe emission control measures under, e.g. large combustion plant directives. Despite a strong 4 increase in traffic volumes, the overall transport-sector emissions were strongly reduced due to 5 the implementation of abatement measures following the EURO standards for vehicles 6 (especially for NOx, CO, NMVOCs and PM), the use of cleaner fuels (with lower S content) and 7 8 partly due to the shift from petrol to diesel passenger cars (emitting less CO, but more particles and NOx). Therefore, our study indicates that a variety of EU air quality policies since 1970 have 9 avoided a dramatic deterioration of air quality in Europe and beyond. For example, fuel quality 10 directives (sulfur), were among the most influential policies impacting air quality globally (e.g., 11 88 % reduction of SO₂, while the EURO norms for vehicles, led to a 50 % reduction of PM_{2.5} 12 from global road transport exhaust emissions. In contrast, the global increased energy 13 consumption in 2010 compared to 1970 off-set between 40% and 75% of the emissions 14 15 reductions by the technological progress with end-of-pipe abatement and less carbon-intensive fuel use. To complete the assessment, the TM5-FASST model was used to estimate the impact 16 on PM_{2.5} and O₃ concentrations, human health and crop production of the considered scenarios 17 compared to the reference case. PM2.5 concentrations were reduced by air quality policies and 18 change in technologies by 4.5 and 5 μ gm⁻³ in central and Western Europe respectively, as well 19 as in Japan, China, USA, India (range 1.5–3.7 µgm⁻³); moreover, ozone concentrations were 20 reduced by 3-12 ppb in several world regions (reducing in the order of 10% of the regional 21 average annual O₃ levels). We estimate that EU policies increased life expectancy not only in 22 23 Europe, but also in Japan and the USA by several months (e.g., 5 months in Europe and 3.5 months in Japan). In addition, the introduction of EURO standards led to the reduction of 24 worldwide ozone levels, contributing to up to 8.3 million Mt increased crop yield, which 25 26 corresponds to 0.3 % of the present world production of maize, wheat, rice and soybeans.

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1 Figures and Tables

2 Table 1 – Emission scenario assumptions. AD (Activity Data), EF (Emission Factors), RED

3 (Reduction Factor), EFF (Efficiency Factor).

Emission sectors	Reference 1970 and 2010	Scenario 1 in 2010: Stagnation of technology & no End-of- Pipe control (STAG_TECH)	Scenario 2 in 2010: Stagnation of energy consumption (STAG_ENERGY)
Agricultural waste burning	EDGAR v4.3	EDGAR v4.3	EDGARv4.3
Energy industry	EDGAR v4.3	AD(2010)*EF(1970)*(1- RED(1970))	EDGARV4.3(2010)*(TJ_1970/EFF_ 1970)/(TJ_2010/EFF_2010)
Solid waste disposal	EDGAR v4.3	EDGAR v4.3	EDGARv4.3
Combustion in Manufacturing Industry	EDGAR v4.3	AD(2010)*EF(1970)*(1- RED(1970))	EDGARV4.3(2010)*(TJ_1970/EFF_ 1970)/(TJ_2010/EFF_2010)
Industrial processes & product use	EDGAR v4.3	EDGAR v4.3	EDGARv4.3
Oil Production & Refining	EDGAR v4.3	EDGAR v4.3	EDGARv4.3
Buildings (Residential & others)	EDGAR v4.3	EDGAR v4.3	EDGARv4.3
Fossil fuel fires	EDGAR v4.3	EDGAR v4.3	EDGARv4.3
Road Transportation	EDGAR v4.3	AD(2010)*EF(1970)*(1- RED(1970))	EDGARV4.3(2010)*(TJ_1970/EFF_ 1970)/(TJ_2010/EFF_2010)
Aviation (international+ domestic)	EDGAR v4.3	EDGAR v4.3	EDGARv4.3
Shipping (international+ domestic)	EDGAR v4.3	EDGAR v4.3	EDGARv4.3
Non-road ground transport	EDGAR v4.3	EDGAR v4.3	EDGARv4.3



- 1
- 2 Figure 1 Overview of historical European Union (in blue) and international (in red) air
- 3 quality regulations. UNECE/CLTRAP covers all European countries, USA, Canada,
- 4 Belarus, Russia, Turkey, Israel, Ukraine, and central Asian states.



7 Figure 2 – Schematic of the considered emission scenarios: REF(1970), REF(2010), STAG ENERGY and STAG TECH. The x axis represents the change in energy 8 consumption form 1970 to 2010 (shown also by the increasing size of the fuel pie charts), 9 10 while the y axis represents the change in abatement measures (EoP) and technologies from 1970 to 2010. The STAG TECH scenario has the same technologies and abatements of the 11 REF(1970) scenario, but assumes increased energy consumption and different fuel mix (as 12 shown in the pie chart composition) as in 2010. The STAG ENERGY scenario considers 13 the energy consumption of 1970 but it includes all the technologies, abatements, fuel mix 14 and energy efficiency of 2010. 15



Figure 3 – (a) Overview of 1970 (only for REF) and 2010 emissions for REF, STAG_TECH
and STAG_ENERGY at the global scale for the power generation, industry and road
transport sectors. (b) The ratios in 2010 of STAG_ENERGY to REF(2010) and
STAG TECH to REF(2010) are presented. The red-line indicates no change relative to the

6 reference emissions in 2010.



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Figure 4 – (a) Overview of 1970 (only for REF) and 2010 emissions for REF, STAG_TECH
and STAG_ENERGY at the European scale for the power generation, industry and road
transport sectors. (b) The ratios in 2010 of STAG_ENERGY to REF(2010) and

11 STAG_TECH to REF(2010) are presented. The red-line indicates no change relative to the 12 reference emissions in 2010.



Figure 5 – Effect of air quality abatements (STAG_TECH scenario) on annual power
generation emissions in Europe (EU27), SO₂ (upper panel) and PM₁₀ (lower panel).



6 Figure 6 – Change between 1970 and 2010 of energy content of major fuels (TJ yr-1) used

7 by EU27 passenger cars. Note the large shift from petrol to diesel.



Figure 7 – Effect of air quality abatements (STAG_TECH scenario) on annual road
transport emissions in Europe (EU27), SO₂ (upper panel) and PM₁₀ (lower panel).





Figure 8 – Regional contributions to PM_{2.5} road transport emissions in 2010 for the STAG_TECH, REF and STAG_ENERGY scenarios. The green arrow (STAG_TECH minus REF) indicates the amount of emissions avoided by the combination of legislation and technological advancements, and the red arrow (REF minus STAG_ENERGY) the additional emissions associated with increased energy use between 1970 and 2010.



Figure 9 - Hotspots of avoided emissions due to progressive implementation of air pollution
policy and better technology in Europe: difference of STAG_TECH and REF emissions in
2010 (t year⁻¹ (0.1°x 0.1° gridcell)⁻¹).





Figure 10 - Relative change between the scenarios (STAG_ENERGY, STAG_TECH and 1 REF 1970) and the reference case (REF(2010)): regional change in a) PM_{2.5} (µg/m³) and 2 3 associated life expectancy (months) and b) in ozone mixing ratios (ppb) and associated impacts on crops. Note that the same color scales are used for deltaPM_{2.5} and deltaO₃ 4 (positive delta are associated with red colors representing negative impacts, while negative 5 delta are in green colors representing improvements) Opposite color scales are applied for 6 change in life expectancy and crop yield compared to the delta one (positive values are 7 reported in green and negative values in red representing good and bad impacts, 8

9 respectively).