LAPPEENRANTA-LAHTI UNIVERSITY OF TECHNOLOGY LUT
School of Engineering Science
Degree Programme of Industrial Engineering and Management
Global Management of Innovation and Technology

Tansu Galimova

Air pollution mitigation during the global energy transition towards 100% renewable energy systems by 2050

Master's Thesis

Examiners: Professor Ville Ojanen
Professor Christian Breyer

Supervisors: Professor Ville Ojanen
Professor Christian Breyer
Manish Ram

ABSTRACT

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Air pollution induced by energy use is linked to causing and aggravating cardiovascular diseases, strokes, acute respiratory diseases and cancer. Particulate matter emanating from combustion processes including traditional biomass poses substantial threat to people's health across the world. The growing use of pollutant emitting fuels exposes already vulnerable populations to even more toxic levels of pollution, predominantly in urban centres around the world. The World Health Organisation estimates that around 9 out of 10 people breath polluted air and around 7 million premature deaths occur every year as a result of exposure to dirty air. The growth of renewables for power generation has proved to bring about the benefits of cleaner air in regions and countries that have high shares of renewable energy installations. This research aims to explore the development of NO_x, SO_x, $PM_{2.5}$, and PM_{10} emissions, which form the major air pollutants in a global energy transition scenario towards 100% renewable energy. Total emissions are projected to drop by almost 92% in 2050 compared to 2015, with annual premature deaths dropping by about 97% from 5.2 million deaths in 2015 to 150 thousand deaths by 2050, and annual costs of damage are drastically reduced by 88.5% from about 4600 b€ in 2015 to 529 b€ by 2050. Defossilisation and shift to renewable forms of energy enables massive decline in GHG emissions as well as emissions of air pollutants that are directly harmful to human health.

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ABBREVIATIONS

BAU	Business as Usual
BEV	Battery Electric Vehicle
BPS	Best Policy Scenario
CIS	Commonwealth of Independent States
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CH_4	Methane
EV	Electric Vehicle
FCEV	Fuel Cell Electric Vehicle
FT	Fisher-Tropsch
GHG	Greenhouse Gas
HDV	Heavy Duty Vehicle
HP	Heat Pump
ICE	Internal Combustion Engine
LDV	Light Duty Vehicle
LNG	Liquified Natural Gas
MDV	Medium Duty Vehicle
MENA	Middle East and North Africa
NO_x	Nitrogen Oxides
N_2O	Nitrous Oxide
PHEV	Plug-in Hybrid Electric Vehicle
PM	Particulate Matter
PV	Photovoltaic
RE	Renewable Energy
SO_x	Sulphur Oxides
VOC	Volatile Organic Compounds
2/3W	Two or Three Wheelers

1. Introduction

1.1. Background

Climate change is one of the greatest existential threats to humankind currently and countries across the world have agreed to mitigate climate change with the Paris Agreement in 2015 (IPCC, 2018). Measures to reduce greenhouse gases (GHG) emissions to limit temperature rise below 1.5°C compared to pre-industrial levels have come to the forefront of global discourse, with carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated gases (EPA, 2012) being the focus of several studies in recent years (Abeydeera *et al*., 2019; Abas *et al*., 2017; Hussain *et al*., 2019). Whereas, air pollution being more of a local issue has not received the same level of global attention. However in recent years, cases of infamous air quality in cities of India, China, some regions of Europe, North America and most big metropolitans around the world have increasingly deteriorating air quality (Egypt Independent, 2018; Daily Sabah, 2020; Pakistan Today, 2020), which have been worsened by issues such as Dieselgate (CLEW, 2020). Given that air pollutants such as nitrogen oxides (NO_x), sulphur oxides (SO_x), heavy metals typically represented as particulate matter (PM), and CO (carbon monoxide) have direct impacts on human health and the environment, air pollution must receive the same prominence as climate change. Afterall, mitigating climate change and reducing air pollution have the same goal of enabling sustainable development globally.

It is increasingly evident that air pollution is linked to cardiovascular diseases, strokes, acute respiratory diseases and cancer (WHO, 2018a; Lelieveld *et al*., 2019; Landrigan *et al*., 2018; Haque and Singh, 2017). It is estimated that 9 out of 10 people breath highly polluted air, which results in more than 7 million deaths a year (WHO, 2018b). According to the recent World Air Quality report (IQAir, 2019), 26 of the top 30 most polluted cities are located in India and Pakistan. China, while being one of the countries with the highest concentration of air pollutants, has been improving its results lately. In 2009, 16 of the top 20 polluted cities in the world were in China (VOA News, 2009). From 2015 to 2019, policies implemented by the centralised government have driven pollution levels of NO_2, SO_2, $PM_{2.5}$, and PM_{10}, down in most regions (CREA, 2020). Annual average concentrations of $PM_{2.5}$ in the largest cities of China have been steadily decreasing with Beijing being a great example having reduced $PM_{2.5}$ levels from 85 $\mu g/m^3$ to 42 $\mu g/m^3$. This is attributed to stringent vehicle emission control policies, promotion of public transport, bicycles, and battery electric vehicles, limiting use of fossil fuels and increasing renewable capacities (Lu *et al.,* 2020). Concentration levels of $PM_{2.5}$ in Indian cities have not changed much with some cities reporting similar levels in both 2015 and 2019, with annual average concentration of $PM_{2.5}$ in Delhi as high as 98.6 μg/m^3 (IQAir, 2020). Coal power plants, fossil fuel driven transport and other activities have contributed to the massive levels of air pollution across the country. Japan has been doing significantly better than its neighbours as average air quality has been ranked as good. However, it is still far from ideal as some regions report unhealthy concentrations of $PM_{2.5}$ of up to 17.6 μg/m^3 (IQAir, 2020). Air pollutant levels in many urban areas across Europe still exceed the EU limit as well as the stringent WHO limits. High concentrations of $PM_{2.5}$ have caused more than 400 thousand premature deaths across Europe in 2016 (EEA, 2019). Canada and the United States have managed to reduce air pollution levels with various emissions regulations imposed on transport and industries, but 20% of the cities in this region still fail to meet the air quality standards set by WHO (IQAir, 2020). Latin America also struggles with air pollution as the populations and urban areas keep growing along with energy consumption. Coupled with weak environmental regulations, this leads to poor air quality with only 14.5% cities meeting the WHO standards (IQAir, 2020). Africa faces its own problems as air quality monitoring is yet to be developed in the region with only some of the urban areas tracking pollutant concentrations. However, as 60% of the population resides in rural areas, many still use traditional biomass or coal for cooking, millions are affected by poor air quality (IQAir, 2020). Russia and other Commonwealth of Independent States (CIS) are lax in their environmental regulations and monitoring, along with wide-spread corruption. Around 15% of urban Russians are estimated to be exposed to polluted air (Moscow Times, 2016). Air pollution is not only a global phenomenon that adversely impacts the environment, but also considerably affects economic activity by increasing health expenditures and reducing productivity levels due to premature deaths and health-related issues.

Thermal power plants, district heating plants, agriculture, heavy industries, and transportation are responsible for majority of air pollutants as well as GHG emissions driving climate change. In particular, energy generation and transportation with fossil fuels has proved to be detrimental for the environment as well as people, mainly in cities. Every year more cities and countries commit to phasing out fossil fuels and transitioning to 100%

renewable energy supply. Examples include cities of Barcelona, Frankfurt, Geneva, Malmo (Bringault *et al*., 2016), Los Angeles, Chicago, Philadelphia (REN21, 2020). States and countries of California, New York, Maine, District of Columbia, Paraguay, Norway, Denmark and many others have also committed to 100% renewable electricity (Think Progress, 2018; EIA, 2019; UCLA, 2019). Denmark is the only country that has set especially ambitious target to meet the total final energy demand for power, heating/cooling, and transport with 100% renewable energy sources (REN21, 2020). The European Commission (EC) envisaged a strategic long-term vision with the European Green Deal (EC, 2019), which outlines feasible pathways for Europe to lead the transition towards a climate-neutral economy by 2050 in line with the objectives of the Paris Agreement.

A need for defossilisation of the present energy system is increasingly acknowledged and pathways towards renewable energy systems are being proposed (CAT, 2018). One such energy system transition scenario is presented in a study by LUT University and Energy Watch Group (Ram *et al*., 2019). The report presents a unique cost optimal global energy transition to 100% renewable system across the power, heat, transport and desalination sectors by mid-century. This research on air pollution is directly based on the results of Ram *et al*. (2019) and Bogdanov *et al*. (2021) and emissions of air pollutants are estimated for the energy transition period from 2015 to 2050 in five-year intervals.

1.2. Research questions

The aim of the thesis is to investigate the total global air pollution potential from emitting sources and analyse its development throughout the energy transition to 100% renewable energy from 2015 to 2050. The following research questions were defined:

RQ1: What are the volumes of air pollutant emissions from thermal power and heat plants and transportation in 2015?

RQ2: How do emissions develop over the years as the world is transitioning to renewable forms of energy?

RQ3: What are the impacts of pollutant emissions on human health and economy?

1.3. Research Methods

The research uses the output of the 100% Renewable Energy Scenario Simulation by LUT Energy System Transition Model for the power, heat, and transport sectors in 145 regions around the world for the period between 2015 and 2050. Pollutant emissions are calculated for each sector based on the supply data and corresponding emission factors found in literature. Economic and health impacts of the pollutants are then estimated using the values of damage costs and mortality rates for each fuel.

1.4. Thesis structure

The thesis is organised as follows: an introduction section followed by a literature review, examining various studies on the topic. Methods and materials for estimating total emissions, associated mortality and damage costs are presented in the next section. Results of this research are presented in the form of total pollution from power, heat, and transport sectors for selected fuels and modes, in the following section. In the next section, results are discussed in comparison to other similar studies and conclusions are drawn in the last section.

2. Literature Review

This section presents existing literature on air pollutant emissions, their sources, and impacts on human health.

2.1. Air Pollutants

As it is stated by the United Nations Environment Program (UNEP), air pollution can be indoors or outdoors and may occur naturally or as a result of human activities. Major sources of air pollution include fossil fuel combustion, industrial and agricultural activities, waste and landfills (EEA, 2013). Some examples of pollutants that affect air quality are nitrogen oxides (NO_x), sulfur oxides (SO_x), carbon monoxide (CO), particulate matter (PM), volatile organic compounds (VOCs), and ozone (O_3) (IEA, 2016). The body of research on emissions of air pollutants and air quality has been growing, but the topic may not yet be studied as extensively as GHG emissions, which is indicated by He *et al*. (2020). Moreover, research trying to quantify air pollution caused by various human activities is further limited. However, the topic is just as important and urgent as climate change because of the major impacts that air quality has on human health, the economy and the climate (UNEP, 2018). There is a growing need for research on future trends in air pollution around the globe and how potential policies and regulations will impact air quality.

2.2. Studies on air pollution

Many environmental issues that our society faces today such as climate change, ozone depletion, air and water pollution, can be attributed to the same sources: extensive and continuously growing use of fossil fuels. Total global primary energy supply has grown by more than 40% in the period between 2000 and 2018 (IEA, 2020a). This led to GHG and air pollutant emissions levels to spike as never before. According to the World Energy Outlook Special Report on Air Pollution (IEA, 2016), energy production and use are accountable for the majority of human-caused emissions of NO_x, SO_x, and PM. The growing world population which is expected to reach 9.8 billion people by 2050 (UN DESA, 2017), together with economic development will further contribute to increased energy demand. Growing utilisation of fossil fuels will put even more strain on energy systems and thus the need for more progress in providing sustainable RE sources is indisputable.

There is an extensive body of research on future energy scenarios for 2050 and 2100 with focus on renewable energy resources by scientists as well as governmental organisations (Allen and Bottoms, 2018). Research on 100% RE systems has been steadily growing with many studies focusing only on the power sector, although increasing number of studies cover multiple sectors. The research by Ram *et al*. (2019) and Bogdanov *et al*. (2021) covers the energy transition to 100% RE in all regions of the world taking into consideration the power, heat, transport, and desalination sectors. The feasibility and viability of 100% RE system is discussed in detail by Brown *et al*. (2018) and Diesendorf and Elliston (2018). 100% RE systems will lead to a drastic reduction in GHG emissions in all regions. Annual emissions are expected to go down to zero GHG emissions by 2050 or even sooner (Ram *et al*., 2019; Bogdanov *et al.,* 2021). As conventional sources of energy will be substituted by renewable forms of energy, it is expected that air pollutant emissions such as NO_x, SO_x, and particulate matter will also shrink. Thus, both climate change and air pollution can be tackled by such sustainable systems (Wuebbles and Sanyal, 2015), which leads to substantial co-benefits. Năstase *et al*. (2018) have contributed to a better understanding of links between air pollution and use of fossil fuels. Trends in GHG and air pollutant emissions were analysed in Romania during the last 30 years with a special focus on new environmental policies imposed since the country joined the European Union in 2007. Since 2005 the country has observed increase in shares of renewable electricity of 7.3% per year of which almost half is hydropower. Wind and solar energy capacities have also been rising. As a result of new policies and increased shares of RE sources, carbon monoxide emissions have reduced by 10.3% in 2014 compared to 2007, whereas values for NO_x and SO_x were down 26.9% and 66.7% respectively (Năstase *et al*., 2018).

Jacobson *et al*. (2019) demonstrate possible pathways for the energy transition to 100% RE sources by 2050 in the world for 143 countries, represented by 24 regions. Such an energy transition results in additional benefits such as lower air pollution, lower risk of mortality associated with outdoor and indoor pollution, avoidance of damage costs associated with global warming, and creation of new jobs. Expected premature mortalities as a result of exposure to air pollution were found to be around 5.28 million per year by 2050 worldwide in the BAU scenario. It also estimates that social costs in the BAU scenario in 2050 are $71 trillion/year, but only \$6.8 trillion/year in a sustainable scenario (Jacobson *et al.*, 2019). Jacobson *et al.* (2019) restrict the use of bioenergy in their pathway for further limiting air pollution.

Guttikunda and Jawahar (2014) provide an analysis of atmospheric emissions from coal-fired power plants in India. The studied emissions in the years 2010-2011 were CO_2, NO_x, SO_2, $PM_{2.5}$, CO, and VOC, which amounted to 665,000, 2000, 2100, 580, 1100, and 100 kilotons, respectively. More than 80 thousand cases of premature deaths, 20 million asthma cases, 160 million restricted activity days, and 3.2-4.6 bUSD of damage costs were estimated in association with those emissions (Guttikunda and Jawahar, 2014). Considering that only coal-based electricity generation was studied, the numbers are staggering and once again show the importance of phasing-out fossil fuels. Cofala *et al.* (2015) have identified possible air pollution pathways in India for future energy scenarios. Analysis of Current Legislation and Best Policy scenarios have shown that NO_x and SO_2 emissions are dramatically increasing in the Current Legislation scenario by 63-69% and 80% respectively in 2025 compared to recorded data from 2010. The Best Policy scenario promises a reduction of sulfur emissions by 62% in 2025 and 46% in 2040 compared to 2010 levels, whereas NO_x emissions are to decrease by 14% and 7% in the same periods. $PM_{2.5}$ emissions are also expected to drop significantly in the Best Policy scenario and will lead to fewer mortality cases from cardiovascular and respiratory health problems (Cofala *et al.*, 2020).

The transport sector is responsible for a large share of atmospheric emissions. Almost a quarter of direct CO_2 emissions are from transportation, with three quarters of it attributable to road transportation that includes cars, buses, trucks, 2 and 3 wheelers (IEA, 2019). Other than CO_2 emissions, the transport sector is also responsible for NO_x, SO_2, methane, black carbon, and other aerosols that emanate from fossil fuel combustion (IPCC, 2015). Finding optimal solutions for the transport sector when it comes to tackling both climate change and air pollution is highly important because certain types of transportation can have low GHG emissions, but their air pollutant emissions can be considerably higher than permissible (Fan *et al.*, 2018).

While road transport is the largest CO_2 emitter, it was found that shipping alone was responsible for 32% of NO_x, 40% of SO_x, 96% of $PM_{2.5}$ emissions, almost 50% of PM_{10}, from all transportation in the European Union (Fan *et al.*, 2018). Aviation is another transport mode which is responsible for high emission levels, causing 5% of global radiative forcing and leading to around 16 thousand premature deaths yearly as a result of poor air quality (Grobler *et al*., 2019). Biggest impact to both climate and air pollution was found to be made by NO_x, CO_2 and contrails making up 97% of total impact. Contribution of NO_x alone was 58% and is seen to be one of the main targets for decreasing harmful impacts of air pollution from aviation. Moreover, the impacts of aviation on pollution were found to be significantly greater than that on climate change per unit of fuel burnt (Grobler *et al*., 2019).

It is widely acknowledged that with the complexity and energy intensity of the transport sector, electrification would be the best option to reduce atmospheric emissions and meet sustainability goals. The number of electric vehicles (EV) sold has already been steadily growing. There were 7.2 million EV in 2019 (IEA, 2020b), which is few, given that about 1.2 billion vehicles are in use in 2020 (Khalili *et al.,* 2019). However, it is important to notice that almost 2.1 million of those vehicles were sold in 2019 alone, owing to huge increase of 40% in sales compared to the year earlier (IEA, 2020b). Knobloch *et al*. (2020) have analysed current and future emissions from EV and heat pumps (HP) in 59 regions of the world. Current technological trajectories, a scenario with climate policies meeting the 2°C goal, and a scenario with only partial policies applied to transport and heating (end-use) were investigated. It was found that current and future emissions of EV and HP are lower in most of the regions and later in the future, even the most inefficient EV have lower life-cycle emissions than the best and most efficient gasoline vehicles in many regions of the world (Knobloch *et al.,* 2020). This is further substantiated by Hoekstra (2019), who states that the potential reduction of GHG by battery-electric vehicles (BEV) is underestimated by scientific literature. He argues that lifecycle GHG emissions of BEV are 95 g/km versus that of diesel cars with 244 g/km. Renewable electricity can bring lifecycle emissions of BEV further down to 10 g/km. Moreover, (Knobloch *et al*., 2020) determined that it is safe to issue policies aimed at end-use electrification even if policies for power industry are limited or complex, which means that having electrified transportation and heating is more beneficial even if the power sector is not decarbonised. Further decarbonisation of electricity generation will bring even more benefits and will help lower atmospheric anthropogenic emissions. As it has been determined for the Eastern coast of the United States by Abel *et al*. (2018), increase in shares of electricity generated by solar PV systems to 17% will lead to significant improvements in air quality across the region. Further, by substituting coal and fossil gas-based power generation, NO_x and SO_x emissions can be reduced by 20% and 15% respectively. $PM_{2.5}$ concentrations also decrease on average by 4.7% in the East coast of the

US, with the greatest improvement in five most polluted cities that struggle to meet the air quality regulations. Avoiding almost 1500 premature deaths and saving 13.1 bUSD of healthcare costs further proves the significance and numerous advantages of fully RE systems (Abel *et al*., 2018).

A modelling study (Markandya *et al.,* 2018) with different future scenarios of climate change mitigation with 1.5-2°C targets have shown that in many cases health co-benefits of policies aiming to fight climate change outweigh potential costs of implementing those strategies. In Europe and the United States, health co-benefits cover between 7-81% and 10-41% of mitigation costs respectively, whereas in China and India the benefits are even greater, with the costs of reducing GHG possibly covered fully by health co-benefits. Moreover, these two regions showed greater benefits in scenarios aiming to keep the temperature rise at 1.5°C with potential net benefits of 3.28-8.4 trillion USD in India and 0.27-2.31 trillion USD in China (Markandya *et al*., 2018). Rauner *et al*. (2020) further analyse potential co-benefits of climate change policies taking into consideration air pollution control scenarios and with special focus on socio-economic features. The research shows increased benefits for densely populated regions of China and India, where highly polluted air in densely populated cities is an ongoing ordeal (Rauner *et al*., 2020).

2.3. Health Impacts of Air Pollution

Multiple studies have investigated harmful impacts of air pollution on human health and well-being (Manisalidis *et al.,* 2020). Air pollution in Europe alone is responsible for 6% of total deaths and half of those deaths are attributed to motor vehicle emissions (Künzli *et al*., 2000). Studies conducted in different regions have shown consistent association between exposure to air pollution and increased probabilities of asthma attacks, chronic bronchitis, restricted activities and higher mortality rates due to lung cancer or cardiopulmonary disease (Dockery *et al*., 1993; Ostro *et al*., 1996; Chen *et al*., 2012; Haque and Singh, 2017; Landrigan, 2017).

Health issues related to air pollution are becoming ever more important considering recent events. The novel coronavirus COVID-19 outbreak which is rapidly spreading across the world, has already taken the lives of more than a million people (as of October 19th, 2020) and continues to devastate societies around the world (WHO, 2020). Several studies across different continents have already presented results on possible links between air pollution and increased rates of coronavirus-related deaths (Pozzer *et al.*, 2020; Wu *et al.*, 2020; Ogen *et al.*, 2020). Wu *et al.* (2020) have found that a small increase in long-term exposure to $PM_{2.5}$ increases fatality rates of COVID-19. The study concluded that an increase of $PM_{2.5}$ by only 1 $\mu g/m^3$ will lead to 8% higher death rates. Another research conducted in Europe's coronavirus hotspots studied links between exposure to NO_2 and coronavirus-related deaths rates (Ogen, 2020). Analysis of air pollution in 66 regions in Italy, Spain, France and Germany concluded that long-term exposure to increased concentrations of NO_2 could be an important contributing factor to increased death rates, as a result of complications of novel coronavirus (Ogen, 2020).

Studying effects of pollution resulting from fuel combustion on human health is important for the assessment of energy security of regions. As stated by Azzuni and Breyer (2020), health is one of 15 dimensions of energy security. Energy systems and people both have impacts on each other as healthy people can increase productivity and allocate resources for energy system development, rather than inefficiently spending it on healthcare, whereas poorly performing energy systems may negatively impact human health and cause diseases such as cancer (Azzuni and Breyer, 2020). This further proves the importance of considering health impacts of air pollution and combustion of fossil fuels to the overall energy system and its security.

3. Materials and Methods

This section describes the methods of estimating global air pollutant emissions from the power, heat, and transport sectors during the global energy transition from 2015 to 2050. Emissions are based on energy supply data for the power, heat, and transport sectors structured in 145 regions across the world, describing an energy transition from the present energy system in 2015 to 100% RE supply by 2050 in 5-year evolutionary steps for least-cost conditions, in a best policy scenario design (Ram *et al*., 2019; Bogdanov *et al*., 2021).

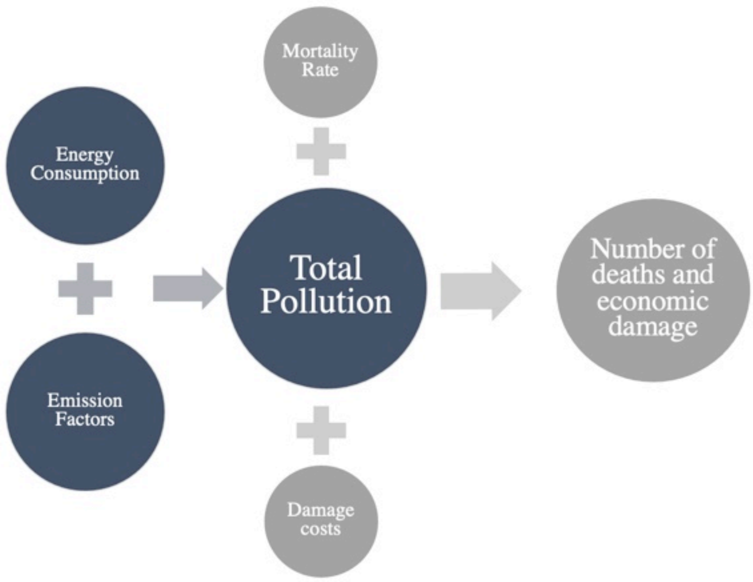

Figure 1. Methodological structure.

3.1. Emission factors

Emission factors of NO_x, SO_x, $PM_{2.5}$ and PM_{10} for different fuel types and regions of the world were adopted from multiple sources. Priority was for governmental sources, as some nations issue recommendations on estimating emission inventories. For example, EMEP/EEA air pollutant emission inventory guidebook issued by European Environmental Agency (EEA, 2019) provides a technical guidance to organisations reporting and preparing emission inventories. Emission factors of pollutants considered in this study are presented in that technical book for key polluting fuels: fossil gas, fossil oil products, coal, and bioenergy. Similarly, data for the United States was adopted from US Environmental Protection Agency (EPA, 2000). Some countries such as Canada, New Zealand, and

Australia report emissions for public electricity and heat sectors enabling emission factors to be derived (Environment and Climate Change Canada, 2020; MfE, 2018; Australian Government, 2012). For countries not officially reporting air pollutant emissions, emission factors were derived from scientific literature and other research or estimated from data of neighbouring countries as proxies. Emission factors for coal were derived for many countries from the extensive global coal power plant emissions dataset by Oberschelp *et al*. (2019). Emission factors were assumed to stay constant through the transition period from 2015 to 2050, as fossil fuel-based electricity and heat will be phased-out by renewable electricity and heat. However, according to Swedish Meteorological and Hydrological Institute's revisions of emission factors (SMED, 2016), current proposed emission factors do not adequately represent the reality and do not factor technological developments in the last decade. Proposed emission factors for bioenergy are assumed for electricity and heat production with the utilisation of the most advanced abatement technologies (SMED, 2016). This study assumes gradual introduction of above-mentioned abatement technologies for bioenergy utilisation in the public power and heat sector with 20% of biomass-based electricity and heat being generated using the best abatement technologies in the year 2030 and with 100% of biomass-based electricity being produced by advanced technologies by mid-century. Emission factors for traditional biomass combustion in open fireplaces and traditional kitchen stoves used in rural areas of developing countries are adopted from literature (Brant *et al*., 2010; Akagi *et al*., 2011; EEA, 2019). Emission factor values for different regions and fuels can be found with respective references in the Appendix (Tables A1-A2).

The transport sector is composed of four modes: road, rail, marine, and aviation. Road transportation is further divided into light duty vehicles (LDV), medium duty vehicles (MDV), heavy duty vehicles (HDV), 2-3 wheelers (2/3W) and buses (BUS), where LDV, 2/3W and BUS represent the passenger fleet and MDV and HDV the freight fleet. Rail, marine and aviation are also divided into these two sections: passenger and freight transportation. Emission factors for all transport modes excluding aviation were derived from energy and environmental regulations of the transport sector for different regions of the world from TransportPolicy.net (TransportPolicy.net, n.d.). Comprehensive data on past emission regulations for each transport mode as well as regulations approved by the governments, but not yet enforced are all extracted from *TransportPolicy.net* (no date). Emission factors for passenger and freight aviation were estimated using several sources including The International Civil Aviation Organization (ICAO, 2015), Wilkerson *et al*. (2010), Lee *et al*. (2010), Simone *et al*. (2013), and Olsen *et al*. (2013). These emission factors were then converted to the desired units (g/ton-km or g/passenger-km) using average fuel burn values (VTT, 2009; EEA, 2019). Detailed emission factors for different transport modes and different regions can be found in the Appendix (Tables A3-A10).

3.2. Estimating total emissions from sectors

Emissions of various pollutants from the power and heat sectors considered in this research were found using Equation (1):

$$Emissions_{i,f} = Emission\ Factor_{i,f,s} * \frac{AR_{i,f,s}}{\eta_{fi,s}} \tag{1}$$

where abbreviations are emissions in a country i, from sector s, from fuel f, of an activity rate AR, with efficiency η.

Emissions from the transport sector with electricity were estimated using the same method for the power sector with emission factors depending on a country and the corresponding fuel for electricity generation.

Emissions from road transportation with liquid hydrocarbons as fuel were measured according to Equation (2):

$$\begin{aligned} Emissions_{i,m,k} = {} & Transportation\ Demand_{i,m,k} * share\ ICE\ vehicles_{m,k} * \\ & share\ Diesel\ or\ Gasoline\ vehicles\ * \\ & share\ fossil\ fuels\ in\ liquid\ HC\ demand_{i,m} * Emission\ factor_{i,m,k} \end{aligned} \tag{2}$$

Emissions from rail, marine, and aviation were found using Equation (3):

$$\begin{aligned} Emissions_{i,m} = {} & Transportation\ Demand_{i,m} * \\ & share\ fossil\ fuels\ in\ liquid\ HC\ demand_{i,m} * Emission\ factor_{i,m} \end{aligned} \tag{3}$$

where abbreviations are a country *i* in which pollutants are emitted, mode of transport *m* and segment *k* that contributes to those emissions, *Demand* is the demand for a particular mode of transport, which can be measured in either TWh or vehicle-km.

Total global emissions per pollutant for a specific year in power and heat sectors are calculated using Equation (4):

$$Total\ Emissions_{p,f,y} = \sum_{i,s} Emissions_{i,f,s,p,y} \tag{4}$$

where *f* represents seven types of fuel used in power and heat: fossil gas, oil, coal, synthetic methane, biogas, modern solid biomass, and traditional biomass.

Total global emissions per pollutant for a specific year for each mode of transport are calculated using Equation (5):

$$Total\ Emissions_{p,f,m,y} = \sum_{i,m} Emissions_{i,f,m,p,y} \tag{5}$$

Emission factors for road transportation used in this research are calculated using weighted averages of emission factors from different time periods for shares of vehicles with different ages. Transport shares for the whole energy transition period, data on vehicle fleet age, shares of internal combustion engine vehicles (ICE), battery electric vehicles (BEV), plug-in hybrid electric vehicles (PHEV), fuel cell electric vehicles (FCEV), and vehicles load factors are from Khalili *et al*. (2019). Demand for transportation of each mode as well as fossil shares in liquid hydrocarbon demand for all countries are from Ram *et al*. (2019). Global shares of diesel and gasoline LDV were found to be 19% and 76%, respectively (Statista, 2020). Estimated shares of diesel and gasoline MDV are averages of the US (EIA, 2015) and EU data (ACEA, 2019) that result in 89% diesel and 10% gasoline. More details are in the Appendix (Table A11).

Total particulate matter emissions are further classified as fine particulate matter ($PM_{2.5}$) and coarse particulate matter (PM_{10}). Shares of PM of different sizes in road transport emissions were taken from European Environment Agency (EEA) and were reported to be 42% for $PM_{2.5}$ and 58% for PM_{10} (EEA, 2007). Respective shares of $PM_{2.5}$ and PM_{10} for rail assumed in this study are 12% and 88% (Kumar *et al*., 2014), and for aviation 26% and 74% (SAEFL, 2003).

Future development of emission factors assumes that countries and regions with more stringent emission regulations pave the way for other countries across the world in 5-year steps. At present the United States and China are found to have the strictest emissions regulations in the world, with the United States limiting NO_x emissions from LDV to 0.17 g/v-km and China limiting particulate matter emissions to 0.003 g/v-km by the year 2025 (*TransportPolicy.net*, no date). All other regions are assumed to adapt similar restrictions by 2050, with more developed regions being early adopters followed by others. Details of the regulations are in the Appendix (Tables A3-A10).

3.3. Estimating costs

Estimations of damage costs of air pollution are based on the findings of the International Monetary Fund (Parry *et al*., 2014). The IMF examines main sources of air pollution, i.e. fossil fuels used for combustion, and identifies pollutants that cause the most damage: NO_x, SO_x, and $PM_{2.5}$. It provides estimated costs of local damage caused by air pollution from coal, fossil gas, and ground-level pollution such as diesel and gasoline for 156 countries.

Damage costs provided in the original report are based on the income data by the World Bank (2017) and mortality value by the OECD (2012) in 2010. For this research, the income data for all countries are updated for 2015 using the same source (*World Bank*, 2017). The mortality value has also been re-calibrated for 2015 to account for inflation using the consumer price index OECD average. The resulting damage costs for NO_x, SO_x, and $PM_{2.5}$ emitted from coal-based and fossil gas-based power and heat, as well as fuels used by road and rail transport can be found for all 145 regions in the Appendix (Tables A12-A14). Damage costs of pollution from oil and biomass-based power and heat production, marine transport, and aviation were adapted from Goodkind *et al*. (2019). The paper provides estimates of damages caused by NO_x, SO_x, and $PM_{2.5}$ emitted during the combustion of different fuels in the United States. Average values for the damages caused by electricity generation and commercial, residential, and industrial combustion were converted from USD_{2011} per ton of pollutant to USD_{2017} per ton of pollutant. These values were later extrapolated to all regions other than the United States using gross domestic product (GDP) per capita, PPP values (in international USD_{2017}) from the World Bank (2017). Damages caused by coarse particulate matter were adapted from CE Delft (2018), which provides estimated general value of damage caused by PM_{10}. This value has been converted from $€_{2015}$ per ton of PM_{10} to USD_{2017} per ton of PM_{10} and further extrapolated to all regions of the world using GDP per capita values. Damage costs for all countries attributed to the key pollutants are presented in the Appendix (Tables A12-A14).

To account for economic growth, damage costs for each pollutant were updated using GDP per capita projections according to Toktarova *et al*. (2019) using Equation (6):

$$Damage\ cost_{i,s,f,m,p,y} = Damage\ cost_{i,s,f,m,p,2015} * \frac{GDP\ per\ capita_{i,y}}{GDP\ per\ capita_{i,2015}} \quad (6)$$

where abbreviations are a country i, sector s, fuel f, transport mode m, pollutant p and year y for which damages are estimated.

Total damage costs due to air pollution were calculated using Equation (7):

$$Total\ damage_{i,s,f,m,p,y} = Damage\ cost_{i,s,f,m,p,y} * Total\ emissions_{i,s,f,m,p,y} \qquad (7)$$

The sum of damages from all pollutants represent the total damage caused by air pollution in each country. The resulting values for all countries and all pollutants were then converted from USD_{2017} to $€_{2017}$ using the average exchange rate for 2017 of USD/€ = 1.0834 (IRS, 2020).

Total damage costs related to air pollution are then estimated for the entire transition period of 2015 to 2050 by using damage costs per ton of pollutant calculated by Equation (6) accounting for GDP growth in each country.

3.4. Estimating mortality

In addition to damages caused by air pollution, the IMF (Parry *et al.*, 2014) also provides mortality rates of different pollutants per ton of emission from coal, fossil oil products, and fossil gas. In this research, arithmetic mean of mortality rates for coal, fossil gas, and oil products were adopted and the resulting values per ton of NO_x, SO_x, and $PM_{2.5}$ were used. Mortality rates of exposure to coarse particulate matter were not provided, so they were obtained by substituting intake fractions of $PM_{2.5}$ to those of PM_{10} in the data (Parry *et al.*, 2014). The intake fraction of PM_{10} was obtained from Humbert *et al*. (2011). Mortality rates for each pollutant for all regions are in the Appendix (Table A15).

Mortality rates per ton of pollutant p from fuel f in sector s or transport mode m were used to estimate the number of deaths in a country i in year y attributable to air pollution according to Equation (8):

$$Total\ number\ of\ deaths_{i,s,f,m,p,y} = Mortality\ rate_{i,s,f,m,p} * Total\ emissions_{i,s,f,m,p,y} \qquad (8)$$

Sum of deaths attributable to each pollutant represents the total number of deaths in a country as a result of poor air quality. These calculations do not take into account the number of people dying, years after being exposed to pollutants, but merely estimates the number of newly caused deaths. In reality the value may be much higher, and some impacts of air pollution may manifest themselves years later (Hansell *et al.,* 2016). Mortality rates per ton of pollutant were assumed to stay steady for the whole period of the energy transition from 2015 to 2050.

4. Results

Firstly, total air pollutant emissions from all three sectors, power, heat, and transport, are presented for 2015, followed by projected developments. Thereafter, a detailed description of pollutant emissions from each source. Economic damages caused to countries due to air pollution is presented next. Finally, impact on mortality is presented in terms of deaths annually as a result of exposure to polluted air.

4.1. Total air pollutant emissions

This research has found that the current energy system, which is heavily reliant on fossils emits enormous amounts of harmful pollutants. As indicated in Figure 2, NO_x emissions are distributed among different sources with road, rail, and marine transport being the largest polluters and other sectors making significant contributions. SO_x emissions are mainly emitted from combustion of coal in the power and heat sectors, along with marine transport. Majority of $PM_{2.5}$ and PM_{10} emissions arise from traditional biomass used for cooking in developing countries and coal combustion. As the energy transition progresses, emissions of all four pollutants start to decline and by 2050 drop by 83.5-99.8% (see Figure 2).

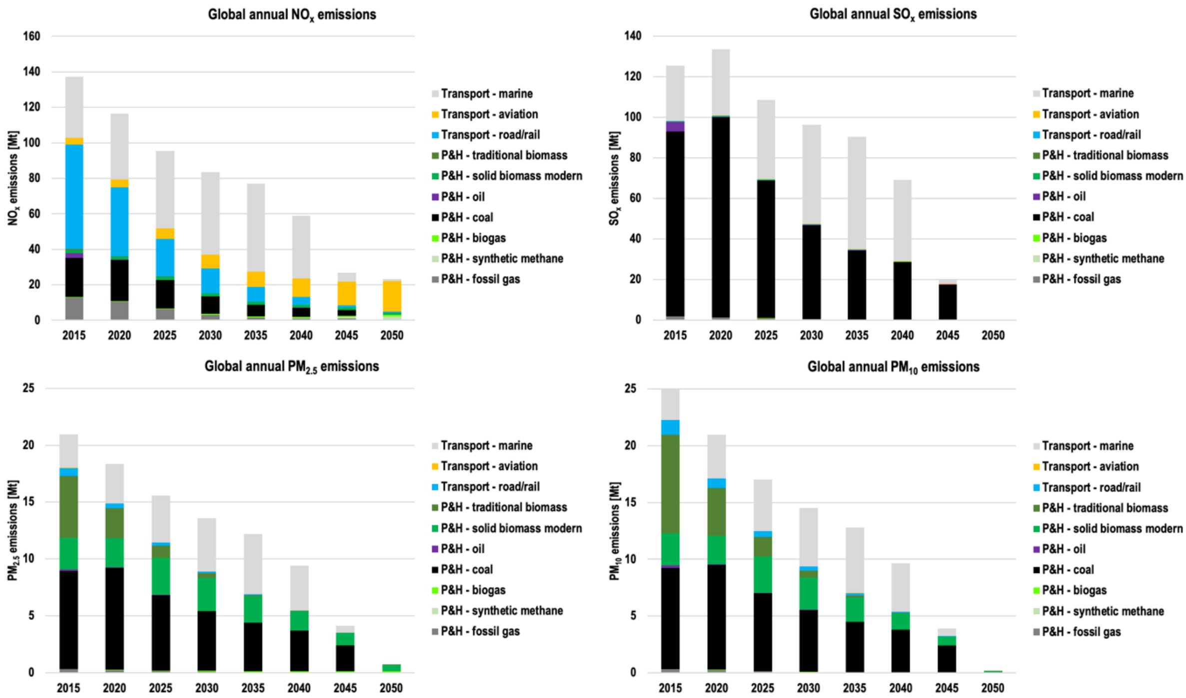

Figure 2. Annual global emissions of NO_x (top left), SO_x (top right), $PM_{2.5}$ (bottom left) and PM_{10} (bottom right) during the energy transition.

In 2015, total NO_x emitted globally is 137 Mt as shown in Figure 3 with developed countries such as France, Germany, the United Kingdom and large emerging economies such as India and China being the largest emitters. In 2050, total NO_x emissions dropped by 83.5% to 23.3 Mt annually as a consequence of the transition towards 100% RE. The global distribution highlights a cleaner world in 2050. Combustion of synthetic jet fuel contributes the lion share of NO_x emissions in 2050.

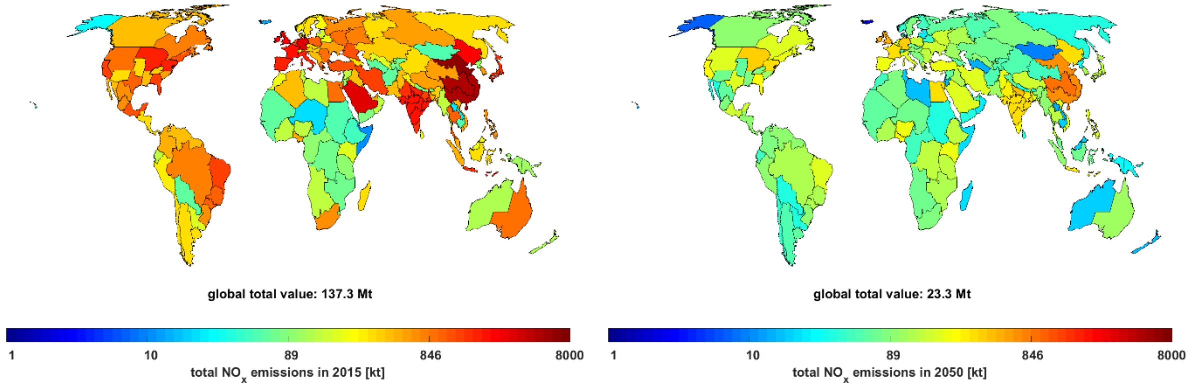

Figure 3. Global distribution of NO_x emissions in 2015 (left) and 2050 (right) for the entire energy system.

In 2015, SO_x emissions are at 125 Mt per year as indicated in Figure 4 and are predominantly in Northeast and South Asia, Eastern Europe, CIS, but also Saudi Arabia and South Africa. As the largest contributor to SO_x emissions, coal, is phased out, and marine transport, the second largest contributor, shifts to synthetic fuels, the emissions practically disappear to almost zero by 2050.

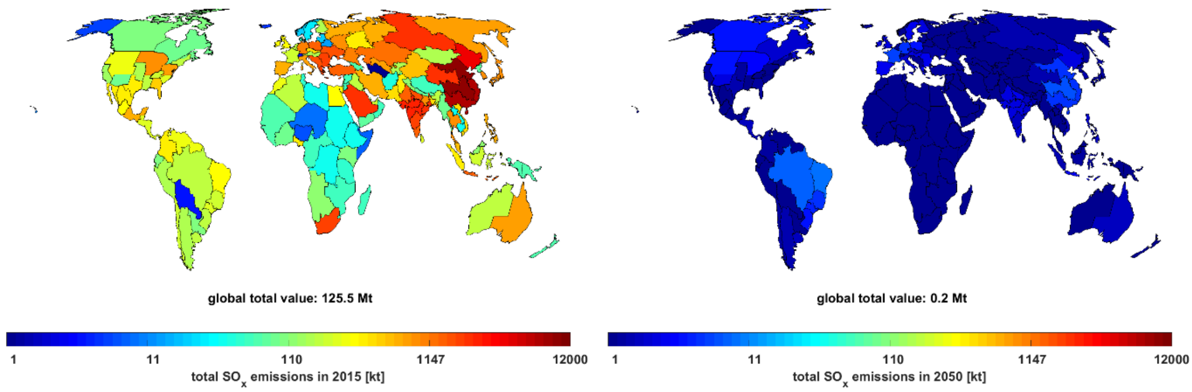

Figure 4. Global distribution of SO_x emissions in 2015 (left) and 2050 (right) for the entire energy system.

$PM_{2.5}$ and PM_{10} emissions that can penetrate deeply into human lungs are especially harmful to human health. In 2015, emissions are 20.95 Mt for $PM_{2.5}$ and 25.5 Mt for PM_{10} per year, with the former declining by 96.7% to 0.7 Mt per year by mid-century and the latter declining by 99.4% to 0.2 Mt annually as demonstrated in Figure 5. This is due to high electrification rates of transportation and phasing out fossil fuels in the power and heat sectors. $PM_{2.5}$ and PM_{10} do not totally disappear as the use of modern biomass for power generation and heat supply increases, which is prevalent in densely populated and Northern regions where it is used due to its availability, but also due to its cost-attractiveness (Mensah *et al.*, 2021; Child *et al*., 2020). The values are, however, low due to the use of advanced abatement techniques in biomass utilisation.

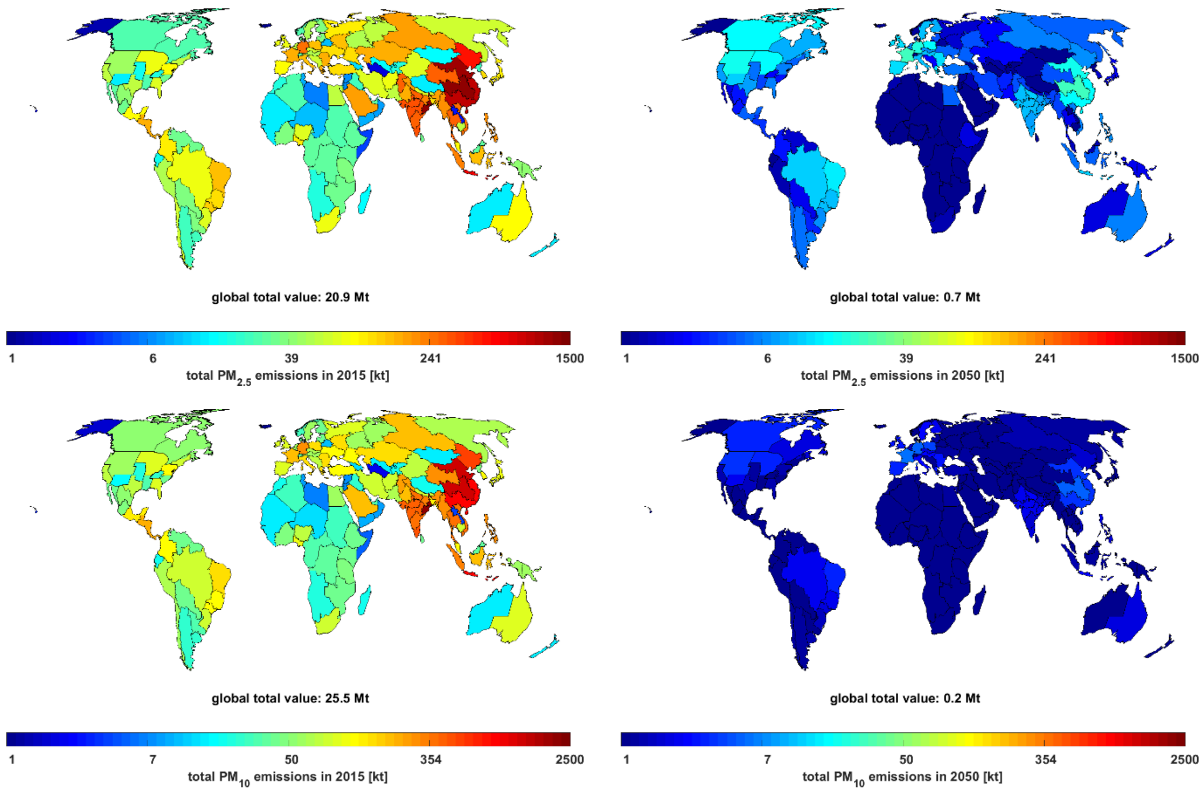

Figure 5. Global distribution of $PM_{2.5}$ (top) and PM_{10} (bottom) emissions in 2015 (left) and 2050 (right) for the entire energy system.

The next part of the results section shows more detailed views on pollutants emitted by each sector.

Coal-based power and heat production was found to be the largest contributor of emissions. In 2015, emissions from coal are 22 Mt of NO_x, staggering 91.1 Mt of SO_x, 8.6 Mt and 8.9 Mt of fine and coarse particulate matter, respectively. These emissions are found to harm millions of people globally with densely populated regions of South and Northeast Asia being hit especially hard, as coal is used extensively and is the most abundant energy source in these regions. As indicated in Figure 6 the CIS countries, European countries, and North America also contribute significantly to total pollutant emissions. However, in a global BPS energy transition to 100% renewables, coal is rapidly phased-out after 2020s. By 2030 coal-related emissions are already at less than 50% levels compared to 2015 and they disappear by 2050, as shown in Figure 2 and the Appendix (Figure A1).

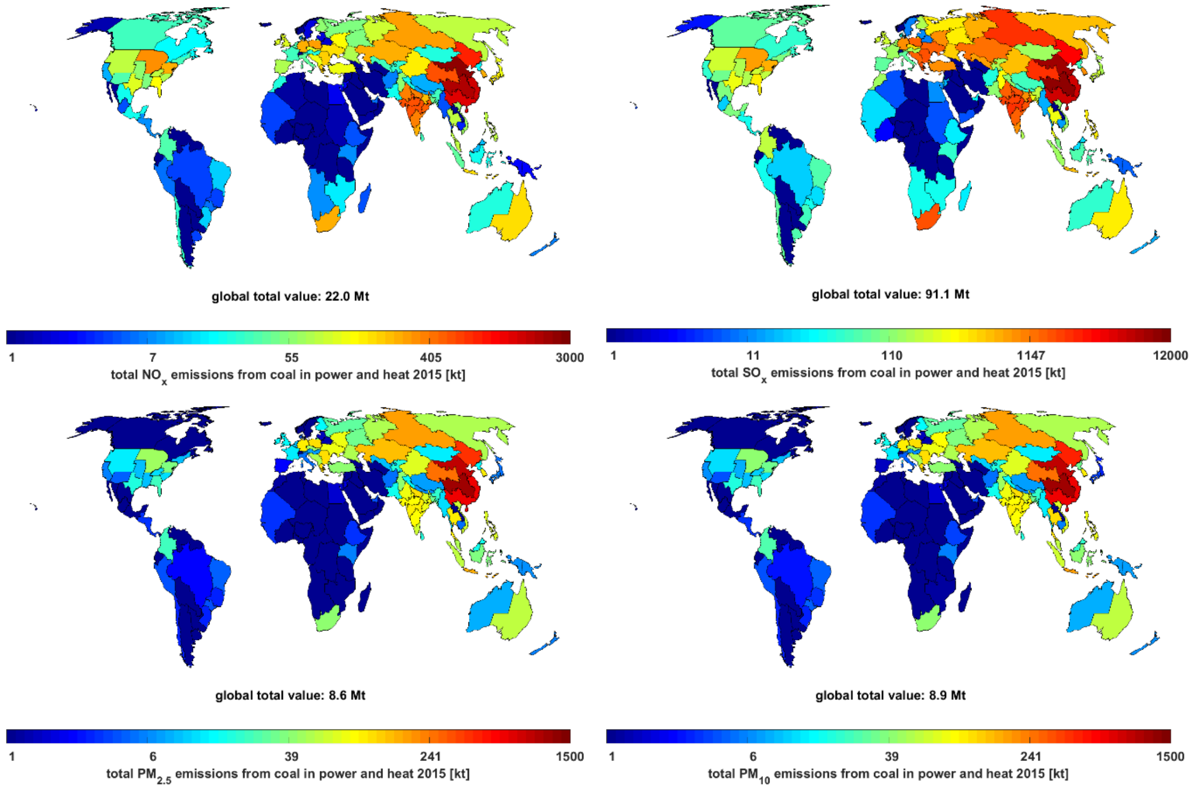

Figure 6. Global distribution of NO_x (top left), SO_x (top right), $PM_{2.5}$ (bottom left) and PM_{10} (bottom right) emissions from coal-based power and heat production in 2015.

Fossil gas-based power and heat supply contributes substantially to air pollution. NO_x volumes emitted from fossil gas combustion are considerable at 13 Mt annually in 2015. Gas has lower sulphur content than coal with some variations from one region to another, so the volumes of SO_x emitted are considerably lower at 1.8 Mt in 2015. $PM_{2.5}$ and PM_{10} are emitted at 0.3 Mt per year each. As indicated in Figure 7, pollutant emissions are distributed fairly around the world but there is a pattern of more developed countries of Europe, North America and MENA having higher emissions form natural gas compared to less developed regions of the world. Emissions from the combustion of natural gas decline rapidly through the transition and as fossil gas is phased out entirely by 2050, air pollutant emissions also disappear as shown in the Appendix (Figure A2).

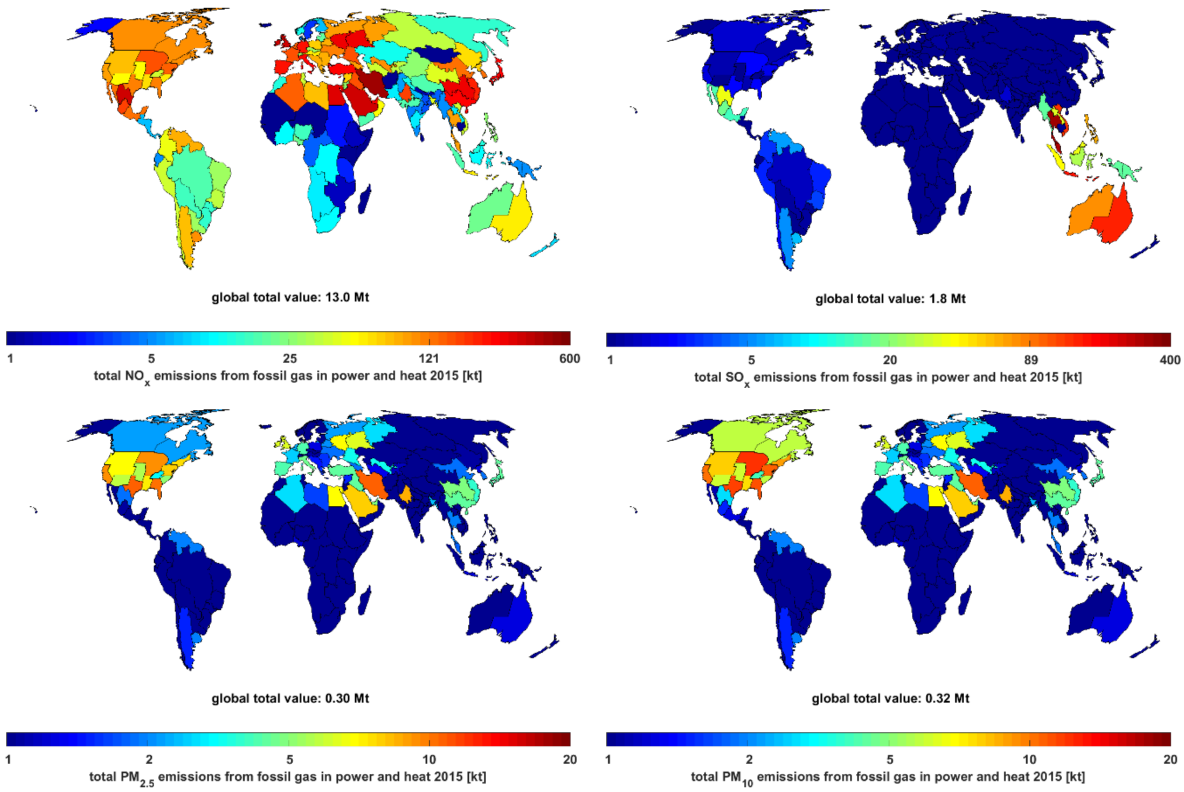

Figure 7. Global distribution of NO_x (top left), SO_x (top right), $PM_{2.5}$ (bottom left) and PM_{10} (bottom right) emissions from fossil gas-based power and heat production in 2015.

Oil is another fuel that contributes significantly to air pollution globally. Its distribution varies across different regions as it is not used for power and heat production as extensively as other energy sources. However, it is used in some countries of the MENA region, and to a lesser extent in North America and Eurasia. In 2015, NO_x emissions from oil combustion are 2.9 Mt as can be seen in Figure 8. SO_x emissions are 4.7 Mt per year, while $PM_{2.5}$ and PM_{10} emissions are 0.2 Mt annually each. Development of emissions from oil use through the transition can be found in the Appendix (Figure A3).

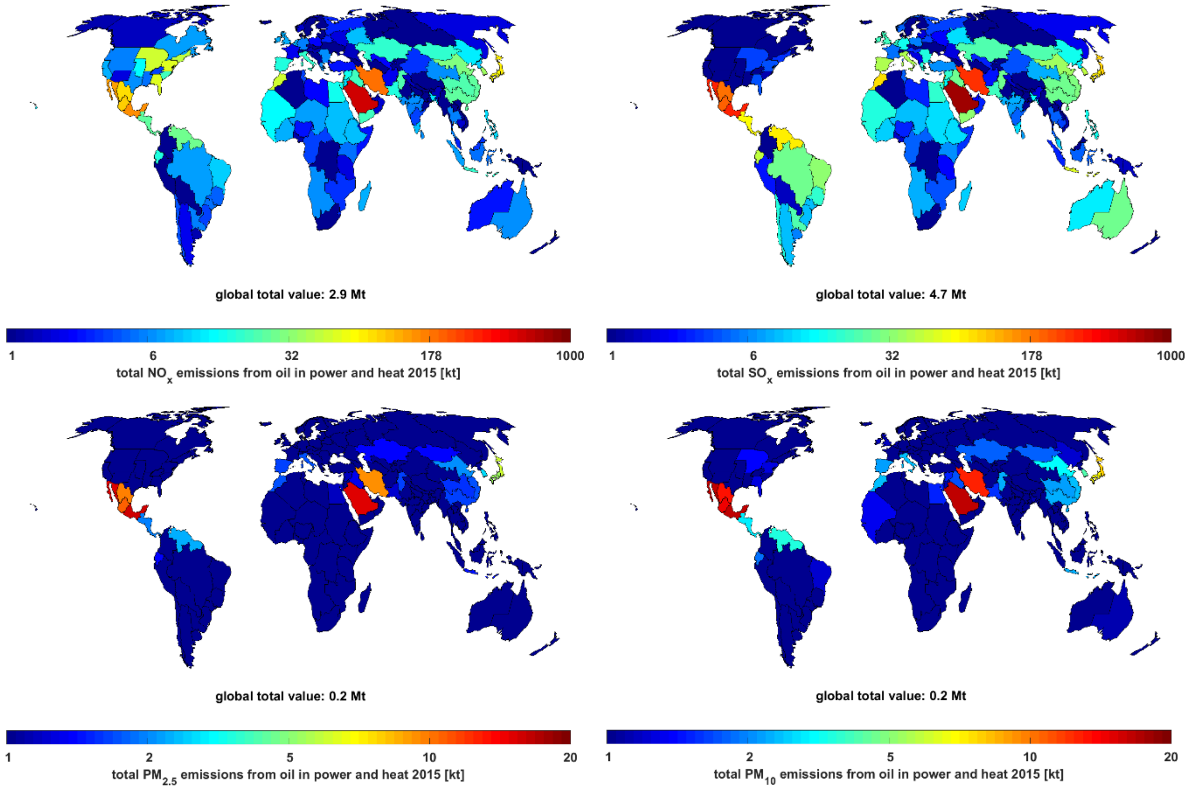

Figure 8. Global distribution of NO_x (top left), SO_x (top right), $PM_{2.5}$ (bottom left) and PM_{10} (bottom right) emissions from oil-based power and heat production in 2015.

Modern solid biomass is not used in the global energy system as extensively as coal, oil, and fossil gas and thus, emissions are considerably lower. However, this energy source emits significant amounts of both fine and coarse particulate matter. $PM_{2.5}$ emissions are at 2.8 Mt per year in 2015. By mid-century, solid biomass $PM_{2.5}$ emissions are expected to decline by 80% to 0.6 Mt per year. NO_x emissions from modern biomass fall from 1.5 Mt per year in 2015 to 1.2 Mt in 2050, whereas SO_x from 0.17 Mt to 0.14 Mt during the same period, as shown in the Appendix (Figure A4). PM_{10} emissions from biomass combustion decline significantly from 2.8 Mt in 2015 to 0.1 by 2050, as highlighted in the Appendix (Figure A5). As indicated in Figure 9, air pollutant emissions from this source are well distributed around the world and unlike other energy resources its presence is more noticeable in sub-Saharan Africa and South America.

Pollutant emissions from biogas-based power and heat production are small in volumes in 2015 and do not experience strong changes over the years. More details are in the Appendix (Figure A6).

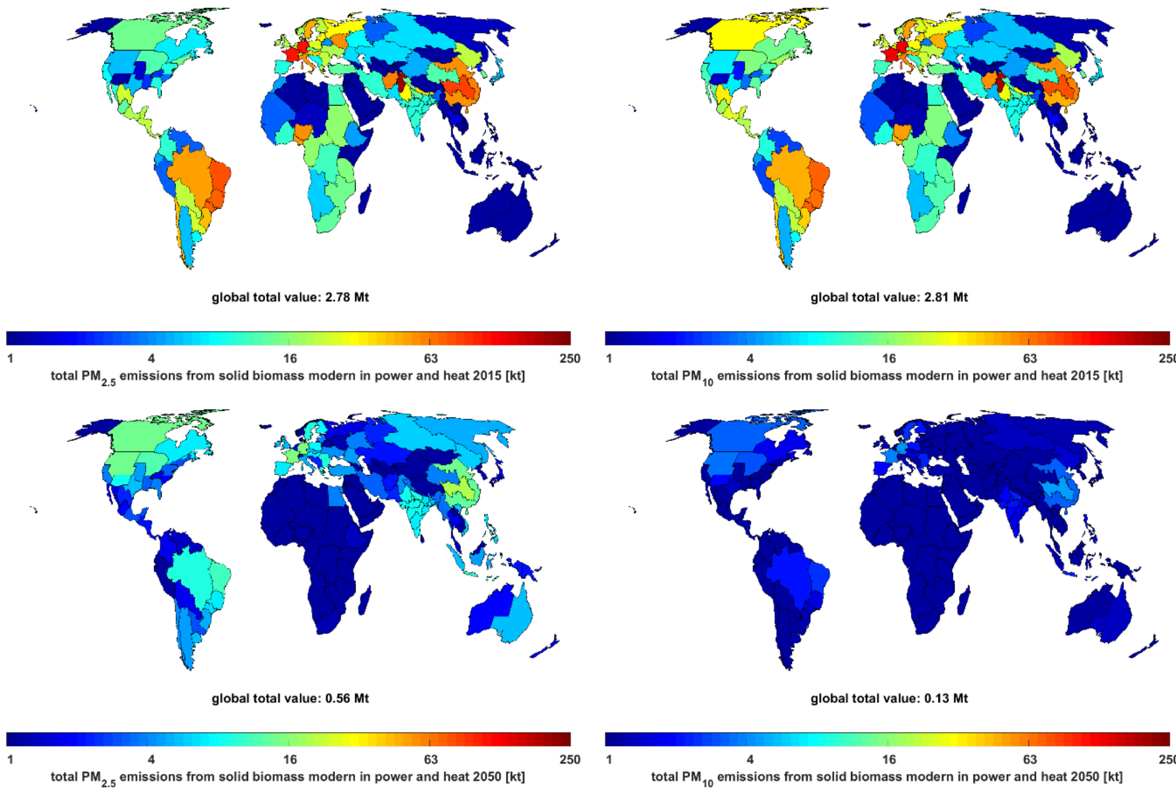

Figure 9. Global distribution of $PM_{2.5}$ (left) and PM_{10} (right) emissions from solid biomass in 2015 (top) and 2050 (bottom).

Traditional biomass used for cooking in developing regions is an important contributor to total pollutant emissions as indicated in Figure 10. Emissions of NO_x and SO_x are relatively small, but traditional biomass use leads to significant emissions of particulate matter. Annually, 5.4 Mt of $PM_{2.5}$ and 8.7 Mt of PM_{10} are emitted in the initial period of the energy transition, mainly in developing regions of sub-Saharan Africa, Latin America, and Asia. Majority of these emissions are observed in South Asia, where population densities are high, which subsequently leads to higher rates of pollution-induced mortality (Clean Cooking Alliance, 2020). Emissions decline over the years as can be seen in the Appendix (Figure A7).

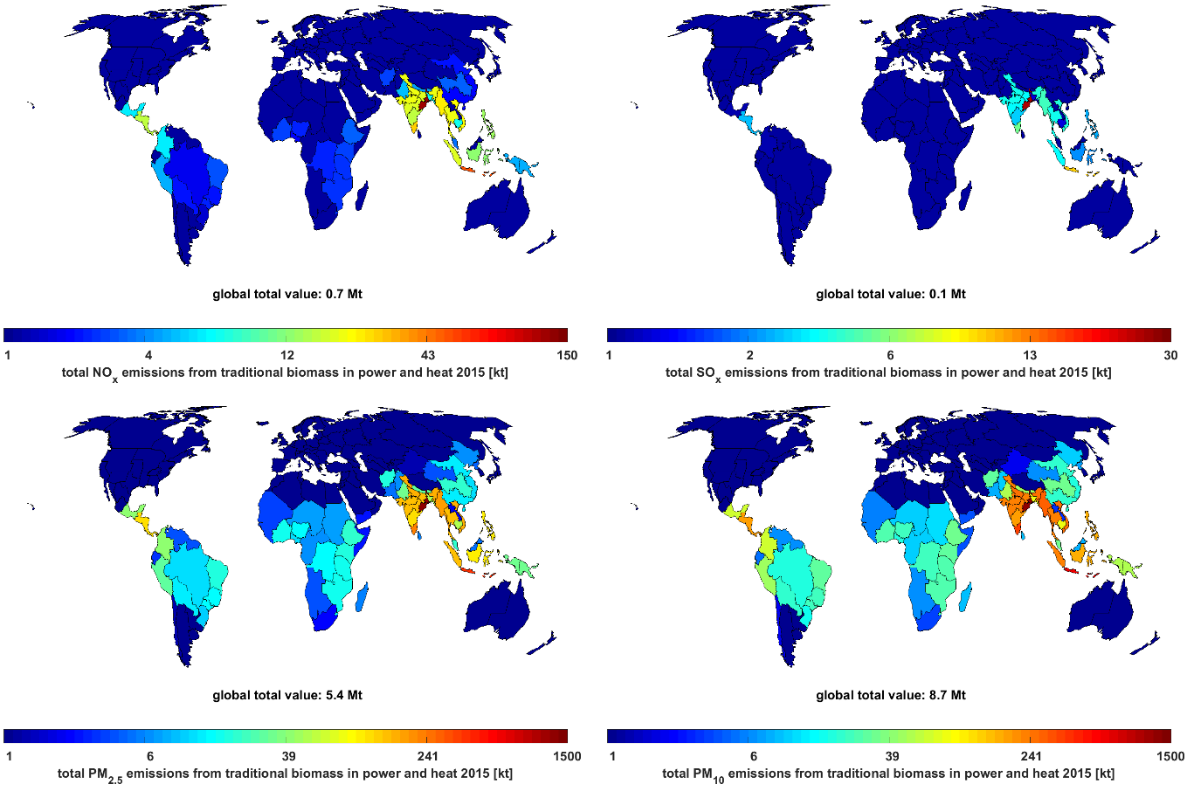

Figure 10. Global distribution of NO_x (top left), SO_x (top right), $PM_{2.5}$ (bottom left) and PM_{10} (bottom right) emissions from traditional biomass use in 2015.

As fossil fuels are phased out during the transition, synthetic methane gains prominence mainly providing seasonal storage. Although synthetic methane has net zero GHG emissions, it contributes to NO_x emissions as indicated in Figure 11 (right). In 2015 this fuel is not used extensively with zero emissions, but as consumption grows, emissions reach 2.34 Mt by mid-century. Detailed development of emissions is presented in the Appendix (Figure A8).

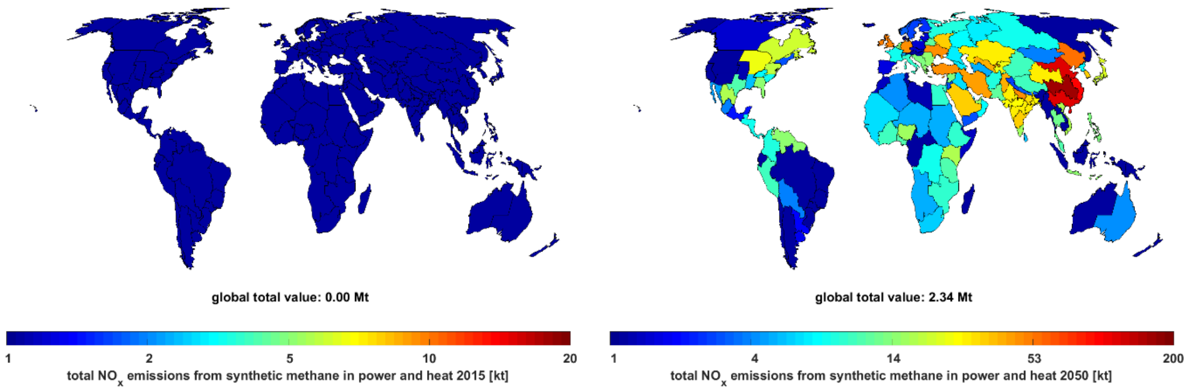

Figure 11. Global distribution of NO_x emissions from synthetic methane in 2015 (left) and 2050 (right).

Distribution of total pollutant emissions from power and heat sectors can be found in the Appendix (Figure A9).

The transport sector has strong impacts on air pollution levels globally. All four main pollutants investigated in this research have very high volumes in 2015 and gradually decrease over the years. NO_x emissions decline by about 80% and SO_x, $PM_{2.5}$ and PM_{10} emissions reach zero by mid-century. Road and rail transport modes experience rapid defossilisation and decrease in air pollutant emissions, due to the relative ease at which they are electrified. Marine and aviation transport on the other hand are sectors, which experience the transition at a later stage due to their strong reliance on liquid hydrocarbons, especially with long distances.

As indicated in Figure 12, road transportation contributes an enormous volume of NO_x. Its shares are fairly distributed around the world with some of the regions characterised by higher population density and more developed economies contributing more than other regions. Western European nations, India, China, parts of North and South America contribute significantly to the total emissions. SO_x, $PM_{2.5}$ and PM_{10} emissions are lower than that of NO_x, at 0.1, 0.7, and 0.9 Mt per year, respectively. Emissions decrease sharply already by 2030, where they are 80% lower compared to 2015 levels. By 2050, road transport emissions of SO_x, $PM_{2.5}$ and PM_{10} are zero, while NO_x emissions drop by 99.6% to 0.17 Mt. Details on the decline of emissions from the transport sector are in the Appendix (Figure A10).

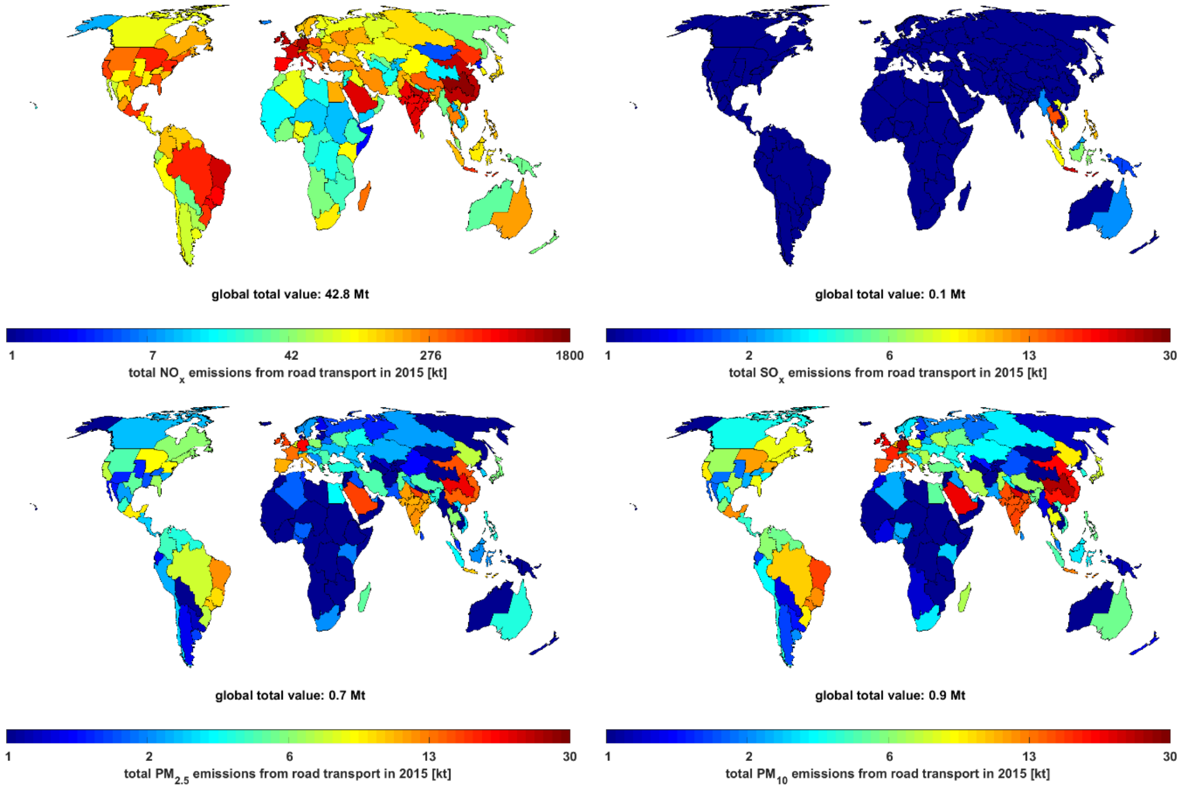

Figure 12. Global distribution of NO_x (top left), SO_x (top right), $PM_{2.5}$ (bottom left) and PM_{10} (bottom right) emissions from road transport in 2015.

Rail transport emissions develop similar to the road transport mode, as they contribute 15.9 Mt of NO_x, 0.06 Mt of SO_x, 0.06 Mt of $PM_{2.5}$ and 0.4 Mt of PM_{10} annually in the beginning of the energy transition period as can be seen in Figure 13. Emissions rapidly decrease with NO_x reaching 0.5 Mt per year and other pollutants reaching zero by mid-century. More details are in the Appendix (Figure A11).

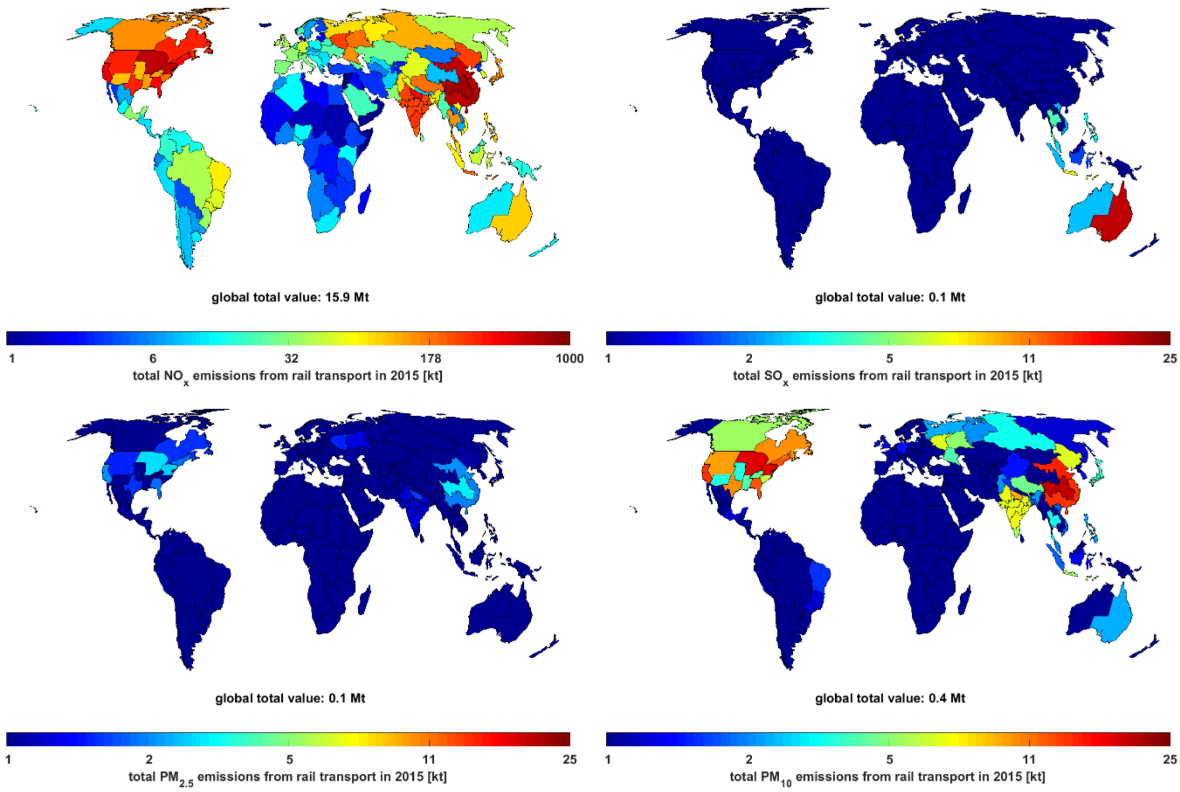

Figure 13. Global distribution of NO_x (top left), SO_x (top right), $PM_{2.5}$ (bottom left) and PM_{10} (bottom right) emissions from rail transport in 2015.

As opposed to road and rail transportation, marine transportation's contribution to air pollution around the world is significantly higher. This is due to the complexity of substituting fossil-based liquid hydrocarbons by batteries or other sources of energy for long distances and hauling heavy loads. In addition, leftovers from oil refineries are still used as marine fuel, which leads to enormous and toxic emissions. Thus, development of emissions from marine transportation follows a different trend than road and rail transportation, as observed in the Appendix (Figure A12). In 2015, NO_x, SO_x, $PM_{2.5}$ and PM_{10} emissions contribute 34.5, 27.2, 3.0 and 3.2 Mt per year, respectively. As opposed to other sources of pollution, emissions from marine sector activity continue to grow after 2015 and peak in 2035, with staggering 49.6 Mt of NO_x, 55.3 Mt of SO_x, 5.3 Mt of $PM_{2.5}$ and 5.8 Mt of PM_{10}. Emissions are mainly concentrated in coastal regions and are not present deep in-land. However, the distribution is fair among coastal regions as most of them engage in international maritime trade. From 2030s onwards, production capacities of synthetic fuels enlarge as costs continue to decline enabling passenger and cargo vessels to switch and defossilise. Rapid contraction in use of dirty oil products leads to 1.3 Mt of NO_x emissions annually and zero emissions of SO_x, $PM_{2.5}$, and PM_{10} by 2050.

Trajectory of emissions development of aviation transport activities follows the marine industry, as can be seen in Figure 14. Emissions from the aviation sector are lower compared to other transport modes, at levels of 3.8 Mt of NO_x, 0.2 Mt of SO_x, 2.1 kt of $PM_{2.5}$ and 6.1 kt of PM_{10}. Figures for emissions other than NO_x can be found in the Appendix (Figure A13). Emissions are distributed around the world in such way that developed economies emit more pollutants than developing countries with the United States, Europe, and China being the largest emitters, while many African countries the least. As quality of life in many regions improves with growing middle class, passenger traffic as well as shipping of goods increases rapidly peaking in 2035. Thereby, NO_x is at 8.7 Mt annually, SO_x at 0.44 Mt per year, $PM_{2.5}$ and PM_{10} at 7.5 and 21.6 kt respectively per year. Similar to marine transport, emissions of SO_x, $PM_{2.5}$ and PM_{10} rapidly decline to zero by mid-century. The notable exception is NO_x that grows to 16.8 Mt per year by 2050, an increase of 343% compared to the level in 2015. As fossil fuels are phased out, the aviation industry increasingly relies on FT fuels for long-haul flights, which results in increasing NO_x emissions.

Total emissions and their distribution in 2015 and 2050 can be found in the Appendix (Figure A14).

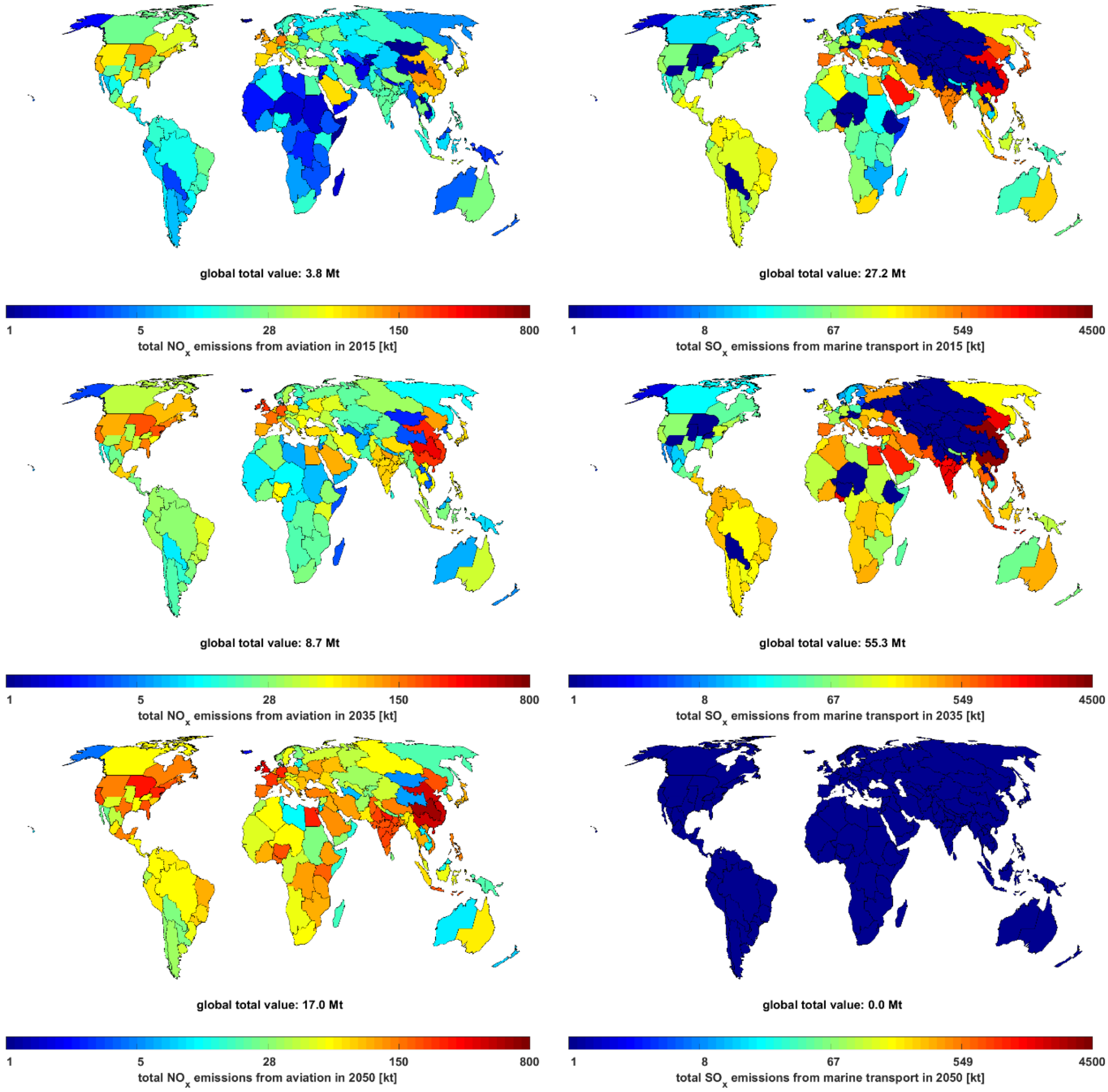

Figure 14. Global distribution of NO_x emissions from aviation (left) and SO_x emissions from marine (right) in 2015 (top), 2035 (centre), and 2050 (bottom).

4.2. Damage costs from air pollution

The resulting damage costs were calculated using the cost of damage for each pollutant and the total emissions of NO_x, SO_x, $PM_{2.5}$ and PM_{10} as described in the previous section. As indicated in Figure 15, air pollutant emissions cause damage of more than 4600 b€ every year and this value only continues to grow toward 2020, after which it stabilises at a value of around 5500 - 5900 b€ annually. This period is then followed by a period of decline in the 2040s and the annual damage costs at 530 b€ by 2050. Unlike total emissions that decrease through the transition period (Figure 2), damage costs stay stable for most of the years. This is primarily due to the dependence of damage costs in each country on corresponding GDP per capita values. During initial periods of the energy transition, emissions are the highest in developed countries such as Europe or North America that also have high GDP per capita. However, as emissions decline across developed regions, they grow rapidly in developing regions, where GDP per capita is expected to grow rapidly.

As indicated in Figure 15, shares of damages imposed by each sector stay roughly equal for almost the whole period with coal-based power and heat supply contributing the most to total damage costs. Through the transition period, coal consistently contributes more than 60% of damages and totally disappears in 2050. The second largest contributor is marine transportation with residual oil products and wastes from refineries as fuel, which produce large amounts of pollutants. With the switch to synthetic fuels these emissions disappear. By mid-century, the power, heat, and transport sectors phase out fossil fuels completely and thus the only sources of pollution and pollution-related damage costs are biomass and biogas-based power and heat production, as well as NO_x emissions from FT fuels and synthetic methane.

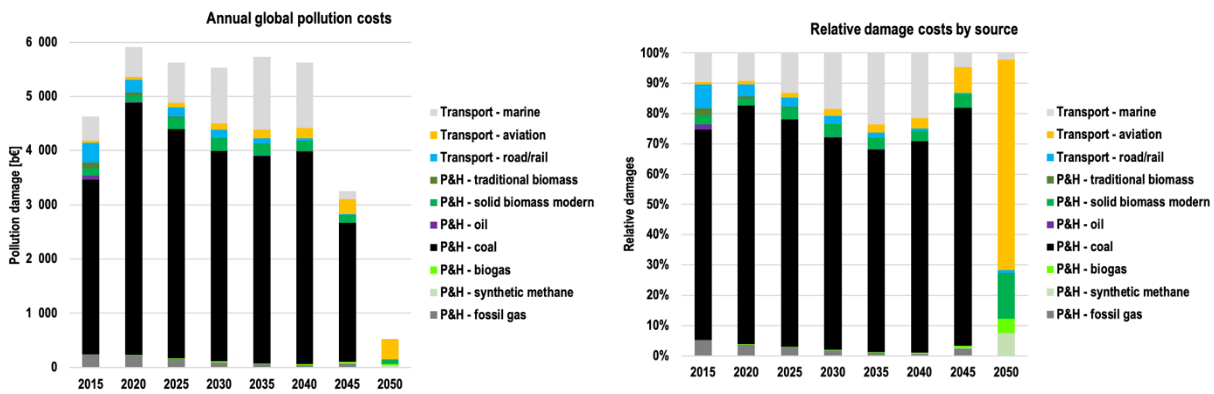

Figure 15. Annual global pollution costs during the energy transition period (left) and its relative shares (right) through the transition.

Damages from coal-based electricity and heat supply are 3200 b€ globally in 2015, representing about 3% of global GDP. Damage from coal is heavily inflicted on almost all regions across the world, apart from some regions that consume less energy in total such as sub-Saharan Africa or regions reliant on other sources of energy, such as MENA or Latin America. China, India, CIS and parts of Europe are heavily polluted by coal as shown Figure 16. By 2050, coal emissions almost disappear and so do corresponding damage costs.

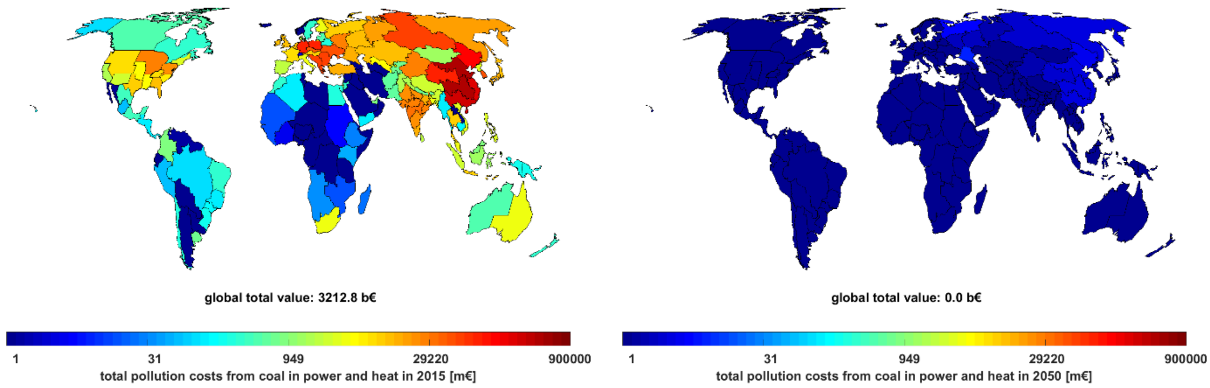

Figure 16. Total pollution costs from coal-based power and heat in 2015 (left) and 2050 (right).

Global damage costs from fossil gas-based electricity and heat supply are also significant with 243 b€ annually in 2015. These costs are distributed more evenly throughout the world, except for sub-Saharan Africa where damage costs are significantly lower than in other regions. The major damages caused by fossil gas in 2015 is in Europe, China, and North America being the regions with highest fossil gas consumption and highest GDP per capita values that translate to high pollution costs. However, fossil gas exits the energy system quite rapidly as electrification of the power and heat sectors increases and fossil fuels are substituted with renewables. Thus, damage costs decline through the transition to zero by 2050.

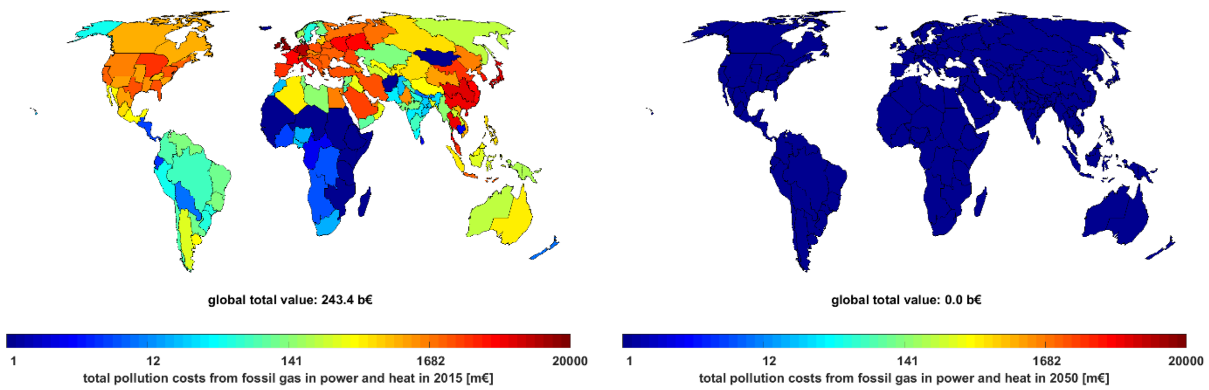

Figure 17. Total pollution costs from fossil gas-based power and heat in 2015 (left) and 2050 (right).

Damages imposed by oil are significant with 80 b€ globally in 2015 as shown in Figure 18. The distribution is fairly even around the world, except some regions such as Japan, Mexico, Iran and Saudi Arabia, where oil consumption for power and heat supply is higher than in other countries, which translates into higher damage costs. Damages done by oil in Saudi

Arabia alone are more than 20 b€ annually. As the energy transition proceeds, inefficient and costly oil-based power and heat plants are substituted by direct electricity from solar PV and wind turbines, and damage costs quickly contract reaching zero.

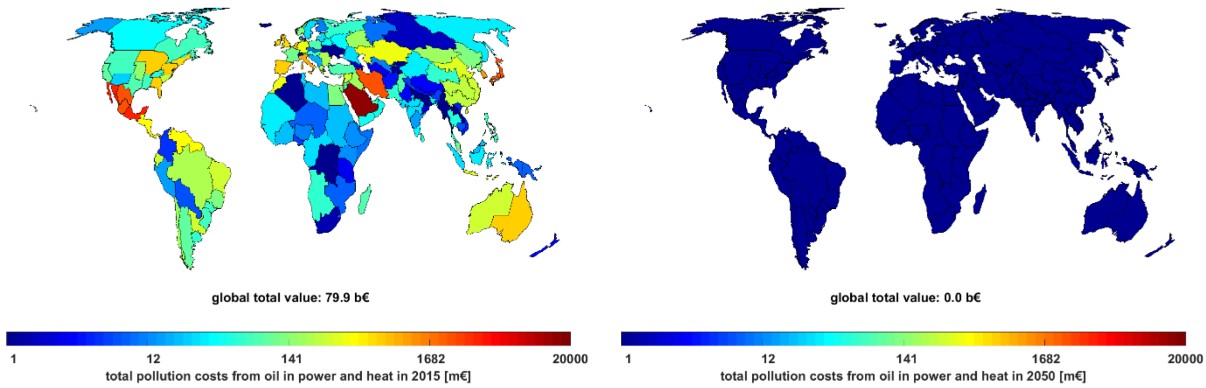

Figure 18. Total pollution costs from oil-based power and heat in 2015 (left) and 2050 (right).

Contribution of modern forms of solid biomass to total air pollution damages is also considerable as indicated in Figure 19, at 139 b€ annually in 2015. Regions with abundant resources utilise it to a higher extent and thus have higher damage costs. North and South America, Western and Northern Europe, as well as parts of China have the highest costs, which can be due to higher GDP per capita that directly impacts valuations of damages induced by pollution. By 2050, the overall costs worldwide decline to 80 b€ annually as the combustion efficiencies improve and more advanced technologies are adopted. Distribution of damage costs become more even compared to the levels in the beginning of the transition (see Figure 19).

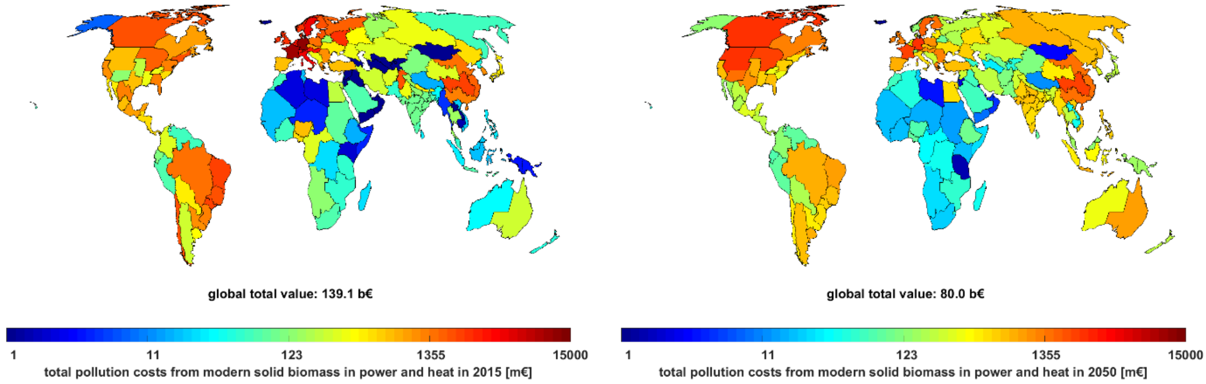

Figure 19. Total pollution costs from modern forms of solid biomass-based power and heat in 2015 (left) and 2050 (right).

Contrary to the overall trend of declining damage costs from energy sources, biogas demonstrates increasing relevance but also damage costs in all regions of the world. Total global value of damage induced by biogas utilisation grows 25-fold, from just 1.1 b€ per year in 2015 to 25.3 b€ per year in 2050 as is indicated in Figure 20. Presently, biogas is mainly available in some developed regions of Europe, North America and Oceania, but later in the transition its distributed wider as more countries begin utilising biomass and waste for biogas production. Thus, damage costs grow worldwide with the highest damages induced in Europe, North and South Americas, along with parts of Northeast Asia.

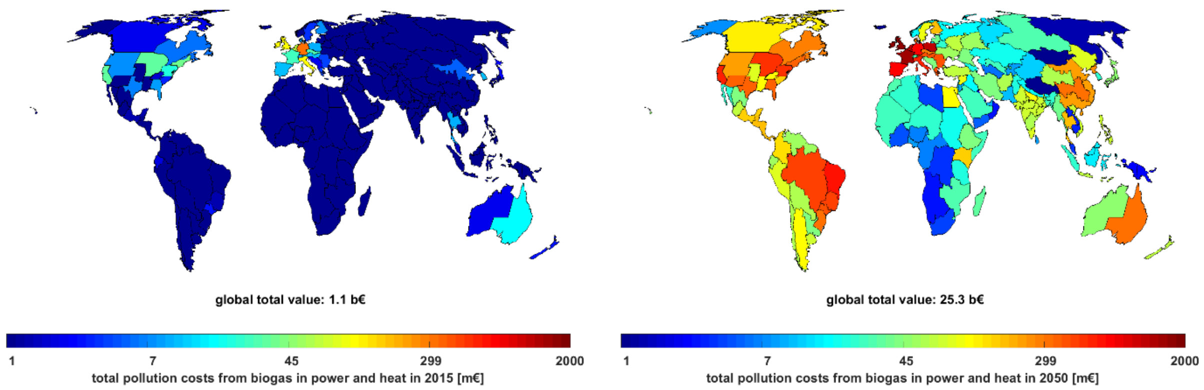

Figure 20. Total pollution costs from biogas-based power and heat production in 2015 (left) and 2050 (right).

As indicated in Figure 21, traditional forms of biomass use impact sub-Saharan Africa, Latin America, South and Southeast Asia the most since they are primarily used for cooking in developing countries. Damage costs are 99 b€ annually in 2015, but according to BPS projections the use of traditional biomass decreases and damage costs almost disappear by mid-century.

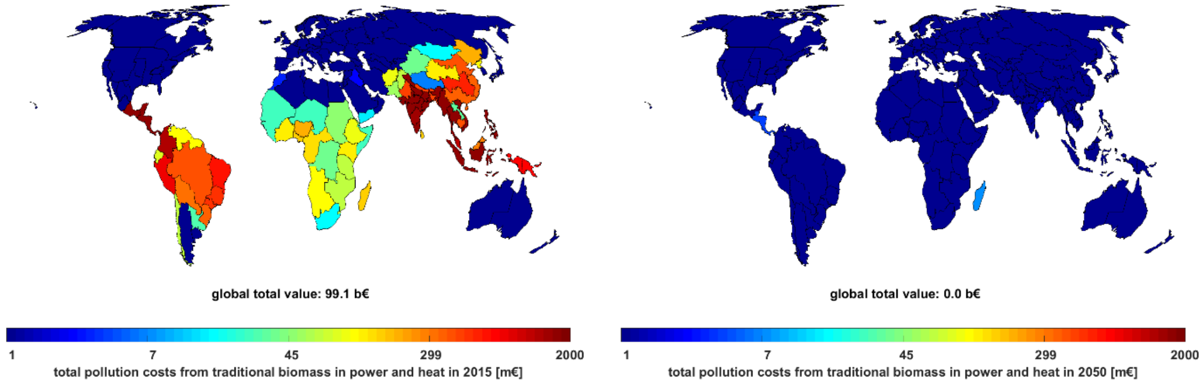

Figure 21. Total pollution costs from traditional biomass use for cooking in 2015 (left) and 2050 (right).

Synthetic methane produced from renewable electricity substitutes fossil fuels increasingly through the transition. Similarly, damage costs from RE-SNG grow from zero in 2015 to 39.8 b€ in 2050 annually as indicated in Figure 22.

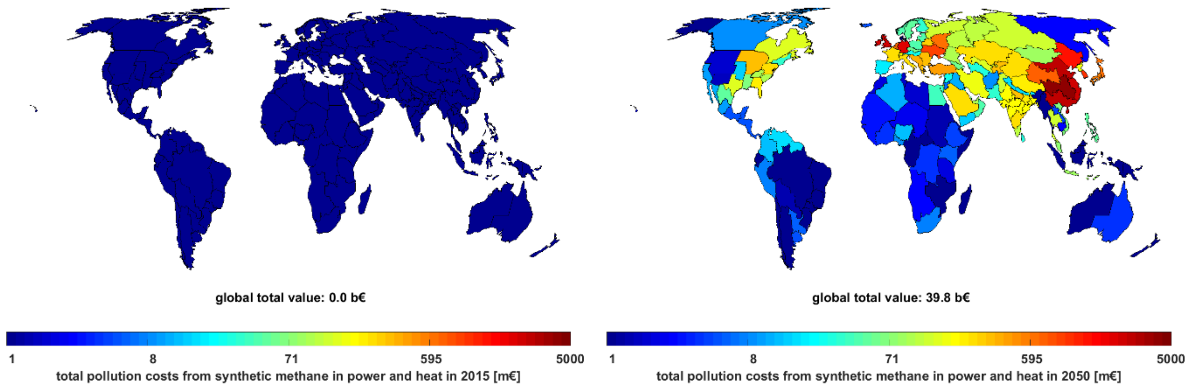

Figure 22. Total pollution costs from synthetic methane-based power and heat in 2015 (left) and 2050 (right).

The transport sector is another important contributor to total global air pollution and damages associated with it are also quite high. It is estimated to be responsible for about 20% of total costs associated with air pollution in the initial period of the transition. Rail and road transportation, in particular, contribute significantly all over the world. As indicated in Figure 23, global damages are 368 b€ annually in 2015 with both developed and developing regions around the world carrying large shares, except Africa that is relatively lower. Rail and road transport are the first to be electrified, so fossil fuels are phased-out at a faster pace than other modes of transport, hence damage costs decrease sharply. By mid-century, damage costs from these sources is 4.4 b€ as they are powered largely by renewable electricity or synthetic hydrocarbons.

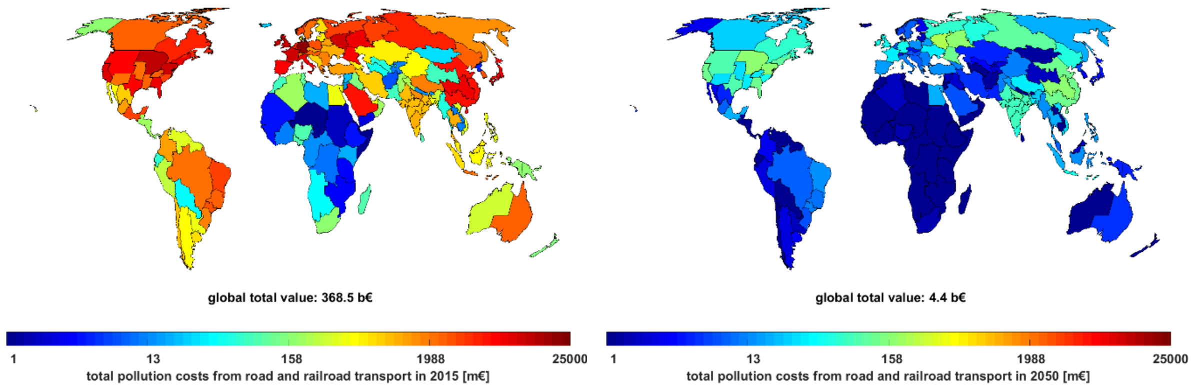

Figure 23. Total pollution costs from road and rail transport in 2015 (left) and 2050 (right).

As discussed previously, marine transportation is harder to defossilise and is reliant on energy-dense fuels for its long-range transportation, which makes it impossible to electrify directly in the same way as road and rail transportation. Transition of marine transportation to renewable sources of energy occurs after 2030s, when costs of producing synthetic fuels decline sufficiently and capacities grow rapidly. Thus, damages associated grow in the initial period of the transition and decline sharply in 2040s, before reaching 11.2 b€ in 2050. As most of the world engages in shipping, the distribution of damage costs is quite fair with the exception of some landlocked regions, as shown in Figure 24. Damages increase 3-fold globally from 438 b€ in 2015 to 1350 b€ in 2035 and then sharply fall in subsequent years.

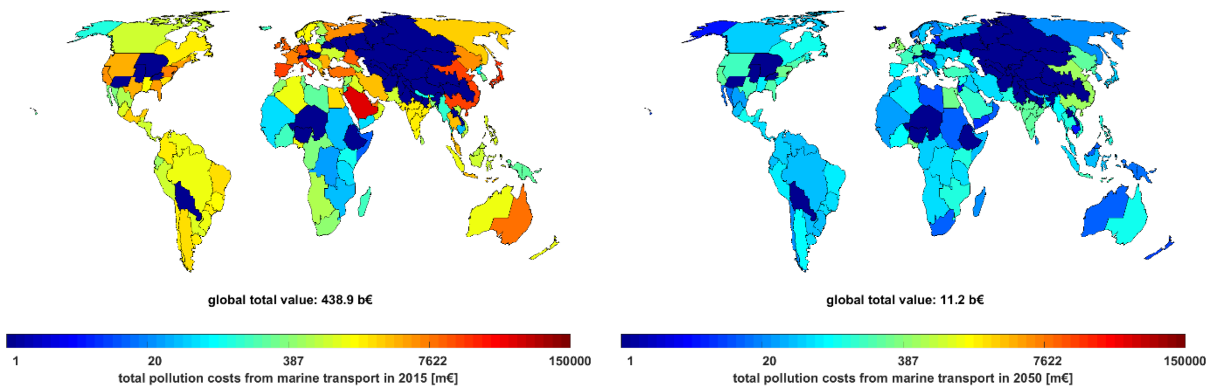

Figure 24. Total pollution costs from marine transport in 2015 (left) and 2050 (right).

Aviation follows a similar trajectory as marine transport, albeit at a much smaller scale. In 2015, global damage costs from aviation are 43 b€ annually and continue through the energy transition until they reach 369 b€ in 2050 and become the largest contributor to pollution-induced costs by mid-century as seen in Figure 25.

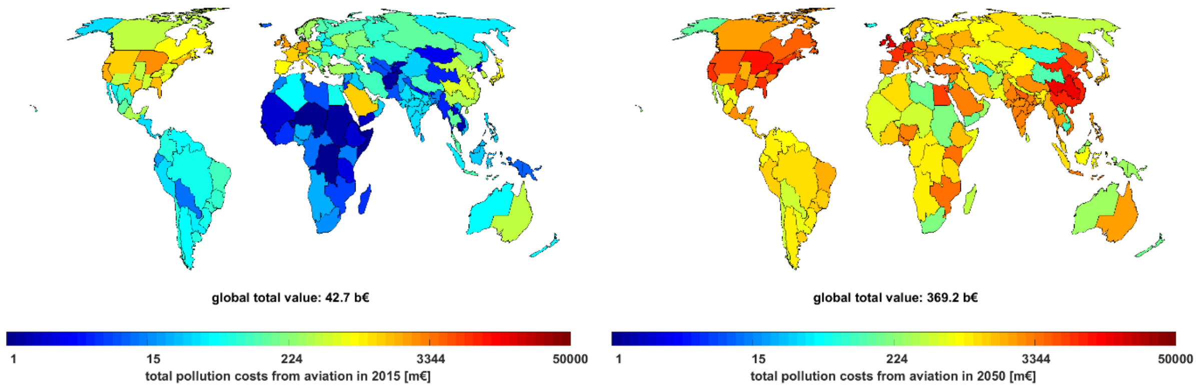

Figure 25. Total pollution costs from aviation in 2015 (left) and 2050 (right).

Total air pollution related damage costs of power, heat, and transport sectors are enormous at more than 5100 b€ in 2015. The peak is in 2020 at 6150 b€ worldwide, after which damage costs gradually decline. As observed in Figure 26, distribution of damage costs is uneven with highly industrialised countries contributing higher shares of total emissions along with higher GDP per capita bearing the most. Distribution of damage costs is more even in 2050, as developing countries catch up with well-developed countries in terms of energy consumption and GDP per capita. China is an exception with its significantly higher than average damage costs, as it is burdened by air pollution resulting from accelerated industrialisation with high population density. However, by 2050, regions across the world are almost free of the burden induced by air pollution and corresponding damage costs at 530 b€ per year, which is about 91% lower than the peak in 2020. Some regions with dense populations have higher damage costs, but the difference is not as striking as in the beginning of the energy transition.

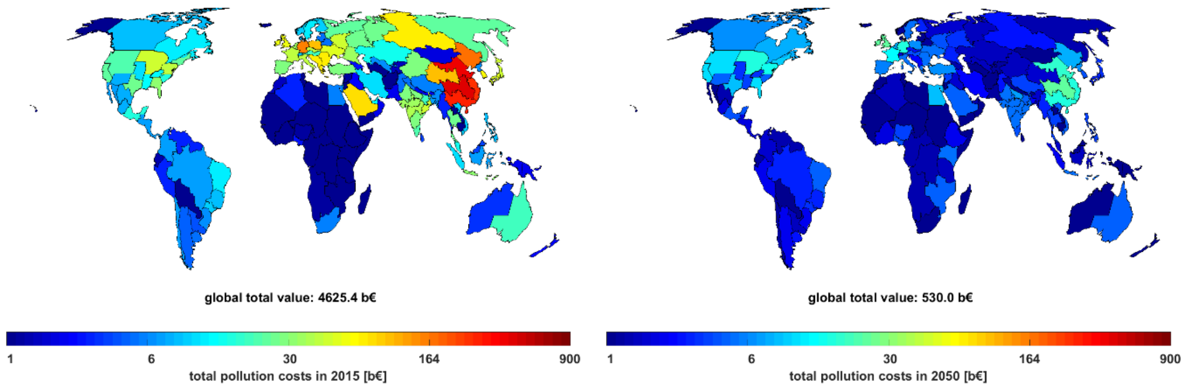

Figure 26. Total pollution costs from all sources in 2015 (left) and 2050 (right).

Development of pollution costs for different fuels and transport modes can be found in the Appendix (Figures A15-S20).

4.3. Mortality due to air pollution

Air pollution is becoming one of the most prominent causes of death with almost 5.2 million lives lost in 2015 alone, as indicated in Figure 27. However, with the transition to cleaner and more sustainable energy sources, deaths are expected to gradually decline until 2050 to about 150 thousand. Coal is known for its harmful air pollutant emissions and this research confirms its adverse effects on human health, as it is estimated to be responsible for about half of total deaths (around 2.6 million) from sources analysed in this research. Marine transport that consumes residual oils and wastes from refineries emits enormous amounts of air pollutants and causes substantial deaths globally. As fossil fuels are substituted by renewable forms of energy, air pollution from biomass and biogas utilisation in the power and heat sectors, and FT fuels and RE-LNG in the transport sector contribute to deaths in 2050.

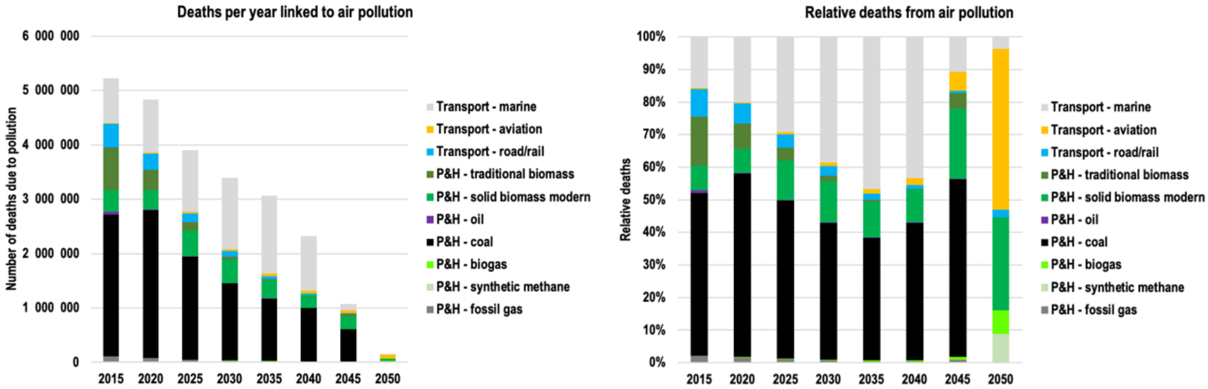

Figure 27. Number of deaths linked to air pollution (left) and shares of different contributors (right) during the transition.

In 2015, 2.6 million people fell victim to pollution from coal burning power plants around the world. As highlighted in Figure 28, the biggest burden of coal-based air pollution is borne by people living in parts of Europe, namely Germany and Poland, CIS, South Asia, and especially China. As the energy transition proceeds, coal is phased out and corresponding deaths decline to zero by 2050.

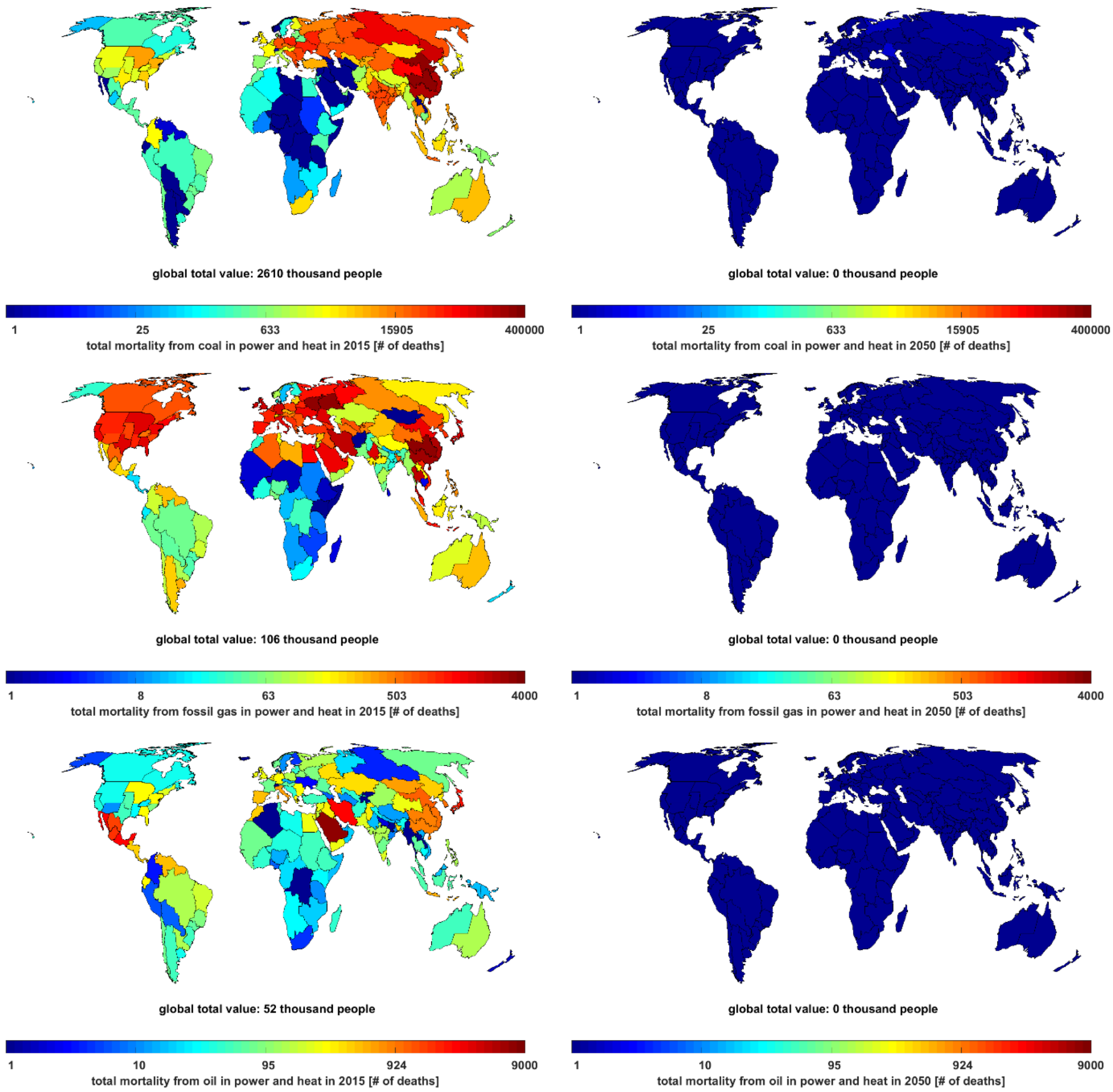

Figure 28. Total mortality from coal (top), fossil gas (centre), and oil (bottom) in 2015 (left) and 2050 (right).

Fossil gas and oil also contribute significantly to deaths caused by air pollution. As indicated in Figure 28, 106 thousand people die due to pollution caused by burning fossil gas and 52 thousand more due to emissions from oil in 2015. Gas-related deaths are more prominent in Europe, MENA, Northeast Asia and North America. Whereas, oil-related deaths occur in few regions such as MENA or Central America, where oil usage in the power and heat sectors is higher than the rest of the world. These two fossil fuels are phased out similar to coal, resulting in no deaths by 2050.

Solid biomass in modern forms of power and heat supply also contributes significantly to pollution-related mortality around the world with 400 thousand fatalities in 2015, which is rather evenly distributed across different regions as indicated in Figure 29. Solid biomass plays an important role in 100% renewable energy systems and is projected to grow further in its relevance for the energy system. Municipal solid waste, waste from agricultural and forestry sectors are all sustainable sources of energy that can and should be utilised in power and heat supply. Development of solid biomass combustion technologies and stringent emission standards lead to fewer emissions. Thereby, total mortality declines over the years to 43 thousand deaths annually in 2050.

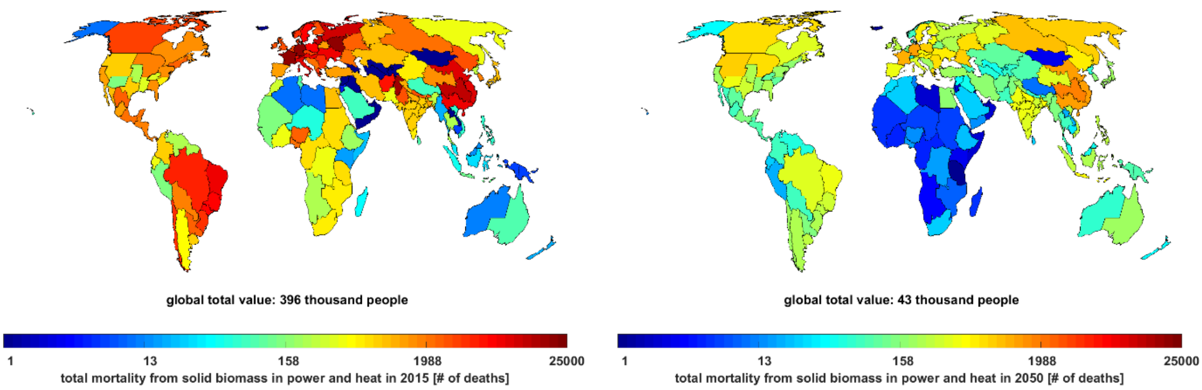

Figure 29. Total mortality from modern forms of solid biomass-based power and heat in 2015 (left) and 2050 (right).

Biogas too plays an increasingly relevant role in the energy system, and its contribution to total air pollution-induced deaths grows over the years. In initial periods of the transition, utilisation of biogas is low, therefore it does not significantly contribute and is accountable for just around 1000 deaths worldwide. As it is more broadly used across different regions, local air pollution increases and so does mortality. As indicated in Figure 30, by 2050 biogas causes 11 thousand deaths in different parts of the world every year, which is a significant number by itself, but much lower compared to other energy resources that it substitutes.

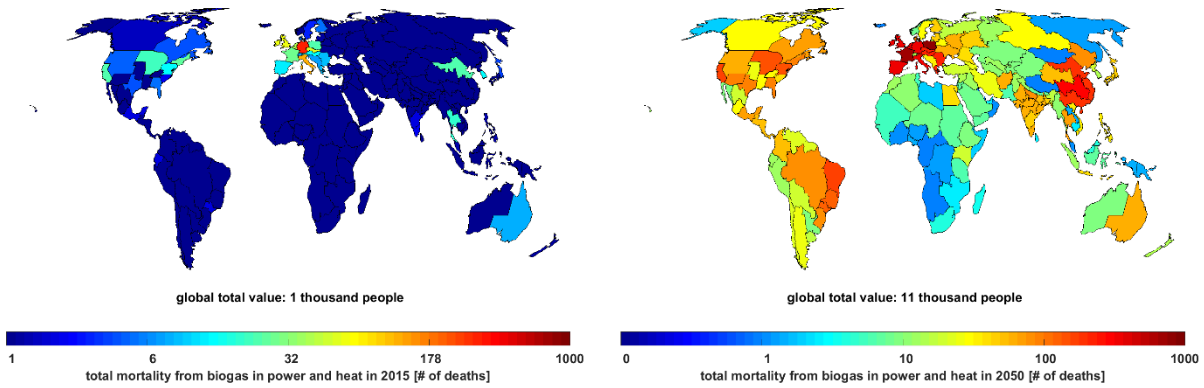

Figure 30. Total mortality from biogas-based power and heat in 2015 (left) and 2050 (right).

Emissions from traditional biomass for cooking are responsible for many pollution-induced deaths, especially in developing regions where access to modern forms of energy is limited and hundreds of millions of people continue to rely on traditional biomass for cooking (Clean Cooking Alliance, 2020). 780 thousand deaths occur annually in 2015, but as the traditional use of biomass is eliminated through the transition, newly caused deaths almost disappear by 2050 as indicated in Figure 31.

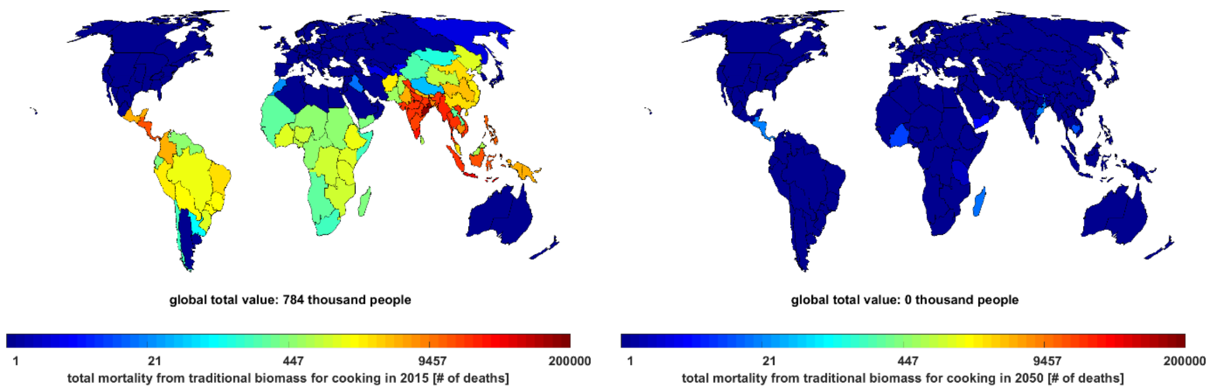

Figure 31. Total mortality from traditional biomass for cooking in 2015 (left) and 2050 (right).

Synthetic methane in the power and heat sectors does not contribute to mortality in 2015, but as its demand grows, so does the mortality as a result of its combustion and related emissions. By mid-century, 13 thousand deaths occur annually as indicated in Figure 32.

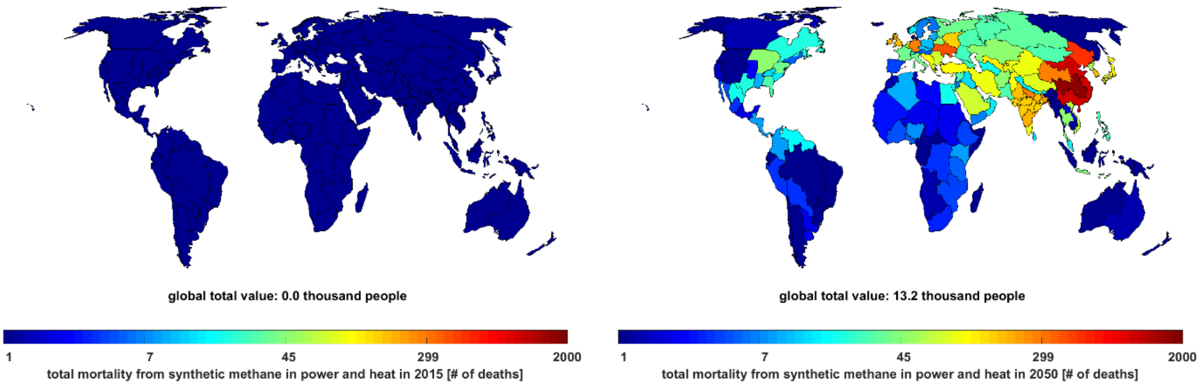

Figure 32. Total mortality from synthetic methane in the power and heat sectors in 2015 (left) and 2050 (right).

Air pollution from road transport causes more than 300 thousand deaths every year in 2015. These deaths are distributed evenly around the world with some exceptional regions that are densely populated being the most impacted. Highly developed regions with large number of private vehicles such as Germany, France, Saudi Arabia, and regions with very dense populations such as China and India, have considerably higher mortality rates than some of the less developed countries of sub-Saharan Africa or Latin America. However, mortality induced by air pollution from road transport declines through the energy transition in all regions of the world. As indicated in Figure 33, about 800 deaths annually by 2050 when all road transport is powered by renewable electricity and synthetic fuels.

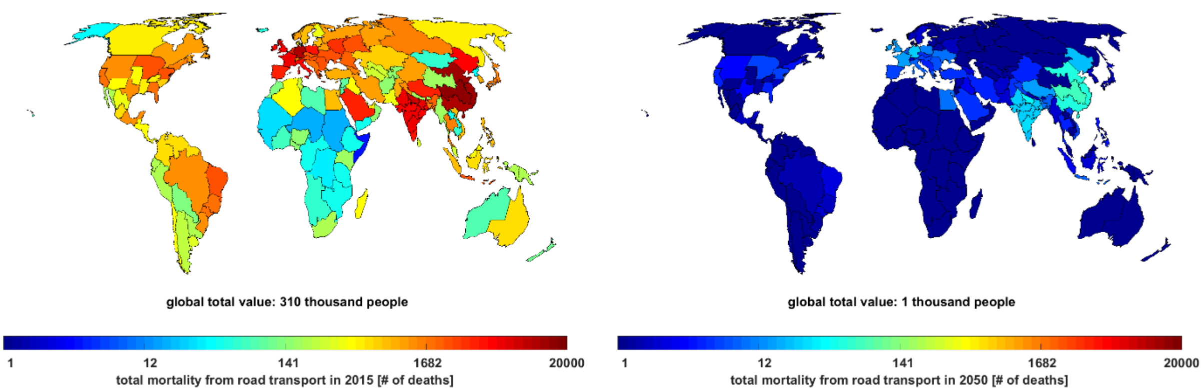

Figure 33. Total mortality from road transport in 2015 (left) and 2050 (right).

As shown in Figure 34, rail is another major transport mode causing 125 thousand fatalities globally every year, mainly in North America, South and Northeast Asia, and CIS countries, where trains are mostly powered by coal-based electricity or diesel. As fossil forms of energy retreat, emissions and consequently mortality decline as in other sectors with about 2700 deaths by 2050.

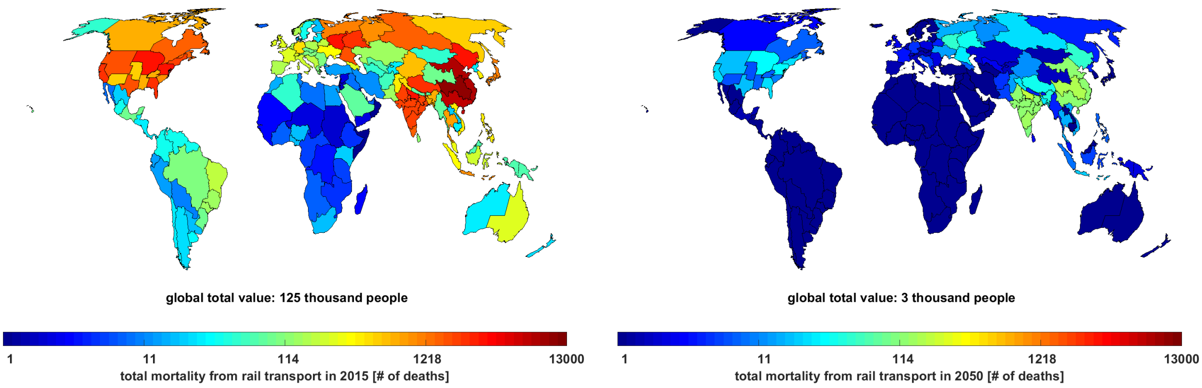

Figure 34. Total mortality from rail transport in 2015 (left) and 2050 (right).

Marine transport, mainly hauling goods is the biggest polluter of all transport modes for the most part of the transition period. Wastes from fossil refineries are used as fuel, and as a consequence marine transport is the largest contributor of deaths caused by air pollution. It is estimated that 823 thousand lives are lost all over the world in 2015. The distribution of lives lost is mostly along the coastal regions as the most populated regions with the highest demand for freight. Regions with strong manufacturing industries, such as China as well as densely populated and developed regions with high consumption of goods, such as the European countries have higher emissions and thus higher mortality resulting from marine transport emissions as indicated in Figure 35. Mortality continues to grow until 2035 at 1.43 million deaths every year. In the following years, marine transportation catches up with other sectors and transport modes in terms of the transition, and mortality rates drop to about 6 thousand deaths annually by 2050.

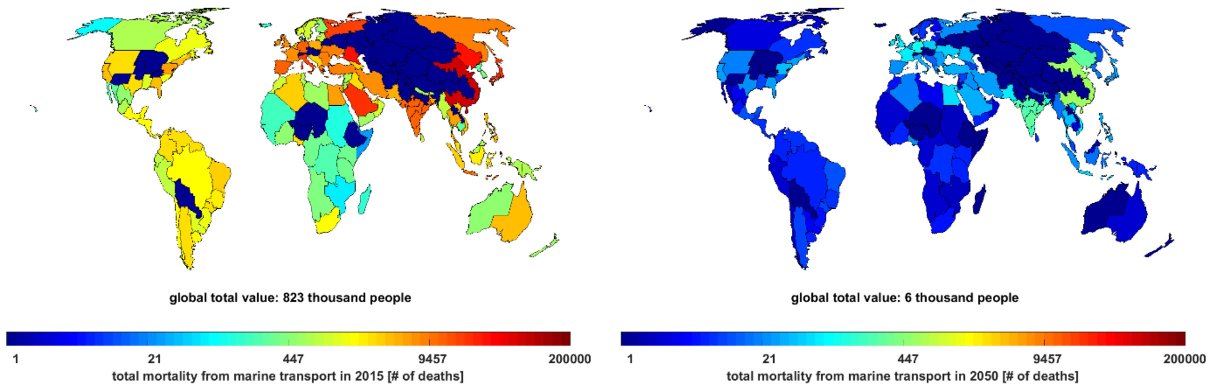

Figure 35. Total mortality from marine transport in 2015 (left) and 2050 (right).

Aviation mainly comprised of passenger movement, contributes significantly to total deaths caused by air pollution with about 18 thousand deaths globally in 2015. As shown in Figure 36, mortality is distributed rather fairly around the world with more developed regions having slightly higher shares of deaths. China, Europe and North America with higher levels of air travel have the most deaths, whereas developing regions in South America and sub-Saharan Africa have lower deaths from aviation emissions due to lesser air travel. Growing populations and quality of life leads to higher overall mobility with more people travelling by air, which causes higher emissions leading to growth in mortality. By 2050, global deaths increase by more than four times to 74 thousand with regional distribution similar to the current status. Mortality in 2050 does not decline to zero, as the energy transition leads to increased utilisation of FT fuels in aviation that is responsible for fatal NO_x emissions. This entails a challenge for the aviation industry to consider innovative options and alternatives for cleaner and greener travel.

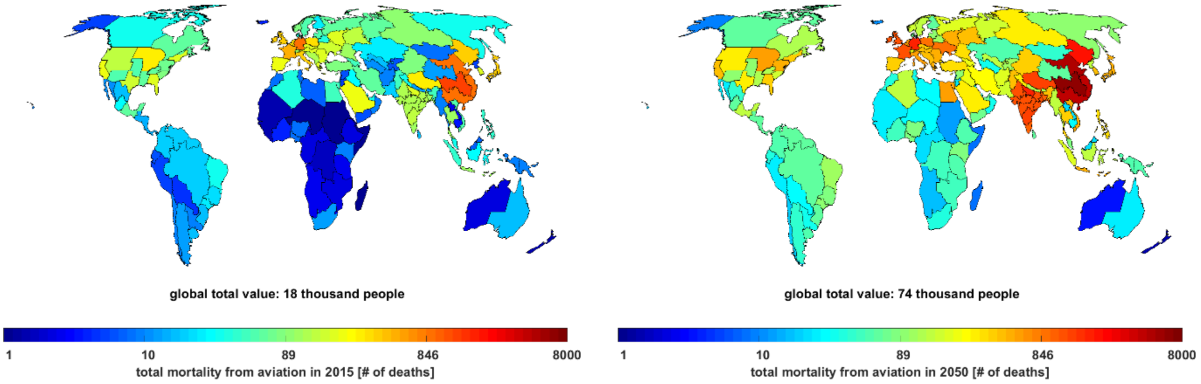

Figure 36. Total mortality from aviation in 2015 (left) and 2050 (right).

Combined air pollution from power, heat, and transport sectors is estimated to cause more than 5.2 million fatalities every year at the beginning of the energy transition period. This is in range with the findings of IHME (2017) that estimate 4.9 million deaths annually by air pollution. Air pollution is considered as the fourth highest risk factor in the world leading to death (IHME, 2017).

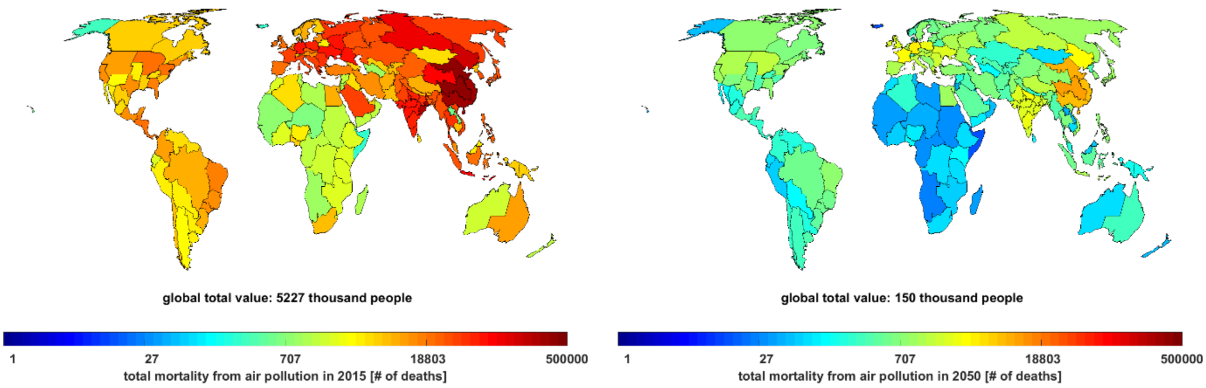

Figure 37. Total mortality from pollution caused by the power, heat, and transport sectors in 2015 (left) and 2050 (right).

Development of pollution-induced mortality for different fuels and transport modes can be found in the Appendix (Figures A21-A26).

The highest absolute number of deaths resulting from air pollution are observed in China with staggering 2.0 million deaths in 2015 (147 deaths/100 thousand inhabitants). The second worst region is India with almost 900 thousand deaths annually in 2015 (66.5 deaths/100 thousand inhabitants). Europe and Eurasia also witness significant number of deaths due to air pollution, as these regions are highly energy intensive with dense populations and large cities. The worst mortality rates per 100 thousand inhabitants are observed neither in India nor China, but in Russia, Baltic countries and Kazakhstan with 327, 279, and 206 deaths per 100 thousand inhabitants, respectively, as indicated in Figure 38. Mortality rates are expected to gradually decrease over the years to a global level of around 150 thousand deaths annually by 2050.

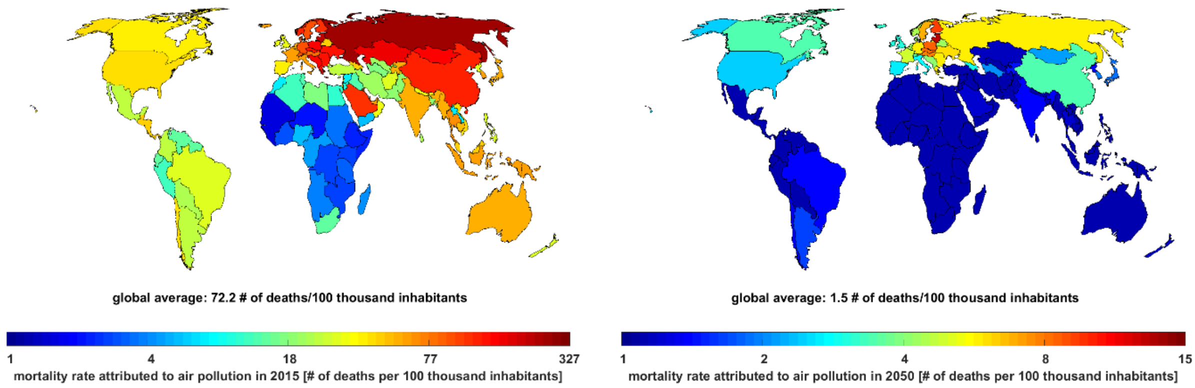

Figure 38. Global mortality rate per 100 thousand inhabitants in 2015 (left) and 2050 (right).

5. Discussion

As the global attention is increasingly on climate change mitigation, the issue of air pollution has generally been viewed as a local menace undermining its global impact. There have been some comprehensive studies on air pollution with sectoral perspectives, including power, heat, and transport, while there are hardly any studies on the development of pollutant emissions during the energy transition to 100% renewable energy with a global perspective. This research is a first of its kind to estimate current levels of air pollution with emphasis on individual pollutants NO_x, SO_x, $PM_{2.5}$ and PM_{10} as well as their development into the future on the basis of a climate compliant global energy transition. In addition, it presents sectoral perspectives of power, heat and transport both on a global level as well as on a regional level with 145 regions. Further, socioeconomic perspectives of air pollution have been analysed with respect to mortality rates and quantification of costs that reach billions of euros annually.

5.1. Validation

Results of this research are well within the range of findings from other research studies on air pollution. NO_x emissions in 2015 were estimated at 40.2 Mt from the power and heat sectors and 97.1 Mt from the transport sector. In comparison, reported emissions from the Emission Database for Global Atmospheric Research (EDGAR) for 2015 were 57.3 Mt and 58.2 Mt for the power and heat sectors and the transport sector, respectively (EC, 2017; Crippa *et al*., 2018; 2020). However, according to Crippa *et al*. (2018) NO_x emissions from the transport sector may have been underestimated by a factor of 2. This correction would lead to 116 Mt of NO_x in the transport sector, closer to the results of this research. There is substantial variation among different studies on air pollution, as the IEA has reported 21.08 Mt of NOx from the power and heat sectors and 57.5 Mt from the transport sector (IEA, 2016), whereas McDuffie *et al*. (2020) have reported 36.3 Mt and 60.5 Mt, respectively.

This research estimates SO_x emissions at 97.9 Mt in the power and heat sectors in 2015 and the corresponding emissions from the transport sector at 27.5 Mt. Other studies have reported emissions ranging from 31 Mt from the power and heat sectors and 10.2 Mt from the transport sector (IEA, 2016) to 82.3 Mt and 13.45 Mt, respectively (EC, 2017; Crippa *et al*., 2018; 2020). SO_x emissions reported by other research are lower than found in this research, but this difference can be owed to the generalised emission factors adopted in this research. Not considering specific combustion technologies per fuel or class of technology could have affected estimates of total emissions. Moreover, the reported uncertainties of studies are quite significant ranging from 14% to 47% depending on the region.

$PM_{2.5}$ emissions are estimated at 17.3 Mt from the power and heat sectors in 2015, by this research. Other studies have reported emissions ranging from 9.55 Mt (McDuffie *et al.*, 2020) to 27.5 Mt (Klimont *et al.*, 2017) in the power and heat sectors, which correspond well with the results of this research. $PM_{2.5}$ emissions from the transport sector are estimated to be 3.66 Mt in 2015, by this research and is comparable to other studies that report emissions ranging from 1.09 Mt (McDuffie *et al.*, 2020) to 3.58 Mt (EC, 2017; Crippa *et al.*, 2018; 2020). However, as stated by Crippa *et al.* (2018) this value may have been underestimated by a factor of 2 and if applied, emissions may be as high as 7.2 Mt. Therefore, PM_{10} emissions from the power and heat sectors reported in this study (20.9 Mt) are comparable to other research where estimates vary from 3.56 Mt (McDuffie *et al.*, 2020) to 39.3 Mt (EC, 2017; Crippa *et al.*, 2018; 2020). 4.52 Mt of PM_{10} estimated in this study for the transport sector are in line with other studies that range from 1.44 Mt (McDuffie *et al.*, 2020) to 6.09 Mt (Klimont *et al.*, 2017).

Estimating and quantifying air pollutants involves many uncertainties, as emission factors of pollutants per ton of fuel depend on the qualities and chemical properties of fuels, combustion techniques, abatement technologies utilised, extent to which regulations are fulfilled by applied technologies, and others. Thus, there is a broad range of possible estimates for each pollutant offered by a number of studies. Overall, results estimated in this research on air pollutant emissions in 2015 seem to be well within range of estimates from similar research on the topic, as indicated in Figure 39. Details of other studies are presented in the Appendix (Table A16).

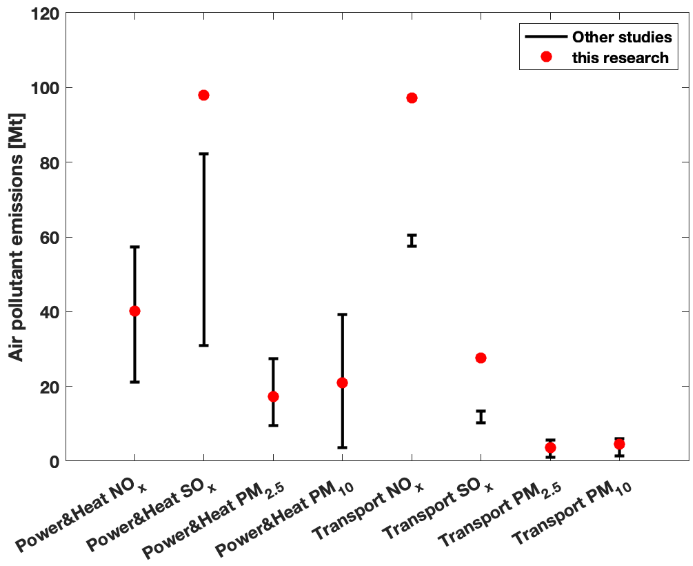

Figure 39. Comparison of results of NO_x, SO_x, $PM_{2.5}$ and PM_{10} emissions from this research and other comparable studies for different energy sectors in and around 2015.

5.2. Health impacts

Global air pollutant emissions do not reflect the impacts on global and local communities and the environment. Therefore, emissions need to be translated into corresponding effects of the pollution on health and the economy. Moreover, as the quality of life globally keeps improving and malnutrition or neonatal deaths decreasing, new causes of death attributable to modern lifestyles such as air pollution gain prominence. Consequently, attention of communities around the world towards issues of poor air quality have heightened in recent years with countries such as China and India being strongly affected by severe and sometimes hazardous air in many of their cities. The issue has been receiving wide scale media and political attention, 30.8 million premature deaths caused by air pollution in China and Taiwan since 2000 (New Scientist, 2020) and the severe state of air quality in New Delhi (Kyodo News, 2020) were well reported recently. Societies around the world are increasingly aware of the adverse health effects of exposure to polluted air and there is clear evidence that air pollution causes strokes, heart diseases, lung cancer, and acute respiratory infections. The World Health Organization estimated 4.2 to 7 million premature deaths attributable to ambient air pollution worldwide (WHO, 2018a; 2018b), whereas the Global Burden of Disease study has concluded that air pollution was responsible for 5 million deaths in 2017, which means that it contributed to 9% of all deaths that year (IHME, 2017). Mortality rates estimated in this study are 5.2 million deaths in 2015 and thus are in range with the findings of other research. Lelieveld *et al.* (2020) have presented significantly higher mortality, with 8.8 million deaths attributable to ambient air pollution with a staggering 233 million years of life lost globally every year.

Substantial discrepancies in results reported by different studies may be owed to high uncertainties related to estimating emissions from each source, its distribution, exposure of populations to pollutant concentrations, as well as the complexity of attributing each particular death to one or the other risk factors. This study may have underestimated deaths attributed to traditional biomass for cooking and indoor air pollution may be responsible for significantly more deaths than reported.

Results of this study do not factor in the fact that people continue to die several decades after being exposed to high concentrations of pollutants as indicated by Hansell *et al.* (2016), who found that air pollution exposure has long lasting effects on human health for decades to come. However, this research shows that for the energy transition to 100% renewable energy, mortality attributable to air pollution gradually decreases by about 97% in 2050 with about 150 thousand deaths. The important finding of this research is demonstrated in Figure 38 as the global average mortality rate per 100 thousand people can decrease from the average value of 72.2 to just 1.5. Moreover, some countries with especially high pollution rates see substantially better results as the maximum rate of 327 deaths per 100 thousand of inhabitants declines 22-fold to the maximum of 15 deaths per 100 thousand.

Fixing air pollution implies eliminating its sources. As energy use in the power, heat, and transport sectors represent almost the entire energy and fuels used, it is crucial for countries around the world to finally phase out fossil fuels that emit both GHG and air pollutants by substituting them with sustainable energy sources. As Hansell *et al.* (2016) conclude the most recent exposure to pollutants has the largest effects, which means that despite the current population already being exposed to pollution, it is still in the best interest of nations to cut harmful emissions as fast as possible to limit the impact.

Moreover, the recent COVID-19 pandemic caused by novel coronavirus has led many to study the links between the disease and long-term exposure to air pollution and the results are daunting. Multiple studies have found that low air quality is an important contributing factor to mortality caused by COVID-19 (Frontera *et al.*, 2020; Petroni *et al.*, 2020; Pozzer *et al*., 2020). Thus, the ban on use of fossil fuels and accelerated transition to sustainable energy are important not only for addressing climate change, but also to solve the air pollution problem as more and more people will continue dying if no changes are made to current energy systems.

5.3. Damage costs

Apart from air pollution-induced mortality, it also adversely affects productivity levels as people spend more time out of work and health expenditures are increasing as people are getting sick. This research has estimated that in 2015 alone, the cost of damage induced by air pollution is 4625 b€ globally with coal combustion being the most damaging of all sources, but with significant inputs of other fuels as well, in particular burning of toxic wastes from fossil refineries in marine transportation. Damage costs of air pollution during majority of the transition period stay high, even though the use of fossil fuels gradually decreases and pollution-induced mortality declines over the years. This phenomenon can be explained by the improving quality of life and rising income levels of developing and emerging regions that are following the steps of industrialised countries. Thus, only partial emission cutback is not an option as it does not bring significant benefits in economic terms. In total, damage costs of air pollution between 2015 and 2050 is estimated to be an enormous 182 trillion euros. It is of highest importance to reflect that in a business-as-usual approach, where energy systems continue relying on fossil fuels, this value will be much higher as annual damage costs decrease by 91% between 2020, when damage costs are at its peak and 2050, when damage costs are at the lowest. Thus, the energy transition does not only benefit the environment and human health, but also saves enormous financial resources that can be used for the benefit of society.

5.4. Implications of the research

Positive news has been appearing as the ongoing COVID-19 pandemic led to air pollution levels artificially going down in spring 2020. Imposed quarantine measures, lockdowns and economic slowdown contributed to lowered NO_2 levels, by as much as 30% in many regions of China as well as Hong Kong (NASA, 2020). European Environment Agency also reported decreased pollution levels in many cities on lockdown. In the week of 16-22 March 2020, NO_2 levels dropped by 55% in Barcelona, 41% in Madrid, and 51% in Lisbon compared to the same week in 2019 (EEA, 2020). As the lockdown measures are lifted, a fast attempt could be observed to return to the normal way of life, thus air pollution levels have started to rebound in many regions and some fear that this may cause even more complications related to the novel virus (The Guardian, 2020; CREA, 2020). The way out is to phase out the fundamental cause of pollutants, fossil fuels and limit combustion processes where possible and use advanced cleaning technologies for exhaust fumes.

Transitioning to a 100% renewable energy system has already been proved to be economically viable and technically feasible (Bogdanov *et al.,* 2019; Ram *et al*., 2019; Hansen *et al*., 2019; Brown *et al*., 2018, Jacobson *et al*., 2019, Diesendorf and Elliston, 2018) and brings additional benefits such as creation of new jobs (Ram *et al*., 2020). This study has presented additional co-benefits of transitioning to a 100% renewable energy system: saving millions of lives and trillions of euros lost to air pollution, annually. This research has proved that phasing out fossil fuels and substituting them with renewable forms of energy would clearly address three main pillars of sustainability. Firstly, there is a potential to decrease toxic emissions and protect the environment. Secondly, millions of lives can be saved all over the world and quality of life improved, especially in highly polluted regions such as India and China that host a third of the world population. Finally, the economy can benefit from increased productivity levels as well as financial resources that can be directed towards pursuing the future goals instead of fixing the issues that could have been avoided.

5.5. Future research

Further research on the topic is needed to estimate the impacts of the pollutants more precisely as there are more harmful pollutants that are being emitted such as carbon monoxide, ozone, heavy metal emissions and others. Moreover, it is crucial to see how emissions would develop in the case that the world is not taking any action towards decreasing the GHG and air pollutant emissions and continues to maintain the current energy system heavily reliant on fossil fuels. Such study would further emphasize the enormous risks associated with fossil fuels and huge potential benefits of renewable forms of energy.

6. Conclusions

This research has attempted to provide answers to the questions formulated in Chapter 1 of this Master's thesis.

Firstly, the volumes of air pollutant emissions from thermal power and heat plants and transportation were estimated for the year 2015. These sectors were found to be responsible for emitting 137.3 Mt of NO_x, 125,5 Mt of SO_x, 20.9 Mt of $PM_{2.5}$, and 25.5 Mt of PM_{10}.

Secondly, implementation of the Best Policy Scenario for transitioning to fully renewable energy system by 2050 enables to drastically decrease harmful emissions over the years and help to reach levels of NO_x, SO_x, $PM_{2.5}$, and PM_{10} at 23.3, 0.2, 0.7, and 0.2 Mt, respectively.

Thirdly, harmful impacts of the present global energy system on human health with millions of lost lives every year due to air pollution are presented in high geo-spatial detail. It was estimated that air pollution kills more than 5 million people annually in the beginning of the energy transition and imposes 4.6 trillion euros of damages. This research further explores how transitioning to a 100% renewable energy system can phase out harmful emissions and respective fatalities, thereby saving enormous societal costs across the globe. By the year 2050 it is possible to decrease mortality levels to 150 thousand people annually and decrease the economic damages by almost 90% compared to the values in 2015.

Governments around the world need to emphasise a quick phase out of coal combustion, transition from use of traditional biomass to modern forms of energy in developing countries and a drastic improvement in emission standards for marine transportation, as findings of this research show that these three are responsible for about 80% of premature deaths and 81% of all costs attributed to air pollution. As the standards of living improve in developing and emerging countries, damage costs from air pollution in those regions will continue to grow due to the increase in income levels. Thus, the current energy system that runs largely on fossil fuels will entail higher damage costs in the coming years, without a rapid energy transition in the near future.

Transitioning to a 100% renewable energy system by mid-century would not only provide secure and steady supply of sustainable energy to communities around the world but also cut GHG emissions that lead to anthropogenic climate change. Moreover, it has the potential to save millions of lives and billions of euros as possible pollution damage is avoided. Raising public awareness on air pollution to the same level as climate change, as well as effectively communicating the importance of banning fossil fuels to policymakers is paramount. Eliminating air pollution globally is not an easy task and it requires strong cooperation among nations as well as strong political will to switch to sustainable energy sources.

Comparable measures as for the COVID-19 pandemic have to be applied to avoid millions of deaths annually caused by air pollution, and the way forward is to fully stop using fossil fuels, while transitioning to a 100% renewable energy system. Such an energy system would combine several most attractive features compared to the current fossil fuel dominant energy system: millions of lives saved every year, substantially lower costs, zero GHG emissions and more jobs.

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Appendix

Table A1. Emission factors for power sector.

Fuel	Units	NO_x	SO_x	$PM_{2.5}$	PM_{10}	Referenc	Notes
Natural Gas							
Australia	kg/GWh_{th}	568.4	2460.3	10.3	10.6	[4]	a
Iran	kg/GWh_{el}	2365.2	0.0			[33]	b
US	kg/GWh_{th}	283.2	5.3	35.6	35.6	[19]	c
Mexico	kg/GWh_{el}	1397.5				[11]	
Canada	kg/GWh_{el}	281.0	18.8	6.0	7.7	[8, 22]	d
Europe	kg/GWh_{th}	486.0	1.0	7.2	7.2	[17]	
New Zealand	kg/GWh_{th}	295.6	1.4	4.4	4.4	[31]	
Taiwan	kg/GWh_{el}	135.5	0.0	0.0	0.0	[27]	
Brazil	kg/GWh_{el}	2000.0	170.0			[23]	
Global	kg/GWh_{th}	384.6	3.1	21.4	21.4		
Oil							
Australia	kg/GWh_{th}	324.4	1620.0	33.8	54.2	[4]	e
US	kg/GWh_{th}	867.0	51.1			[19]	f
Europe	kg/GWh_{th}	372.6	974.7	36.2	51.1	[17]	g
Iran	kg/GWh_{el}	4031.0	7147.7			[33]	h
Canada	kg/GWh_{el}	1249.0	9.5	25.6	29.3	[8]	i
New Zealand	kg/GWh_{th}	234.0	1.7	2.8	10.9	[31]	
Mexico	kg/GWh_{el}	7577.2	18167.2	834.7	1185.0	[11]	
Taiwan	kg/GWh_{el}	949.3	3020.3	97.1	97.1	[27]	
Brazil	kg/GWh_{el}	1000.0	4430.0			[23]	
Global	kg/GWh_{th}	537.4	666.8	36.2	51.1		j
Coal							
Albania	kg/GWh_{el}	1799.3	64291.5	358.1	362.9	[34]	k
Argentina	kg/GWh_{el}	1139.2	18681.5	43.3	43.9	[34]	k
Austria	kg/GWh_{el}	595.0	11282.4	43.4	30.0	[34]	k
Bosnia	kg/GWh_{el}	1482.5	32427.0	173.9	176.5	[34]	k
Bangladesh	kg/GWh_{el}	1172.2	1727.1	43.9	44.5	[34]	k
Belgium	kg/GWh_{el}	825.9	2925.7	37.1	28.5	[34]	k
Bulgaria	kg/GWh_{el}	1602.8	10995.8	163.0	95.0	[34]	k

Brazil	kg/GWh$_{el}$	1256.4	4928.1	61.1	57.0	[34]	k
Botswana	kg/GWh$_{el}$	1376.2	6230.5	62.7	63.6	[34]	k
Canada	kg/GWh$_{el}$	1944.0	4496.7	47.0	54.4	[34]	k
Chile	kg/GWh$_{el}$	1282.2	3295.0	28.7	28.4	[34]	k
China	kg/GWh$_{el}$	1204.9	1046.2	79.8	71.0	[34]	k
Colombia	kg/GWh$_{el}$	1526.8	3377.4	408.7	844.4	[34]	k
Czech	kg/GWh$_{el}$	1593.6	2554.4	94.9	65.2	[34]	k
Germany	kg/GWh$_{el}$	791.7	884.2	34.0	20.7	[34]	k
Denmark	kg/GWh$_{el}$	690.0	815.1	22.8	11.5	[34]	k
Dominican	kg/GWh$_{el}$	1201.7	2203.7	41.8	42.4	[34]	k
Spain	kg/GWh$_{el}$	1983.5	2006.0	49.4	30.5	[34]	k
Finland	kg/GWh$_{el}$	1611.6	1676.6	35.4	24.9	[34]	k
France	kg/GWh$_{el}$	1737.8	3124.8	65.3	57.5	[34]	k
UK	kg/GWh$_{el}$	1731.7	2037.4	29.3	19.5	[34]	k
Guadeloupe	kg/GWh$_{el}$	1379.1	2529.0	48.0	48.6	[34]	k
Greece	kg/GWh$_{el}$	1600.0	36261.4	444.2	424.6	[34]	k
Guatemala	kg/GWh$_{el}$	1333.5	3359.3	23.5	24.1	[34]	k
Croatia	kg/GWh$_{el}$	1163.7	613.1	23.9	9.9	[34]	k
Hungary	kg/GWh$_{el}$	1413.3	1713.6	161.7	77.6	[34]	k
Indonesia	kg/GWh$_{el}$	1306.6	4432.9	161.5	142.8	[34]	k
Ireland	kg/GWh$_{el}$	1291.1	1349.0	25.0	22.3	[34]	k
Israel	kg/GWh$_{el}$	1156.8	3802.4	41.4	39.0	[34]	k
India	kg/GWh$_{el}$	3171.4	10267.2	211.3	205.6	[34]	k
Italy	kg/GWh$_{el}$	728.6	892.8	19.8	10.7	[34]	k
Japan	kg/GWh$_{el}$	763.4	1007.7	28.6	16.7	[34]	k
Kyrgyzstan	kg/GWh$_{el}$	1538.6	6137.9	79.5	80.6	[34]	k
Cambodia	kg/GWh$_{el}$	1509.4	8737.2	67.2	68.1	[34]	k
North Korea	kg/GWh$_{el}$	1431.4	3667.5	1161.7	2924.8	[34]	k
South Korea	kg/GWh$_{el}$	758.4	768.9	32.0	18.2	[34]	k
Kazakhstan	kg/GWh$_{el}$	1542.9	3311.7	238.8	225.0	[34]	k
Morocco	kg/GWh$_{el}$	1206.1	6866.9	54.1	54.8	[34]	k
Montenegro	kg/GWh$_{el}$	1290.3	4332.7	46.6	47.2	[34]	k
Macedonia	kg/GWh$_{el}$	1445.5	51649.0	287.6	291.6	[34]	k
Myanmar	kg/GWh$_{el}$	1353.5	8002.6	60.3	61.1	[34]	k

Mongolia	kg/GWh_{el}	1505.0	9222.5	255.7	259.2	[34]	k
Moldova	kg/GWh_{el}	1393.9	20387.4	14.4	7.4	[34]	k
Mauritius	kg/GWh_{el}	1518.0	9078.8	48.2	48.9	[34]	k
Mexico	kg/GWh_{el}	1152.9	5354.1	34.8	35.3	[34]	k
Malaysia	kg/GWh_{el}	1252.9	927.7	38.2	29.2	[34]	k
Namibia	kg/GWh_{el}	1395.4	8345.7	62.1	62.9	[34]	k
Netherlands	kg/GWh_{el}	381.1	323.2	20.5	8.4	[34]	k
Norway	kg/GWh_{el}	1599.1	8908.0	86.9	88.0	[34]	k
New Zealand	kg/GWh_{el}	1238.9	2449.2	185.1	187.6	[34]	k
Panama	kg/GWh_{el}	1397.0	3519.4	51.0	51.7	[34]	k
Peru	kg/GWh_{el}	1146.8	18805.4	43.6	44.2	[34]	k
Philippines	kg/GWh_{el}	1288.1	6546.4	99.5	89.2	[34]	k
Pakistan	kg/GWh_{el}	1415.3	1186.8	5.8	6.3	[34]	k
Poland	kg/GWh_{el}	1752.4	5670.3	94.3	70.8	[34]	k
Portugal	kg/GWh_{el}	557.8	493.9	17.2	7.1	[34]	k
Romania	kg/GWh_{el}	2120.1	13184.4	259.5	198.5	[34]	k
Russia	kg/GWh_{el}	1430.0	18923.9	328.6	258.5	[34]	k
Sweden	kg/GWh_{el}	509.2	1390.2	37.3	29.1	[34]	k
Serbia	kg/GWh_{el}	1434.5	14169.9	285.8	289.6	[34]	k
Slovenia	kg/GWh_{el}	1839.6	1643.5	66.6	43.3	[34]	k
Slovakia	kg/GWh_{el}	2155.8	16885.8	132.1	98.7	[34]	k
Thailand	kg/GWh_{el}	1375.2	4058.6	81.3	42.5	[34]	k
Turkey	kg/GWh_{el}	1310.1	12032.5	143.4	116.5	[34]	k
Taiwan	kg/GWh_{el}	647.5	835.2	30.8	18.8	[34]	k
Tanzania	kg/GWh_{el}	1535.4	6918.3	98.2	99.5	[34]	k
Ukraine	kg/GWh_{el}	1235.8	10532.6	202.0	202.8	[34]	k
United States	kg/GWh_{el}	926.9	2010.0	61.3	49.8	[34]	k
Uzbekistan	kg/GWh_{el}	1419.9	50759.0	282.6	286.4	[34]	k
Vietnam	kg/GWh_{el}	1323.5	2038.6	148.8	118.8	[34]	k
South Africa	kg/GWh_{el}	1206.7	7282.5	80.9	82.1	[34]	k
Zimbabwe	kg/GWh_{el}	1728.9	4248.0	77.0	99.1	[34]	k
Modern							
Europe	kg/GWh_{th}	291.6	38.9	478.8	558.0	[17]	
US	kg/GWh_{th}	202.9	132.1	432.8	616.3	[3]	

China	kg/GWh_{el}	50.0	10.0			[29]	
Brazil	kg/GWh_{el}	890.0	490.0			[23]	
Global	kg/GWh_{th}	247.3	85.5	455.8	587.1		l
Biogas							
US	kg/GWh_{th}	256.9	10.8	21.7	21.7	[9]	
Brazil	kg/GWh_{el}	2992.4	443.6	0.0	0.0	[10, 37]	m
New Zealand	kg/GWh_{th}	469.9	10.1	14.8	17.4	[31]	
Future							
Global	kg/GWh_{th}	192.0	21.6	15.3	20.9	[39]	n
Traditional biomass							
Global	kg/GWh_{th}	232.0	39.6	1914.0	2880.0	[2, 6, 17]	o

Notes: a) Arithmetic mean of EF for OCGT, CCGT, and general combustion of natural gas; b) Arithmetic mean of values from Table 6,7,8 of [33]; c) Arithmetic mean for emission factors from 3 different types of turbines; d) Derived from emissions data and generated electricity from two sources; e) Arithmetic mean of distillate oil and fuel oil; f) Arithmetic mean of EF for different types of turbines combusting distillate oil; g) Arithmetic mean of heavy fuel oil and gas oil; h) Arithmetic mean for different oil products; i) EF derived from total electricity generated and reported total emissions from power sector; j) Arithmetic mean of EF for combustion of heavy fuel oil and gas oil in Europe and distillate oil in the US; k) Derived from data on electricity generation and total pollutant emissions; l) Arithmetic mean of values for Europe and the US; m) EF derived from electricity generation from [10], total emissions derived from [37]; n) Arithmetic mean of EF for wood fuels, waste, and other biomass; o) Arithmetic mean of EF from [2] and [17] for NO_x, [6] and [17] for $PM_{2.5}$, value for residential biomass and for open fireplace from [17] for PM_{10}.

Table A2. Emission factors for heat sector.

Fuel	Unit	NO_x	SO_x	$PM_{2.5}$	PM_{10}	Referenc	Notes
Natural Gas							
Europe	kg/GWh_{th}	486	1.01	7.2	7.2	[17]	
Canada	kg/GWh_{th}	147		2.8		[36]	
New Zealand	kg/GWh_{th}	240	1.44	4.8	4.8	[31]	a
Oil							
US	kg/GWh_{th}	867	51.1			[19]	
Europe	kg/GWh_{th}	248	650	24.1	34.1	[17]	b
Canada	kg/GWh_{th}	110.6		22.1		[36]	
New Zealand	kg/GWh_{th}	1040.5	1.7	35.5	39.5	[31]	c
Global	kg/GWh_{th}	537.4	666.8	37.18	51.1		d
Coal							
Europe	kg/GWh_{th}	820.8	4500	11.8	28.05	[17]	e
New Zealand	kg/GWh_{th}	509.4	1595	1385.5	1587	[31]	f
Modern							
US	kg/GWh_{th}	549.4	38.7	279	377.5	[19]	g
New Zealand	kg/GWh_{th}	147.6	61.2	2384	2384	[31]	g
France	kg/GWh_{th}	356.4	9.72		93.6	[21]	
Germany	kg/GWh_{th}	302.4	6.84			[21]	
Global	kg/GWh_{th}	328.6	28.77	975	864.6		h
Biogas							
Canada	kg/GWh_{th}	263.2		144		[36]	
New Zealand	kg/GWh_{th}	470	10.1	14.8	17.4	[31]	
Global	kg/GWh_{th}	366.5	10.1	79.4	17.4		i
Future							
Global	kg/GWh_{th}	192	21.6	97	20.9	[39]	j

Notes: a) Arithmetic mean of EF for large scale and residential combustion of natural gas; b) Arithmetic mean of EF for heavy fuel oil and gas oil combustion; c) Arithmetic mean of EF for oil and diesel in large scale combustion; d) Arithmetic mean of EF for heavy fuel oil and gas oil combustion in Europe and oil combustion in the US; e) Arithmetic mean of EF for brown and hard coal in large scale and residential combustion; f) Arithmetic mean of EF for brown and hard coal in large scale combustion; g) Arithmetic mean of EF for combustion of different types of wood residues; h) Arithmetic mean of EF for Europe and US; i) Arithmetic mean of EF for Canada and New Zealand; j) Arithmetic mean of EF for wood, waste, pellets and other biomass combustion in district and residential heat.

Table A3. Emission factors for 2-3 wheelers [42].

Region	Country	Fuel	Pollutant	2015	2020	2025	2030	2035	2040	2045	2050
Global	Global	Diesel	NO_x [g/vkm]	0.285	0.244	0.192	0.128	0.098	0.072	0.060	0.060
			PM [g/vkm]	0.048	0.040	0.027	0.010	0.009	0.005	0.005	0.005
		Gasoline	NO_x [g/vkm]	0.259	0.230	0.182	0.120	0.092	0.077	0.060	0.060
			PM [g/vkm]	0.048	0.040	0.019	0.011	0.011	0.005	0.005	0.005
Europe	EU	Diesel	NO_x [g/vkm]	0.400	0.170	0.060	0.060	0.060	0.060	0.060	0.060
			PM [g/vkm]	0.048	0.005	0.005	0.005	0.005	0.005	0.005	0.005
		Gasoline	NO_x [g/vkm]	0.275	0.170	0.060	0.060	0.060	0.060	0.060	0.060
			PM [g/vkm]	0.048	0.005	0.005	0.005	0.005	0.005	0.005	0.005
SAARC	India	Diesel	NO_x [g/vkm]	0.155	0.095	0.095	0.060	0.060	0.060	0.060	0.060
			PM [g/vkm]	0.048	0.015	0.015	0.005	0.005	0.005	0.005	0.005
		Gasoline	NO_x [g/vkm]	0.310	0.343	0.275	0.170	0.060	0.060	0.060	0.060
			PM [g/vkm]	0.048	0.005	0.005	0.005	0.005	0.005	0.005	0.005
Southeast Asia	Indonesia	Diesel	NO_x [g/vkm]	0.650	0.650	0.475	0.400	0.400	0.170	0.060	0.060
			PM [g/vkm]	0.100	0.100	0.100	0.050	0.048	0.005	0.005	0.005
		Gasoline	NO_x [g/vkm]	0.400	0.400	0.350	0.275	0.275	0.170	0.060	0.060
			PM [g/vkm]	0.100	0.100	0.100	0.050	0.048	0.005	0.005	0.005
	Vietnam	Diesel	NO_x [g/vkm]	0.475	0.400	0.400	0.170	0.060	0.060	0.060	0.060
			PM [g/vkm]	0.100	0.100	0.100	0.005	0.005	0.005	0.005	0.005
			NO_x [g/vkm]	0.350	0.200	0.170	0.060	0.060	0.060	0.060	0.060

		Gasoline	PM [g/vkm]	0.048	0.048	0.005	0.005	0.005	0.005	0.005	0.005
	Region	Gasoline	NO_x [g/vkm]	0.375	0.300	0.260	0.168	0.168	0.115	0.060	0.060
			PM [g/vkm]	0.048	0.048	0.052	0.027	0.026	0.005	0.005	0.005
Northeast Asia	China	Not Specified	NO_x [g/vkm]	0.217	0.217	0.170	0.060	0.060	0.060	0.060	0.060
			PM [g/vkm]	0.048	0.048	0.005	0.005	0.005	0.005	0.005	0.005
	South Korea	Not Specified	NO_x [g/vkm]	0.275	0.275	0.217	0.170	0.060	0.060	0.060	0.060
			PM [g/vkm]	0.048	0.048	0.005	0.005	0.005	0.005	0.005	0.005
	Region	Not Specified	NO_x [g/vkm]	0.246	0.246	0.193	0.115	0.060	0.060	0.060	0.060
			PM [g/vkm]	0.048	0.048	0.005	0.005	0.005	0.005	0.005	0.005
North America	United States & Canada	Not Specified	NO_x [g/vkm]	0.073	0.073	0.060	0.060	0.060	0.060	0.060	0.060
			PM [g/vkm]	0.048	0.048	0.005	0.005	0.005	0.005	0.005	0.005

Table A4. Emission factors for LDV [42].

Region	Country	Fuel	Pollutant	2015	2020	2025	2030	2035	2040	2045	2050
Global	Global	Diesel	NO_x [g/vkm]	0.209	0.143	0.084	0.066	0.044	0.029	0.020	0.017
			PM [g/vkm]	0.025	0.020	0.008	0.006	0.004	0.003	0.003	0.003
		Gasoline	NO_x [g/vkm]	0.052	0.045	0.048	0.042	0.033	0.028	0.021	0.019
			PM [g/vkm]	0.009	0.005	0.005	0.006	0.005	0.004	0.004	0.003
Europe	EU	Diesel	NO_x [g/vkm]	0.080	0.080	0.035	0.028	0.017	0.017	0.017	0.017
			PM [g/vkm]	0.005	0.005	0.003	0.003	0.003	0.003	0.003	0.003
		Gasoline	NO_x [g/vkm]	0.060	0.060	0.035	0.031	0.018	0.018	0.018	0.018
			PM [g/vkm]	0.005	0.005	0.003	0.003	0.003	0.003	0.003	0.003
Eurasia	Russia	Diesel	NO_x [g/vkm]	0.250	0.180	0.080	0.08	0.035	0.028	0.017	0.017
			PM [g/vkm]	0.025	0.005	0.005	0.005	0.003	0.003	0.003	0.003
		Gasoline	NO_x [g/vkm]	0.080	0.060	0.060	0.035	0.031	0.018	0.018	0.018
			PM [g/vkm]	0.009	0.005	0.005	0.003	0.003	0.003	0.003	0.003
SAARC	India	Diesel	NO_x [g/vkm]	0.483	0.103	0.080	0.080	0.035	0.028	0.017	0.017
			PM [g/vkm]	0.058	0.005	0.005	0.005	0.003	0.003	0.003	0.003
		Gasoline	NO_x [g/vkm]	0.138	0.072	0.060	0.060	0.035	0.031	0.018	0.018
			PM [g/vkm]	0.009	0.005	0.005	0.005	0.003	0.003	0.003	0.003
Northeast Asia	China	Diesel	NO_x [g/vkm]	0.250	0.120	0.035	0.028	0.017	0.017	0.017	0.017
			PM [g/vkm]	0.025	0.045	0.003	0.003	0.003	0.003	0.003	0.003
		Gasoline	NO_x [g/vkm]	0.080	0.060	0.035	0.031	0.018	0.018	0.018	0.018
			PM [g/vkm]	0.026	0.045	0.003	0.003	0.003	0.003	0.003	0.003

	South Korea	Diesel	NO_x [g/vkm]	0.103	0.080	0.035	0.028	0.017	0.017	0.017	0.017
			PM [g/vkm]	0.005	0.005	0.003	0.003	0.003	0.003	0.003	0.003
		Gasoline	NO_x [g/vkm]	0.033	0.033	0.035	0.031	0.018	0.018	0.018	0.018
			PM [g/vkm]	0.026	0.005	0.003	0.003	0.003	0.003	0.003	0.003
	Japan	Diesel	NO_x [g/vkm]	0.080	0.080	0.035	0.028	0.017	0.017	0.017	0.017
			PM [g/vkm]	0.005	0.005	0.003	0.003	0.003	0.003	0.003	0.003
		Gasoline	NO_x [g/vkm]	0.080	0.060	0.035	0.031	0.018	0.018	0.018	0.018
			PM [g/vkm]	0.007	0.005	0.003	0.003	0.003	0.003	0.003	0.003
	Region	Diesel	NO_x [g/vkm]	0.144	0.093	0.035	0.028	0.017	0.017	0.017	0.017
			PM [g/vkm]	0.012	0.018	0.003	0.003	0.003	0.003	0.003	0.003
		Gasoline	NO_x [g/vkm]	0.064	0.051	0.035	0.031	0.018	0.018	0.018	0.018
			PM [g/vkm]	0.026	0.018	0.003	0.003	0.003	0.003	0.003	0.003
Southeast Asia	Australia	Diesel	NO_x [g/vkm]	0.215	0.180	0.180	0.08	0.044	0.028	0.017	0.017
			PM [g/vkm]	0.015	0.005	0.005	0.0045	0.003	0.003	0.003	0.003
		Gasoline	NO_x [g/vkm]	0.070	0.060	0.060	0.06	0.044	0.031	0.018	0.018
			PM [g/vkm]	0.009	0.009	0.005	0.005	0.005	0.005	0.004	0.004
	Thailand	Diesel	NO_x [g/vkm]	0.320	0.215	0.180	0.180	0.080	0.044	0.028	0.017
			PM [g/vkm]	0.043	0.015	0.005	0.005	0.0045	0.003	0.003	0.003
		Gasoline	NO_x [g/vkm]	0.090	0.070	0.060	0.060	0.060	0.044	0.031	0.018
			PM [g/vkm]	0.009	0.005	0.005	0.005	0.0045	0.012	0.005	0.004
	Vietnam	Diesel	NO_x [g/vkm]	0.250	0.250	0.215	0.180	0.180	0.08	0.044	0.028
			PM [g/vkm]	0.478	0.025	0.015	0.005	0.0045	0.0045	0.003	0.003
			NO_x [g/vkm]	0.080	0.080	0.070	0.060	0.060	0.06	0.044	0.031

		Gasoline	PM [g/vkm]	0.009	0.009	0.005	0.005	0.0045	0.0045	0.012	0.005
	Regional	Diesel	NO_x [g/vkm]	0.478	0.413	0.192	0.147	0.101	0.08	0.029	0.020
			PM [g/vkm]	0.052	0.043	0.008	0.005	0.004	0.0045	0.003	0.003
		Gasoline	NO_x [g/vkm]	0.080	0.077	0.063	0.060	0.055	0.06	0.031	0.022
			PM [g/vkm]	0.009	0.009	0.005	0.005	0.007	0.0045	0.007	0.004
South America	Brazil	Diesel	NO_x [g/vkm]	0.080	0.080	0.044	0.044	0.028	0.017	0.017	0.017
			PM [g/vkm]	0.025	0.025	0.012	0.012	0.005	0.004	0.004	0.004
		Gasoline	NO_x [g/vkm]	0.080	0.080	0.044	0.044	0.031	0.018	0.018	0.018
			PM [g/vkm]	0.012	0.012	0.012	0.012	0.005	0.004	0.004	0.004
	Argentina	Diesel	NO_x [g/vkm]	0.215	0.180	0.080	0.044	0.044	0.028	0.017	0.017
			PM [g/vkm]	0.015	0.005	0.025	0.012	0.012	0.005	0.004	0.004
		Gasoline	NO_x [g/vkm]	0.070	0.060	0.060	0.044	0.044	0.031	0.018	0.018
			PM [g/vkm]	0.005	0.005	0.005	0.012	0.012	0.005	0.004	0.004
	Region	Diesel	NO_x [g/vkm]	0.148	0.130	0.062	0.044	0.036	0.022	0.017	0.017
			PM [g/vkm]	0.020	0.015	0.019	0.012	0.009	0.004	0.004	0.004
		Gasoline	NO_x [g/vkm]	0.075	0.070	0.052	0.044	0.037	0.025	0.018	0.018
			PM [g/vkm]	0.005	0.005	0.009	0.012	0.009	0.004	0.004	0.004
North America	United States & Canada	Diesel	NO_x [g/vkm]	0.044	0.028	0.017	0.017	0.017	0.017	0.017	0.017
			PM [g/vkm]	0.012	0.005	0.004	0.003	0.003	0.003	0.003	0.003
		Gasoline	NO_x [g/vkm]	0.044	0.031	0.018	0.018	0.018	0.018	0.018	0.018
			PM [g/vkm]	0.012	0.005	0.004	0.003	0.003	0.003	0.003	0.003
	Mexico	Diesel	NO_x [g/vkm]	0.249	0.068	0.044	0.028	0.017	0.017	0.017	0.017
			PM [g/vkm]	0.050	0.050	0.012	0.005	0.004	0.003	0.003	0.003

		Gasoline	NO_x [g/vkm]	0.249	0.068	0.044	0.031	0.018	0.018	0.018	0.018
			PM [g/vkm]	0.012	0.012	0.012	0.005	0.004	0.003	0.003	0.003

Table A5. Emission factors for MDV [42].

Region	Country	Fuel	Pollutant	2015	2020	2025	2030	2035	2040	2045	2050
Global	Global	Diesel	NO_x [g/vkm]	0.236	0.171	0.104	0.056	0.039	0.023	0.019	0.019
			PM [g/vkm]	0.026	0.024	0.005	0.004	0.004	0.003	0.003	0.003
		Gasoline	NO_x [g/vkm]	0.092	0.073	0.055	0.037	0.020	0.010	0.009	0.009
			PM [g/vkm]	0.021	0.014	0.005	0.006	0.004	0.003	0.003	0.003
Europe	EU	Diesel	NO_x [g/vkm]	0.168	0.103	0.084	0.034	0.019	0.019	0.019	0.019
			PM [g/vkm]	0.005	0.005	0.005	0.004	0.003	0.003	0.003	0.003
		Gasoline	NO_x [g/vkm]	0.075	0.075	0.067	0.015	0.009	0.009	0.009	0.009
			PM [g/vkm]	0.005	0.005	0.005	0.004	0.003	0.003	0.003	0.003
Eurasia	Russia	Diesel	NO_x [g/vkm]	0.244	0.244	0.232	0.168	0.103	0.084	0.034	0.019
			PM [g/vkm]	0.005	0.005	0.005	0.005	0.005	0.005	0.004	0.003
		Gasoline	NO_x [g/vkm]	0.084	0.075	0.075	0.067	0.015	0.009	0.009	0.009
			PM [g/vkm]	0.021	0.005	0.005	0.005	0.004	0.003	0.003	0.003
SAARC	India	Diesel	NO_x [g/vkm]	0.483	0.213	0.168	0.103	0.084	0.034	0.019	0.019
			PM [g/vkm]	0.058	0.023	0.005	0.005	0.005	0.004	0.003	0.003
		Gasoline	NO_x [g/vkm]	0.138	0.085	0.075	0.075	0.067	0.015	0.009	0.009
			PM [g/vkm]	0.021	0.005	0.005	0.005	0.005	0.004	0.003	0.003
Northeast Asia	China	Diesel	NO_x [g/vkm]	0.323	0.152	0.043	0.034	0.019	0.019	0.019	0.019
			PM [g/vkm]	0.042	0.045	0.003	0.003	0.003	0.003	0.003	0.003
		Gasoline	NO_x [g/vkm]	0.072	0.072	0.043	0.015	0.009	0.009	0.009	0.009
			PM [g/vkm]	0.045	0.045	0.003	0.003	0.003	0.003	0.003	0.003

	South Korea	Diesel	NO_x [g/vkm]	0.103	0.103	0.043	0.034	0.019	0.019	0.019	0.019
			PM [g/vkm]	0.005	0.005	0.003	0.003	0.003	0.003	0.003	0.003
		Gasoline	NO_x [g/vkm]	0.034	0.034	0.034	0.015	0.009	0.009	0.009	0.009
			PM [g/vkm]	0.045	0.031	0.003	0.003	0.003	0.003	0.003	0.003
	Japan	Diesel	NO_x [g/vkm]	0.115	0.043	0.034	0.019	0.019	0.019	0.019	0.019
			PM [g/vkm]	0.006	0.003	0.003	0.003	0.003	0.003	0.003	0.003
	Regional	Diesel	NO_x [g/vkm]	0.181	0.100	0.040	0.029	0.019	0.019	0.019	0.019
			PM [g/vkm]	0.017	0.018	0.003	0.003	0.003	0.003	0.003	0.003
		Gasoline	NO_x [g/vkm]	0.053	0.069	0.039	0.020	0.013	0.013	0.013	0.013
			PM [g/vkm]	0.045	0.031	0.003	0.003	0.003	0.003	0.003	0.003
Southeast Asia	Australia	Diesel	NO_x [g/vkm]	0.232	0.232	0.103	0.084	0.034	0.019	0.019	0.019
			PM [g/vkm]	0.005	0.005	0.005	0.005	0.004	0.003	0.003	0.003
		Gasoline	NO_x [g/vkm]	0.072	0.072	0.072	0.067	0.015	0.009	0.009	0.009
			PM [g/vkm]	0.021	0.014	0.012	0.012	0.005	0.004	0.003	0.003
	Thailand	Diesel	NO_x [g/vkm]	0.320	0.320	0.232	0.103	0.084	0.034	0.019	0.019
			PM [g/vkm]	0.043	0.043	0.005	0.005	0.005	0.004	0.003	0.003
		Gasoline	NO_x [g/vkm]	0.090	0.072	0.072	0.067	0.015	0.009	0.009	0.009
			PM [g/vkm]	0.021	0.014	0.012	0.012	0.005	0.004	0.003	0.003
	Vietnam	Diesel	NO_x [g/vkm]	0.323	0.323	0.232	0.103	0.084	0.034	0.019	0.019
			PM [g/vkm]	0.042	0.042	0.005	0.005	0.005	0.004	0.003	0.003
		Gasoline	NO_x [g/vkm]	0.097	0.097	0.072	0.072	0.067	0.015	0.009	0.009
			PM [g/vkm]	0.021	0.014	0.012	0.012	0.012	0.005	0.004	0.003
			NO_x [g/vkm]	0.278	0.278	0.189	0.097	0.067	0.029	0.019	0.019

	Region	Diesel	PM [g/vkm]	0.030	0.030	0.005	0.005	0.004	0.003	0.003	0.003
		Gasoline	NO_x [g/vkm]	0.086	0.080	0.072	0.069	0.033	0.011	0.009	0.009
			PM [g/vkm]	0.021	0.014	0.012	0.012	0.007	0.004	0.003	0.003
South America	Brazil	Diesel	NO_x [g/vkm]	0.215	0.215	0.084	0.034	0.019	0.019	0.019	0.019
			PM [g/vkm]	0.035	0.035	0.012	0.005	0.004	0.003	0.003	0.003
		Gasoline	NO_x [g/vkm]	0.165	0.165	0.067	0.015	0.009	0.009	0.009	0.009
			PM [g/vkm]	0.021	0.014	0.012	0.005	0.004	0.003	0.003	0.003
North America	United States & Canada	Diesel	NO_x [g/vkm]	0.084	0.034	0.019	0.019	0.019	0.019	0.019	0.019
			PM [g/vkm]	0.012	0.005	0.004	0.003	0.003	0.003	0.003	0.003
		Gasoline	NO_x [g/vkm]	0.067	0.015	0.009	0.009	0.009	0.009	0.009	0.009
			PM [g/vkm]	0.012	0.005	0.004	0.003	0.003	0.003	0.003	0.003
	Mexico	Diesel	NO_x [g/vkm]	0.249	0.105	0.084	0.034	0.019	0.019	0.019	0.019
			PM [g/vkm]	0.047	0.062	0.012	0.005	0.004	0.004	0.004	0.004
		Gasoline	NO_x [g/vkm]	0.249	0.105	0.067	0.015	0.009	0.009	0.009	0.009
			PM [g/vkm]	0.021	0.014	0.012	0.005	0.004	0.004	0.004	0.004

Table A6. Emission factors for HDV [42].

Region	Country	Fuel	Pollutant	2015	2020	2025	2030	2035	2040	2045	2050
Global	Global	Diesel	NO_x [g/kWh$_{th}$]	5.397	3.898	1.657	1.259	1.229	0.736	0.709	0.686
			PM [g/kWh$_{th}$]	0.106	0.083	0.030	0.028	0.026	0.021	0.020	0.020
Europe	EU	Diesel	NO_x [g/kWh$_{th}$]	1.100	0.878	0.686	0.686	0.686	0.686	0.686	0.686
			PM [g/kWh$_{th}$]	0.026	0.020	0.020	0.020	0.020	0.020	0.020	0.020
Eurasia	Russia	Diesel	NO_x [g/kWh$_{th}$]	7.033	4.082	1.100	0.878	0.686	0.686	0.686	0.686
			PM [g/kWh$_{th}$]	0.064	0.051	0.026	0.020	0.020	0.020	0.020	0.020
SAARC	India	Diesel	NO_x [g/kWh$_{th}$]	10.870	0.939	0.878	0.686	0.686	0.686	0.686	0.686
			PM [g/kWh$_{th}$]	0.237	0.020	0.020	0.020	0.020	0.020	0.020	0.020
Northeast Asia	China	Diesel	NO_x [g/kWh$_{th}$]	8.951	4.082	1.100	0.878	0.686	0.686	0.686	0.686
			PM [g/kWh$_{th}$]	0.064	0.051	0.026	0.020	0.020	0.020	0.020	0.020
	South Korea	Diesel	NO_x [g/kWh$_{th}$]	1.100	0.878	0.686	0.686	0.686	0.686	0.686	0.686
			PM [g/kWh$_{th}$]	0.026	0.020	0.020	0.020	0.020	0.020	0.020	0.020
	Japan	Diesel	NO_x [g/kWh$_{th}$]	1.023	0.816	0.686	0.686	0.686	0.686	0.686	0.686
			PM [g/kWh$_{th}$]	0.026	0.020	0.020	0.020	0.020	0.020	0.020	0.020
	Region	Diesel	NO_x [g/kWh$_{th}$]	3.691	1.925	0.824	0.750	0.686	0.686	0.686	0.686
			PM [g/kWh$_{th}$]	0.038	0.031	0.022	0.020	0.020	0.020	0.020	0.020
Southeast Asia	Indonesia	Diesel	NO_x [g/kWh$_{th}$]	17.903	17.903	5.115	1.100	0.878	0.686	0.686	0.686
			PM [g/kWh$_{th}$]	0.384	0.384	0.064	0.026	0.020	0.020	0.020	0.020
	Australia	Diesel	NO_x [g/kWh$_{th}$]	5.115	5.115	1.100	0.878	0.686	0.686	0.686	0.686
			PM [g/kWh$_{th}$]	0.064	0.064	0.026	0.020	0.020	0.020	0.020	0.020

	Thailand	Diesel	NO_x [g/kWh$_{th}$]	12.788	12.788	7.033	5.115	5.115	1.100	0.878	0.686
			PM [g/kWh$_{th}$]	0.332	0.332	0.064	0.064	0.064	0.026	0.020	0.020
	Region	Diesel	NO_x [g/kWh$_{th}$]	11.935	11.935	4.416	2.364	2.226	0.824	0.750	0.686
			PM [g/kWh$_{th}$]	0.260	0.260	0.051	0.037	0.035	0.022	0.020	0.020
South America	Brazil	Diesel	NO_x [g/kWh$_{th}$]	5.115	4.082	0.686	0.686	0.686	0.686	0.686	0.686
			PM [g/kWh$_{th}$]	0.077	0.061	0.034	0.034	0.020	0.020	0.020	0.020
	Argentina	Diesel	NO_x [g/kWh$_{th}$]	8.951	4.082	0.686	0.686	0.686	0.686	0.686	0.686
			PM [g/kWh$_{th}$]	0.051	0.041	0.034	0.034	0.020	0.020	0.020	0.020
	Region	Diesel	NO_x [g/kWh$_{th}$]	7.033	4.082	0.686	0.686	0.686	0.686	0.686	0.686
			PM [g/kWh$_{th}$]	0.064	0.051	0.034	0.034	0.020	0.020	0.020	0.020
North America	United States & Canada	Diesel	NO_x [g/kWh$_{th}$]	0.686	0.686	0.686	0.686	0.686	0.686	0.686	0.686
			PM [g/kWh$_{th}$]	0.034	0.034	0.020	0.020	0.020	0.020	0.020	0.020
	Mexico	Diesel	NO_x [g/kWh$_{th}$]	8.951	2.510	0.686	0.686	0.686	0.686	0.686	0.686
			PM [g/kWh$_{th}$]	0.767	0.408	0.034	0.034	0.034	0.020	0.020	0.020

Table A7. Emission factors for buses [42].

Region	Country	Fuel	Pollutant	2015	2020	2025	2030	2035	2040	2045	2050
Global	Global	Diesel	NO_x [g/km]	0.980	0.547	0.061	0.045	0.018	0.015	0.015	0.015
			PM [g/km]	0.012	0.009	0.007	0.006	0.004	0.004	0.004	0.004
Europe	EU	Diesel	NO_x [g/km]	0.08	0.08	0.027	0.015	0.015	0.015	0.015	0.015
			PM [g/km]	0.005	0.005	0.005	0.004	0.004	0.004	0.004	0.004
Eurasia	Russia	Diesel	NO_x [g/km]	0.215	0.08	0.08	0.027	0.015	0.015	0.015	0.015
			PM [g/km]	0.012	0.005	0.005	0.005	0.004	0.004	0.004	0.004
South America	Argentina	Diesel	NO_x [g/km]	3.5	2	0.124	0.124	0.027	0.015	0.015	0.015
			PM [g/km]	0.02	0.02	0.0124	0.0124	0.005	0.004	0.004	0.004
North America	United States	Diesel	NO_x [g/km]	0.124	0.027	0.015	0.015	0.015	0.015	0.015	0.015
			PM [g/km]	0.0124	0.005	0.004	0.004	0.004	0.004	0.004	0.004

Table A8. Emission factors for rail [42].

Region	Country	Pollutant	2015	2020	2025	2030	2035	2040	2045	2050
Global	Global	NO_x [g/kWh_{th}]	22.132	17.146	17.146	17.146	12.172	7.477	2.187	2.187
		PM [g/kWh_{th}]	0.585	0.456	0.455	0.455	0.321	0.148	0.067	0.067
North America	United States	NO_x [g/kWh_{th}]	31.038	24.168	24.168	24.168	17.934	13.011	3.558	3.558
		PM [g/kWh_{th}]	1.126	0.865	0.865	0.865	0.433	0.238	0.082	0.082
Europe	EU	NO_x [g/kWh_{th}]	9.207	6.410	6.410	6.410	6.410	1.943	0.816	0.816
		PM [g/kWh_{th}]	0.288	0.209	0.209	0.209	0.209	0.057	0.051	0.051

Notes: Assumed efficiencies of heavy duty diesel engines at 39% in 2015, and 49% after 2020 [7].

Table A9. Emission factors for aviation.

Region	Country	Fuel	Pollutant	2015	2020	2025	2030	2035	2040	2045	2050
Global	Passenger	Jet Gasoline	NO_x [g/p-km]	0.499	0.448	0.448	0.448	0.378	0.308	0.308	0.308
			PM [g/p-km]	0.001	0.002	0.002	0.002	0.001	0.001	0.001	0.001
			SO_x [g/p-km]	0.026	0.024	0.024	0.024	0.020	0.016	0.016	0.016
Global	Freight	Jet Gasoline	NO_x [g/t-km]	5.901	5.927	5.927	5.927	5.927	5.927	5.927	5.927
			PM [g/t-km]	0.013	0.021	0.021	0.021	0.021	0.021	0.021	0.021
			SO_x [g/t-km]	0.313	0.313	0.313	0.313	0.313	0.313	0.313	0.313

Note: Emission factors are taken from [24, 28, 35, 38, 44]. Average fuel burn per p-km taken from [17], average fuel burn per t-km taken from [43].

Table A10. Emission factors for marine transport.

Region	Type	Fuel	Pollutant	2015	2020	2025	2030	2035	2040	2045	2050
Global	Passenger Ships	Diesel	NO_x [g/kWh$_{th}$]	11.875	11.875	11.875	11.875	11.486	10.318	2.544	2.544
			SO_x [g/kWh$_{th}$]	4.808	4.808	4.808	1.095	1.095	1.095	1.095	1.095
			$PM_{2.5}$ [g/kWh$_{th}$]	0.701	0.701	0.701	0.701	0.701	0.701	0.301	0.301
			PM_{10} [g/kWh$_{th}$]	0.769	0.769	0.769	0.769	0.769	0.769	0.338	0.338
Global	Cargo Ships	Diesel	NO_x [g/kWh$_{th}$]	11.582	11.582	11.582	10.712	10.064	8.769	2.544	2.544
			SO_x [g/kWh$_{th}$]	10.894	10.894	10.894	9.470	9.470	9.470	1.095	1.095
			$PM_{2.5}$ [g/kWh$_{th}$]	1.100	1.100	1.100	1.100	1.100	1.100	0.301	0.301
			PM_{10} [g/kWh$_{th}$]	1.200	1.200	1.200	1.200	1.200	1.200	0.338	0.338
Global	Passenger &	LNG	NO_x [g/kWh$_{th}$]	0.612	0.612	0.612	0.612	0.612	0.612	0.612	0.612
ECA (US & Canada)	Passenger & Cargo	Diesel	NO_x [g/kWh$_{th}$]	2.544	2.544	2.544	2.544	2.544	2.544	2.544	2.544
			$PM_{2.5}$ [g/kWh$_{th}$]	0.301	0.301	0.301	0.301	0.301	0.301	0.301	0.301
			PM_{10} [g/kWh$_{th}$]	0.338	0.338	0.338	0.338	0.338	0.338	0.338	0.338
ECA (Baltic & North Sea)	Passenger & Cargo	Diesel	NO_x [g/kWh$_{th}$]	10.318	2.544	2.544	2.544	2.544	2.544	2.544	2.544
			$PM_{2.5}$ [g/kWh$_{th}$]	0.301	0.301	0.301	0.301	0.301	0.301	0.301	0.301
			PM_{10} [g/kWh$_{th}$]	0.338	0.338	0.338	0.338	0.338	0.338	0.338	0.338

Note: Emission factors are taken from [12, 20, 40, 42].

Table A11. Shares of diesel and gasoline cars.

Vehicle type	Region	Gasoline share	Diesel share	Reference
LDV	Global	76%	19%	[41]
MDV	Global	10%	89%	arithmetic mean
LDV	United States	99.1%	0.9%	[18]
MDV/HDV	United States	19.5%	80.5%	[18]
LDV	New Zealand	91.5%	8.5%	[32]
MDV	New Zealand	29%	71%	[32]
HDV/Bus	New Zealand	3%	97%	[32]
LDV	China	99.5%	0.5%	[16]
LDV	EU-28	53.9%	42%	[1]
MDV/HDV	EU-28	1%	98.3%	[1]

Table A12. Damage costs for 145 regions for NO_x in USD_{2017} per ton of emission.

Note: The list of the regions and descriptions can be found in the supplementary to [5].

Region	Coal	Natural	Oil	Oil	Biomass	Aviation	Marine
NO	30682	17380	8380	10883	10310	19669	8492
DK	27392	27316	1744	9322	8831	16848	7274
SE	17820	21592	4568	9091	8612	16431	7094
FI	15749	16474	2849	7925	7508	14323	6184
BLT	31959	39718	3599	5187	4914	9375	4047
PL	40749	39775	2802	4901	4642	8857	3824
IBE	14209	14967	3253	6032	5714	10901	4707
FR	32598	36800	4308	7658	7255	13840	5976
BNL	46921	59900	3294	12523	11863	22633	9772
BRI	30682	50598	3551	10212	9674	18456	7968
DE	50113	51490	5789	9004	8530	16273	7026
CRS	52008	53029	2475	5769	5465	10426	4502
AUH	43087	42916	3403	7095	6722	12823	5537
BKN-W	31711	33267	1990	3316	3141	5992	2587
BKN-E	27126	26072	2250	4225	4002	7635	3297
IT	27616	30329	3625	7111	6737	12853	5549
CH	30682	50598	3551	11633	11021	21025	9078
TR	9424	10671	1772	4574	4333	8267	3569
UA	22437	20946	2163	1899	1799	3432	1482
IS	30682	33886	1152	9097	8618	16442	7099
DZ	11426	3341	528	2024	1917	3658	1579
BHQ	11426	13265	1349	12801	12127	23136	9989
EG	11426	4647	671	1859	1761	3359	1450
IR	11426	4354	958	2233	2115	4035	1742
IQ	11426	2246	451	1813	1717	3277	1415
IL	21435	21492	3224	6617	6269	11959	5163
JWG	11426	2793	231	1753	1661	3168	1368
KW	11426	5898	2308	9642	9134	17425	7523

Region	Coal	Natural	Oil	Oil	Biomass	Aviation	Marine
LB	11426	5850	521	2866	2715	5180	2236
LY	11426	1717	234	1938	1836	3503	1512
MA	1418	1653	493	1254	1188	2266	978
OM	11426	7360	1917	5309	5029	9595	4142
SA	11426	7360	1917	8602	8149	15546	6712
TN	11426	3490	446	1850	1752	3343	1443
AE	11426	6864	872	11467	10863	20725	8948
YE	11426	5898	54	442	419	800	345
SY	11426	2039	318	4529	4291	8186	3534
RU-NW	16728	19147	8876	4495	11612	8124	3508
RU-C	16728	19147	8876	4495	11612	8124	3508
RU-S	16728	19147	8876	4495	11612	8124	3508
RU-V	16728	19147	8876	4495	11612	8124	3508
RU-U	16728	19147	8876	4495	11612	8124	3508
RU-SI	16728	19147	8876	4495	11612	8124	3508
RU-FE	16728	19147	8876	4495	11612	8124	3508
BY	12917	29111	4194	3219	3049	5818	2512
CAU	12917	10360	1204	2273	2153	4108	1774
KZ	4232	10092	1224	4271	4046	7719	3333
PAM	3060	15167	198	671	635	1212	523
UZ	4784	4052	259	1070	1014	1934	835
TM	12917	7488	533	2285	2164	4129	1783
JP-E	30182	30858	7979	6976	6608	12607	5443
JP-W	30182	30858	7979	6976	6608	12607	5443
KR	35084	34996	5866	6835	6475	12352	5333
KP	25586	28708	251	3381	3203	6111	2639
CN-NE	25612	27385	1517	2232	2114	4033	1741
CN-N	25612	27385	1517	2232	2114	4033	1741
CN-E	25612	27385	1517	2232	2114	4033	1741
CN-C	25612	27385	1517	2232	2114	4033	1741
CN-S	25612	27385	1517	2232	2114	4033	1741

Region	Coal	Natural	Oil	Oil	Biomass	Aviation	Marine
CN-TB	25612	27385	1517	2232	2114	4033	1741
CN-NW	25612	27385	1517	2232	2114	4033	1741
CN-XU	25612	27385	1517	2232	2114	4033	1741
MN	6688	28708	1132	1938	1836	3503	1512
NZ	674	557	718	7115	6741	12860	5552
AU-E	1485	1184	2464	8443	7999	15260	6588
AU-W	1485	1184	2464	8443	7999	15260	6588
ID-	5394	5843	972	1785	1691	3225	1393
ID-SU	5394	5843	972	1785	1691	3225	1393
ID-JV+TL	5394	5843	972	1785	1691	3225	1393
ID-KL-	5394	5843	972	1785	1691	3225	1393
MY-	7234	7090	1371	4359	4130	7879	3402
MY-	7234	7090	1371	4359	4130	7879	3402
PH	3507	4001	516	1284	1216	2320	1002
MM	2129	4959	298	751	711	1356	586
TH	12721	11157	775	2866	2715	5180	2237
LA	3910	4959	214	1151	1090	2079	898
VN	7762	3876	570	1132	1072	2046	883
KH	4980	4959	166	623	590	1126	486
IN-E	9022	7559	365	959	909	1733	748
IN-CE	9022	7559	365	959	909	1733	748
IN-W	9022	7559	365	959	909	1733	748
IN-CW	9022	7559	365	959	909	1733	748
IN-N	9022	7559	365	959	909	1733	748
IN-NW	9022	7559	365	959	909	1733	748
IN-UP	9022	7559	365	959	909	1733	748
IN-S	9022	7559	365	959	909	1733	748
IN-CS	9022	7559	365	959	909	1733	748
IN-NE	9022	7559	365	959	909	1733	748
BD	8484	7808	770	651	616	1176	508
NP+BT	7938	6479	70	1143	1083	2065	892

Region	Coal	Natural	Oil	Oil	Biomass	Aviation	Marine
PK-S	2695	3292	210	752	713	1360	587
PK-N	2695	3292	210	752	713	1360	587
AF	7938	1141	70	389	369	703	304
LK	7040	6060	189	2091	1981	3779	1631
WW	109	557	43	500	473	903	390
WS	516	399	51	542	514	980	423
WN	516	557	14	263	249	475	205
NIG-S	516	904	237	970	919	1752	757
NIG-N	516	904	237	970	919	1752	757
SER	516	307	23	447	423	807	349
ETH	516	557	25	313	296	565	244
SOMDJ	516	557	34	789	748	1426	616
KENUG	516	370	28	517	489	934	403
TZRB	516	188	21	297	281	537	232
CAR	516	263	76	1632	1546	2950	1274
COG	516	557	148	187	177	339	146
SW	641	563	214	2065	1957	3733	1612
ZAFLS	1319	1558	446	480	454	867	374
SE	208	112	28	1658	2154	1846	1433
IOCE	304	557	27	2198	2083	3973	1715
CAM	1483	693	347	2032	1925	3673	1586
CO	1764	1645	1921	2503	2372	4524	1953
VE	2604	1191	539	1899	1799	3431	1482
EC	2604	680	222	2092	1982	3780	1632
PE	384	785	660	2129	2017	3848	1662
CSA	2604	387	240	1740	1649	3145	1358
BR-S	2067	3327	1415	2648	2508	4786	2066
BR-SP	2067	3327	1415	2648	2508	4786	2066
BR-SE	2067	3327	1415	2648	2508	4786	2066
BR-N	2067	3327	1415	2648	2508	4786	2066
BR-NE	2067	3327	1415	2648	2508	4786	2066

Region	Coal	Natural	Oil	Oil	Biomass	Aviation	Marine
AR-NE	5243	3584	2312	4208	3987	7606	3284
AR-E	5243	3584	2312	4208	3987	7606	3284
AR-W	5243	3584	2312	4208	3987	7606	3284
CL	1555	1791	2168	4156	3937	7510	3243
CA-W	3544	7607	3486	8400	7957	15180	6554
CA-E	3544	7607	3486	8400	7957	15180	6554
US-NENY	16223	15729	4511	10292	9750	18601	8031
US-MA	16223	15729	4511	10292	9750	18601	8031
US-CAR	16223	15729	4511	10292	9750	18601	8031
US-S	16223	15729	4511	10292	9750	18601	8031
US-TVA	16223	15729	4511	10292	9750	18601	8031
US-MW	16223	15729	4511	10292	9750	18601	8031
US-C	16223	15729	4511	10292	9750	18601	8031
US-TX	16223	15729	4511	10292	9750	18601	8031
US-SW	16223	15729	4511	10292	9750	18601	8031
US-NW	16223	15729	4511	10292	9750	18601	8031
US-CA	16223	15729	4511	10292	9750	18601	8031
US-GU	16223	15729	4511	10292	9750	18601	8031
US-AK	16223	15729	4511	10292	9750	18601	8031
US-HI	16223	15729	4511	10292	9750	18601	8031
MX-NW	2462	2985	2158	3391	3213	6129	2646
MX-N	2462	2985	2158	3391	3213	6129	2646
MX-C	2462	2985	2158	3391	3213	6129	2646
MX-S	2462	2985	2158	3391	3213	6129	2646

Table A13. Damage costs for 145 regions for SO_x in USD_{2017} per ton of emission.

Note: The list of the regions and descriptions can be found in the supplementary to [5].

Region	Coal	Natural	Ground-	Oil	Biomass	Aviation	Marine
NO	41103	20579	41015	28112	22795	37887	21905
DK	35709	35558	8574	24081	19526	32453	18763
SE	23374	26997	22431	23484	19042	31648	18298
FI	19199	20782	13978	20472	16599	27589	15951
BLT	37561	49570	17501	13399	10864	18057	10440
PL	55741	51355	13572	12659	10264	17060	9864
IBE	18276	19956	15864	15581	12633	20998	12140
FR	44627	50244	21157	19782	16040	26659	15413
BNL	71085	84510	16216	32349	26230	43595	25205
BRI	41103	66886	17325	26379	21389	35550	20554
DE	74827	78953	28251	23259	18859	31345	18123
CRS	69839	71677	12020	14902	12083	20083	11611
AUH	56555	57072	16550	18328	14861	24700	14281
BKN-W	40517	43529	9601	8565	6945	11543	6674
BKN-E	33655	34147	10899	10913	8848	14707	8503
IT	35175	41740	17630	18370	14895	24756	14313
CH	41103	66886	17325	30050	24366	40498	23414
TR	12039	15760	8633	11816	9581	15924	9207
UA	29464	27610	10526	4905	3977	6610	3822
IS	41103	45464	5683	23500	19054	31670	18310
DZ	17790	4831	2574	5228	4239	7046	4074
BHQ	17790	16837	6662	33067	26812	44564	25765
EG	17790	8888	3213	4801	3893	6470	3741
IR	17790	5971	4663	5767	4676	7773	4494
IQ	17790	2999	2193	4683	3797	6311	3649
IL	33234	33993	15891	17093	13860	23036	13318
JWG	17790	4128	1131	4529	3672	6103	3529
KW	17790	8539	11412	24905	20194	33564	19406

Region	Coal	Natural	Ground-	Oil	Biomass	Aviation	Marine
LB	17790	8927	2560	7403	6003	9977	5768
LY	17790	2184	1146	5006	4059	6747	3901
MA	2347	2686	2382	3238	2626	4364	2523
OM	17790	9894	9400	13713	11119	18481	10685
SA	17790	9894	9400	22220	18017	29945	17313
TN	17790	4640	2169	4778	3874	6439	3723
AE	17790	9112	4278	29622	24019	39921	23081
YE	17790	8539	256	1143	927	1540	890
SY	17790	3095	1536	11700	9487	15768	9116
RU-NW	23488	29563	43309	11612	9415	15649	9048
RU-C	23488	29563	43309	11612	9415	15649	9048
RU-S	23488	29563	43309	11612	9415	15649	9048
RU-V	23488	29563	43309	11612	9415	15649	9048
RU-U	23488	29563	43309	11612	9415	15649	9048
RU-SI	23488	29563	43309	11612	9415	15649	9048
RU-FE	23488	29563	43309	11612	9415	15649	9048
BY	17986	36183	20475	8315	6742	11206	6479
CAU	17986	13667	5818	5871	4761	7913	4575
KZ	5075	11614	5903	11032	8946	14868	8596
PAM	3898	21985	942	1732	1404	2334	1350
UZ	6468	5242	1236	2765	2242	3726	2154
TM	17986	9066	2563	5902	4785	7953	4598
JP-E	45823	58766	39298	18019	14611	24284	14040
JP-W	45823	58766	39298	18019	14611	24284	14040
KR	48586	47841	28772	17654	14315	23793	13756
KP	36563	45712	1214	8735	7082	11771	6806
CN-NE	36356	42182	7293	5765	4674	7769	4492
CN-N	36356	42182	7293	5765	4674	7769	4492
CN-E	36356	42182	7293	5765	4674	7769	4492
CN-C	36356	42182	7293	5765	4674	7769	4492
CN-S	36356	42182	7293	5765	4674	7769	4492

Region	Coal	Natural	Ground-	Oil	Biomass	Aviation	Marine
CN-TB	36356	42182	7293	5765	4674	7769	4492
CN-NW	36356	42182	7293	5765	4674	7769	4492
CN-XU	36356	42182	7293	5765	4674	7769	4492
MN	7670	45712	5506	5007	4059	6747	3901
NZ	2207	1824	3530	18380	14903	24770	14321
AU-E	2759	2808	12124	21810	17685	29393	16994
AU-W	2759	2808	12124	21810	17685	29393	16994
ID-	9994	12180	4675	4610	3738	6213	3592
ID-SU	9994	12180	4675	4610	3738	6213	3592
ID-JV+TL	9994	12180	4675	4610	3738	6213	3592
ID-KL-	9994	12180	4675	4610	3738	6213	3592
MY-	10828	10128	6684	11261	9130	15176	8774
MY-	10828	10128	6684	11261	9130	15176	8774
PH	6008	7885	2481	3316	2688	4468	2583
MM	2521	8932	1418	1939	1572	2613	1511
TH	16560	16618	3689	7404	6003	9978	5769
LA	4586	8932	1017	2972	2410	4005	2316
VN	11132	6259	2708	2924	2371	3941	2278
KH	7869	8932	781	1610	1305	2169	1254
IN-E	12434	10852	1735	2477	2009	3339	1930
IN-CE	12434	10852	1735	2477	2009	3339	1930
IN-W	12434	10852	1735	2477	2009	3339	1930
IN-CW	12434	10852	1735	2477	2009	3339	1930
IN-N	12434	10852	1735	2477	2009	3339	1930
IN-NW	12434	10852	1735	2477	2009	3339	1930
IN-UP	12434	10852	1735	2477	2009	3339	1930
IN-S	12434	10852	1735	2477	2009	3339	1930
IN-CS	12434	10852	1735	2477	2009	3339	1930
IN-NE	12434	10852	1735	2477	2009	3339	1930
BD	12589	12742	3651	1681	1363	2265	1309
NP+BT	10949	9449	330	2952	2393	3978	2300

Region	Coal	Natural	Ground-	Oil	Biomass	Aviation	Marine
PK-S	3577	4606	1001	1943	1576	2619	1514
PK-N	3577	4606	1001	1943	1576	2619	1514
AF	10949	1539	330	1005	815	1354	783
LK	9210	9710	886	5401	4379	7278	4208
WW	206	928	207	1291	1047	1740	1006
WS	792	584	244	1400	1135	1887	1091
WN	792	928	66	678	550	914	529
NIG-S	792	1521	1138	2505	2031	3376	1952
NIG-N	792	1521	1138	2505	2031	3376	1952
SER	792	371	109	1154	936	1555	899
ETH	792	928	117	808	655	1089	630
SOMDJ	792	928	167	2039	1653	2748	1589
KENUG	792	502	131	1335	1082	1799	1040
TZRB	792	285	100	767	622	1034	598
CAR	792	326	370	4216	3418	5682	3285
COG	792	928	705	484	392	652	377
SW	801	729	1031	5335	4326	7190	4157
ZAFLS	2049	3261	2162	1239	1004	1669	965
SE	256	183	133	987	2037	1662	1588
IOCE	646	928	129	5679	4605	7653	4425
CAM	2276	1037	1685	5249	4256	7074	4090
CO	2834	2502	9382	6467	5243	8715	5039
VE	4942	2007	2647	4904	3977	6609	3821
EC	4942	1121	1080	5403	4381	7282	4210
PE	476	1874	3225	5500	4460	7413	4286
CSA	4942	559	1162	4495	3645	6058	3503
BR-S	2777	5948	6945	6840	5546	9218	5329
BR-SP	2777	5948	6945	6840	5546	9218	5329
BR-SE	2777	5948	6945	6840	5546	9218	5329
BR-N	2777	5948	6945	6840	5546	9218	5329
BR-NE	2777	5948	6945	6840	5546	9218	5329

Region	Coal	Natural	Ground-	Oil	Biomass	Aviation	Marine
AR-NE	12568	7437	11399	10871	8814	14650	8470
AR-E	12568	7437	11399	10871	8814	14650	8470
AR-W	12568	7437	11399	10871	8814	14650	8470
CL	2130	3007	10667	10734	8704	14466	8364
CA-W	5024	11562	17077	21697	17593	29240	16906
CA-E	5024	11562	17077	21697	17593	29240	16906
US-NENY	22284	24685	22118	26586	21557	35830	20716
US-MA	22284	24685	22118	26586	21557	35830	20716
US-CAR	22284	24685	22118	26586	21557	35830	20716
US-S	22284	24685	22118	26586	21557	35830	20716
US-TVA	22284	24685	22118	26586	21557	35830	20716
US-MW	22284	24685	22118	26586	21557	35830	20716
US-C	22284	24685	22118	26586	21557	35830	20716
US-TX	22284	24685	22118	26586	21557	35830	20716
US-SW	22284	24685	22118	26586	21557	35830	20716
US-NW	22284	24685	22118	26586	21557	35830	20716
US-CA	22284	24685	22118	26586	21557	35830	20716
US-GU	22284	24685	22118	26586	21557	35830	20716
US-AK	22284	24685	22118	26586	21557	35830	20716
US-HI	22284	24685	22118	26586	21557	35830	20716
MX-NW	3068	4930	10554	8761	7103	11806	6826
MX-N	3068	4930	10554	8761	7103	11806	6826
MX-C	3068	4930	10554	8761	7103	11806	6826
MX-S	3068	4930	10554	8761	7103	11806	6826

Table A14. Damage costs for 145 regions for $PM_{2.5}$ and PM_{10} in USD_{2017} per ton of emission.

Note: The list of the regions and descriptions can be found in the supplementary to [5].

	$PM_{2.5}$							**PM_{10}**
Region	**Coal**	**Natural**	**Ground-**	**Oil**	**Biomass**	**Aviation**	**Marine**	
NO	51424	27368	1081386	116330	81926	105387	77375	54137
DK	47258	47310	222452	99647	70177	90272	66278	46373
SE	29161	35568	584066	97176	68437	88034	64635	45223
FI	22991	25039	365113	84712	59659	76743	56345	39423
BLT	48046	62229	472651	55444	39047	50228	36878	25802
PL	70355	64565	372083	52383	36891	47455	34841	24377
IBE	22363	24564	423873	64473	45406	58408	42883	30004
FR	55492	61182	550694	81857	57648	74156	54445	38094
BNL	87108	103102	418482	133859	94271	121266	89034	62294
BRI	51424	84056	462109	109155	76873	98886	72602	50798
DE	92754	97788	753243	96245	67781	87191	64016	44790
CRS	87405	89847	326024	61665	43428	55864	41016	28697
AUH	71316	72354	446674	75842	53412	68707	50445	35295
BKN-W	51270	55328	266925	35441	24960	32107	23573	16493
BKN-E	41361	42142	298476	45157	31802	40909	30035	21015
IT	44458	53210	475752	76014	53533	68863	50559	35375
CH	51424	84056	462109	124348	87573	112650	82708	57868
TR	14998	19445	231816	48895	34435	44295	32522	22754
UA	36455	33831	283753	20296	14294	18387	13500	9445
IS	51424	56999	145389	97242	68483	88094	64679	45254
DZ	21552	5952	68903	21634	15236	19599	14390	10068
BHQ	21552	19893	169933	136834	96366	123961	91012	63679
EG	21552	10858	91619	19867	13991	17998	13214	9245
IR	21552	7273	125630	23865	16807	21620	15874	11106
IQ	21552	3796	59400	19378	13647	17555	12889	9018
IL	40206	41222	408022	70730	49812	64076	47045	32916
JWG	21552	5056	29701	18739	13197	16976	12464	8721

	$PM_{2.5}$							PM_{10}
Region	**Coal**	**Natural**	**Ground-**	**Oil**	**Biomass**	**Aviation**	**Marine**	
KW	21552	10395	289198	103058	72580	93363	68547	47960
LB	21552	11326	66364	30634	21574	27752	20375	14256
LY	21552	2610	30306	20716	14589	18767	13779	9641
MA	2897	3301	65909	13400	9437	12139	8913	6236
OM	21552	12163	246289	56746	39963	51407	37743	26408
SA	21552	12163	246289	91945	64753	83295	61156	42789
TN	21552	5625	58787	19771	13924	17911	13151	9201
AE	21552	10737	111616	122576	86325	111044	81529	57043
YE	21552	10395	7513	4729	3330	4284	3145	2201
SY	21552	3952	42592	48414	34096	43859	32202	0
RU-NW	28787	37065	1155143	48051	33840	43530	31960	22361
RU-C	28787	37065	1155143	48051	33840	43530	31960	22361
RU-S	28787	37065	1155143	48051	33840	43530	31960	22361
RU-V	28787	37065	1155143	48051	33840	43530	31960	22361
RU-U	28787	37065	1155143	48051	33840	43530	31960	22361
RU-SI	28787	37065	1155143	48051	33840	43530	31960	22361
RU-FE	28787	37065	1155143	48051	33840	43530	31960	22361
BY	22008	45844	544999	34408	24232	31171	22886	16013
CAU	22008	16957	161005	24295	17110	22010	16160	11306
KZ	6055	14432	164443	45653	32151	41358	30365	21245
PAM	4693	27530	27545	7167	5047	6493	4767	3335
UZ	7824	6295	35825	11440	8056	10364	7609	5324
TM	22008	10955	72240	24421	17198	22123	16243	11365
JP-E	55285	71388	1011715	74563	52512	67549	49594	34700
JP-W	55285	71388	1011715	74563	52512	67549	49594	34700
KR	63516	62761	752509	73055	51449	66182	48591	33998
KP	45575	57352	33338	36144	25455	32744	24041	0
CN-NE	45533	53167	205230	23854	16799	21610	15866	11101
CN-N	45533	53167	205230	23854	16799	21610	15866	11101
CN-E	45533	53167	205230	23854	16799	21610	15866	11101

	PM2.5							PM10
Region	**Coal**	**Natural**	**Ground-**	**Oil**	**Biomass**	**Aviation**	**Marine**	
CN-C	45533	53167	205230	23854	16799	21610	15866	11101
CN-S	45533	53167	205230	23854	16799	21610	15866	11101
CN-TB	45533	53167	205230	23854	16799	21610	15866	11101
CN-NW	45533	53167	205230	23854	16799	21610	15866	11101
CN-XU	45533	53167	205230	23854	16799	21610	15866	11101
MN	8549	57352	148781	20717	14590	18768	13780	9641
NZ	2788	2304	91708	76056	53563	68901	50587	35394
AU-E	3461	3548	313089	90252	63560	81761	60029	42001
AU-W	3461	3548	313089	90252	63560	81761	60029	42001
ID-	12199	15014	131331	19076	13434	17281	12688	8877
ID-SU	12199	15014	131331	19076	13434	17281	12688	8877
ID-	12199	15014	131331	19076	13434	17281	12688	8877
ID-KL-	12199	15014	131331	19076	13434	17281	12688	8877
MY-	13094	12289	178913	46596	32816	42213	30993	21685
MY-	13094	12289	178913	46596	32816	42213	30993	21685
PH	7220	9578	69894	13720	9663	12430	9126	6385
MM	3153	10966	41496	8022	5650	7268	5336	3733
TH	19951	20353	107553	30638	21577	27756	20378	14258
LA	5590	10966	29681	12299	8661	11142	8180	5723
VN	13846	7625	79563	12100	8522	10962	8048	5631
KH	9604	10966	23530	6660	4691	6034	4430	3099
IN-E	15513	13571	50914	10251	7219	9287	6818	4771
IN-CE	15513	13571	50914	10251	7219	9287	6818	4771
IN-W	15513	13571	50914	10251	7219	9287	6818	4771
IN-CW	15513	13571	50914	10251	7219	9287	6818	4771
IN-N	15513	13571	50914	10251	7219	9287	6818	4771
IN-NW	15513	13571	50914	10251	7219	9287	6818	4771
IN-UP	15513	13571	50914	10251	7219	9287	6818	4771
IN-S	15513	13571	50914	10251	7219	9287	6818	4771
IN-CS	15513	13571	50914	10251	7219	9287	6818	4771

	$PM_{2.5}$							PM_{10}
Region	**Coal**	**Natural**	**Ground-**	**Oil**	**Biomass**	**Aviation**	**Marine**	
IN-NE	15513	13571	50914	10251	7219	9287	6818	4771
BD	14925	15443	107931	6954	4898	6300	4625	3236
NP+BT	11778	45125	10020	12214	8602	11065	8124	5684
PK-S	4668	5813	29026	8041	5663	7285	5348	3742
PK-N	4668	5813	29026	8041	5663	7285	5348	3742
AF	11778	1912	9851	4159	2929	3768	2766	1935
LK	10952	11984	27012	22348	15738	20245	14864	10400
WW	252	1152	5886	5342	3762	4840	3553	2486
WS	959	738	6891	5795	4081	5249	3854	2697
WN	959	1152	1979	2808	1977	2543	1867	1307
NIG-S	959	1889	32046	10365	7299	9390	6894	4823
NIG-N	959	1889	32046	10365	7299	9390	6894	4823
SER	959	429	3235	4776	3363	4326	3176	2222
ETH	959	1152	3551	3344	2355	3029	2224	1556
SOMDJ	959	1152	4455	8437	5941	7643	5611	3926
KENUG	959	620	3948	5523	3890	5003	3673	2570
TZRB	959	359	3006	3175	2236	2876	2112	1478
CAR	959	400	10112	17446	12286	15805	11604	8119
COG	959	1152	20557	2002	1410	1814	1332	932
SW	973	939	28589	22076	15547	19999	14684	10274
ZAFLS	2436	4033	59188	5125	3610	4643	3409	2385
SE	329	221	3876	2442	2836	1949	1431	1001
IOCE	804	1152	3772	23499	16550	21289	15630	10936
CAM	2903	1232	45872	21722	15298	19678	14448	10109
CO	3502	3108	249519	26759	18845	24242	17798	12453
VE	6248	2550	68649	20294	14292	18385	13498	9444
EC	6248	1372	29232	22359	15746	20255	14871	10405
PE	592	2340	85423	22761	16029	20619	15139	10592
CSA	6248	668	31738	18601	13100	16851	12372	8657
BR-S	3638	7284	181118	28303	19933	25641	18825	13171

	$PM_{2.5}$							PM_{10}
Region	**Coal**	**Natural**	**Ground-**	**Oil**	**Biomass**	**Aviation**	**Marine**	
BR-SP	3638	7284	181118	28303	19933	25641	18825	13171
BR-SE	3638	7284	181118	28303	19933	25641	18825	13171
BR-N	3638	7284	181118	28303	19933	25641	18825	13171
BR-NE	3638	7284	181118	28303	19933	25641	18825	13171
AR-NE	15725	9307	292367	44983	31680	40751	29920	20934
AR-E	15725	9307	292367	44983	31680	40751	29920	20934
AR-W	15725	9307	292367	44983	31680	40751	29920	20934
CL	2615	3751	275511	44418	31282	40240	29544	20671
CA-W	6282	14758	448858	89782	63230	81336	59717	41782
CA-E	6282	14758	448858	89782	63230	81336	59717	41782
US-	27838	30299	579450	110015	77479	99666	73175	51198
US-MA	27838	30299	579450	110015	77479	99666	73175	51198
US-CAR	27838	30299	579450	110015	77479	99666	73175	51198
US-S	27838	30299	579450	110015	77479	99666	73175	51198
US-TVA	27838	30299	579450	110015	77479	99666	73175	51198
US-MW	27838	30299	579450	110015	77479	99666	73175	51198
US-C	27838	30299	579450	110015	77479	99666	73175	51198
US-TX	27838	30299	579450	110015	77479	99666	73175	51198
US-SW	27838	30299	579450	110015	77479	99666	73175	51198
US-NW	27838	30299	579450	110015	77479	99666	73175	51198
US-CA	27838	30299	579450	110015	77479	99666	73175	51198
US-GU	27838	30299	579450	110015	77479	99666	73175	51198
US-AK	27838	30299	579450	110015	77479	99666	73175	51198
US-HI	27838	30299	579450	110015	77479	99666	73175	51198
MX-NW	3699	6050	279007	36251	25530	32841	24112	16870
MX-N	3699	6050	279007	36251	25530	32841	24112	16870
MX-C	3699	6050	279007	36251	25530	32841	24112	16870
MX-S	3699	6050	279007	36251	25530	32841	24112	16870

Table A15. Mortality rates attributable to NO_x, SO_x, $PM_{2.5}$, PM_{10} emissions per ton of pollutant.

Note: The list of the regions and descriptions can be found in the supplementary to [5].

	NO_x	**SO_x**	**$PM_{2.5}$**	**PM_{10}**
NO	0.0053	0.0080	0.0408	0.1449
DK	0.0032	0.0045	0.0180	0.1057
SE	0.0026	0.0042	0.0377	0.1057
FI	0.0023	0.0035	0.0268	0.1065
BLT	0.0073	0.0100	0.0563	0.2879
PL	0.0079	0.0115	0.0482	0.1877
IBE	0.0026	0.0043	0.0369	0.1080
FR	0.0049	0.0077	0.0444	0.1040
BNL	0.0056	0.0091	0.0344	0.1060
BRI	0.0033	0.0052	0.0247	0.1033
DE	0.0063	0.0106	0.0552	0.1087
CRS	0.0089	0.0127	0.0417	0.1888
AUH	0.0068	0.0099	0.0444	0.1487
BKN-W	0.0078	0.0110	0.0492	0.1885
BKN-E	0.0056	0.0080	0.0394	0.1483
IT	0.0043	0.0067	0.0405	0.1089
CH	0.0053	0.0080	0.0408	0.1449
TR	0.0022	0.0037	0.0268	0.0700
UA	0.0090	0.0133	0.0697	0.2873
IS	0.0053	0.0080	0.0408	0.1449
DZ	0.0022	0.0042	0.0285	0.0828
BHQ	0.0022	0.0042	0.0285	0.0828
EG	0.0022	0.0042	0.0285	0.0828
IR	0.0022	0.0042	0.0285	0.0828
IQ	0.0022	0.0042	0.0285	0.0828
IL	0.0035	0.0062	0.0366	0.0987
JWG	0.0022	0.0042	0.0285	0.0828

	NO_x	SO_x	$PM_{2.5}$	PM_{10}
KW	0.0022	0.0042	0.0285	0.0828
LB	0.0022	0.0042	0.0285	0.0828
LY	0.0022	0.0042	0.0285	0.0828
MA	0.0010	0.0021	0.0204	0.0670
OM	0.0022	0.0042	0.0285	0.0828
SA	0.0022	0.0042	0.0285	0.0828
TN	0.0022	0.0042	0.0285	0.0828
AE	0.0022	0.0042	0.0285	0.0828
YE	0.0022	0.0042	0.0285	0.0828
SY	0.0022	0.0042	0.0285	0.0828
RU-NW	0.0046	0.0098	0.1245	0.2859
RU-C	0.0046	0.0098	0.1245	0.2859
RU-S	0.0046	0.0098	0.1245	0.2859
RU-V	0.0046	0.0098	0.1245	0.2859
RU-U	0.0046	0.0098	0.1245	0.2859
RU-SI	0.0046	0.0098	0.1245	0.2859
RU-FE	0.0046	0.0098	0.1245	0.2859
BY	0.0041	0.0084	0.1008	0.2547
CAU	0.0041	0.0084	0.1008	0.2547
KZ	0.0017	0.0024	0.0196	0.1517
PAM	0.0041	0.0084	0.1008	0.2547
UZ	0.0029	0.0042	0.0161	0.1392
TM	0.0041	0.0084	0.1008	0.2547
JP-E	0.0050	0.0103	0.0817	0.0900
JP-W	0.0050	0.0103	0.0817	0.0900
KR	0.0055	0.0091	0.0641	0.0863
KP	0.0085	0.0139	0.0601	0.0946
CN-NE	0.0097	0.0153	0.0543	0.0968
CN-N	0.0097	0.0153	0.0543	0.0968
CN-E	0.0097	0.0153	0.0543	0.0968
CN-C	0.0097	0.0153	0.0543	0.0968

	NO_x	SO_x	$PM_{2.5}$	PM_{10}
CN-S	0.0097	0.0153	0.0543	0.0968
CN-TB	0.0097	0.0153	0.0543	0.0968
CN-NW	0.0097	0.0153	0.0543	0.0968
CN-XU	0.0097	0.0153	0.0543	0.0968
MN	0.0085	0.0139	0.0601	0.0946
NZ	0.0001	0.0005	0.0068	0.0903
AU-E	0.0003	0.0011	0.0197	0.0914
AU-W	0.0003	0.0011	0.0197	0.0914
ID-PG+NG	0.0026	0.0057	0.0338	0.0712
ID-SU	0.0026	0.0057	0.0338	0.0712
ID-JV+TL	0.0026	0.0057	0.0338	0.0712
ID-KL-SW	0.0026	0.0057	0.0338	0.0712
MY-W+SG	0.0016	0.0029	0.0213	0.0719
MY-E+BN	0.0016	0.0029	0.0213	0.0719
PH	0.0022	0.0046	0.0241	0.0679
MM	0.0020	0.0040	0.0251	0.0763
TH	0.0036	0.0054	0.0216	0.0747
LA	0.0020	0.0040	0.0251	0.0763
VN	0.0038	0.0062	0.0310	0.0717
KH	0.0020	0.0040	0.0251	0.0763
IN-E	0.0059	0.0088	0.0281	0.0740
IN-CE	0.0059	0.0088	0.0281	0.0740
IN-W	0.0059	0.0088	0.0281	0.0740
IN-CW	0.0059	0.0088	0.0281	0.0740
IN-N	0.0059	0.0088	0.0281	0.0740
IN-NW	0.0059	0.0088	0.0281	0.0740
IN-UP	0.0059	0.0088	0.0281	0.0740
IN-S	0.0059	0.0088	0.0281	0.0740
IN-CS	0.0059	0.0088	0.0281	0.0740
IN-NE	0.0059	0.0088	0.0281	0.0740
BD	0.0082	0.0139	0.0662	0.0730

	NO_x	SO_x	$PM_{2.5}$	PM_{10}
NP+BT	0.0054	0.0081	0.0279	0.0728
PK-S	0.0026	0.0039	0.0168	0.0670
PK-N	0.0026	0.0039	0.0168	0.0670
AF	0.0054	0.0081	0.0279	0.0728
LK	0.0025	0.0037	0.0094	0.0717
WW	0.0004	0.0009	0.0077	0.0431
WS	0.0004	0.0009	0.0077	0.0431
WN	0.0004	0.0009	0.0077	0.0431
NIG-S	0.0004	0.0009	0.0077	0.0431
NIG-N	0.0004	0.0009	0.0077	0.0431
SER	0.0004	0.0009	0.0077	0.0431
ETH	0.0004	0.0009	0.0077	0.0431
SOMDJ	0.0004	0.0009	0.0077	0.0431
KENUG	0.0004	0.0009	0.0077	0.0431
TZRB	0.0004	0.0009	0.0077	0.0431
CAR	0.0004	0.0009	0.0077	0.0431
COG	0.0004	0.0009	0.0077	0.0431
SW	0.0003	0.0004	0.0038	0.0420
ZAFLS	0.0006	0.0013	0.0116	0.0442
SE	0.0004	0.0009	0.0077	0.0431
IOCE	0.0004	0.0009	0.0077	0.0431
CAM	0.0010	0.0025	0.0310	0.0681
CO	0.0009	0.0024	0.0417	0.0522
VE	0.0010	0.0025	0.0310	0.0681
EC	0.0010	0.0025	0.0310	0.0681
PE	0.0003	0.0010	0.0164	0.0373
CSA	0.0010	0.0025	0.0310	0.0681
BR-S	0.0011	0.0024	0.0299	0.0686
BR-SP	0.0011	0.0024	0.0299	0.0686
BR-SE	0.0011	0.0024	0.0299	0.0686
BR-N	0.0011	0.0024	0.0299	0.0686

	NO_x	SO_x	$PM_{2.5}$	PM_{10}
BR-NE	0.0011	0.0024	0.0299	0.0686
AR-NE	0.0012	0.0034	0.0341	0.0787
AR-E	0.0012	0.0034	0.0341	0.0787
AR-W	0.0012	0.0034	0.0341	0.0787
CL	0.0006	0.0017	0.0306	0.0801
CA-W	0.0009	0.0021	0.0291	0.1049
CA-E	0.0009	0.0021	0.0291	0.1049
US-NENY	0.0019	0.0036	0.0335	0.1060
US-MA	0.0019	0.0036	0.0335	0.1060
US-CAR	0.0019	0.0036	0.0335	0.1060
US-S	0.0019	0.0036	0.0335	0.1060
US-TVA	0.0019	0.0036	0.0335	0.1060
US-MW	0.0019	0.0036	0.0335	0.1060
US-C	0.0019	0.0036	0.0335	0.1060
US-TX	0.0019	0.0036	0.0335	0.1060
US-SW	0.0019	0.0036	0.0335	0.1060
US-NW	0.0019	0.0036	0.0335	0.1060
US-CA	0.0019	0.0036	0.0335	0.1060
US-GU	0.0019	0.0036	0.0335	0.1060
US-AK	0.0019	0.0036	0.0335	0.1060
US-HI	0.0019	0.0036	0.0335	0.1060
MX-NW	0.0010	0.0024	0.0369	0.0517
MX-N	0.0010	0.0024	0.0369	0.0517
MX-C	0.0010	0.0024	0.0369	0.0517
MX-S	0.0010	0.0024	0.0369	0.0517

Table A16. Global emission volumes from literature.

		this study	**EDGAR v5 [13, 14, 16]**	**IEA [25]**	**CEDS-GBD [30]**	**Klimont *et al.* [26]**
Year		2015	2015	2015	2015	2015
Power and Heat	NO_X [Mt]	40.22	57.33	21.08	36.30	
	SO_X [Mt]	97.95	82.3	31	42.96	
	$PM_{2.5}$ [Mt]	17.29	25.05		9.55	27.5
	PM_{10} [Mt]	20.95	39.31	18.9	3.56	23.3
Transport	NO_X [Mt]	97.12	58.17	57.5	60.48	
	SO_X [Mt]	27.55	13.45	10.2	11.35	
	$PM_{2.5}$ [Mt]	3.66	3.58	3.6	1.09	5.54
	PM_{10} [Mt]	4.52	3.58		1.44	6.09

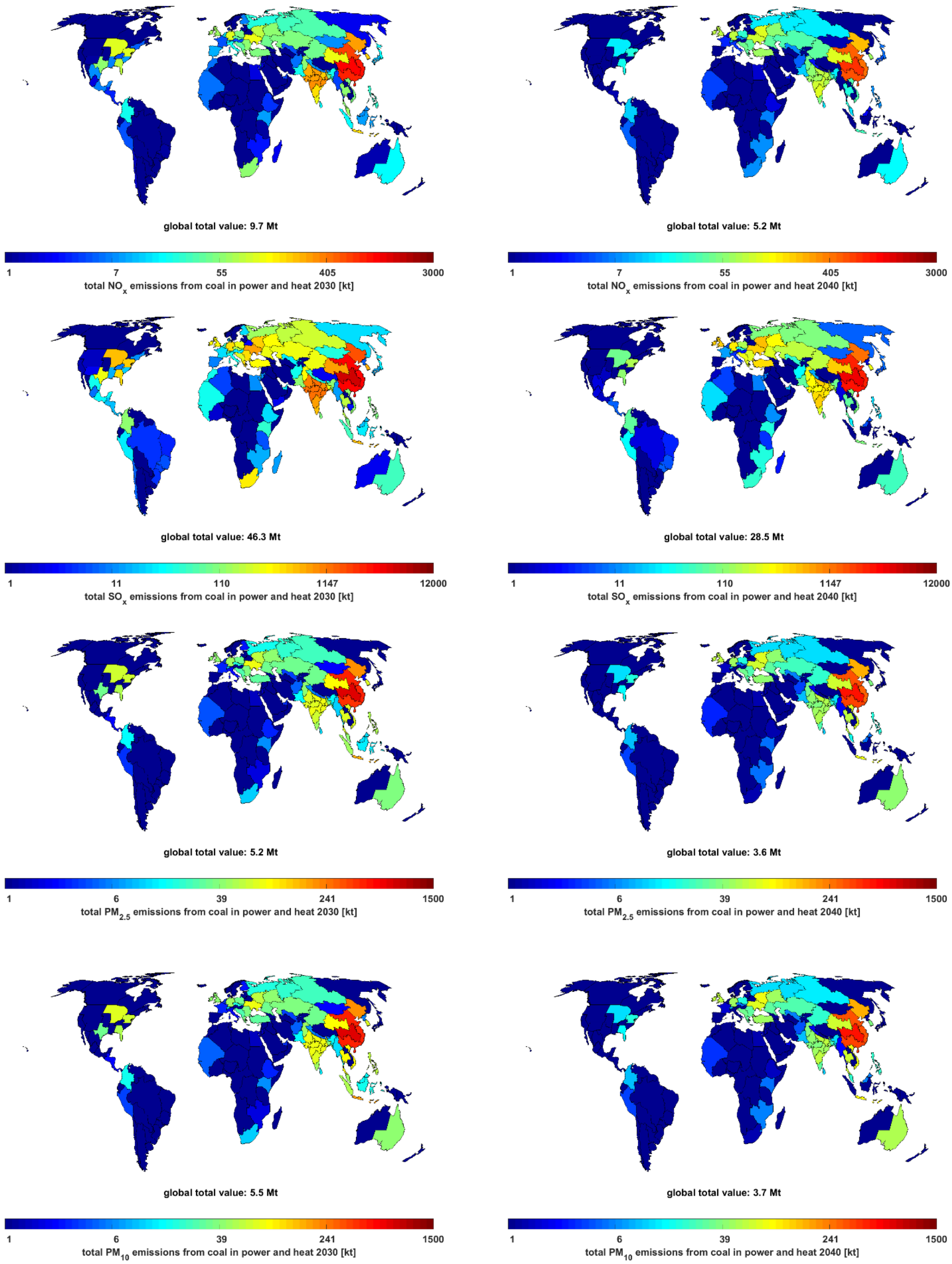

Figure A40. Global distribution of NO_x, SO_x, $PM_{2.5}$, PM_{10} emissions from coal-based power and heat production in 2030 (left) and 2040 (right). All pollutant emission values are zero in 2050.

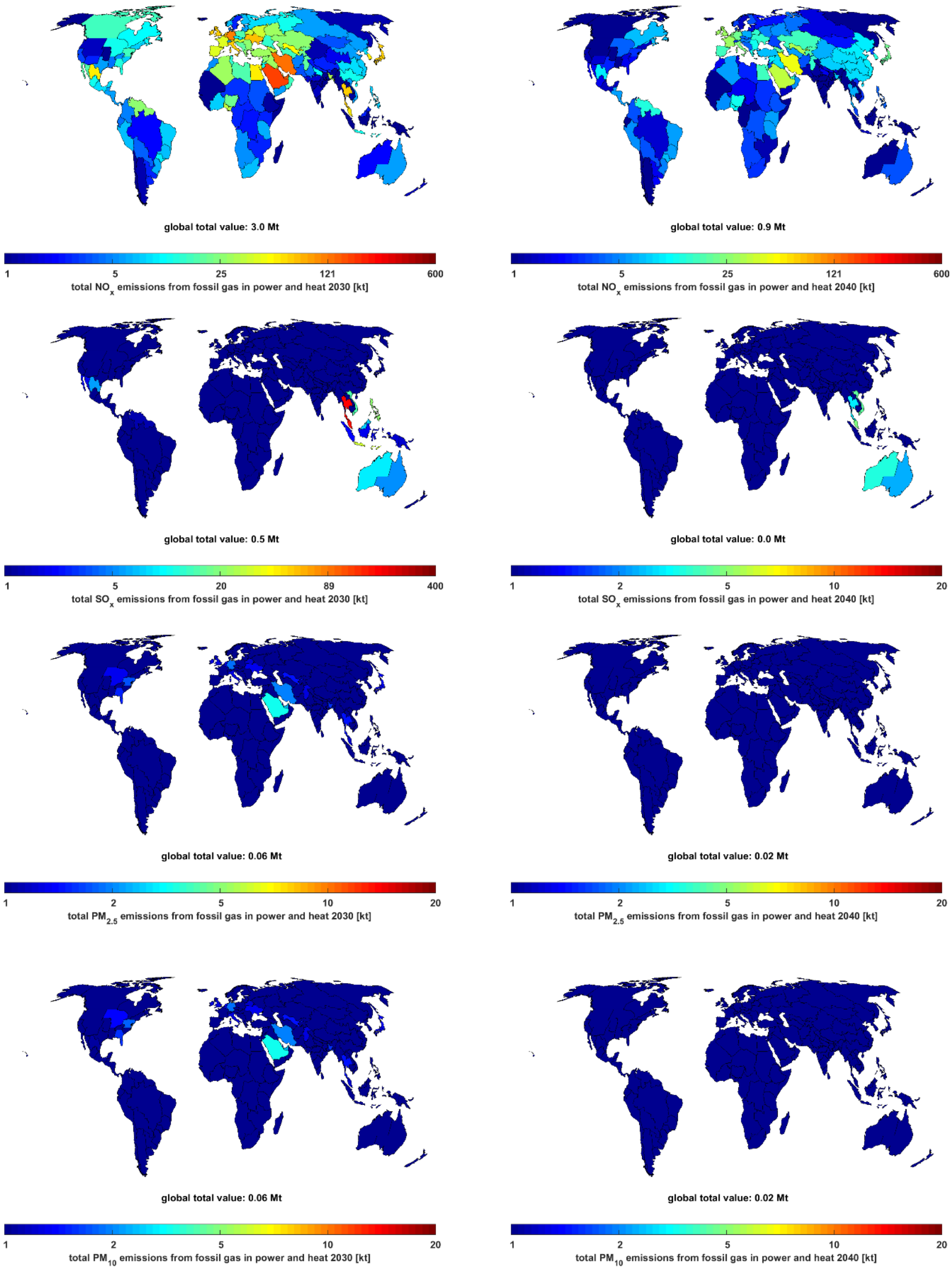

Figure A41. Global distribution of NO_x, SO_x, $PM_{2.5}$, PM_{10} emissions from fossil gas-based power and heat production in 2030 (left) and 2040 (right). All pollutant emission values are zero in 2050.

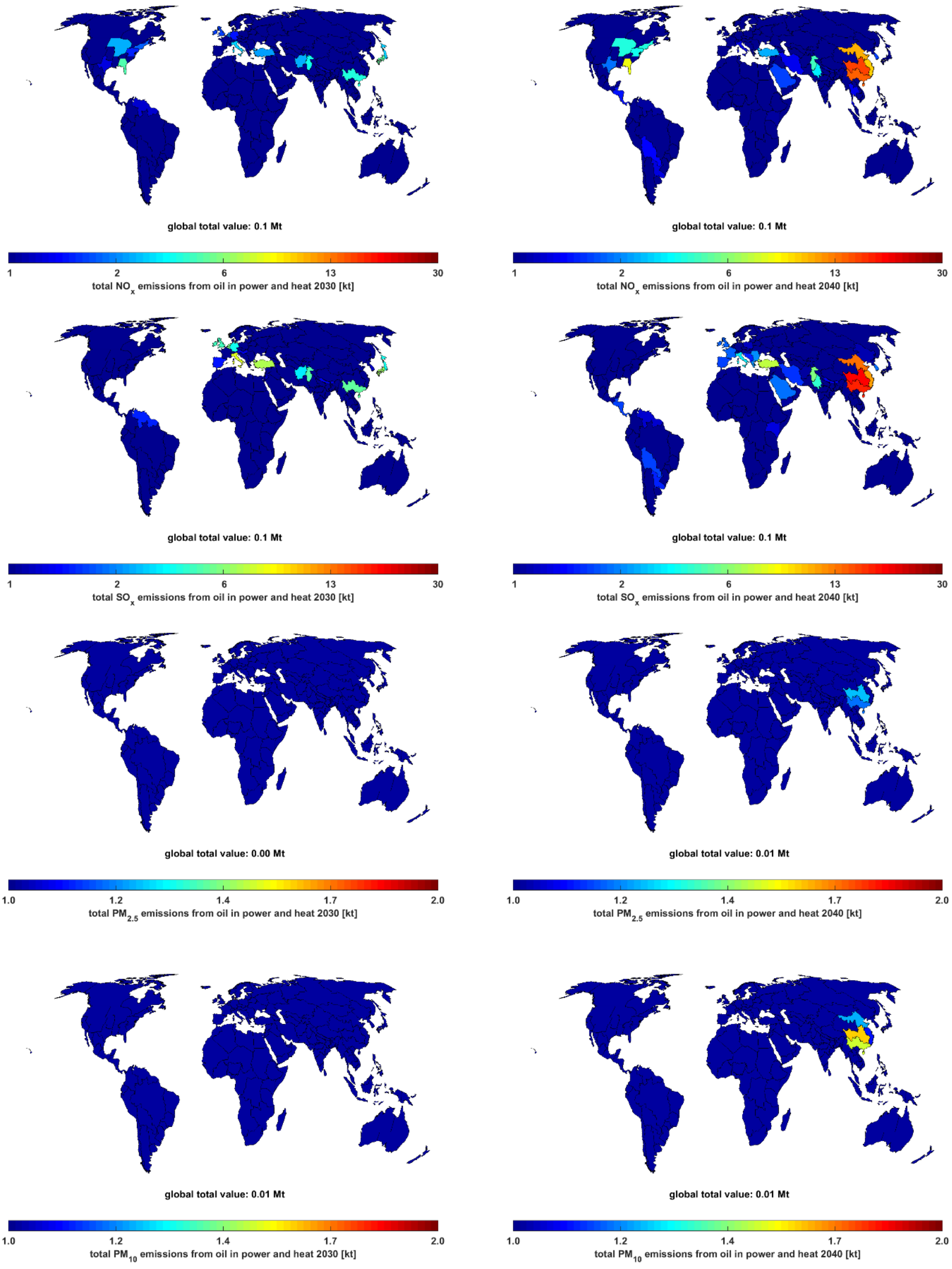

Figure A42. Global distribution of NO_x, SO_x, $PM_{2.5}$, PM_{10} emissions from oil-based power and heat production in 2030 (left) and 2040 (right). Volumes of all pollutants are zero in 2050.

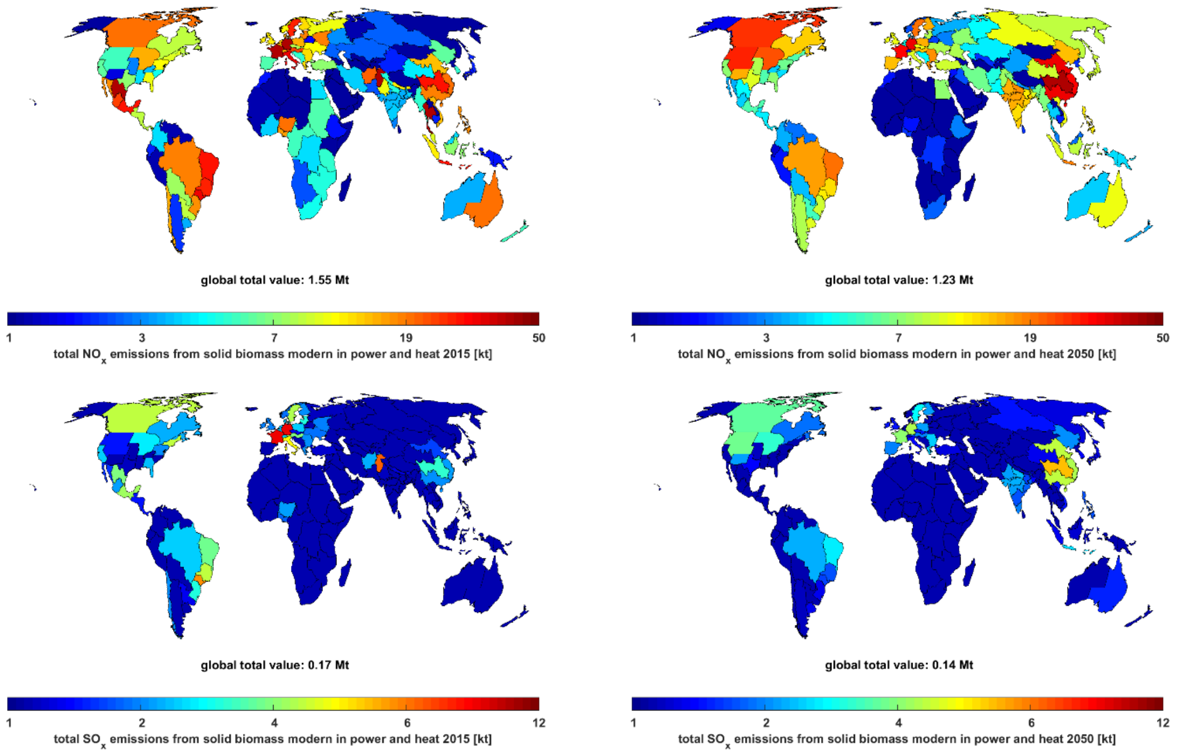

Figure A43. Global distribution of NO_x, SO_x, $PM_{2.5}$, PM_{10} emissions from modern solid biomass-based power and heat production in 2015 (left) and 2050 (right).

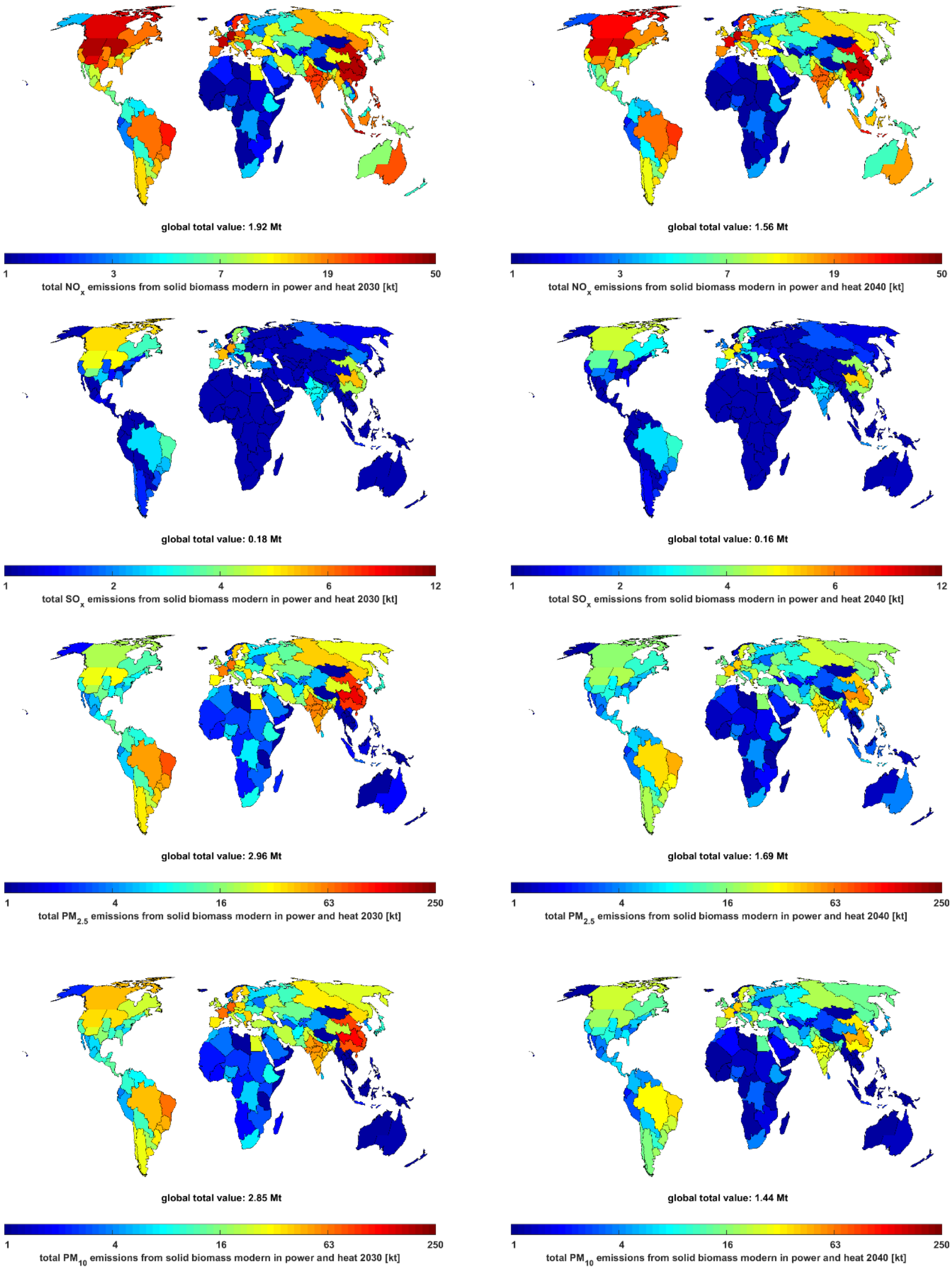

Figure A44. Global distribution of NO_x, SO_x, $PM_{2.5}$, PM_{10} emissions from modern solid biomass-based power and heat production in 2030 (left) and 2040 (right).

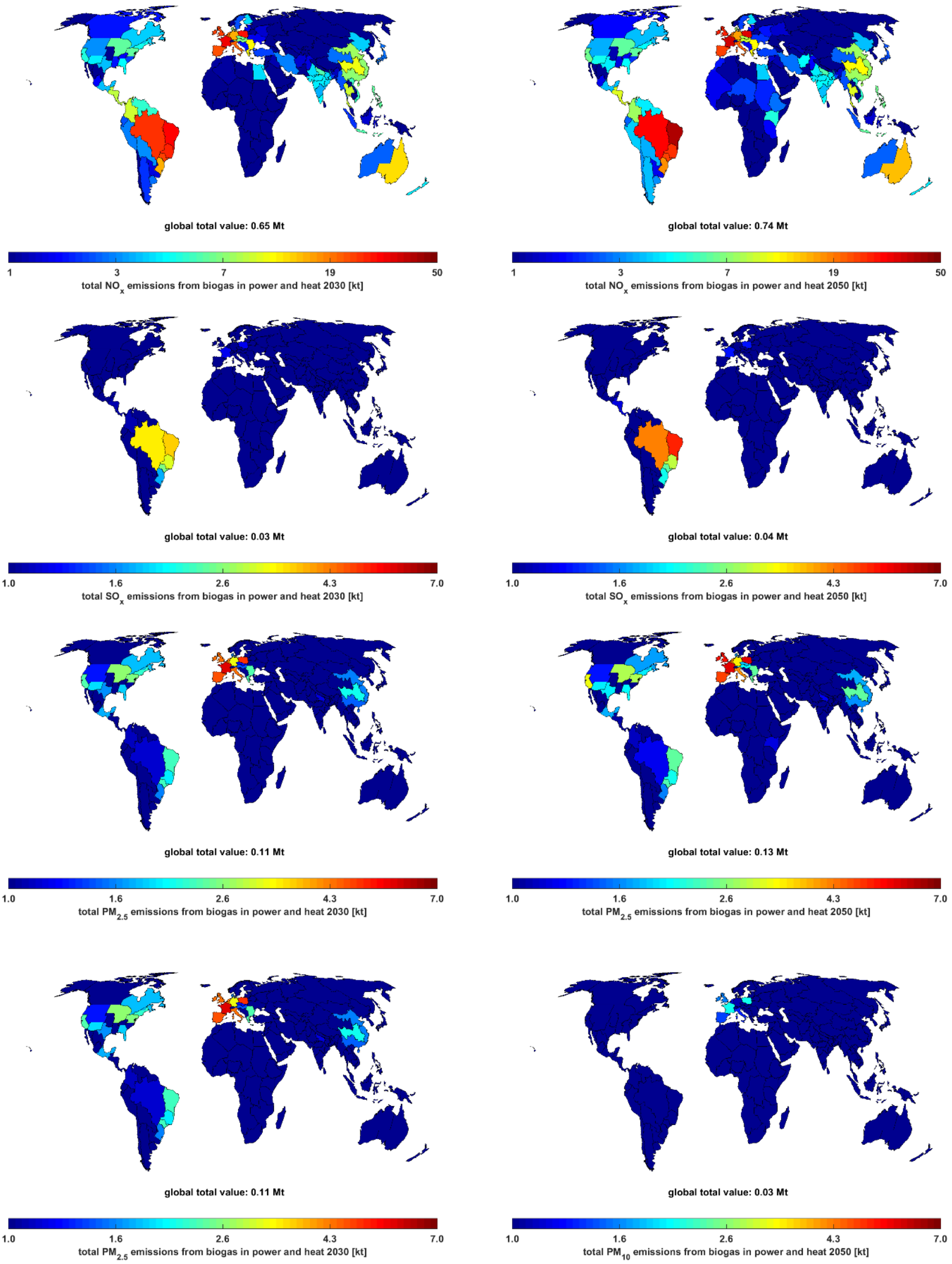

Figure A45. Global distribution of NO_x, SO_x, $PM_{2.5}$, PM_{10} emissions from biogas-based power and heat production in 2030 (left) and 2050 (right).

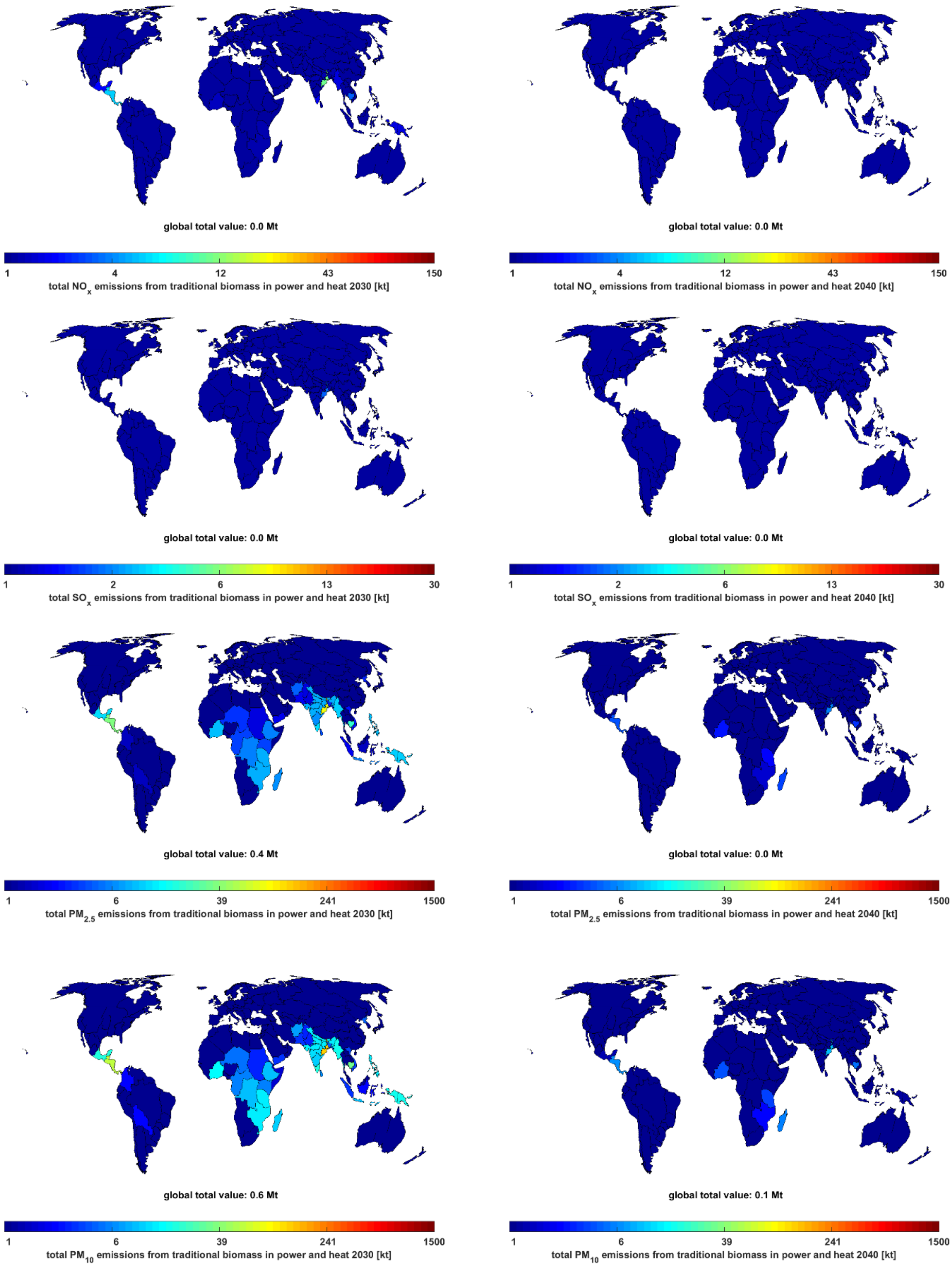

Figure A46. Global distribution of NO_x, SO_x, $PM_{2.5}$, PM_{10} emissions from traditional biomass use in 2030 (left) and 2040 (right). Main pollutant emissions are zero in 2050.

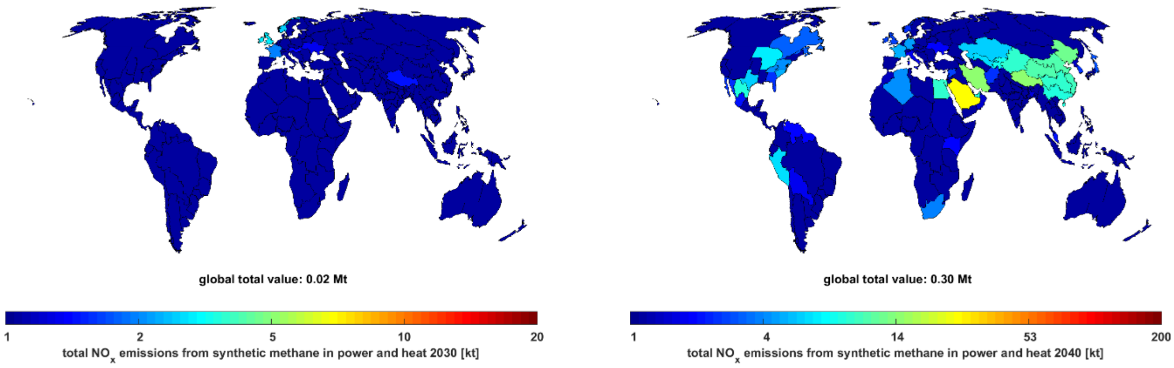

Figure A47. Global distribution of NO_x emissions from synthetic methane-based power and heat production in 2030 (left) and 2040 (right).

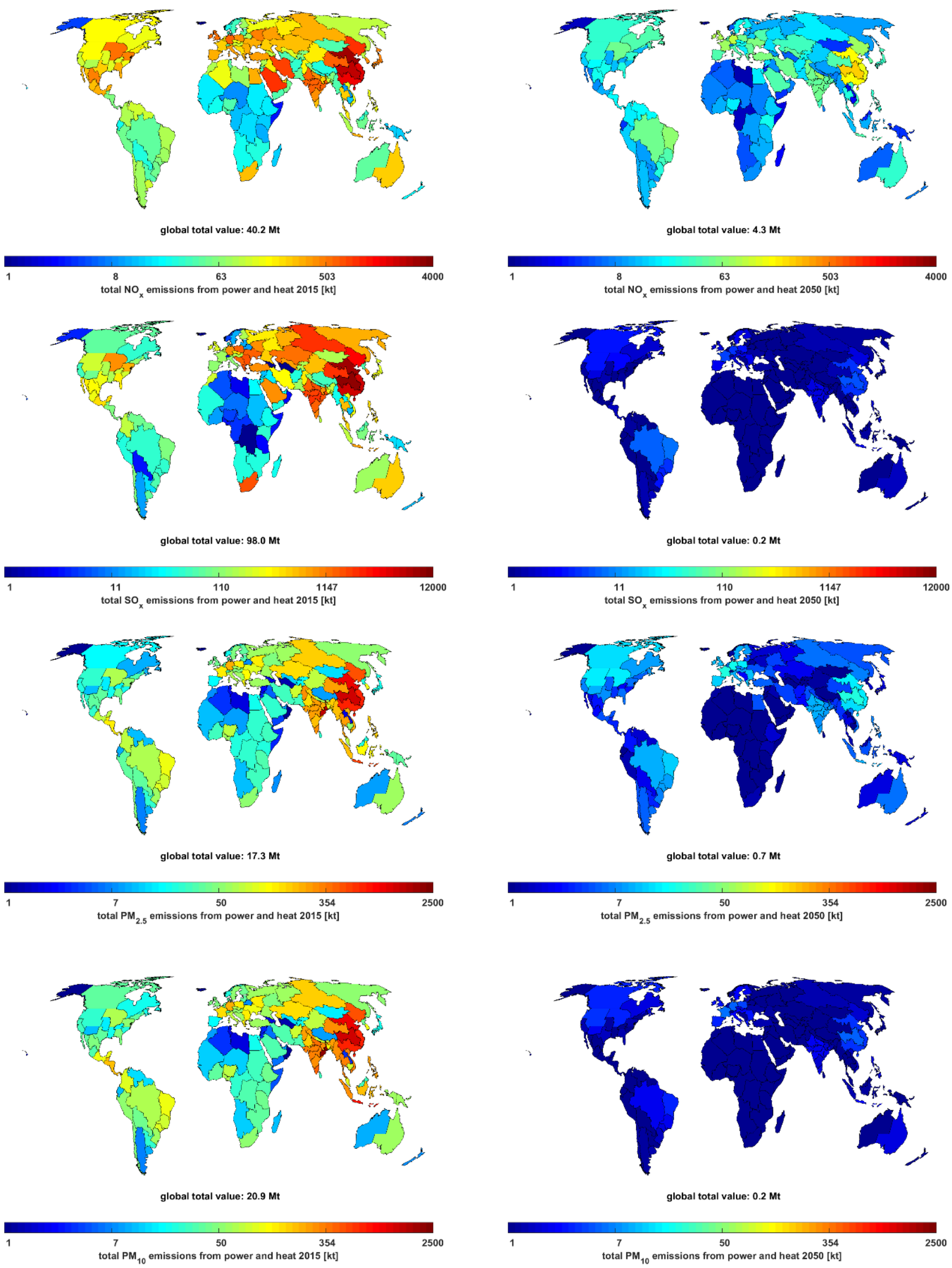

Figure A48. Global distribution of NO_x, SO_x, $PM_{2.5}$, PM_{10} emissions from power and heat sectors in 2015 (left) and 2050 (right).

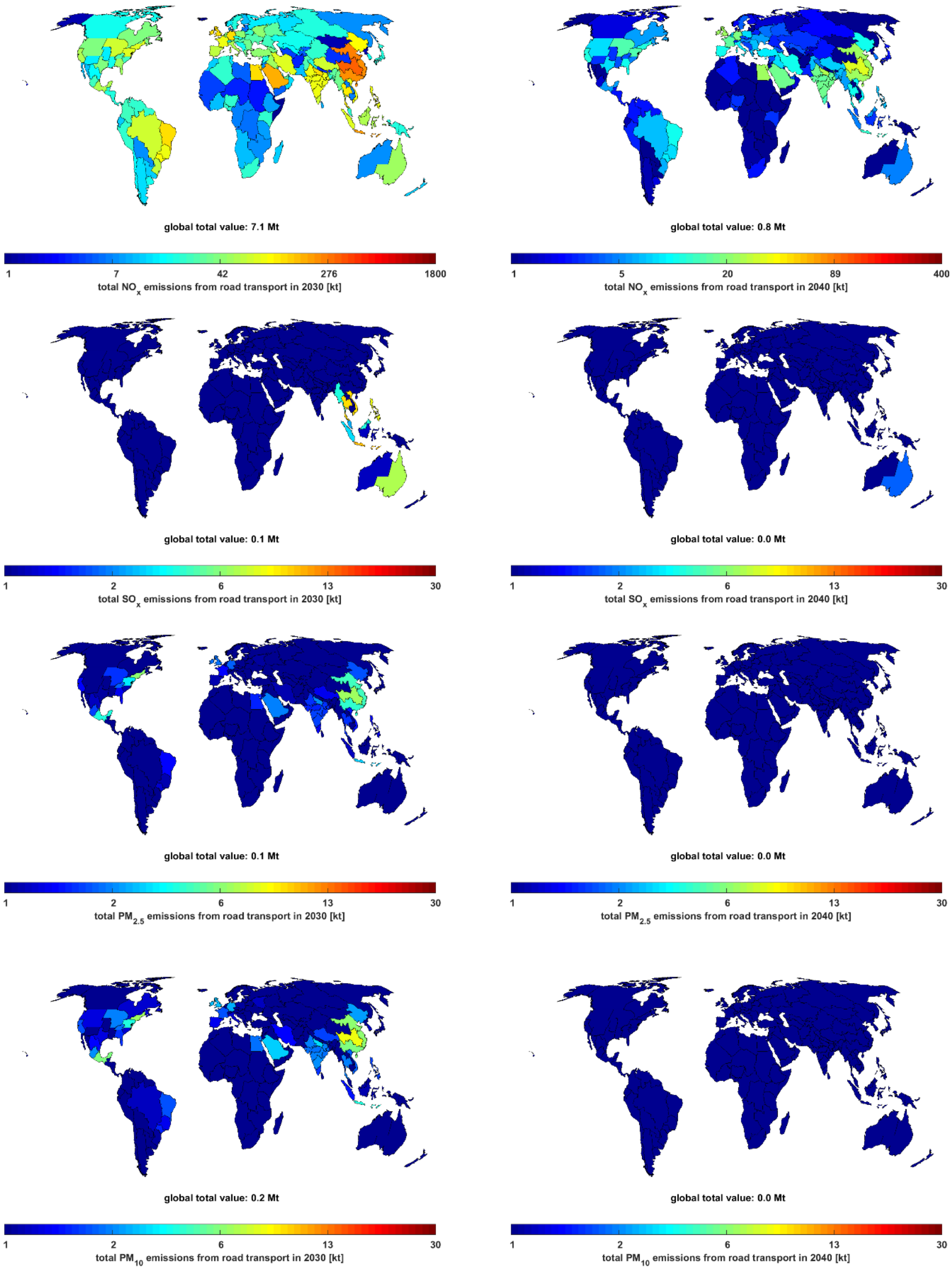

Figure A49. Global distribution of NO_x, SO_x, $PM_{2.5}$, PM_{10} emissions from road transport in 2030 (left) and 2040 (right). By 2050 the volume of NO_x is 0.17 Mt, all other pollutants are zero.

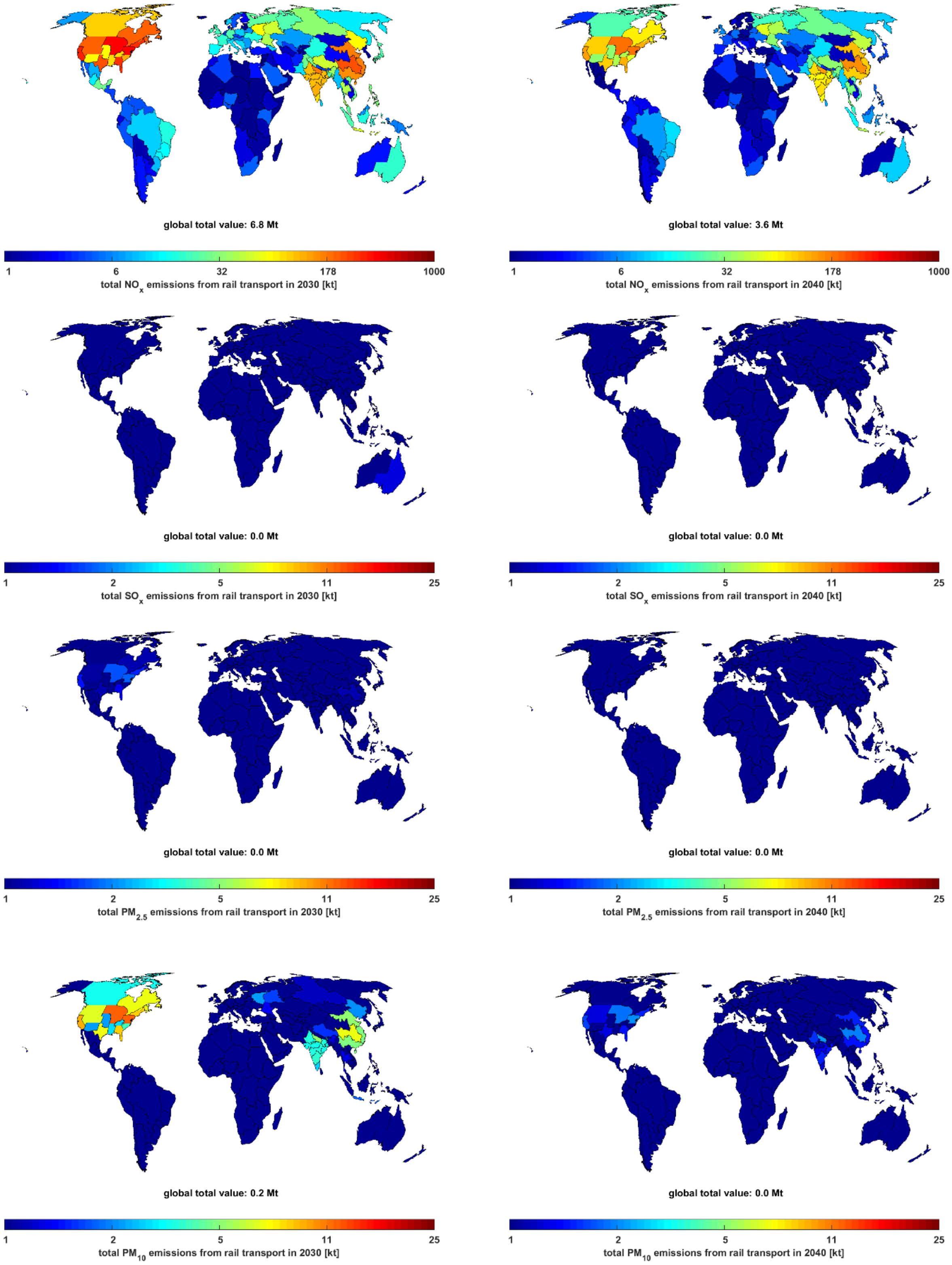

Figure A50. Global distribution of NO_x, SO_x, $PM_{2.5}$, PM_{10} emissions from rail transport in 2030 (left) and 2040 (right). NO_x emissions are 0.53 Mt in 2050 and other pollutants are zero.

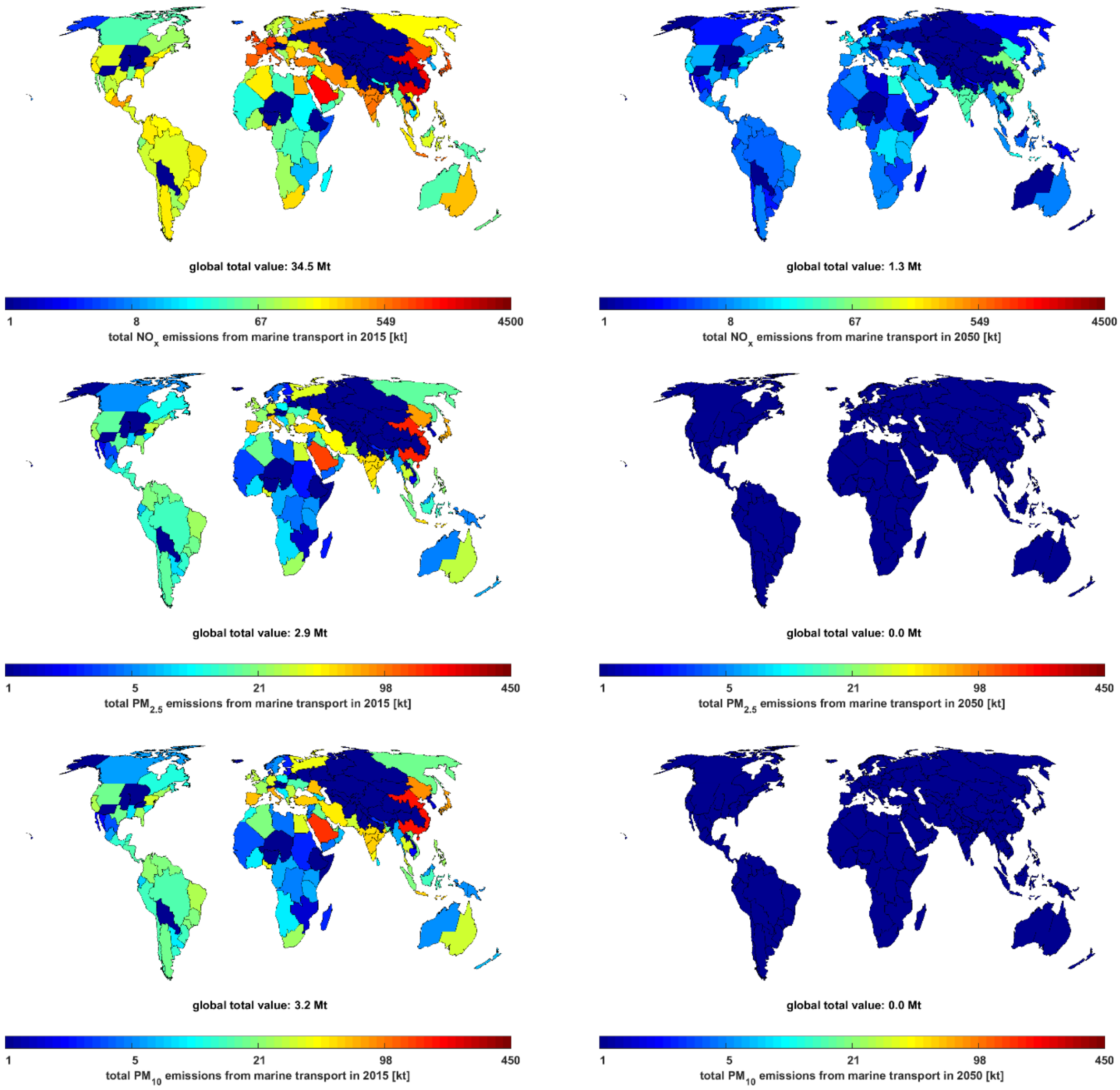

Figure A12. Global distribution of NO_X, $PM_{2.5}$, PM_{10} emissions from marine transport in 2015 (left) and 2050 (right).

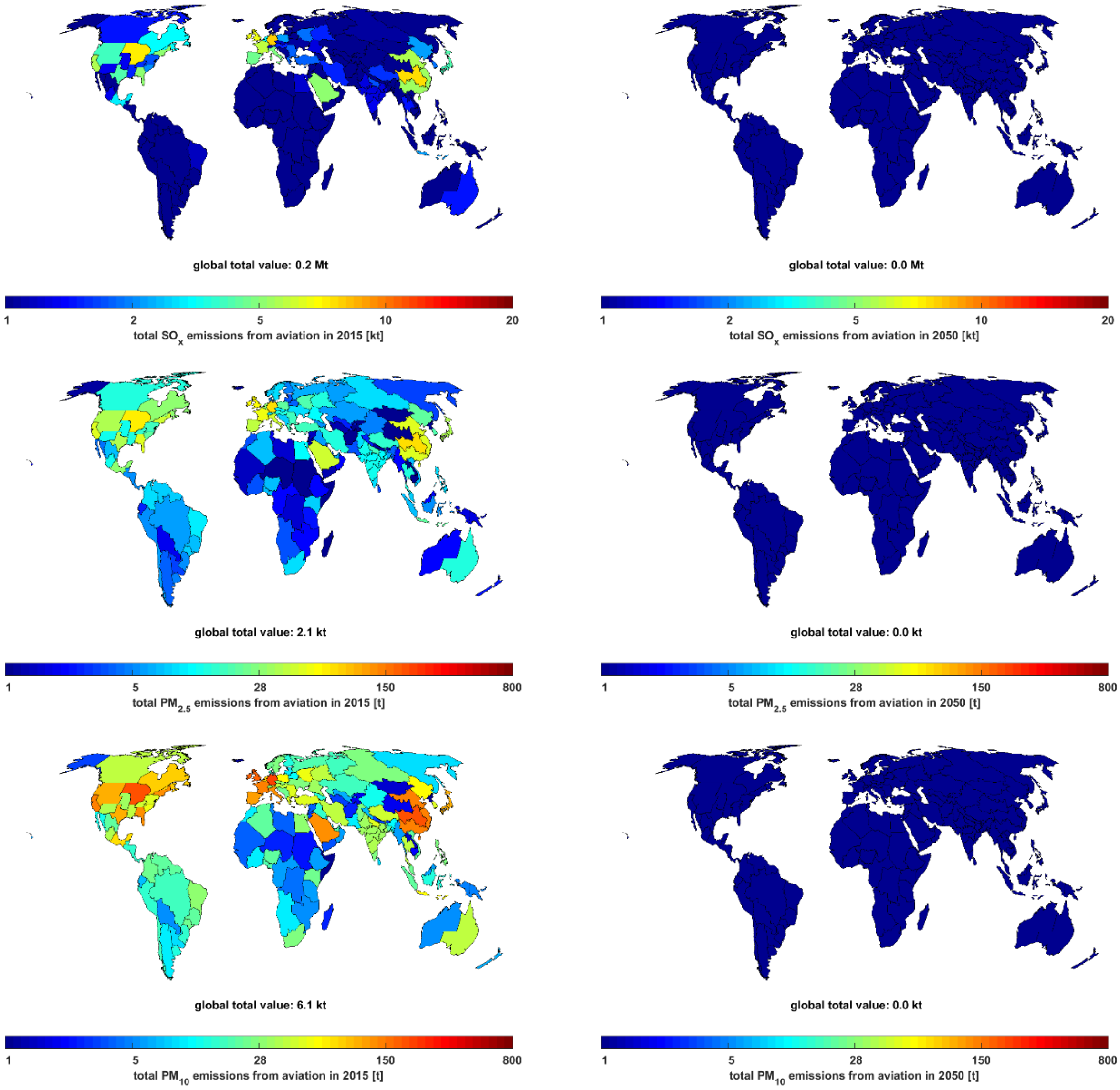

Figure A13. Global distribution of SO_X, $PM_{2.5}$, PM_{10} emissions from aviation in 2015 (left) and 2050 (right).

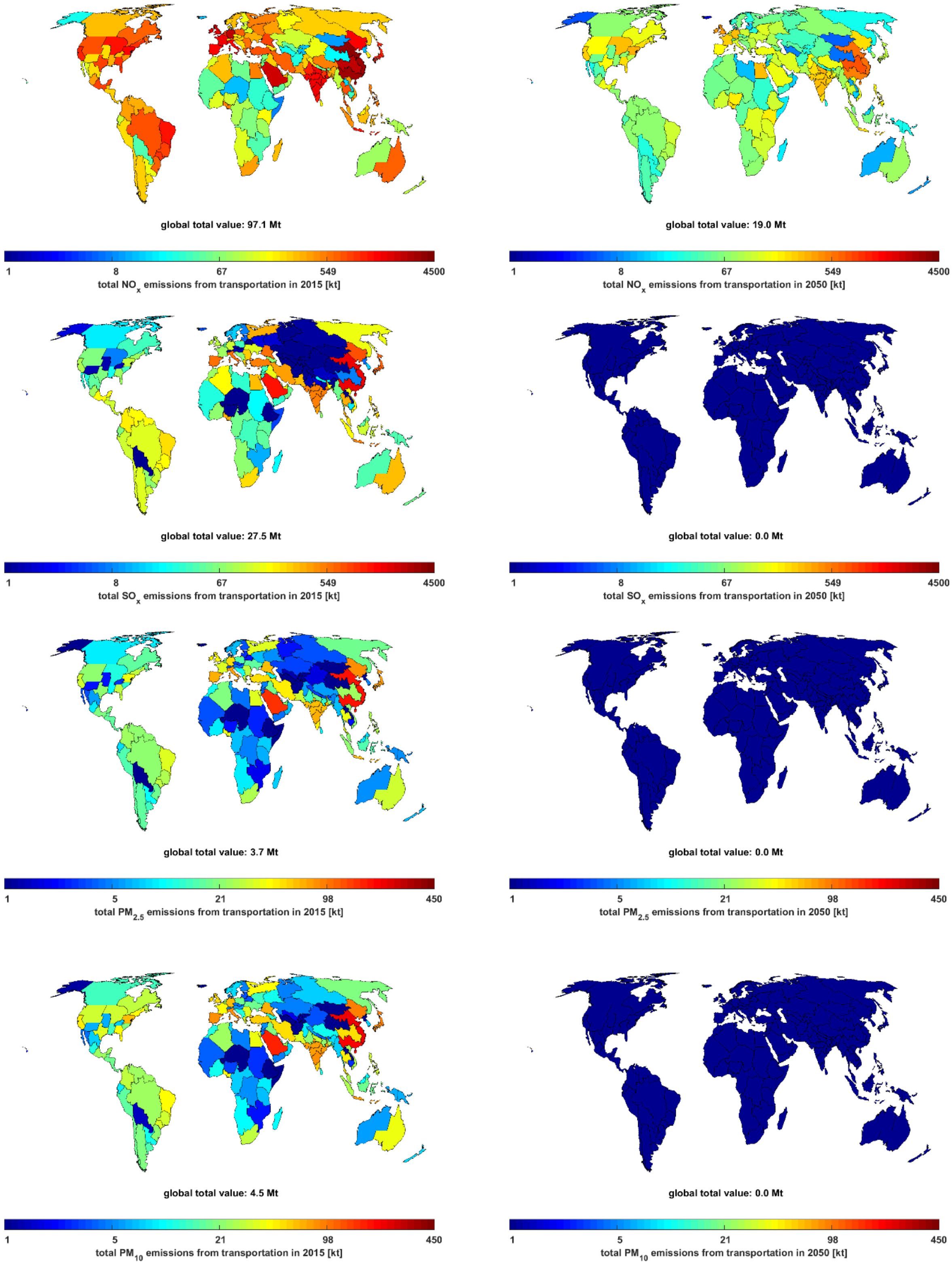

Figure A51. Global distribution of NO_x, SO_x, $PM_{2.5}$, PM_{10} emissions from transport sector in 2015 (left) and 2050 (right).

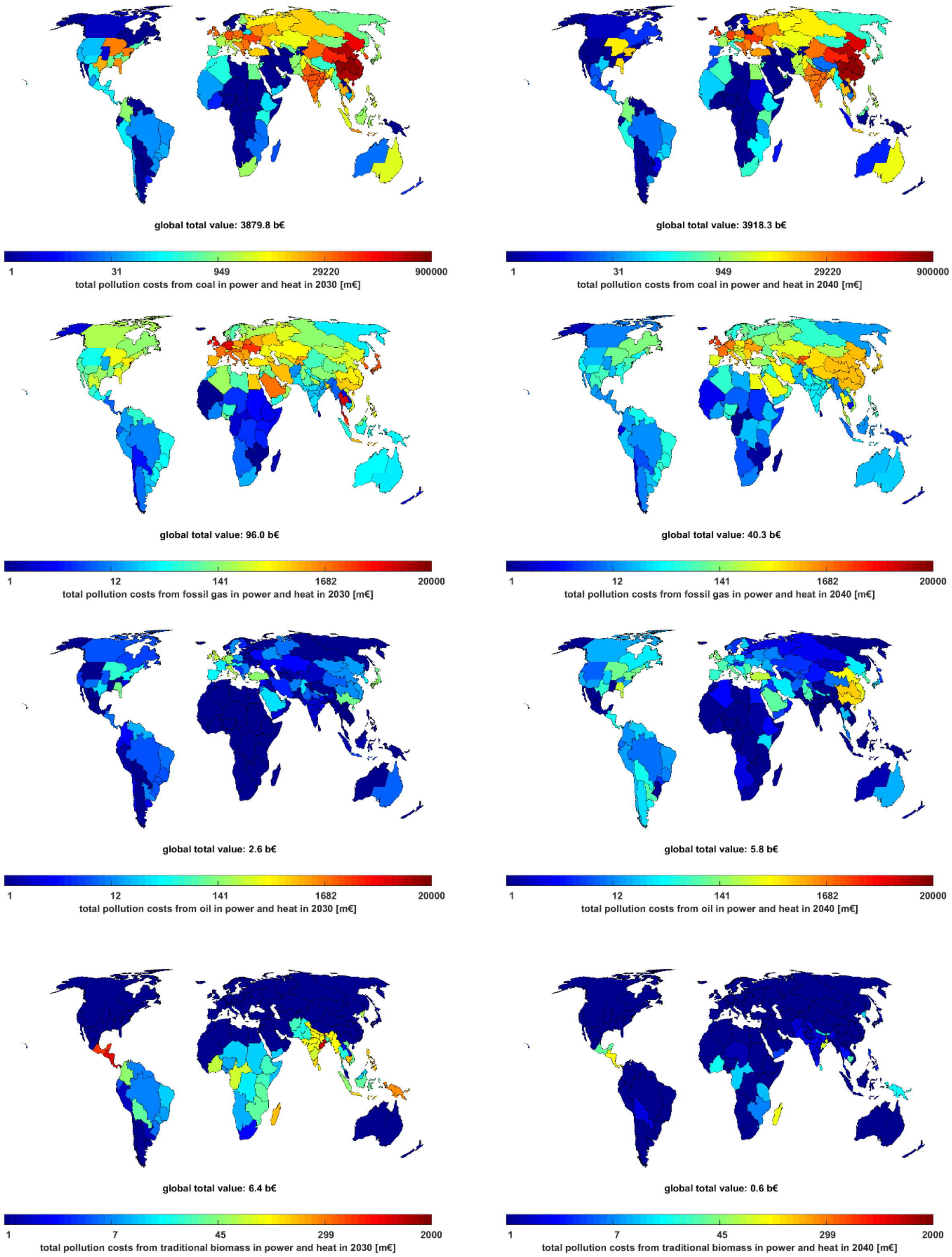

Figure A52. Global distribution of pollution costs from coal, fossil gas, oil, and traditional biomass in 2030 (left) and 2040 (right).

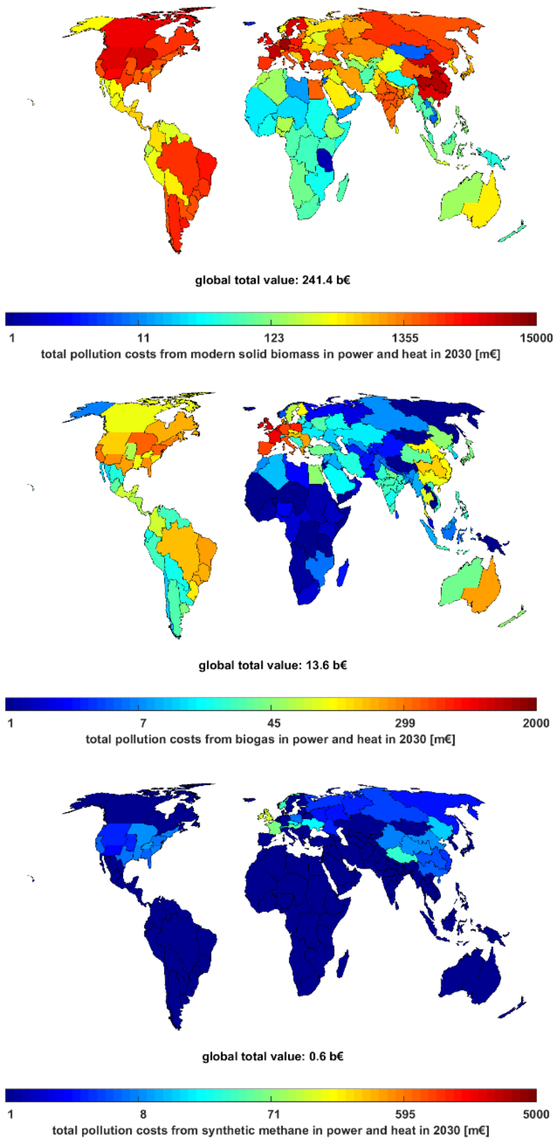

Figure A53. Total pollution costs from modern solid biomass, biogas, and synthetic methane in 2030 (left) and 2040 (right).

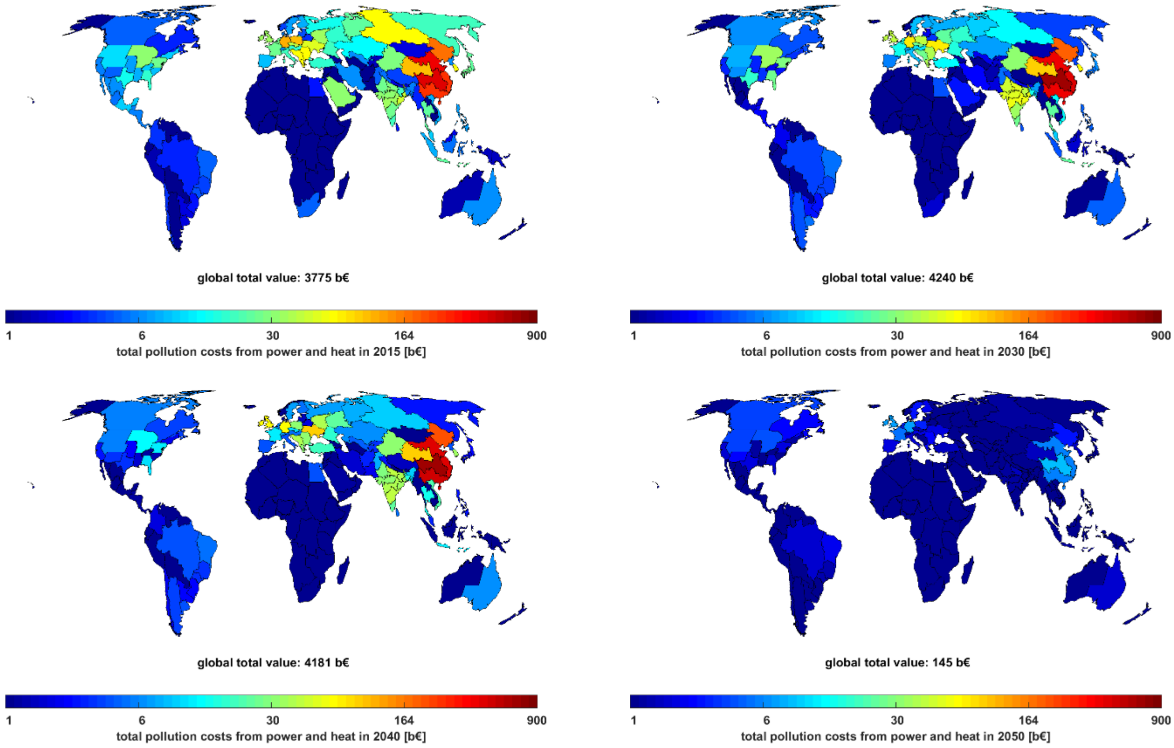

Figure A54. Total pollution costs from power and heat sectors in 2015 (top left), 2030 (top right), 2040 (bottom left), and 2050 (bottom right).

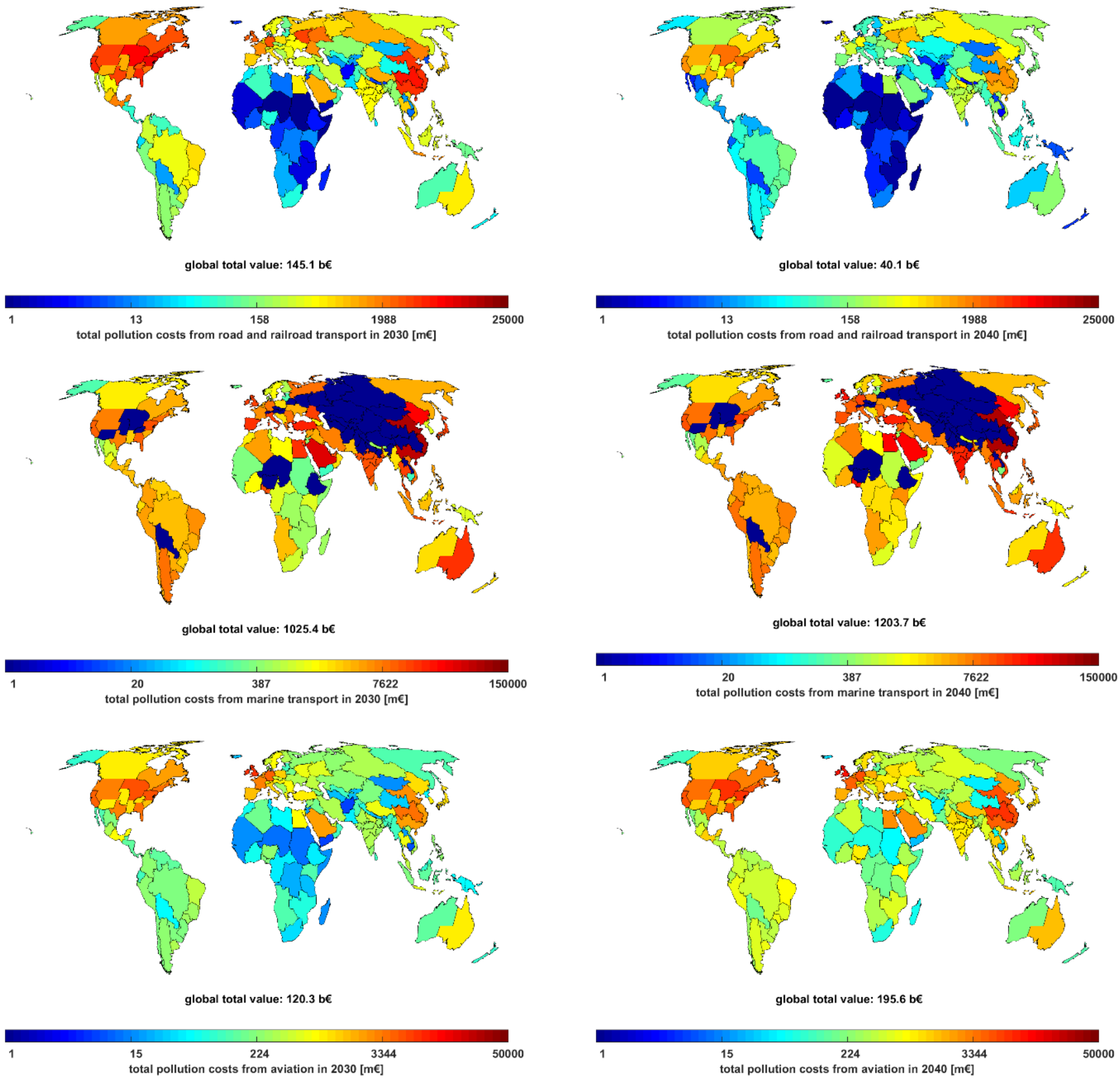

Figure A55. Total pollution costs from road and rail transport, marine, and aviation in 2030 (left) and 2040 (right).

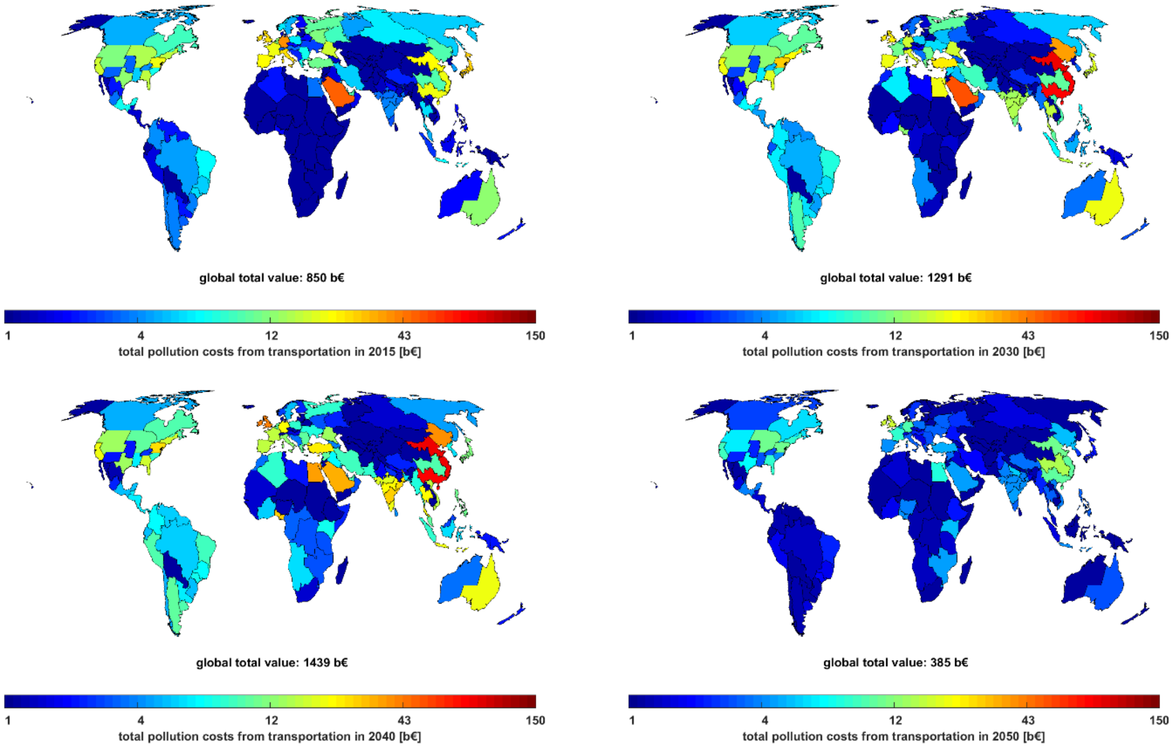

Figure A56. Total pollution costs from transportation in 2015 (top left), 2030 (top right), 2040 (bottom left), and 2050 (bottom right).

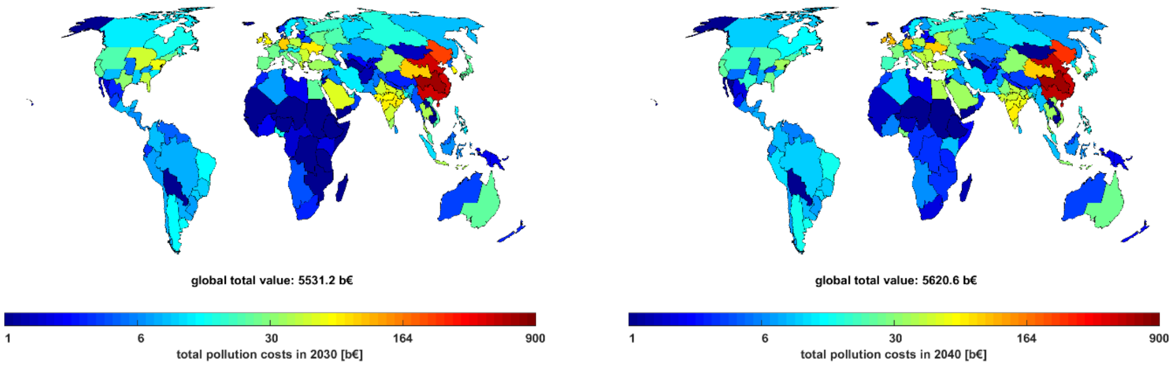

Figure A57. Total pollution costs from power, heat and transport sectors in 2030 (left) and 2040 (right).

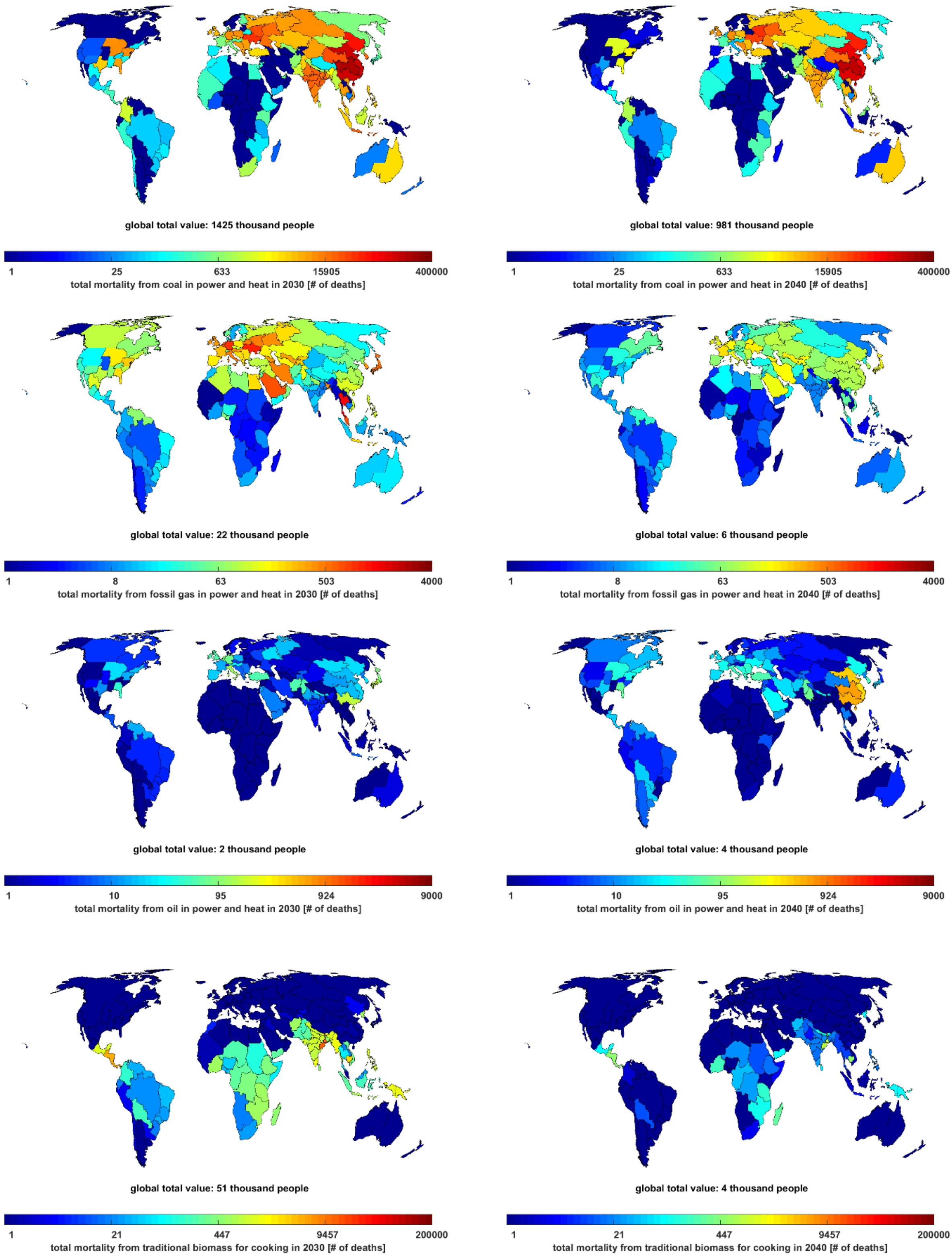

Figure A58. Total mortality from coal, fossil gas, oil, and traditional biomass in 2030 (left) and 2040 (right).

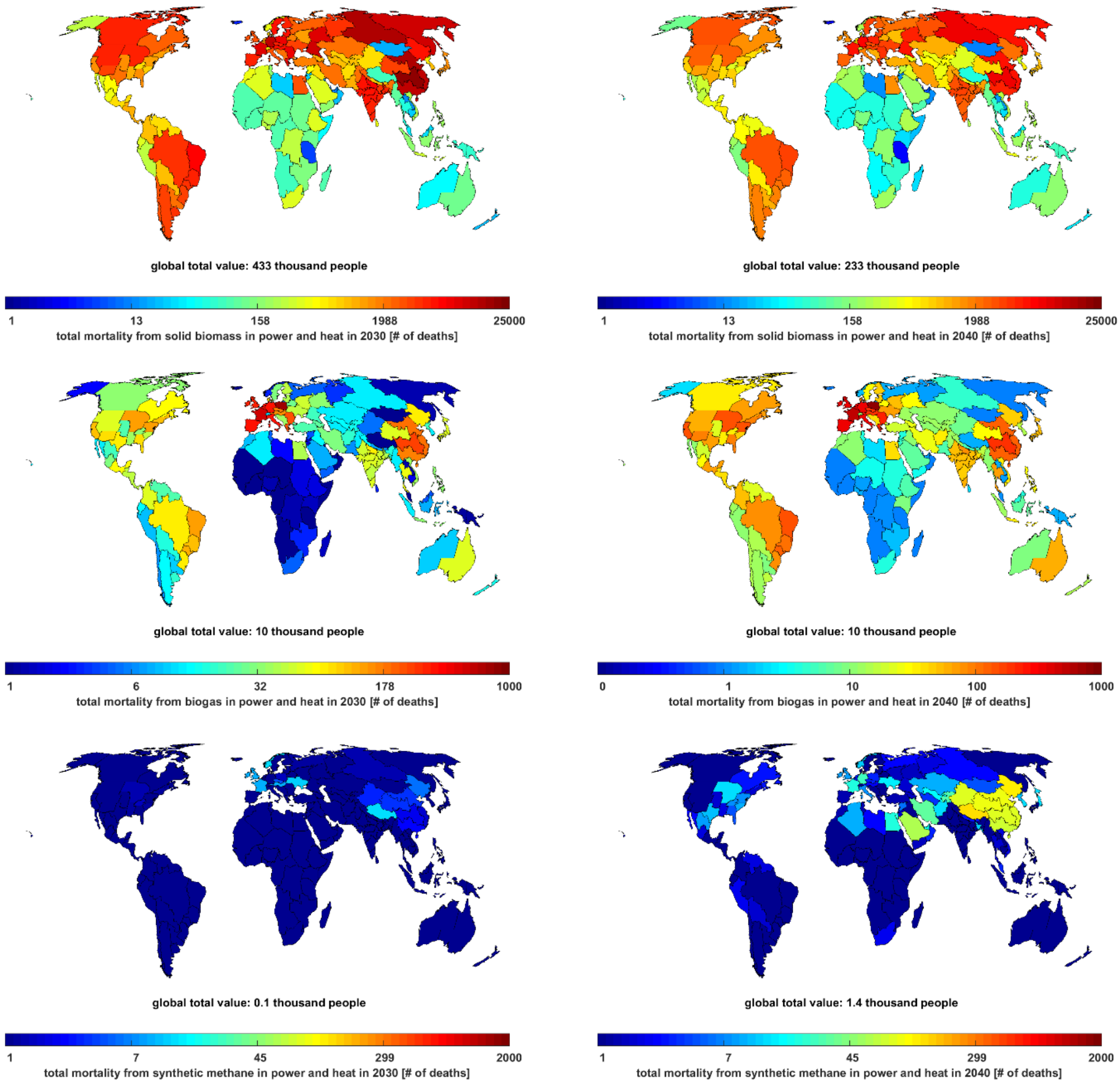

Figure A59. Total mortality from modern solid biomass, biogas, and synthetic methane in 2030 (left) and 2040 (right).

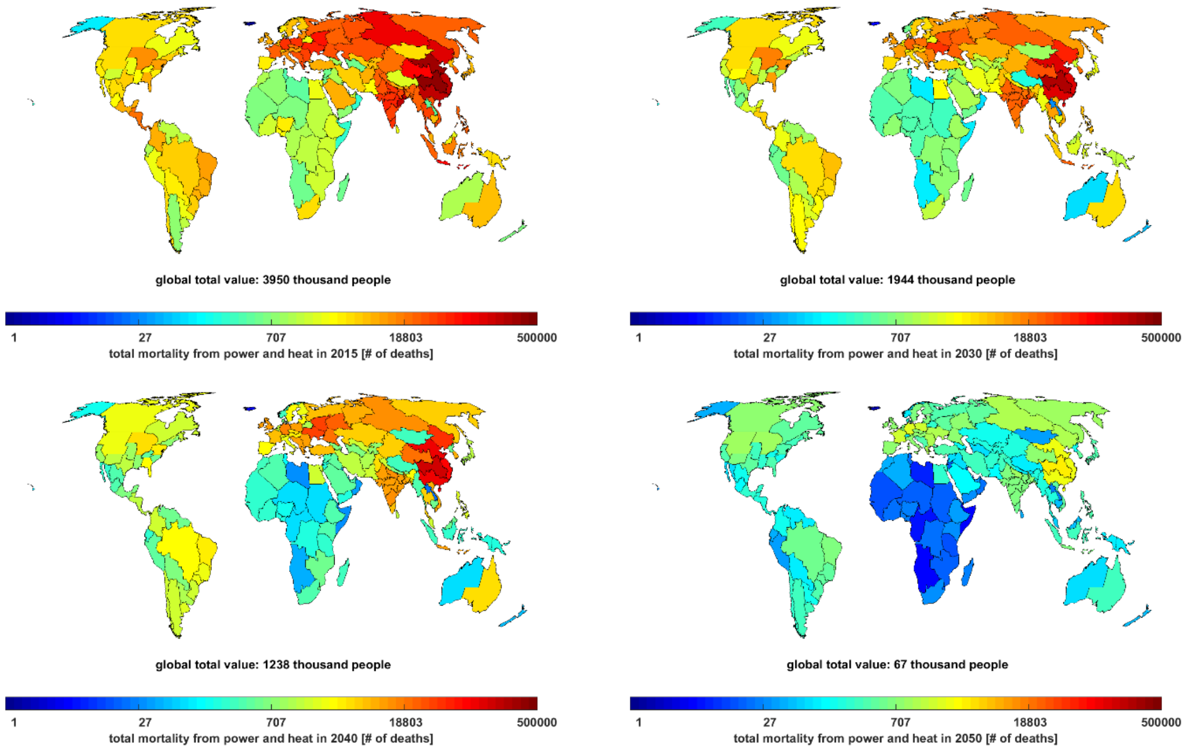

Figure A60. Total mortality from power and heat in 2015 (top left), 2030 (top right), 2040 (bottom left), and 2050 (bottom right).

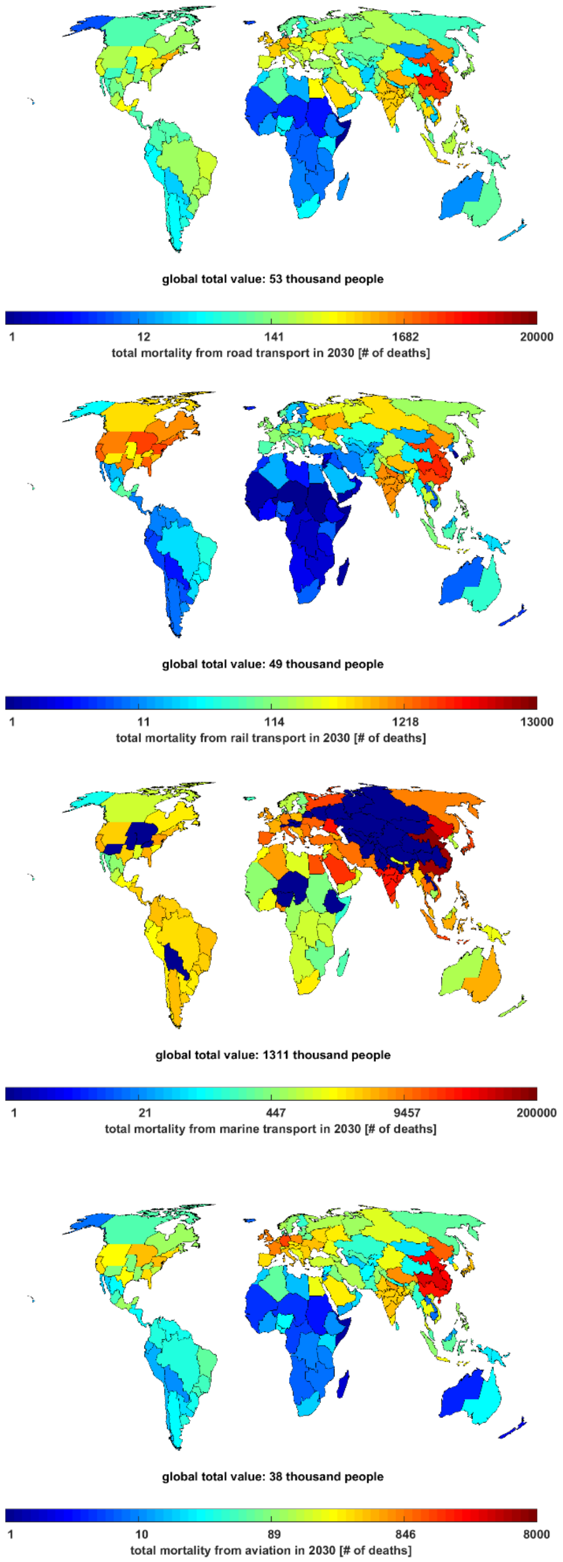

Figure A61. Total mortality from road, railroad, aviation, and marine transport in 2030 (left) and 2040 (right).

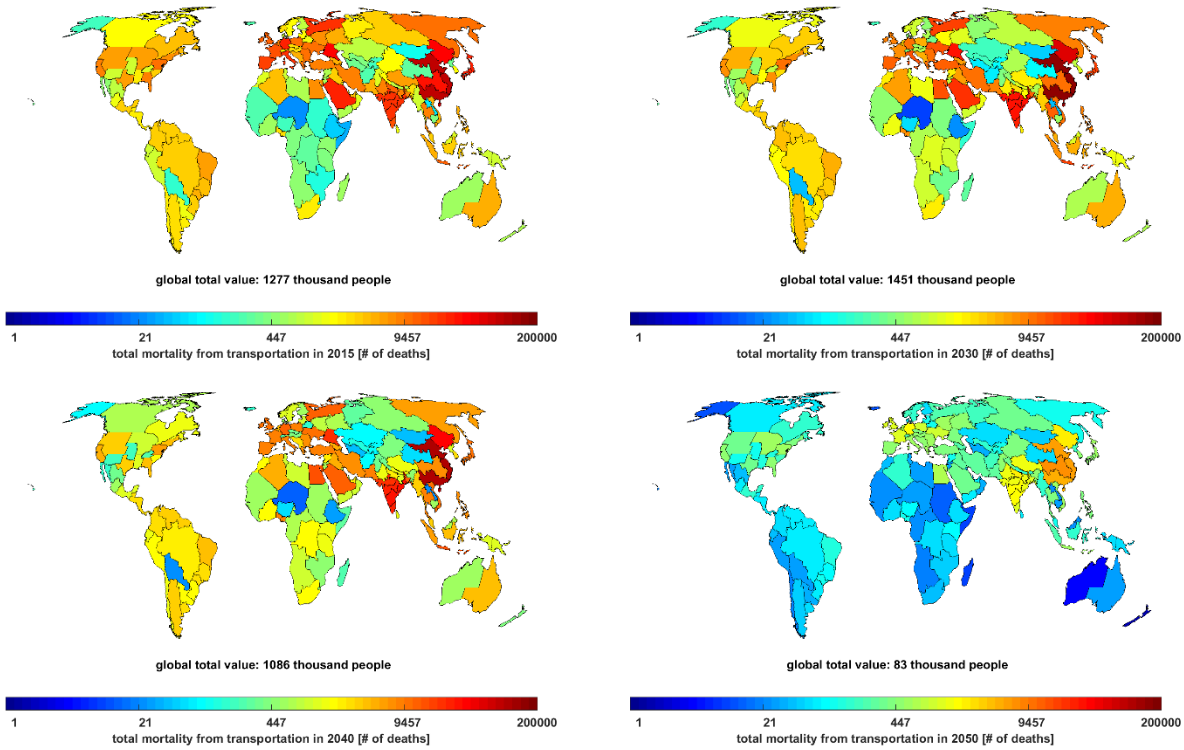

Figure A62. Total mortality from transportation in 2015 (top left), 2030 (top right), 2040 (bottom left) and 2050 (bottom right).

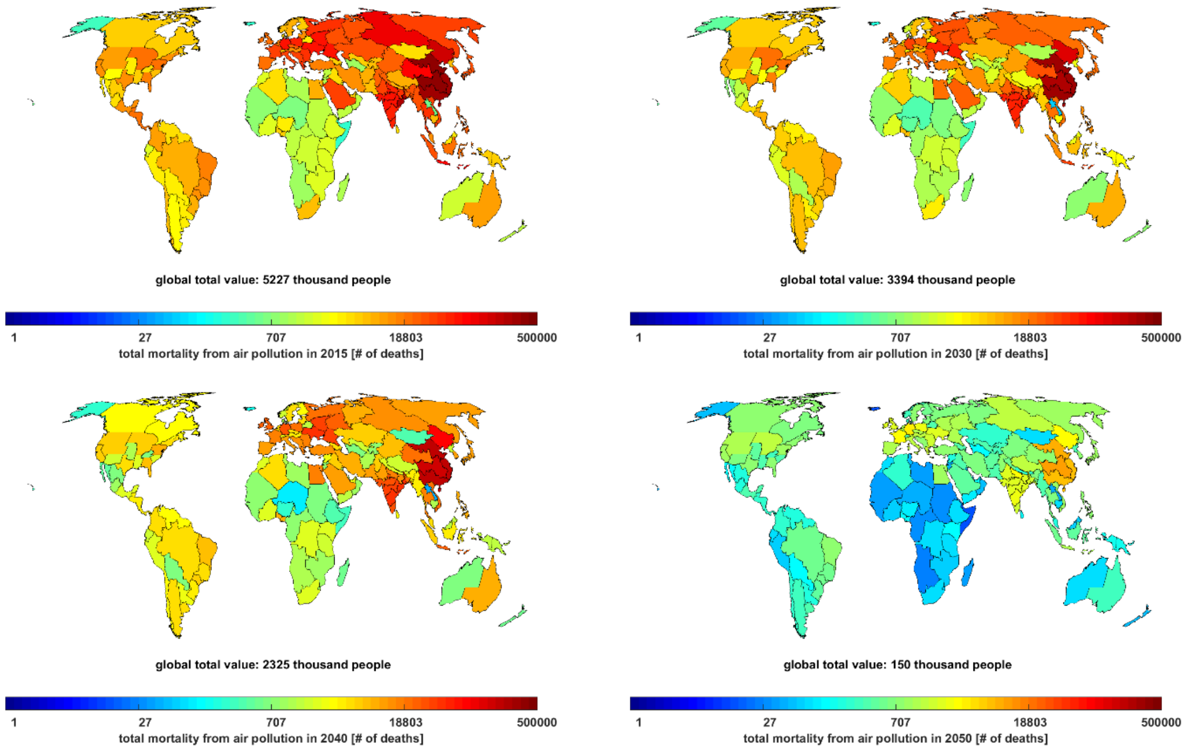

Figure A63. Total mortality from air pollution in power, heat and transport sectors in 2015 (top left), 2030 (top right), 2040 (bottom left), and 2050 (bottom right).

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