UNIT COSTS OF AIR EMISSIONS IN VIETNAM FOR ENERGY SYSTEM MODELLING

Scientific Report from DCE – Danish Centre for Environment and Energy No. 441 2021

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Data sheet

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Abstract:	Aarhus University has performed model calculations with a chemistry transport model (DEHM) and an integrated modelling system for estimation of external costs of health effects (EVA) for Vietnam with the purpose of calculating unit costs of air pollution for emission sectors in Vietnam and on the basis of these calculations deliver input to energy system modelling in Vietnam. Unit costs are health related external costs of air pollution per kg emission of air pollutants.
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Contents

Preface

The consortium of the Danish companies: Ea Energy Analyses (lead), COWI and Viegand Maagøe, has been contracted in relation to capacity building and technical assistance in Vietnam.

The overall objective of the present project is that Vietnam's energy system becomes more sustainable through implementation of cost-optimized policy and planning to enable, commission, develop and analyze comprehensive long-term energy scenarios.

The objective of the specific project is to estimate health effect costs related to air pollution from fuel consumption, including fuels for power production, industrial consumption and transport.

The Danish Center for Environment and Energy (DCE) at Aarhus University has addressed this objective, formulated as Task 1: Pollution costs assessment. Aarhus University is contracted by Ea Energy Analyses, and the Department of Environmental Science has carried out the task.

Aarhus University has performed model calculations with a chemistry transport model (DEHM) and an integrated modelling system for estimation of external costs of health effects (EVA) for Vietnam with the purpose of calculating unit costs of air pollution for emission sectors in Vietnam and on the basis of these calculations deliver input to energy system modelling in Vietnam. Unit costs are health related external costs of air pollution per kg emission of air pollutants.

Ea Energy Analyses and the Danish company Energy Modelling Lab have integrated the unit costs of air pollution into energy system models in order to model different scenarios for energy system optimization which accounts for air pollution costs.

The report includes a description of the DEHM model and EVA-system for estimation of the external costs of health effects of air pollution and the derived unit costs of air pollution for Vietnam. Furthermore, it includes a summary/literature review of existing studies in Vietnam/Southeast Asia with modelling of health impacts of air pollution. Selected studies are identified for comparison with our findings.

Summary

Background and aim

The present report provides a specific technical input to capacity building and technical assistance in Vietnam.

Aarhus University has performed model calculations with a chemistry transport model (DEHM) and an integrated modelling system for estimation of external costs of air pollution for health effects (EVA-system) for Vietnam. It is the first time that the EVA-system has been applied for Vietnam. The purpose is to calculate unit costs of air pollution for emission sectors in Vietnam and on the basis of these calculations deliver input to energy system modelling in Vietnam. Unit costs are health related external costs of air pollution per kg emission of air pollutants.

The external costs (also known as externalities) refer to the economic concept of uncompensated social or environmental effects. For example, when people buy fuel for a car, they pay the market price of that fuel, but not for the derived, non-market costs of burning that fuel, such as air pollution.

The Danish company Energy Modelling Lab will integrate the unit costs of air pollution into an energy system model in order to model different scenarios for energy system optimization which accounts for air pollution costs.

Methodology

EVA-system

Aarhus University has developed a model system for economic valuation of air pollution (EVA-system). The EVA-system is able to estimate the external costs of health effects of air pollution, and hence the unit costs of air pollution to be used as input in energy system optimization.

The EVA-system is based on the impact-pathway method. It can calculate all-cause acute and chronic mortality and morbidity based on exposure-response functions for health effects of air pollution.

Based on information of the spatial and temporal variation of emissions from different emission sectors, air quality models are used to estimate air quality concentrations. Human exposure is calculated based on population data, and using exposure-response functions, the health effects of air pollution are estimated. Based on economic valuation of the different health endpoints the total external costs of air pollution can be calculated as well as the external costs related to different emission sectors. The unit costs, that is, the health effect costs per one unit of emission emitted can be calculated by dividing the aggregate cost for a specific emission sector with the emission emitted of that sector. Unit costs may be expressed as euros per kg emission.

External costs of air pollution are country specific and to adjust the costs to Vietnamese conditions we used the OECD benefit transfer methodology to transform costs of mortality and morbidity from one country to another. Data to adjust for difference in income per capita and relative price differences have been obtained from The World Bank for 2016 as standard costs for health effects represent 2016 prices in the EVA-system. This implies that costs of health effects in Vietnam are estimated to be 9.7% of the standard costs of

health effects in the EVA-system for Denmark. This means that the OECD benefit transfer factor is 0.097.

DEHM model

In the present application of the EVA-system for Vietnam the regional air quality model, DEHM has been used. Aarhus University has developed the DEHM model. DEHM (Danish Eulerian Hemispheric Model) is a three-dimensional, offline, large-scale, Eulerian, atmospheric CTM (chemistry-transport model) with zooming capability (with 2-way nested grids of higher resolution) developed to study long-range transport of air pollution in the Northern Hemisphere. The model is routinely used for operational air pollution forecasting, for describing transport and fluxes of CO_2, transport of persistent organic pollutants (POPs) and impacts from climate change on future air pollution levels. DEHM has lately been evaluated in several model inter-comparisons and applied in model ensemble studies. DEHM is also used routinely as a part of the Danish Air Quality Monitoring Program (both for Denmark and Greenland) and is further a part of the European Copernicus Atmospheric Monitoring Service (CAMS), delivering operational input to the ensemble air pollution forecasts for Europe.

DEHM includes capability for two-way nested domains to obtain higher resolution. The mother domain covers most of the Northern Hemisphere with a resolution of 150 km×150 km in a horizontal grid. Further sub-domains can be setup covering areas of interest with a higher resolution. For Vietnam we have setup the model with three domains, where the inner domain covers the country with a 16.67 km x 16.67 km grid resolution.

DEHM also has a tagging capability that enables calculation of the concentration contribution of each emission sector and hence the costs of air pollution from each emission sector.

Emission dataset from 2010

The DEHM model requires emissions of SO_2 (sulphur dioxide), CO (carbon monoxide), NO_x (nitric oxides), NMVOC (non-methane volatile organic compounds), NH_3 (ammonia) and $PPM_{2.5}$ (primary emitted particles less than 2.5 µm in diameter).

We have identified the global emission dataset - HTAP_v2 emissions – as the emission dataset with the highest quality for Asia and Vietnam, which is considered to be the best available emission data for this region, and there is not a newer complete dataset available. This dataset was used as the standard emission inventory in a model inter-comparison study where a total of 14 chemical transport models (CTMs) participated in the first topic of the Model Inter-Comparison Study for Asia (MICS-Asia) phase III.

Meteorological data

Meteorological data from 2019 is calculated using the meteorological model (WRF - Weather Research and Forecasting model), setup on the same domains as DEHM.

As the emission dataset is from 2010 then calculated concentrations and associated health effects will also represent conditions in 2010.

Comparison with other studies
We have conducted a smaller summary/literature review of existing studies in Vietnam/Southeast Asia with modelling of health impacts of air pollution, and compared our findings with these studies where possible.

Main findings

Total costs of air pollution in Vietnam
Total costs of all air pollution in Vietnam due to domestic and foreign emission sources are estimated to 43 billion euro based on emissions from 2010 (and 2016 prices for health costs). About half of these costs are from domestic emission sources and about half are from foreign emission sources.

Total costs of Vietnamese emissions
The total costs of emissions in Vietnam to health effects in Vietnam are approx. 17 billion euro. Approx. 57% of the costs are related to emissions of $PPM_{2.5}$ and the rest of the costs are related to emissions of NO_x, SO_x, NH_3 and NMVOC.

The residential emission sector (SNAP02) contributes by far with the largest costs which in Vietnam includes a lot of emissions from use of biomass for cooking and also heating. International bodies have standardised reporting on emissions in the so-called SNAP categories. SNAP stands for Selected Nomenclature for Air Pollution.

The total costs of emissions from Vietnam in Vietnam and beyond are approx. 47 billion euro indicating that Vietnamese emissions also have a large health impact abroad as air pollution is transported over large distances. Similarly, Vietnam is also affected by emissions from neighbouring countries and beyond. In total 37% of all costs from Vietnamese emissions fall within Vietnam and 63% outside Vietnam.

Health effects of air pollution
The number of annual premature deaths in Vietnam due to all air pollution due to domestic and foreign emission sources is estimated to approx. 179,000 based on emissions from 2010 with the EVA-system.

The number of annual premature deaths in Vietnam due to emissions in Vietnam is estimated to approx. 83,000. The population of Vietnam was approx. 89 mill. in 2010. Emissions in Vietnam cause an additional approx. 142,000 annual premature deaths outside Vietnam, hence the total number of annual premature deaths due to emissions in Vietnam is approx. 224,000.

Main results

The main purpose of the present study is to estimate unit costs of air pollution for Vietnam.

Table 1 summarizes the unit costs for each emission sector and for each of the pollutants of Vietnamese emissions. The unit costs are given for Vietnamese emission under two assumptions. 'Vietnam only' which means that only costs within Vietnam is included in the unit costs whereas 'total in Vietnam and abroad' also include costs that falls outside Vietnam due to Vietnamese emissions.

Residential emissions (SNAP02) and road transport emissions (SNAP07) have the highest unit costs.

Table 1. Unit costs per kg emission for different emission sectors in Vietnam in 2016 (emissions from 2010 and health costs from 2016).

Unit costs; **Euros per kg of SO_x, NO_x, NH_x, $PPM_{2.5}$ and NMVOC.**

OECD benefit transfer factor (0.097)

Unit costs - in Vietnam only (Euro/kg)

Species emissions	SO_x	NO_x	NH_x	NMVOC	$PPM_{2.5}$
Species Impacts	SO_2+SO_4	O_3-O_3neg +NO_3+NO_2	NH_4	SOA	$PM_{2.5}$
SNAP01 - Energy production and transformation	2	3	-	-	4
SNAP02 - Residential	4	8	2	1	24
SNAP03 - Industry	2	4	-	0	5
SNAP07 - Road/land transport	2	5	-	0	13
SNAP08 - Aviation	-	-		-	-
SNAP10 - Agriculture	0	0	1	0	0
Ship transport, EEZ Vietnam	1	1	0	6	2

Unit costs - total in Vietnam and abroad (Euro/kg)

Species emissions	SO_x	NO_x	NH_x	NMVOC	$PPM_{2.5}$
Species Impacts	SO_2+SO_4	O_3-O_3neg +NO_3+NO_2	NH_4	SOA	$PM_{2.5}$
SNAP01 - Energy production and transformation	7	10	-	-	10
SNAP02 - Residential	20	25	6	2	54
SNAP03 - Industry	7	11	-	1	13
SNAP07 - Road/land transport	9	14	-	0	31
SNAP08 - Aviation	-	-		-	-
SNAP10 - Agriculture	0	0	4	0	0
Ship transport, EEZ Vietnam[a]	6	4	0	25	7

Note '-' means that emissions are low and therefore there are large uncertainties on the prediction of concentrations and hence health impacts and related costs, and therefore also on the unit costs.

[a]Ship emissions within the Exclusive Economic Zone (EEZ) of Vietnam have been included and named Ship transport, EEZ Vietnam.

Comparison with other studies

We have compared our findings where relevant and possible with identified selected studies from Vietnam/Southeast Asia within air quality and health impacts and related external impacts of air pollution.

A study by WHO states that Vietnam's annual population weighted mean concentration of $PM_{2.5}$ is 30 µg/m^3 in 2012, which exceeds the recommended guideline of 10 µg/m^3 by the WHO and the limit value of European Union of 25 µg/m^3. Annual mean concentration of $PM_{2.5}$ in Vietnam is approx. three times higher than levels in Denmark. In our study, we calculated a population weighted mean of 29 µg/m^3 for $PM_{2.5}$ for Vietnam for 2010, which is close to what WHO estimates for 2012.

In our study we estimate the number of premature deaths due to all air pollution in Vietnam due to domestic and foreign emission sources to approx. 179,000. This is substantially higher that WHO (2018) that estimates approx.

60,000. In Denmark, estimation of premature death due to air pollution has been carried out every year for a number of years with the EVA-system. The most recent estimate for 2019 is 4,600 premature deaths due to all air pollution in Denmark due to domestic and foreign emission sources. Denmark has a population of 5.8 mill. and Vietnam 96.5 mill. If we extrapolate the number of premature deaths in Denmark to Vietnam using population data, we would expect approx. 77,000 premature deaths in Vietnam. We calculate approx. 179,000 with the EVA-system for Vietnam or more than twice as much. This is reasonable as concentration levels of $PM_{2.5}$ in Vietnam are about three times higher than in Denmark and $PM_{2.5}$ dominates the number of premature deaths.

The Word Bank has estimated the Gross Domestic Product (GDP) of Vietnam in 2016 (Purchasing Power Parity (PPP) adjusted) to 634 billion USD equivalent to 513 billion euro (World Bank, 2016). We use a price level of 2016 level as the standard health costs represent 2016. We estimate the total external costs to approx. 43 billion euros due to all air pollution due to domestic and foreign emission sources (2016 prices with emissions from 2010). This is approx. 8% of GDP and roughly 50% higher compared to other studies for Vietnam (4.5-5.6%).

Uncertainty assessment

We have carried out a structural overview of the uncertainties in the different parts of the EVA-system, and how it may affect the calculated unit costs of air pollution for Vietnam. Overall we assess the calculated unit costs of air pollution for Vietnam to be best available with medium uncertainty.

1 Economic Valuation of Air Pollution (EVA)

This chapter describes the model for economic valuation of air pollution (EVA-system) and how it is applied for Vietnam to estimate the external costs of health effects of air pollution, and hence the unit costs of air pollution to be used as input in energy system optimization.

1.1 Overall impact-pathway methodology

The EVA system (Brandt et al., 2013a,b; Geels et al., 2015; Im et al., 2018, 2019) is based on the impact-pathway chain method (Friedrich and Bickel, 2001). With recent developments, EVAv6 can calculate all-cause acute and chronic mortality and morbidity based on linear exposure-response functions, as well as with cause-specific mortality based on non-linear functions following Burnett et al. (2018).

In Table 1.1 the impact pathway is illustrated. Based on information of the spatial and temporal variation of emissions from different emission sectors, air quality models are used to estimate air quality concentrations. Human exposure is calculated based on population data, and based on exposure-response functions the health effects of air pollution is estimated. Based on economic valuation of the different health endpoints the total external costs of air pollution can be calculated as well as the external costs related to different emission sectors. The unit costs, that is, the health effect costs per one unit of emission emitted can be calculated by dividing the cost for a specific emission sector with the emission emitted of that sector. Unit costs may be expressed as Euros per kg emission.

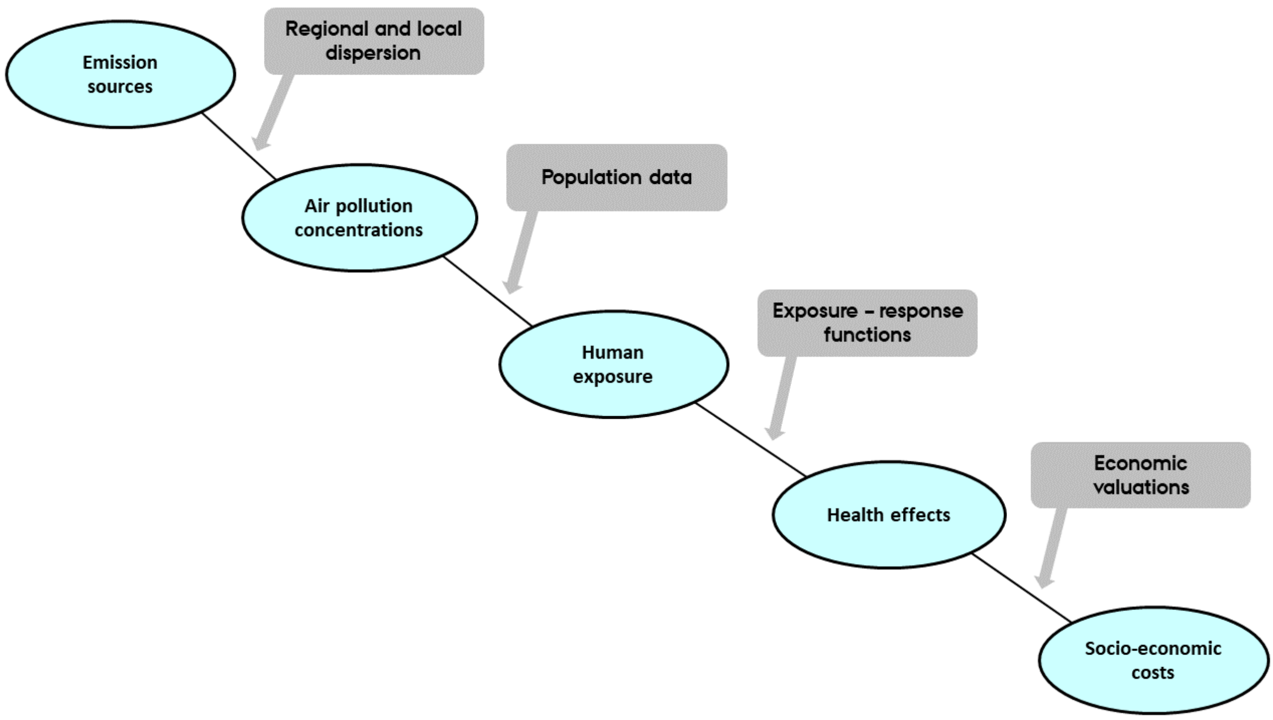

Figure 1.1. The impact pathway chain method used to calculate health effect costs of air pollution in the EVA-system.

In the EVA-system two air quality model may be used for estimation of concentrations of air pollutants – a large-scale model (DEHM) and a local-scale model (UBM). In the case of Vietnam it has been possible to use the DEHM model but not UBM. UBM requires that emission data of a spatial resolution of 1 km x 1 km that is not available for Vietnam.

A global emission dataset for 2010 suitable for Vietnam has been used together with data from a meteorological model (WRF) representing 2019.

External costs of air pollution are country specific and to adjust the costs to Vietnamese conditions we used the OECD benefit transfer methodology to transform unit costs of mortality and morbidity from Denmark to Vietnam.

More details on the different components of the EVA-system is described in the following.

1.2 DEHM-model

DEHM (Danish Eulerian Hemispheric Model) is a three-dimensional, offline, large-scale, Eulerian, atmospheric CTM (chemistry-transport model) with zooming capability (with 2-way nested grids of higher resolution) developed to study long-range transport of air pollution in the Northern Hemisphere (Christensen, 1997; Frohn et al., 2002; Brandt et al., 2012). The model is routinely used for operational air pollution forecasting (Brandt et al., 2001a, b, c, 2003), for describing transport and fluxes of CO_2 (Geels et al., 2002; Lansø et al., 2015), transport of persistent organic pollutants (POPs) (Hansen et al., 2008) and impacts from climate change on future air pollution levels (Hedegaard et al., 2008; 2013; Hansen et al., 2015a,b). DEHM has lately been evaluated in several model inter-comparisons and applied in model ensemble studies (Vautard et al., 2012; Solazzo et al., 2012a, b, 2013; AMAP, 2015; Solazzo et al., 2017; Im et al., 2018a,b). DEHM is also used routinely as a part of the Danish Air Quality Monitoring Program (both for Denmark and Greenland) and is further a part of the European Copernicus Atmospheric Monitoring Service (CAMS), delivering operational input to the ensemble air pollution forecasts for Europe.

DEHM includes capability for two-way nested domains to obtain higher resolution. The mother domain covers most of the Northern Hemisphere with a resolution of 150 km×150 km in a horizontal grid. Further sub-domains can be setup covering areas of interest with a higher resolution. For Vietnam we have setup the model with a third domain covering the country with a 16.67 km x 16.67 km resolution (Figure 1.2).

The vertical grid extends up to 100 hPa, corresponding to 15–18 km altitude and is divided into 29 vertical layers. The thickness of the lowest layer is approx. 20 m while the upper layers are relatively thick (2000 m). This is chosen in order to get a good description of the boundary layer, where emission and deposition processes take place.

The model describes concentration fields of 58 chemical compounds and 8 classes of particulate matter ($PM_{2.5}$, PM_{10}, Total Suspended Particles (TSP), sea salt <2.5 µm, sea salt >2.5 µm, fresh black carbon, aged black carbon and organic carbon). The model includes a full description of secondary inorganic aerosols (SIA) as well as a module for secondary organic aerosols (SOA). A total of 122 chemical reactions are included in the description of the conversion of the 58 chemical compounds.

The health effects in the EVA system are linked to concentrations of $PM_{2.5}$, NO_2, O_3 and SO_2.

$PM_{2.5}$ includes the following components in the EVA system: The primarily emitted particles ($PPM_{2.5}$) and secondary particles. The primarily emitted particles ($PPM_{2.5}$) contain mineral dust, BC (Black Carbon) and OC (Organic Carbon). The secondary particles include SIA and SOA, which are formed in the atmosphere from emissions of gases. Secondary Inorganic Aerosols (SIA) are formed in the atmosphere from emissions of NO_x (forming nitrate=NO_3), SO_2 (forming sulphate=SO_4) and NH_3 (forming ammonium=NH_4). Secondary organic aerosols (SOA) are formed in the atmosphere from anthropogenic and natural emissions of VOCs. In addition, $PM_{2.5}$ also contains sea salt.

O_3 is not emitted as emission but formed in the atmosphere based on emissions of NO_x, NMVOC and also CO.

The DEHM model is driven by a meteorological model, WRF (Weather Research and Forecasting model; https://www.mmm.ucar.edu/weather-research-and-forecasting-model).

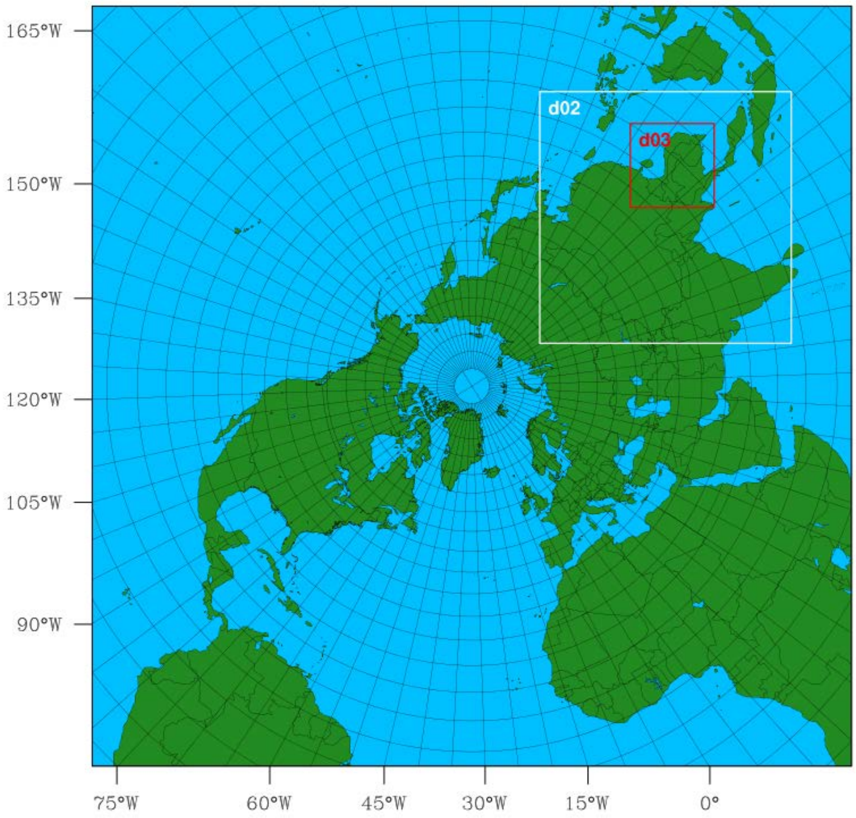

Figure 1.2. Illustration of model domain and sub-domains of the DEHM model for the Vietnamese case.

1.3 Exposure-response functions in EVA-system

The EVA-system estimates premature mortality, related to short-term (acute) exposure to O_3, $PM_{2.5}$, SO_2 and NO_2, and long-term (chronic) exposure to $PM_{2.5}$ and NO_2. EVA requires gridded surface concentrations of these pollutants, along with gridded population density data over fixed age intervals, corresponding to babies (under one year), children (under 16), adults (above 16 and above 30), and elderlies (above 65). The linear exposure-response functions (ERFs) used in EVA are those recommended by the WHO (Héroux et al., 2015; WHO, 2013). Adjustments are included in order to minimize the risk of double counting of premature deaths due to short-term and long-term exposures.

The health impacts are calculated using an ERF of the following form:

$$R = \alpha \times \delta_c \times P$$

where R is the response of the mortality rate or the years of life lost (in cases or days), δ_c denotes the pollutant concentration, P denotes the affected share of the population, and α an empirically determined constant for the particular health outcome.

The applied ERFs recommended by WHO in e.g. Héroux et al., 2015 are based on a comprehensive review and only pollutant/health outcome pairs supported by sufficient evidence for a causal association are included in the recommendations. The underlying studies are larger meta-studies like Hoek et al., 2013 that includes studies from Europe, the US and Asia, where data are most extensive and up-to-date, although there are ongoing studies in Europe, and in particular in the Nordic region to develop regional-specific ERFs (e.g. the NordicWelfAir project: https://projects.au.dk/nordicwelfair/). The EVA model system was compared to other similar systems in Anenberg et al. (2015).

EVA calculates the number of lost life years with respect to the age distribution, applying the relative risk, RR= 1.062 (1.040-1.083) for all cause chronic mortality due to $PM_{2.5}$. The latency period sums to a number of year of life lost (YOLL) per 100,000 individuals for an annual $PM_{2.5}$ increase of 10 μg m^{-3} following Andersen et al. (2008). The YOLL is then converted to number of cases by dividing by 10.6 following Watkiss et al. (2005). The counterfactual $PM_{2.5}$ concentration is assumed to be 0 μg m^{-3} following the EEA European Environmental Agency methodology, meaning that the impacts have been estimated for the simulated total (anthropogenic and natural) $PM_{2.5}$ mass. Chronic mortality is also included for NO_2, but only for annual averaged levels above 20 μg/m^3 and with a RR of 1.055.

Regarding short-term exposure and acute mortality, the number of cases related to exposure to O_3, NO_2, $PM_{2.5}$ and SO_2 are estimated in the EVA system using RR ranging from 1.0027 to 1.0123. For O_3 the sum of Ozone Means Over 35 ppb (SOMO35) is applied, which is based on the daily maximum of 8-hour mean O_3 concentrations. The effect related to NO_2 is included as an annual mean of the daily maximum NO_2 concentration, while annual mean concentrations are used for $PM_{2.5}$ and SO_2.

The morbidity outcomes include bronchitis, asthmatic children and lung cancer. As a main application of the EVA system in the assessment of costs, the system also includes ERFs related to hospital admissions (cardiovascular and respiratory) as well as restricted activity days and work days lost. This distinction enables accounting for the different costs associated with days of reduced well-being and actual sick days. Details on the ERFs for the different morbidity and mortality outcomes are presented in Table 1.1.

Table 1.1. The health endpoints and relative risks used in EVA – based on the WHO recommendations (the RR for SO_2 is taken from the ExternE project). The standard costs are given for Denmark in 2016 prices.

Health endpoint	Pollutant	Range	Ages	RR per 10 µg/m3	Standard costs in EVA-system (Denmark)
Acute mortality	O_3	>35 ppb	all	1.0029	4242611 Euro/case
	NO_2 (daily max)	no thresh.	all	1.0027	
	$PM_{2.5}$	no thresh.	all	1.0123	
	SO_2	no thresh.	all	0.072	
Acute mortality infants	$PPM_{2.5}$ (from PPM_{10})	no thresh.	Infants	1.0400	6362416 Euro/case
Chronic mortality	$PM_{2.5}$	no thresh.	>30	1.062	149594 Euro/YOLL
	NO_2	>20ug/m3	>30	1.0550	
Hospital admissions (HA):					
Cardiovascular HA/incl. stroke	$PM_{2.5}$	no thresh.	all	1.0091	15999 Euro/case
Cardiovascular HA/excl. stroke	O_3	>35 ppb	>65	1.0089	15877 Euro/case
Respiratory HA	$PM_{2.5}$	no thresh.	all	1.0190	9940 Euro/case
Respiratory HA	O_3	>35 ppb	>65	1.0044	
Respiratory HA	NO_2	no thresh.	all	1.0180	
Bronchitis (KOL)/children	$PM_{2.5}$ (from PM_{10})	no thresh.	6-18	1.0480	162 Euros/case
Bronchitis (KOL)/adults	$PM_{2.5}$ (from PM_{10})	no thresh.	>18	1.1170	38933 Euros/case
Asthma symptoms/children	$PM_{2.5}$ (from PM_{10})	no thresh.	5-19	1.0280	1325 Euros/day
Days with restricted activity (sick days) ($PM_{2.5}$)	$PM_{2.5}$	no thresh.	all	1.0470	148 Euros/day
Working days lost ($PM_{2.5}$)	$PM_{2.5}$	no thresh.	20-65	1.0460	273 Euros/day
Days with minor restricted activity (O_3)	O_3	>35 ppb	all	1.0154	78 Euros/day
Lung cancer morbidity	$PM_{2.5}$	no thresh.	above 30	1.14	72697 Euros/case

1.4 Population data

EVA used the global population density from Socioeconomic Data and Applications Center (SEDAC: (http://sedac.ciesin.columbia.edu/data/collection/gpw-v4/sets/browse) on a 2.5-minute spatial resolution. In these data, the age breakdown is available for the year 2010. Therefore the age distribution in other years in the assessment have been scaled by a dataset for country specific age distributions for the years 1950-2020 originally given by 5 years intervals and subsequently interpolated to the actual year in EVAv6 (United Nations, Department of Economic and Social Affairs, Population Division (2019). World Population Prospects 2019; https://population.un.org/wpp/). The resulting world population is e.g. 7.34 billion people in the year 2015 and 7.79 billion people in the year 2020 based on these data.

1.5 Transfer of health effect costs

The EVA model system applies a set of standard costs for acute and chronic mortality, derived for Denmark. To apply the EVA system for other countries, the standard set for standard costs can either be replaced by a set of locally developed standard costs that applies for the specific country or the standard set of standard costs can be transformed into another country using the OECD benefit transfer methodology formula (OECD 2012: 138);

$$VSL_{VN} = VSL_{DK} \, (Y_{VN}/Y_{DK})^{ß}$$

Where VSL is the value of statistical life, and Y is GDP per capita (purchasing power parity adjusted) and ß is the income elasticity (of 0.9).

Data was been obtained from The World Bank (https://data.worldbank.org) and results are provided as 2016-prices. We find that costs of health effects in Vietnam are estimated to be 9.7% of the standard costs of health effects in EVA.

The cost per case (e.g. the cost of a premature death) reflects the current socio-economics of Vietnam. In the future, the cost per case will increase in Vietnam due to rapid economic growth.

The derived unit costs of air pollution (Euros per kg emission) embed the current socio-economics of Vietnam and the unit costs of air pollution will also increase in the future due to economic growth. Furthermore, future increase in the population will also increase the unit costs as more people will be exposed to emitted air pollution, other things equal.

For application of the unit costs derived in this report in scenarios for the future development of Vietnam's energy system, costs per case should be adjusted with the projected development of the per capita income, and further the unit costs should be indexed with projected population growth.

The unit costs of air pollution embed a relation between emitted air emissions and the resulting concentration contribution. This relation is expected to be relatively robust over time as less emissions will lead to lower concentrations and higher emissions will lead to higher concentrations maintaining the relative relationship.

2 Emission data

In this chapter we describe the emission data requirements of DEHM and the emission data used for Vietnam.

2.1 Emission requirements of DEHM

The DEHM model requires emissions of SO_2 (sulphur dioxide), CO (carbon monoxide), NO_x (nitric oxides), NMVOC (non-methane volatile organic compounds), NH_3 (ammonia) and $PPM_{2.5}$ (primary emitted particles less than 2.5 µm in diameter).

International bodies have standardised reporting on emissions in the so-called SNAP categories. SNAP stands for Selected Nomenclature for Air Pollution. The classification was developed in the EMEP/EEA (Air Pollutant Emission Inventory Guidebook) project and has been synchronised with the IPCC/OECD (Integrated Pollution Prevention and Control) nomenclature of source categories for activities resulting in emissions. SNAP11 – Other sources and sinks is only relevant for greenhouse gas emissions.

Emissions are reported for these SNAP categories for the national land and water territory. For air quality modelling an extra emission section is added to reflect international shipping in international waters. We devote this SNAP15.

Table 2.1. SNAP emission sectors.

SNAP Code	SNAP Description
01	Combustion in the production and transformation of energy
02	Non-industrial combustion plants
03	Industrial combustion plants
04	Industrial processes without combustion
05	Extraction and distribution of fossil fuels and geothermal energy
06	Use of solvents and other products
07	Road Transport
08	Other mobile sources and machinery
09	Waste treatment and disposal
10	Agriculture
11	Other sources and sinks (nature)

2.2 Global emission data set available in DEHM

There are several global emission data sets already incorporated in DEHM:

- **RCP** historical emission data for the period 1850-2000 combined with projections for 2005, 2010, 2020 etc. Data are constructed in 2009, so our opinion is that they are obsolete.
- **ECLIPSE** emissions version 4a (constructed in 2013) and version 6b (constructed in 2019) by IIASA for the years 1990, 1995, 2000, 2005,

2010, 2015, 2020 up to 2050. Have been used in AMAP (Arctic Monitoring and Assessment Programme). Data are on a 0.5 x 0.5 degree resolution.

- **HTAP_v2** emissions for the year 2010, used in AQMEII (Air Quality Modelling Evaluation International Initiative) produced by JRC (Joint research Centre, Italy – under the European Union). Data are based on: MICS Asia, EPA US/Canada, EMEP/TNO Europe, and EDGARv4.3 for the rest of the world. Data are on a 0.1 x 0.1 degree resolution. HTAP is the Hemispheric Transport of Air Pollution, under UN-ECE.

Based on our experience, the global emission dataset - HTAP_v2 emissions – is of the highest quality for Asia and Vietnam, and is considered to be the best available emission data for this region. This dataset was used as the standard emission inventory used in an Asian model inter-comparison study where a total of 14 chemical transport models (CTMs) participated in the first topic of the Model Inter-Comparison Study for Asia (MICS-Asia) phase III (Chen et al., 2019).

However, data are for the year 2010. The advantage is that the MICS Asia data have been used in model inter comparisons for Asia and thereby have been validated within models and against measurement data.

The ECLIPSE data includes an emission inventory for the year 2020, which is present time. However, data are in a coarser spatial resolution, and the quality for Asia is not known. There might be problems with the spatial distribution of the emissions. We e.g. have experienced that Norwegian North Sea oil exploration emissions were allocated to Oslo and not out at the sea, since a population density proxy was used.

The two possible data sets HTAP and ECLIPSE is divided into a different set of emission sectors:

HTAP emission sectors

- Agriculture
- Aviation
- Energy production and transformation
- Industry
- Residential
- Ship transport
- Road/land transport

ECLIPSE emission sectors

- Agriculture
- Agriculture (waste burning on fields)
- Residential and commercial
- Power plants, energy conversion, extraction
- Industry (combustion and processing)
- Solvents
- Surface transportation
- Upstream production field flaring or venting
- Waste
- International shipping

2.3 Use of HTAP_v2 emissions in DEHM

We used the HTAP_v2 emissions due to higher quality in both total emissions and better spatial distribution of the emissions (i.e. emissions are located in the right locations), and the fact that these emissions have already been applied and evaluated in a model inter-comparison study for Asia.

The down side is that these data are only available for the emission year 2010. However, we do not see that as a problem to use 2010 emission data for the 2019 meteorological year, since we are interested in a response in atmospheric concentrations due to an emission reduction per sector. This response will change between years partly due to different meteorology and different emissions and different "background chemistry" due to the overall pollution levels in the region, which depends on regional and global emissions. However, changes in the atmospheric response is probably smaller than the changes in actual air pollution concentrations between years, so we believe that using the HTAP_v2 emission data will give the best possible unit prices for Vietnam.

Note that we here use the standard SNAP nomenclature although this categorization has not used in the original emission dataset of HTAP_v2.

Ship emissions within the Exclusive Economic Zone (EEZ) of Vietnam have been included and named Ship transport, EEZ Vietnam.

Total emissions and distribution on emission sectors

The applied HTAP_v2 emission data for Vietnam is shown in Table 2.2.

Table 2.2. HTAP_v2 emission data for Vietnam for 2010 (ktonnes). Giving as kg-S, kg-C, kg-N, kg-NMVOC, kg-$PPM_{2.5}$

Emission sector	SO_2	CO	NO_x	NMVOC	NH_3	$PPM_{2.5}$
SNAP01 - Energy production and transformation	53	4	26	2	0	6
SNAP02 - Residential	40	2552	26	1083	160	2
SNAP03 - Industry	132	43	34	153	5	135
SNAP07 - Road/land transport	36	714	41	835	1	2
SNAP08 - Aviation	0	1	2	0		0
SNAP10 - Agriculture					346	
Ship transport, EEZ Vietnam	133	21	160	16		
Total	395	3335	289	2089	512	145

Emissions in Table 2.2 are given as kg-S, kg-C and kg-N. To convert e.g. S to SO_2 based on the molecular mass a conversion factor of 2.00 has to be used, and hence the total emission of SO_2 is 2x395=790 ktonnes in SO_2 units, and similar factors of 2.33 for CO, 3.29 for NO_x (kton-NO_2) and 1.21 for NH_3.

Spatial distribution of emissions

In this section, we present selected maps of the spatial distribution of the total emissions from the emission sectors for SO_2, NO_x, NH_3, and $PPM_{2.5}$. The illustration is for all land-based emissions on a grid with resolution of 16.7 km x 16.7 km.

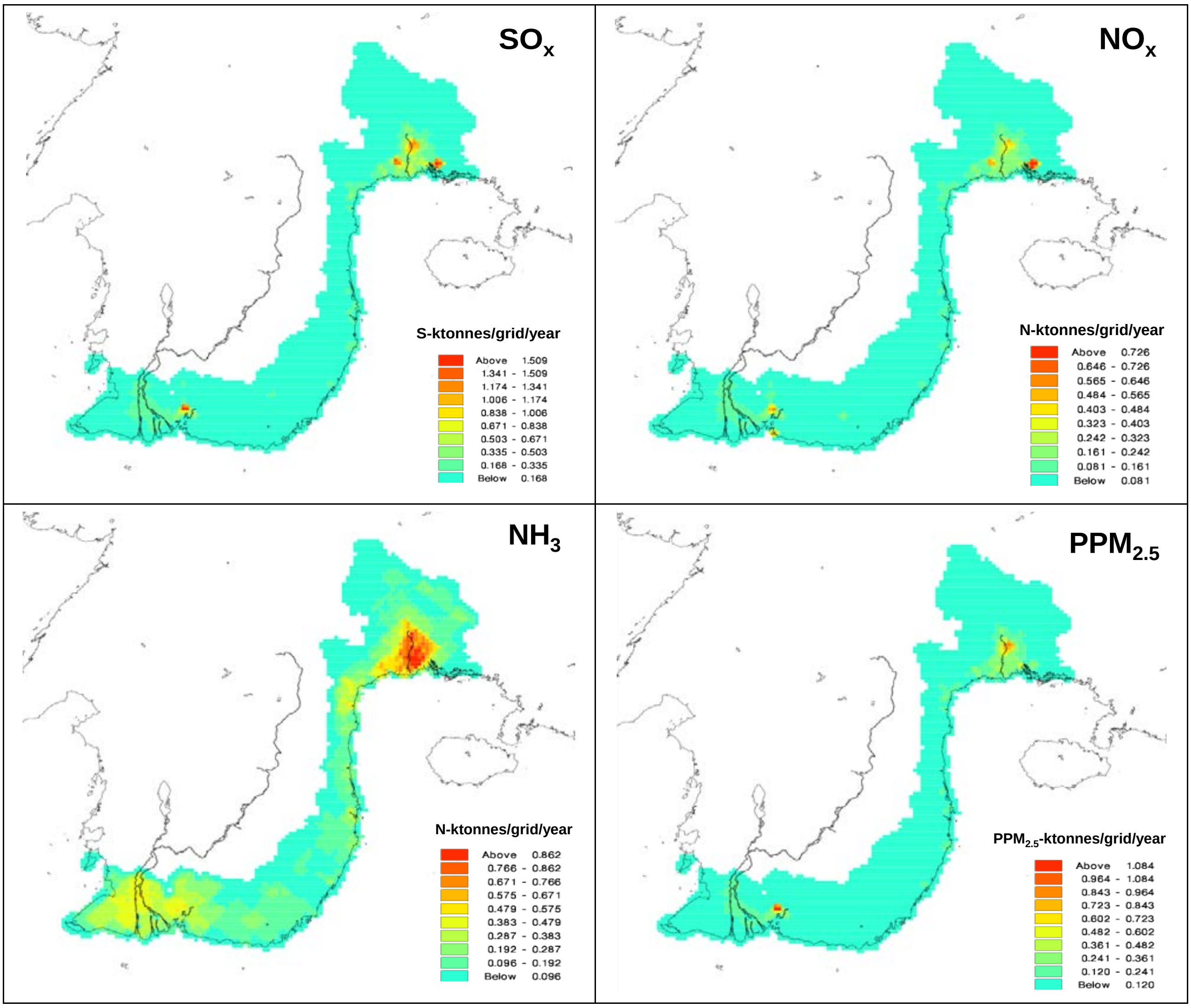

Figure 2.1. Spatial distribution of the total emissions from all emission sectors for HTAP_v2 emissions from 2010 for Vietnam.

The spatial distribution of emissions from each emission sector is also available but not shown as seven emission sectors and six pollutants is all together 42 maps.

Compare HTAP_v2 emission data to national Vietnamese emission inventory

There are no international obligations for countries outside the UNECE to draw up emissions inventories for air pollution. Therefore, Vietnam is not obliged to report on emissions for air pollution. That is not to say that Vietnam does not have emission inventories but we have not been able to locate such data within the present project.

The DEHM model requires emissions of SO_2, CO, NO_x, NMVOC, NH_3 and $PPM_{2.5}$.

Apart from major greenhouse gas emissions (CO_2, CH_4, N_2O), there are four pollutants recommended to be reported under the UNFCCC for climate change (SO_2, NO_x, NMVOC and CO). The most recent report from Vietnam is the second national communications (MNRE, 2010). This communication reports emissions of SO_2, NO_x, NMVOC and CO for the year 2000.

The third national communications (MNRE, 2019) reports the emission inventories for 2014 but for some reason emissions from the energy sector for SO_2, NO_x, NMVOC and CO are not included. Maybe because it is not obligatory to report for these pollutants. Furthermore, there is no information on NH_3 and $PPM_{2.5}$ as this is not reported under UNFCCC. There are no more recent communications.

Hence, it is not possible to assess the trends in air pollutants from 2000 to 2014 due to lack of information. However, CO_2 emissions from the I) Energy sector increased 3-fold (from 45,900 to 147,525 ktonnes) and II) Industrial processes increased about 4-fold (from 10,006 to 38,620 ktonnes) indicating that air emissions also have increased from 2000 to 2014.

In Table 2.3 we compare the total emissions of Vietnam used for modelling of air concentrations, health effects and external costs (HTAP_v2 emissions from 2010) with the emissions for 2000 from the second national communications for available pollutants.

Table 2.3. Comparison of emissions (ktonnes)

Emission data source	NO_x	CO	NMVOC
HTAP_v2 emissions from 2010 (kg-N, kg-C)	129	3314	2073
HTAP_v2 emissions from 2010 (kg)	424	7732	2073
Second communication from 2000 (kg)	313	4344	364

As expected the emissions are much higher in 2010 compared to 2000.

For calculation of units costs for air pollution the absolute emissions and hence the resulting concentrations of air pollutants are less crucial as the units costs are calculated based on a change in emissions resulting in a change in concentrations, and this relationship is calculated the chemistry transport model (DEHM). The unit costs reflect the costs of air pollution divided by the emissions causing the impacts.

However, if the emissions are either too low or too high it will be reflected in the total costs of air pollution that will be either too low or too high. Similarly, if the relative emissions between the emission sectors are not correct, this will also be reflected in the costs of each emission sector.

3 Concentrations of air pollutants

In this chapter we will illustrate the spatial distribution of concentrations of air pollutants modelled with DEHM and based on the HTAP_v2 emissions dataset. Note that the geography of the figures is not completely aligned north-south. This is due to the definition of the grid net for the domain of the DEHM model, see former Figure 1.2.

We present concentration maps for $PM_{2.5}$, NO_2, O_3 and SO_2 that are the pollutants that contribute to health effects in the EVA-system. These maps are based on emissions from all emission sections in all countries as well as natural emissions. To be able to estimate the health effects and associated external costs for each emission sector to derive unit costs of air pollution, we have also calculated the contribution of each emission sector to concentrations. For the seven emission sectors and four pollutants it is all together 28 maps that are not shown.

Spatial distribution of $PM_{2.5}$

In Figure 3.1 the spatial distribution of concentrations of $PM_{2.5}$ is shown.

It is seen that there is a north-sourth gradient with higher concentrations in the north-east compared to the south of Vietnam. There is a clear influence of long-range transport from China. Higher concentrations are also seen in the regions of Hanoi and Ho Chi Minh.

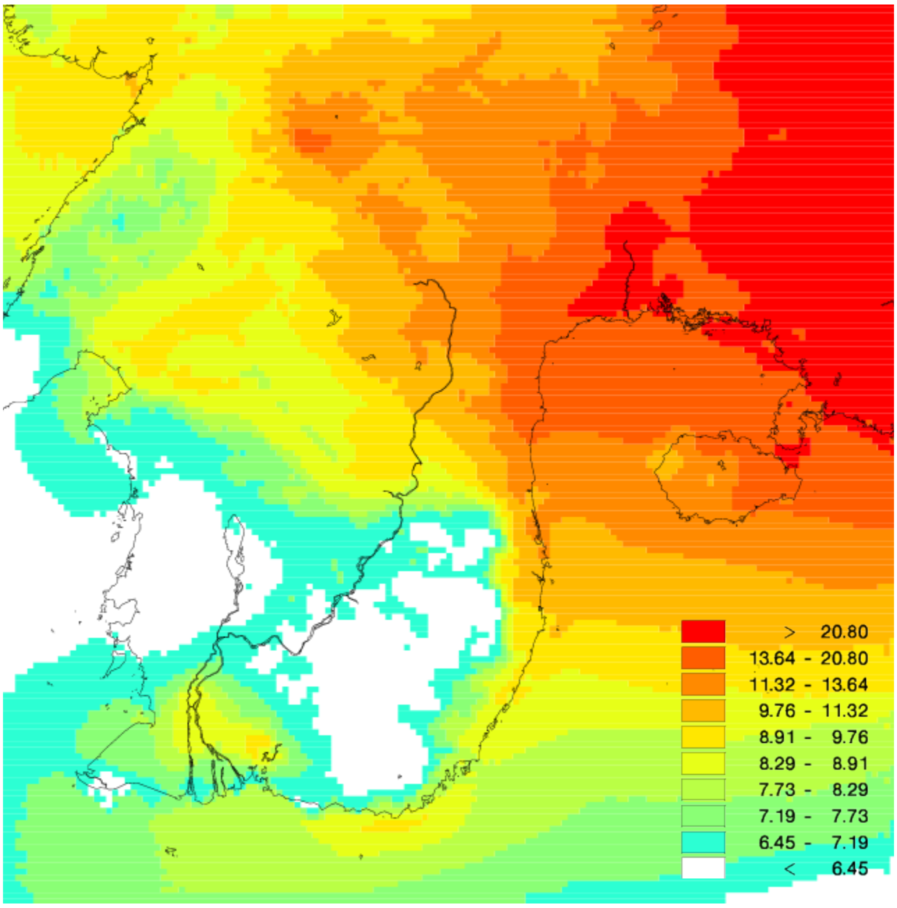

Figure 3.1. Spatial distribution annual mean concentrations of $PM_{2.5}$ based on emissions from 2010 and meteorology from 2019 ($\mu g/m^3$).

Spatial distribution of NO_2

In Figure 3.2 the spatial distribution of concentrations of NO_2 is shown.

NO_x emissions from transport contribute significantly to NO_2 concentrations and the spatial pattern of NO_2 different from $PM_{2.5}$. Higher NO_2 conentrations are seen in larger urban areas. Ship routes are also clearly seen.

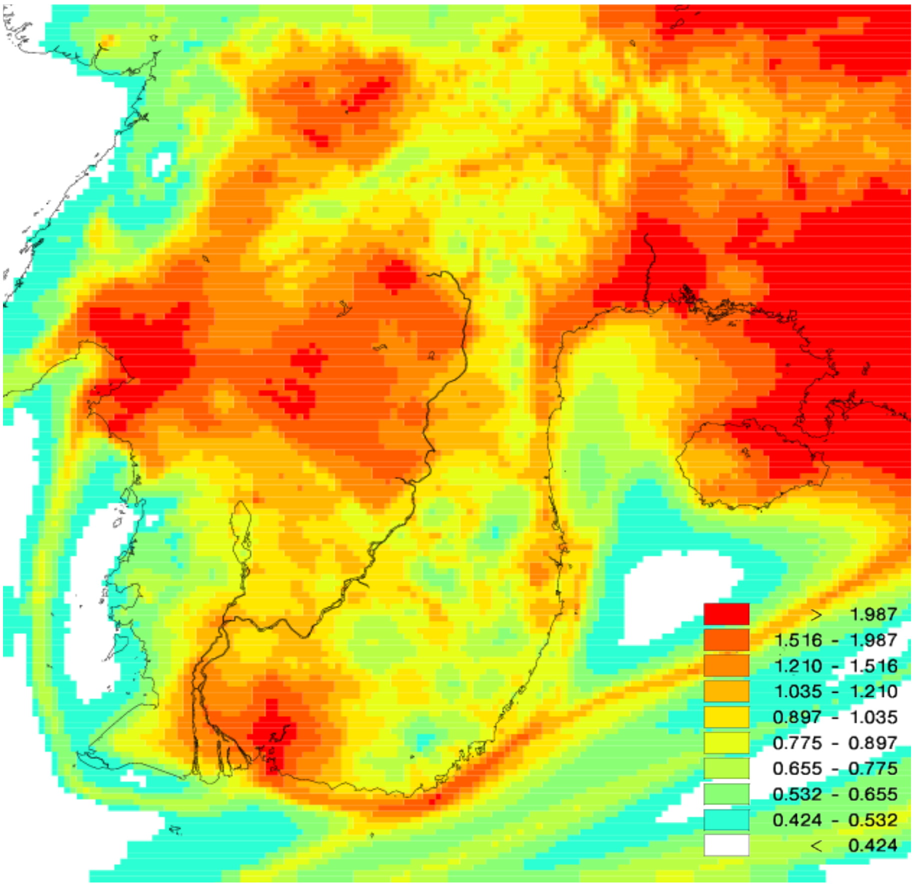

Figure 3.2. Spatial distribution annual mean concentrations of NO_2 based on emissions from 2010 and meteorology from 2019 (µg/m^3).

Spatial distribution of O_3

In Figure 3.3 the spatial distribution of concentrations of O_3 is shown.

Local emissions of NO_x deplete ozone and therefore ozone concentrations are generally lower where local NO_x emissions are present.

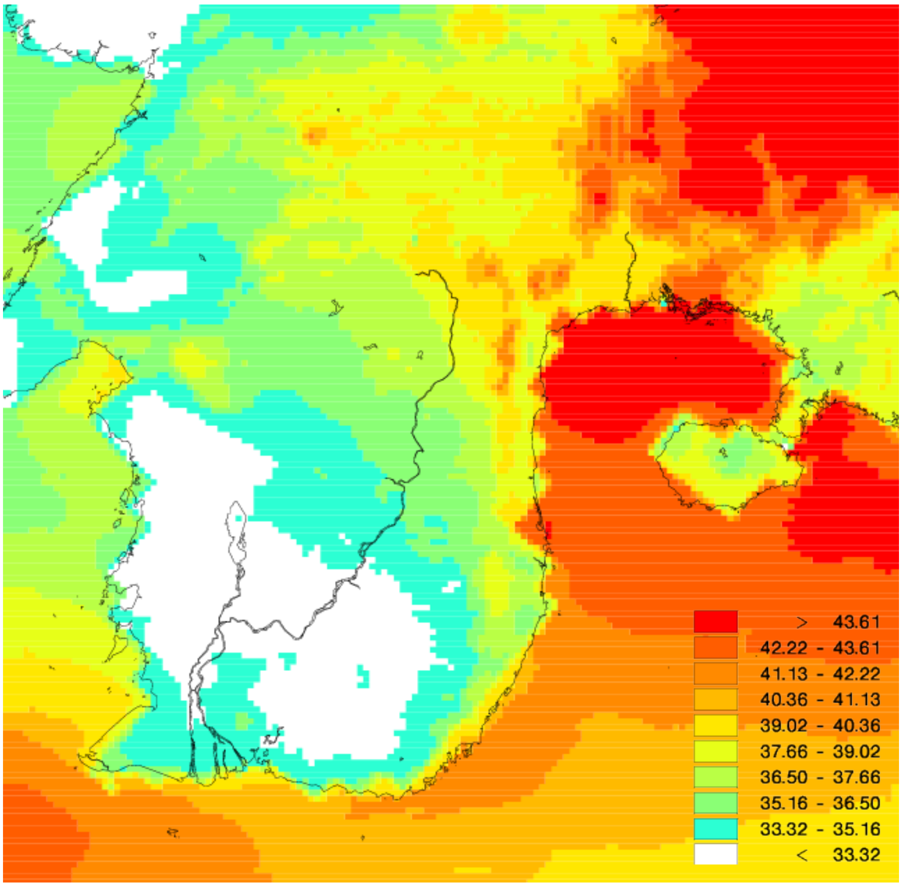

Figure 3.3. Spatial distribution annual mean concentrations of O_3 based on emissions from 2010 and meteorology from 2019 (µg/m^3).

Spatial distribution of SO_2

In Figure 3.4 the spatial distribution of concentrations of SO_2 is shown.

The spatial distribution of SO_2 is very similar to NO_2 as it is also dominated by combustion sources.

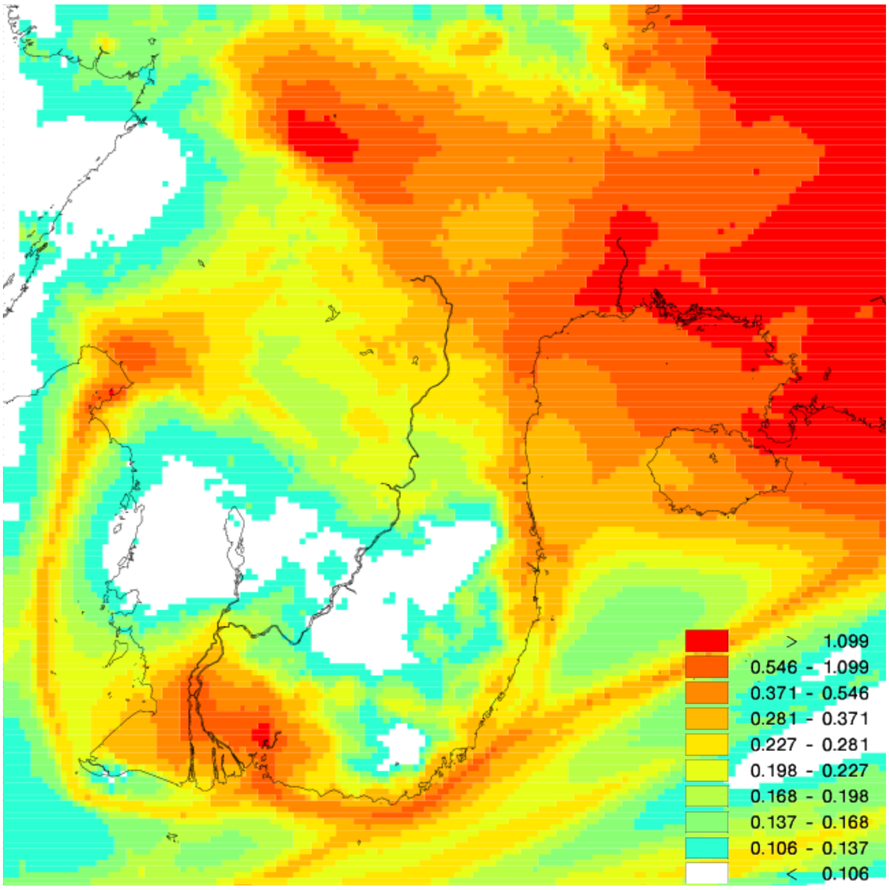

Figure 3.4. Spatial distribution annual mean concentrations of SO_2 based on emissions from 2010 and meteorology from 2019 (µg/m^3).

4 Unit costs of air pollution

In this chapter we present total and unit costs of air pollution. Unit costs are health related external costs of air pollution per kg emission of air pollutants. The Ea Energy Analyses and Danish company Energy Modelling Lab have integrated the unit costs of air pollution into energy models in order to model different scenarios for energy system optimization, which accounts for air pollution costs.

The unit costs have been calculated with the DEHM and EVA-system. Total health related costs for each pollutant and each emission sector have been calculated and divided by the emissions of each pollutant and each emission sector to derive the unit costs. Emissions are described in chapter 3 and figures for health effects are given in Appendix 1.

4.1 Total costs of all air pollution in Vietnam

Total costs of all air pollution in Vietnam due to domestic and foreign emission sources are estimated to 43 billion euro based on emissions from 2010 (and 2016 prices for health costs). About half of these costs are from domestic emission sources and about half are from foreign emission sources.

The Word Bank has estimated the Gross Domestic Product (GDP) of Vietnam in 2016 (Purchasing Power Parity (PPP) adjusted) to 634 billion USD equivalent to 513 billion euro (World Bank, 2016). We use a price level of 2016 level as the standard health costs represent 2016. This means that costs of all air pollution in Vietnam is approx. 8% of GDP which is high.

In the following we present the costs related to air emissions in Vietnam.

4.2 Total costs of Vietnamese air emissions

Table 4.1 gives the total costs for each emission sector and the different pollutants. Total costs are given for ‘Vietnam only’, which means that only health impacts within Vietnam are included and not health impacts that arise outside Vietnam due to emissions in Vietnam. ‘Total in Vietnam and abroad’ means total costs that reflects health impacts in Vietnam and abroad due to emissions in Vietnam.

The total costs of emissions in Vietnam to health effects in Vietnam are approx. 17 billion euro. The majority of the costs are related to $PM_{2.5}$ and at a substantially lower level follows NO_x, SO_x, NH_3 and NMVOC.

The residential emission sector (SNAP02) has by far the largest costs, which in Vietnam includes a lot of emissions from use of biomass for cooking and also heating.

The total costs in Vietnam and abroad of emissions in Vietnam are approx. 47 billion euro indicating that Vietnamese emissions also have a large health impact abroad as air pollution is transported over large distances. Similarly, Vietnam is also affected by emissions from neighbouring countries and beyond.

Table 4.1. Total costs of Vietnamese air emissions in 2010 (2016-prices).

OECD benefit transfer factor (0.097)						
Total costs - in Vietnam only (billion euro)						
Species emissions	SO_x	NO_x	NH_x	NMVOC	$PPM_{2.5}$	Total
Species Impacts	SO_2+SO_4	O_3-O_3neg NO_3+NO_2	NH_4	SOA	$PM_{2.5}$	
SNAP01 - Energy production and transformation	0.2	0.3	0.1	0.0	0.0	0.6
SNAP02 - Residential	0.4	0.7	0.3	0.9	8.7	11.0
SNAP03 - Industry	0.4	0.4	0.2	0.0	0.8	2.0
SNAP07 - Road/land transport	0.2	0.6	0.1	0.1	0.1	1.1
SNAP08 - Aviation	0.0	0.1	0.0	0.0	0.0	0.1
SNAP10 - Agriculture	0.2	0.2	0.4	0.0	0.0	0.8
Ship transport, EEZ Vietnam	0.4	0.6	0.2	0.1	0.0	1.3
Total	1.7	3.0	1.4	1.2	9.6	16.9
Total costs - total in Vietnam and abroad (billion euro)						
Species emissions	SO_x	NO_x	NH_x	NMVOC	$PPM_{2.5}$	Total
Species Impacts	SO_2+SO_4	O_3-O_3neg NO_3+NO_2	NH_4	SOA	$PM_{2.5}$	
SNAP01 - Energy production and transformation	0.8	0.8	0.4	0.1	0.1	2.2
SNAP02 - Residential	1.7	2.2	1.2	2.1	19.3	26.4
SNAP03 - Industry	1.8	1.2	0.9	0.2	2.1	6.3
SNAP07 - Road/land transport	0.7	1.9	0.4	0.4	0.2	3.6
SNAP08 - Aviation	0.0	0.2	0.0	0.0	0.0	0.3
SNAP10 - Agriculture	1.6	0.6	1.5	0.0	0.0	3.7
Ship transport, EEZ Vietnam	1.5	1.9	0.8	0.4	0.0	4.7
Total	8.1	8.8	5.3	3.2	21.7	47.2

In Table 4.2 the distribution of costs in Vietnam and outside Vietnam is shown for Vietnamese emissions. In total 37% of all costs from Vietnamese emissions fall within Vietnam and 67% outside Vietnam.

Table 4.2. Distribution of costs in Vietnam and outside Vietnam of Vietnamese emissions (%).

Emission sector	In Vietnam	Outside Vietnam
SNAP01 - Energy production and transformation	27%	73%
SNAP02 - Residential	42%	58%
SNAP03 - Industry	31%	69%
SNAP07 - Road/land transport	29%	71%
SNAP08 - Aviation	43%	57%
SNAP10 - Agriculture	22%	78%
Ship transport, EEZ Vietnam	27%	73%
Total	37%	63%

4.3 Unit costs

Table 4.3 gives the unit costs for each emission sector and the different pollutants.

Unit costs are given for 'Vietnam only', which means that only health impacts within Vietnam are included and not health impacts that arise outside Vietnam due to emissions in Vietnam. 'Total in Vietnam and abroad' means unit costs that reflects health impacts in Vietnam and abroad due to emissions in Vietnam.

Note that unit costs in Table 4.3 are given per kg-N, kg-S, whereas kg-$PPM_{2.5}$ and kg-NMVOC are the total mass.

Table 4.3. Unit costs per kg emission for different emission sectors in Vietnam in 2010 (2016-prices).

Unit costs; **Euros per kg-N, kg-S, kg-C, kg-$PPM_{2.5}$**, kg-NMVOC

OECD benefit transfer factor (0.097)

Unit costs - in Vietnam only (Euro/kg)					
Species emissions	SO_x	NO_x	NH_x	NMVOC	$PPM_{2.5}$
Species Impacts	SO_2+SO_4	O_3-O_3neg +NO_3+NO_2	NH_4	SOA	$PM_{2.5}$
SNAP01 - Energy production and transformation	3	11	-	-	4
SNAP02 - Residential	9	27	2	1	24
SNAP03 - Industry	3	13	-	0	5
SNAP07 - Road/land transport	4	15	-	0	13
SNAP08 - Aviation	-	-		-	-
SNAP10 - Agriculture			1		
Ship transport, EEZ Vietnam	3	4		6	2

Unit costs - total in Vietnam and abroad (Euro/kg)					
Species emissions	SO_x	NO_x	NH_x	NMVOC	$PPM_{2.5}$
Species Impacts	SO_2+SO_4	O_3-O_3neg +NO_3+NO_2	NH_4	SOA	$PM_{2.5}$
SNAP01 - Energy production and transformation	14	32	-	-	10
SNAP02 - Residential	40	82	7	2	54
SNAP03 - Industry	13	36	-	1	13
SNAP07 - Road/land transport	18	46	-	0	31
SNAP08 - Aviation	-	-		-	-
SNAP10 - Agriculture	0	0	4	0	0
Ship transport, EEZ Vietnam	11	12	0	25	7

Note '-' means that emissions are low and therefore there are large uncertainties on the prediction of concentrations and hence health impacts and related costs, and therefore also on the unit costs.

The unit costs for 'Total in Vietnam and abroad' is substantially higher than 'Vietnam only' with a factor of 2-5 depending on emission sector and pollutant. This means that emissions in Vietnam cause more external costs outside Vietnam than within Vietnam.

In Table 4.3 unit costs are given as per kg-N for NO_x etc. In Table 4.4 the unit costs are given for the mass of NO_x (in NO_2 units) etc. by conversion based on the molecular mass. See former section 3.3 for conversion factors.

Table 4.4. Unit costs per kg emission for different emission sectors in Vietnam in 2010 (2016-prices).

Unit costs; **Euros per kg of SO_x, NO_x, NH_x, $PPM_{2.5}$, NMVOC.**

OECD benefit transfer factor (0.097)

Unit costs - in Vietnam only (Euro/kg)

Species emissions	SO_x	NO_x	NH_x	NMVOC	$PPM_{2.5}$
Species Impacts	SO_2+SO_4	O_3-O_3neg +NO_3+NO_2	NH_4	SOA	$PM_{2.5}$
SNAP01 - Energy production and transformation	2	3	-	-	4
SNAP02 - Residential	4	8	2	1	24
SNAP03 - Industry	2	4	-	0	5
SNAP07 - Road/land transport	2	5	-	0	13
SNAP08 - Aviation	-	-		-	-
SNAP10 - Agriculture	0	0	1	0	0
Ship transport, EEZ Vietnam	1	1	0	6	2

Unit costs - total in Vietnam and abroad (Euro/kg)

Species emissions	SO_x	NO_x	NH_x	NMVOC	$PPM_{2.5}$
Species Impacts	SO_2+SO_4	O_3-O_3neg +NO_3+NO_2	NH_4	SOA	$PM_{2.5}$
SNAP01 - Energy production and transformation	7	10	-	-	10
SNAP02 - Residential	20	25	6	2	54
SNAP03 - Industry	7	11	-	1	13
SNAP07 - Road/land transport	9	14	-	0	31
SNAP08 - Aviation	-	-		-	-
SNAP10 - Agriculture	0	0	4	0	0
Ship transport, EEZ Vietnam	6	4	0	25	7

Note '-' means that emissions are low and therefore there are large uncertainties on the prediction of concentrations and hence health impacts and related costs, and therefore also on the unit costs.

5 Comparison with other studies

In the following, we present selected studies from Vietnam/Southeast Asia within air quality and health impacts and related external impacts of air pollution. We compare our findings where relevant and possible.

The identified studies are based on information from literature search in literature databases for identification of journal papers, internet search for identification of reports etc., and known studies from the project participants.

The literature search is indicative and therefore not necessary complete as limited resources have been available for this task.

Air quality assessment

Vietnam is one of the fastest growing economies in Asia, with high average annual growth in GDP for many years. Within the last decade annual growth has been between 5.2% and 7.1%, and 7.0% for the most recent year of 2019 (World Bank, 2021). This fast growth and industrialization led to high air pollution, which is one of the most serious environmental problems currently faced by Vietnam. Vietnam is one of the most polluted countries in the world, ranked 170th out of 180 countries for air quality in a recent survey (Environmental Performance Index, Yale University, 2016).

According to the United Nations (2007), Hanoi and Ho Chi Minh City were two of the cities suffering from the most serious air pollution in the world and are now among the top 15 polluted cities in Southeast Asia. Fine particulate matter ($PM_{2.5}$) is the most concerning air pollutant in Vietnam in relation to health impacts. In 2019, Hanoi had only eight days with $PM_{2.5}$ lower than the national standard of 50 $\mu g/m^3$ (Thang, N.D., 2020). The air quality in Ho Chi Minh City was not much better, with only 36 days below the standard.

Based on WHO (2018), annual mean $PM_{2.5}$ concentrations in 2016 in Hanoi and Ho Chi Min City were 48 $\mu g/m^3$ and 42 $\mu g/m^3$, respectively. Based on WHO (2016) the country's population weighted annual mean $PM_{2.5}$ concentration in 2012 is 26 $\mu g/m^3$, which exceeds the recommended guideline of 10 $\mu g/m^3$ by the WHO and the limit value of European Union of 25 $\mu g/m^3$. Annual mean concentration of $PM_{2.5}$ in Vietnam of 26 $\mu g/m^3$ is approx. three times higher than levels in Denmark (Ellermann et al., 2021). In our study, we calculated a population weighted mean of 29 $\mu g/m^3$ for $PM_{2.5}$ for 2010 which is very close to the estimate of WHO for 26 $\mu g/m^3$ for 2012.

Nyguen et al. (2020) used a regional air quality modelling system to analyse the sources of $PM_{2.5}$ pollution in Hanoi, Vietnam, in December 2010. Emission perturbation simulations were conducted to investigate the contribution of local and non-local emission sources on total $PM_{2.5}$. Results showed that local and non-local sources contributed equally to the total $PM_{2.5}$ in Hanoi. Local emission sources comprised 57% of the total $PM_{2.5}$ concentrations for the high $PM_{2.5}$ pollution levels, while only comprising 42% of the total $PM_{2.5}$ for low levels of $PM_{2.5}$ concentrations. In Hanoi's urban areas, local sources contributed more to the total $PM_{2.5}$ than non-local sources. In contrast, non-local sources were the main contributors to the $PM_{2.5}$ in Hanoi's rural areas. Additional sensitivity simulations showed that the industrial and residential sectors collectively comprised 79% of the total $PM_{2.5}$ concentrations while the transport and power sectors comprised only 2% and 3%, respectively.

Since $PM_{2.5}$ originates from primary emitted particles and secondary particles formed in the atmosphere, and is transported over long distances, it also follows that the regional contribution of $PM_{2.5}$ can be large. This is also the case for a city as Hanoi that has many local sources for $PM_{2.5}$.

In the present report, we find that approx. 50% of external costs of all air pollution in Vietnam due to domestic and foreign emission sources that to a large extend is dominated by $PM_{2.5}$ is due to emissions in Vietnam (incl. ship emissions in EEZ) and 50% is due to emissions from foreign emission sources.

Health impacts and related external costs of air pollution

Some studies were identified that use the overall methodology of the impact-pathway approach. This is using either measured or modelled air quality data in combination with exposure-response relations and population data to estimate health impacts of air pollution and potentially also the related external costs.

According to WHO (2018) up to 60,000 deaths in Vietnam in 2016 were related to air pollution.

Truong D.D. (2020) reported that about 50,000 Vietnamese died per year due to air pollution, three times the number of deaths due to traffic accidents. The losses due to worsening air quality in Vietnam amounted to between $10.8-13.6 billion a year, being equal to 4.5 - 5.6% of GDP. Similarly, Thang (2020) reported that on average, air quality being below the World Health Organization's standard reduces life expectancy by one year and costs the country about 5 % of GDP per year, with transportation being among the main causes of this pollution.

Hieu et al. (2013) overviewed the air quality and pollution caused by road traffic in central Hanoi (5 old districts) and the related health outcomes due to particulate matters (PM_{10} and $PM_{2.5}$), using dose-response functions to quantify the number of extra deaths resulting from traffic-related particulate matters. Assessment of the health risk caused by traffic shows that in 2009, mobility caused 3,200 extra deaths by traffic related PM_{10}.

Koplitz et al. (2017) studied the Burden of Disease from Rising Coal-Fired Power Plant Emissions in Southeast Asia based on a detailed analysis of coal-fired power plants presently planned or under construction in Southeast Asia. Based on a chemical transport model they modelled the contribution from emissions to air quality and the resulting exceed premature deaths for eleven countries in Southeast Asia including Vietnam.

In this report, we estimate the number of premature deaths in Vietnam due to emissions in Vietnam to be approx. 83,000 based on emissions from 2010 with the EVA-system. Emissions in Vietnam cause an additional approx. 142,000 annual premature deaths outside Vietnam, hence the total number of annual premature deaths due to emission in Vietnam is approx. 224,000.

The number of premature deaths due to all air pollution due to domestic and foreign emission sources is estimated to approx. 179,000. This is substantially higher that WHO (2018) mentioned above (60,000). In Denmark, estimation of premature death due to air pollution has been carried out every year for a number of years with the EVA-system. The most recent estimate for 2019 is 4,600 premature deaths due to all air pollution in Denmark due to domestic and foreign emission sources. Denmark has a population of 5.8 mill. and Vietnam 96.5 mill. If we extrapolate the number of premature deaths in Denmark to Vietnam using population data, we would expect approx. 77,000 premature death in Vietnam. We calculate approx. 179,000 with the EVA-system for Vietnam or more than twice as much. This is reasonable as concentration levels $PM_{2.5}$ in Vietnam are about 2-3 times higher than in Denmark and $PM_{2.5}$ dominates the number of premature deaths.

The Word Bank has estimated the Gross Domestic Product (GDP) of Vietnam in 2016 (Purchasing Power Parity (PPP) adjusted) to 634 billion USD equivalent to 513 billion euro (World Bank, 2016). We estimate the total external costs to approx. 43 billion euros due to all air pollution due to domestic and foreign emission sources (2016 prices with emissions from 2021). This is approx. 8% of GDP and roughly 50% higher compared to the above studies (4.5-5.6%).

A recent study by Amann et al. (2018), using the GAINS-Vietnam tool, found that based on local emission inventories and meteorological information, road traffic is not the dominating source of $PM_{2.5}$ pollution in the Hanoi Province in contrast to wide-spread perceptions. They found that traffic contributes to about one quarter of $PM_{2.5}$ levels, while the other 75% originate from other sectors, notably large power and industrial plants, the residential sector and the open burning of agricultural waste. Their analysis suggested that, despite the adopted policy measures, Hanoi's air quality could deteriorate in the future as a consequence of the anticipated further increase in economic activities. It is estimated that without additional policy measures, by 2030 $PM_{2.5}$ concentrations in northern Vietnam could be 25-30% higher than in 2015. This would imply that almost 85% of the population in northern Vietnam would be exposed to air quality that does not conform with the national ambient air quality standard for $PM_{2.5}$. The authors also suggested that effective improvements of Hanoi's air quality require coordination with neighbouring provinces, as the analysis indicated that only about one third of (population-weighted exposure to) $PM_{2.5}$ in Hanoi originates from emission sources within the same province, while the majority is imported from outside. The GAINS model system is developed by the International Institute for Applied Systems Analysis (IIASA) in Austria. GAINS is an integrated assessment tool for air quality management and giving all necessary input data it can estimate the health impacts of air pollution and related external costs, and analyse cost-effective measures to reduce air pollution. GAINS stands for Greenhouse Gases and Air Pollutants Interaction and Synergy. The main difference between the EVA model system and GAINS, is the complexity of the air pollution models applied, where a state-of-the-art long-range transport air pollution model is applied in the EVA model system.

The USAID Vietnam low emission energy program (V-LEEP) (USAID, 2021) has conducted a technical report on the impact analysis of integrating significant renewable energy in Vietnam's power sector, based on PLEXOS. In this study the unit costs of emissions is based on older unit costs for Europe from the ExternE project, and has such not been calculated directly for Vietnam, as done in this report using the DEHM-EVA model system.

The EVA (Economic Valuation of Air pollution) model system has been adapted and applied to China for the first time and used to examine the contribution of emission sectors in China and quantifies their relative adverse impact on human health by using the associated external costs to compare the sectors (Bregnbæk et al., 2021, in preparation). The methodology is very similar to the one in the present report.

6 Assessment of uncertainties

In this chapter, we provide a structural overview of the uncertainties in the different parts of the EVA-system, and how it may affect the calculated unit costs of air pollution for Vietnam. This is to provide an overall assessment of the validity the calculated unit costs.

The EVA-system is based on the impact pathway. Based on information of the spatial and temporal variation of emissions from different emission sectors, air quality models are used to estimate air quality concentrations. Human exposure is calculated based on population data, and based on exposure-response functions the health effects of air pollution is estimated. Based on economic valuation of the different health endpoints the total external costs of air pollution can be calculated as well as the external costs related to different emission sectors. The unit costs, that is, the health effect costs per one unit of emission emitted is calculated by dividing the health-related external cost for a specific emission sector with the emission emitted of that sector. Unit costs may be expressed as Euros per kg emission.

In Table 6.1 we assess the different parts of the EVA-system concerning the uncertainty on method and data, how sensitive it is to the calculated unit costs of air pollution and justification for the chosen data. We have given an indication of the uncertainty and sensitivity by assigning a qualitative value (high, low, medium). For justification we classify in Best in class and Best available.

Overall we assess the calculated unit costs of air pollution for Vietnam to be best available with medium uncertainty.

Table 6.1. Summary of uncertainties, sensitivity to unit costs of air pollution and justification for the individual parts in the EVA-modelling system

Part	Uncertainty	Sensitivity	Notes/justification
Emission inventories from 2010	As data is 10 years old, there can be shifts in emissions due to sectoral shifts in the economic and changes in technology. (medium)	Unit cost of air pollution is the total health related cost divided by the total emissions of the specific air pollutant. Uncertainty in the spatial distribution of emissions or emissions between emission sectors will influence the resulting unit cost.	No more recent emission inventory exists. Best available dataset. International recognized as used in model inter-comparison study for Asia.
Meteorological data from 2019 applied.	Data based on state-of-the-art international recognized meteorological model (WRF - Weather Research and Forecasting model). (low)	There are differences between different meteorological years that will influence concentrations and hence the unit cost.	2019 meteorological data is the most recent data available. WRF is best in class.
Air quality model (DEHM)	State-of-the-art international recognized chemistry-transport model and validated against observed concentrations in numerous studies. (low)	The unit costs of air pollution embed a relation between emitted air emissions and the resulting concentration contribution. This relation is expected to be relatively robust as less emissions will lead to lower concentrations and higher emissions will lead to higher concentrations maintaining the relative relationship.	Best in class. We calculated a population weighted mean of 29 µg/m^3 for $PM_{2.5}$ for 2010 which is very close to the estimate of WHO for 26 µg/m^3 for 2012.
Population data	For Vietnam based on global population density from Socioeconomic Data and Applications Center. (low)	Uncertainty in population and age distribution will affect number of health effects and hence unit costs.	Best available.
Exposure-response functions	Linear exposure-response functions used in EVA are those recommended by the WHO. (medium)	Uncertainty in exposure-response functions will affect number of health effects and hence unit costs.	Best available, although still associated with uncertainty.
Total health impacts	We calculate approx. 179,000 premature deaths in Vietnam due to domestic and foreign emissions or more than twice as much as for Denmark if population weighted. This is reasonable as concentration levels of $PM_{2.5}$ in Vietnam are about 2-3 times higher than in Denmark and $PM_{2.5}$ dominates the number of premature deaths. (medium)	Uncertainty in total health impacts will affect unit costs.	Best available.
Cost per case of health effects	Valuation of cost per case is based on Danish and European studies. For value of statistical life (VSL) it is in accordance with guidelines from the Danish Ministry of Finance. However, still wide range when comparing differently studies in literature. (medium)	Final unit costs are depending on cost per case with the cost per case for statistical life as the most important as costs of premature deaths constitutes the majority of total costs.	Best available data.
Transfer of standard costs from Denmark to Vietnam	OECD benefit transfer methodology used. (medium)	Final unit costs are directly proportional to estimated costs.	Best available method in the absence of standard costs for Vietnam derived from Vietnamese data.
Total external costs	We estimate total external costs of air pollution in Vietnam to approx. 8% of GDP which is roughly 50% higher compared to another study by Truong (2020) (4.5-5.6%). (Medium)	Final unit costs are directly proportional to estimated costs.	Best available.
Resulting unit costs	Medium	-	Best available.

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Appendix 1 Health effects

The absolute figures for health effects are shown in the below table A.1

The figures for health effects are included here as they are the basis for calculation of the unit costs of air pollution.

Note that cases of health effects are in thousands.

A few key figures will be highlighted.

The number of annual premature deaths due to all air pollution due to domestic and foreign emission sources is estimated to approx. 179,000 based on emissions from 2010 with the EVA-system.

The number of annual premature deaths in Vietnam due to emissions in Vietnam is estimated to approx. 83,000. Emissions in Vietnam cause an additional approx. 142,000 annual premature deaths outside Vietnam, hence the total number of annual premature deaths due to emission in Vietnam is approx. 224,000.

Table A.1 Number of cases (in thousands) of health effects due to all air pollution (domestic and foreign emission sources), number of cases in Vietnam for each emission section, number of cases outside Vietnam, number of cases in Vietnam and outside due to Vietnam emissions. Various percentage indicators are also given. Emissions are from 2010 and meteorology from 2019.

Health effects	All air pollution	SNAP01	SNAP02	SNAP03	SNAP07	SNAP08	SNAP10	Ship transport, EEZ	Sum Snap1-10	No. of cases outside Vietnam	Total number of cases in Vietnam and abroad from Vietnam emissions	% Ships Vietnam EEZ of all air pollution	% Vietnam land emissions of all air pollution	% of cases inside Vietnam from Vietnam emissions	% of cases outside Vietnam from Vietnam emissions
Acute mortality ($PM_{2.5}$, SO_2, NO_2, O_3)	43.6	0.9	12.9	2.6	1.8	0.2	1.0	2.0	19.6	34.4	54.0	4	45	36	64
Chronic mortality ($PM_{2.5}$, NO_2)	135.5	1.8	47.8	7.4	2.5	0.2	3.4	4.1	63.2	107.1	170.3	3	47	37	63
Total premature deaths ($PM_{2.5}$, SO_2, NO_2, O_3)	179.1	2.8	60.7	10.1	4.3	0.5	4.4	6.1	82.8	141.5	224.3	3	46	37	63
Hospital admissions due to respiratory symptoms ($PM_{2.5}$,NO_2,O_3)	89.7	1.5	29.4	5.1	3.8	0.7	2.0	3.7	42.5	68.6	111.2	4	47	38	62
Hospital admissions due to cardio-vascular diseases ($PM_{2.5}$,O_3)	61.0	1.2	20.1	3.8	1.8	0.1	1.0	2.2	28.1	51.4	79.5	4	46	35	65
Episodes with asthma among children ($PM_{2.5}$)	25.3	0.3	8.7	1.4	0.5	0.0	0.6	0.8	11.6	19.8	31.4	3	46	37	63
Episodes with bronchitis among adults ($PM_{2.5}$)	146.3	2.0	51.6	8.1	2.8	0.3	3.6	4.5	68.4	114.9	183.4	3	47	37	63
Episodes with bronchitis among children ($PM_{2.5}$)	786.7	9.6	266.1	40.5	13.9	1.2	15.0	21.9	346.3	574.2	920.5	3	44	38	62
Working days lost ($PM_{2.5}$)	56.2	0.8	19.8	3.1	1.1	0.1	1.4	1.7	26.2	44.5	70.7	3	47	37	63
Days with restricted activity (sick days) ($PM_{2.5}$)	194683	2678	68238	10818	3690	344	4884	6037	90652	152756	243408	3	47	37	63
Days with minor restricted activity (O_3)	69.8	4.2	9.2	6.8	7.0	0.4	0.0	6.6	27.6	63.8	91.5	9	40	30	70
Lung cancer morbidity ($PM_{2.5}$)	2.5	0.0	0.9	0.1	0.0	0.0	0.1	0.1	1.2	2.0	3.1	3	47	37	63
Acute infant mortality ($PM_{2.5}$)	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	2	42	38	62

UNIT COSTS OF AIR EMISSIONS IN VIETNAM FOR ENERGY SYSTEM MODELLING

Aarhus University has performed model calculations with a chemistry transport model (DEHM) and an integrated modelling system for estimation of external costs of health effects (EVA) for Vietnam with the purpose of calculating unit costs of air pollution for emission sectors in Vietnam and on the basis of these calculations deliver input to energy system modelling in Vietnam. Unit costs are health related external costs of air pollution per kg emission of air pollutants

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