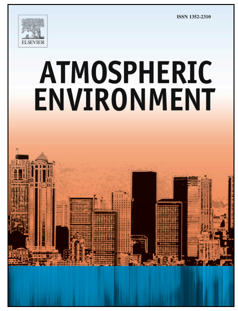
DIDEM - An integrated model for comparative health damage costs calculation of air pollution

Accepted Manuscript



DIDEM - An integrated model for comparative health damage costs calculation of air pollution

Marco Ravina, Deborah Panepinto, Maria Chiara Zanetti

PII: S1352-2310(17)30755-0

DOI: 10.1016/j.atmosenv.2017.11.010

Reference: AEA 15667

To appear in: *Atmospheric Environment*

Received Date: 11 September 2017

Revised Date: 3 November 2017

Accepted Date: 6 November 2017

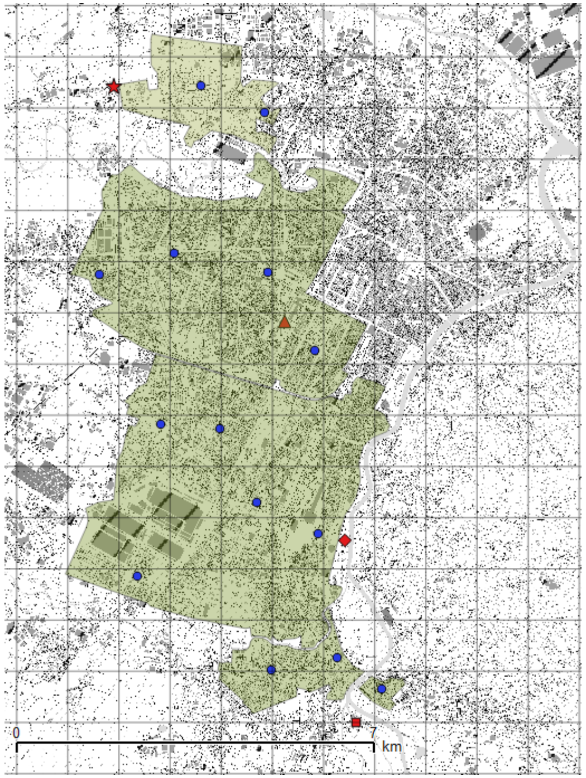
- NO_x, $PM_{2.5}$, PM_{10} emission flow (present and alternative scenario)
- Emission source geometry and location (present and alternative scenario)

DIDEM integrated model

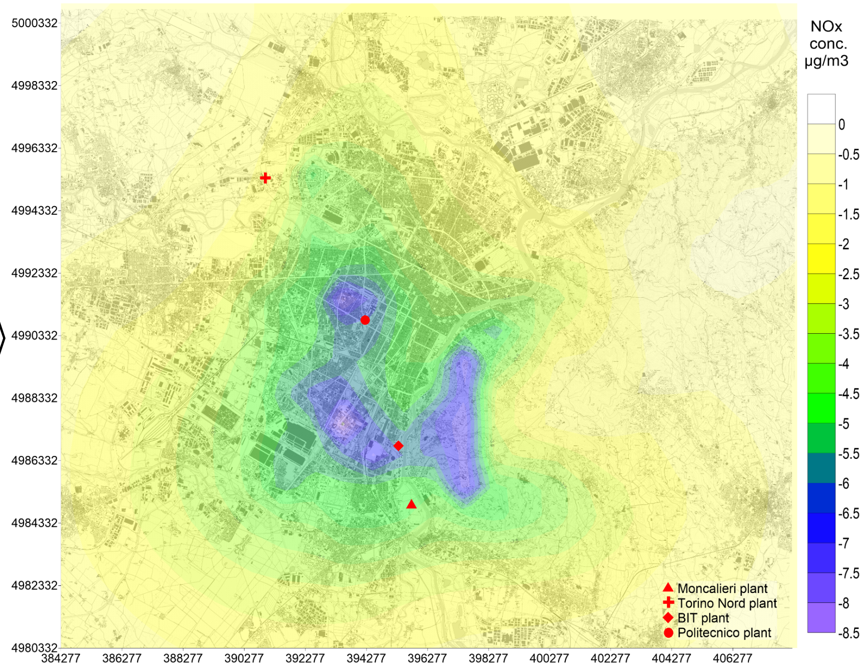
CALPUFF dispersion model

- Delta-concentration maps of NO_x, $PM_{2.5}$, PM_{10}
- Delta-external costs distribution map
- Tables of overall delta-external costs, including uncertainty estimates

Emission scenarios



Estimation of delta-concentrations



Calculation of delta-external costs

Confidence level on CRF data (Setting)	Delta external costs MEAN (€/y)	
	€/y	€$_{cent}$/kWh
High (Setting 1)	- 8,550,000	-0.472
Medium (Setting 2)	- 58,815,000	-3.244

DIDEM - An integrated model for comparative health damage costs calculation of air pollution

Marco Ravina*, Deborah Panepinto, Maria Chiara Zanetti

* Corresponding author

Marco Ravina
DIATI (Department of Engineering for Environment, Land and Infrastructures)
Politecnico di Torino
Corso Duca degli Abruzzi, 24
10129 Torino, Italy
Phone +39 011 0907632
Fax +39 011 0907699
marco.ravina@polito.it

Deborah Panepinto
DIATI (Department of Engineering for Environment, Land and Infrastructures)
Politecnico di Torino
Corso Duca degli Abruzzi, 24
10129 Torino, Italy
Phone +39 011 0907660
Fax +39 011 0907699
deborah.panepinto@polito.it

Maria Chiara Zanetti
DIATI (Department of Engineering for Environment, Land and Infrastructures)
Politecnico di Torino
Corso Duca degli Abruzzi, 24
10129 Torino, Italy
Phone +39 011 0907696
Fax +39 011 0907699
mariachiara.zanetti@polito.it

Abstract

Air pollution represents a continuous hazard to human health. Administration, companies and population need efficient indicators of the possible effects given by a change in decision, strategy or habit. The monetary quantification of health effects of air pollution through the definition of external costs is increasingly recognized as a useful indicator to support decision and information at all levels. The development of modelling tools for the calculation of external costs can provide support to analysts in the development of consistent and comparable assessments. In this paper, the DIATI Dispersion and Externalities Model (DIDEM) is presented. The DIDEM model calculates the delta-external costs of air pollution comparing two alternative emission scenarios. This tool integrates CALPUFF's advanced dispersion modelling with the latest WHO recommendations on concentration-response functions. The model is based on the impact pathway method. It was designed to work with a fine spatial resolution and a local or national geographic scope. The modular structure allows users to input their own data sets. The DIDEM model was tested on a real case study, represented by a comparative analysis of the district heating system in Turin, Italy.

Additional advantages and drawbacks of the tool are discussed in the paper. A comparison with other existing models worldwide is reported.

Keywords: air pollution, impact pathway, modelling, health, external costs, heating network

Abbreviations

ARPA Piedmont's Regional Agency for Environmental Protection
BenMAP Environmental Benefits Mapping and Analysis Program
CALPUFF California Puff Model
CHP Combined heat and power
CRF Concentration – response function
DeNOx Selective catalytic reduction for nitrogen oxides removal
DEHM Danish Eulerian Hemispheric Model
DH District heating
DIATI Department of Engineering for Environment, Land and Infrastructures, Turin Polytechnic, Italy
DIDEM DIATI Dispersion and Externalities Model
EMEP European Monitoring and Evaluation Programme
EEA European Environmental Agency
EVA Economic Valuation of Air pollution
EU European Union
GIS Geographic information system
GUI Graphical User's Interface
HIA Health Impact Assessment
HMDB Health Mortality and Morbidity Database
HFA-DB Health for All Database
HRAPIE Health risks of air pollution in Europe
IPA Impact pathway approach
kWh_t kWh of thermal energy
kWh_{el} kWh of electrical energy
LEAP-IBC Long-range Energy Alternatives Planning System - Integrated Benefits Calculator
LCA Life Cycle Assessment
LPG Liquefied petroleum gases
MWh_t MWh of thermal energy
MWh_{el} MWh of electrical energy
NEEDS New Energy Externalities Developments for Sustainability
NewExt New Elements for the Assessment of External Costs from Energy Technologies
NO_x nitrous oxides
O_3 ozone
OML Operational Meteorological Air quality model
$PM_{2.5}$ particulate matter <2.5 µm
PM_{10} particulate matter <10 µm
REVIHAAP Review of evidence on health aspects of air pollution
TM5-FASST Tracer model 5, Fast Scenario Screening Tool
TSP Total suspended particulate
US EPA United States Environmental Protection Agency
UTM ED50 Universal Transverse of Mercator, European Datum 1950

WHO World Health Organization

1. INTRODUCTION

Although several natural sources (volcanoes, fire, etc.) may release pollutants in the environment, anthropogenic activities are the major cause of environmental air pollution. Hazardous chemicals can escape to the environment by accident, or during the usual operation of industrial facilities and other activities. In both cases, adverse effects on human health and the environment may be observed. By definition, an air pollutant is any substance which may harm humans, animals, vegetation or material. As far as humans are concerned, air pollutants represent a potential hazard to human health. The determination of human health risk connected to air pollution impacts is based on clinical, epidemiological, and/or animal studies, which define how an exposure to a substance is associated with health effects (Kampa and Castanas, 2008).

Impacts of air pollution may be observed both at the local and the global scale. At the global scale, greenhouse gas emission generates impacts on the climate system, bringing changes in temperature and weather patterns (Kirtman et al., 2013), crop loss, and increased incidence of certain diseases. At the local scale, the emission of macro- and micro-pollutants generates impacts on humans and ecosystems (Panepinto et al., 2014). These unexpected or unwanted impacts are defined as externalities, i.e. those effects on the wellbeing of an unrelated group or individual outside the market mechanism that controls the price of energy. External costs, or damage costs, are the monetary value of externalities.

To quantify and compare environmental impacts, LCA (Life Cycle Assessment) methods are the most widely used tools at present. LCA analysis consider all the process steps, including resource consumption, conversion systems, and residual and waste re-immission into the environment (Blengini et al., 2011). Beside LCA methods, other important tools, such as models for the calculation of environmental balances, or pollutant dispersion models, are used. Many studies about these latter are reported in bibliography, including local case studies (Viggiano et al., 2014a), or methodological dissertations (Viggiano et al., 2014b).

Considering health effects of air pollution, decades of toxicological, clinical and epidemiological research support the association between exposure to ambient air pollution and detrimental human health effects, including respiratory disease, cardiovascular disease, and premature death (Anenberg et al., 2016). Driven by these research findings, many countries issued strict regulation on ambient concentration limits of air pollutants, in particular for particulate matter, ozone, nitrogen oxide sulphur oxide and carbon monoxide. The definition of the regulation limits is based on technical and scientific evidence, including estimates of the total pollution health burden posed by the pollutants at current concentrations, as well as the health benefits of reducing air pollution levels.

Health impact and health burden assessment depend strongly on air pollution epidemiology and exposure science. Recent advances in these two disciplines have improved the cross-linkage of atmospheric science and epidemiology, allowing analysts to quantify an increasing number of health outcomes in far greater detail than was previously possible.

A variety of studies have quantified health impacts associated with air pollution at global (Lim et al., 2010; Cohen et al., 2004; Anenberg et al., 2010; Chambliss et al., 2014), regional (Aneneberg et al., 2009; Likhvar et al., 2015) national (Hubbell et al., 2005; He et al., 2010; Nawadha, 2013) and local scale (Wesson et al., 2010; Fann et al., 2011; Guttikunda and Jawahar, 2012; Kheirbeck et al., 2013). Comparative analysis of health effects under different emission reduction scenarios has been the basis supporting air quality policy development in the European Union (Holland et al., 2005; Amann, 2013), United States (US EPA, 2012) and other countries.

Several modelling tools have been developed for calculating health effects and external costs of air pollution. The use of modelling tools has the advantage of supporting analysts in the development of assessment, and offers consistency and comparability among the analysis. These tools have been often designed for a particular objective, and vary in methodological approach, technical complexity, geographical scope, resolution and other factors, such as usability and accessibility (Anenberg et al., 2016). One of the most recognized and used method of analysis is the impact pathway approach, first developed within the ExternE project series (University of Stuttgart; European Commission, 2005; Figure 1). Impact pathway assessment is a bottom-up-approach in which environmental benefits and costs are estimated by following the pathway from source emissions via quality changes of air, soil and water to physical impacts, before being expressed in monetary benefits and costs (European Commission, 1995; Rabl and Spadaro, 1999; Holland, 2014a).

At present, the main challenge in modelling health effects and costs of air pollution is the quantification of the overall uncertainty associated to the assessment chain. Such uncertainty may be limited by improving one of the key steps of the methodology (air quality modelling, exposure modelling, impact assessment or monetary valuation).

In this paper, a new integrated tool for the calculation of environmental impacts, human health effects and external costs associated to air pollution is presented. This model has been conceived to quantify and minimize the overall uncertainty, by incorporating the following features:

- The integration of a detailed and advanced pollutant dispersion model (CALPUFF) with the calculation of health concentration-response functions (CRFs), implemented following the latest WHO recommendations;
- The implementation of different confidence levels on CRFs data reported by the WHO, resulting in a precise estimation of uncertainty associated to the calculation of health effects;
- The implementation of updated monetary values of health effects introduced by the EU's Clean Air Policy Package.

This model was developed at the Department of Engineering for Environment, Land and Infrastructures (DIATI) of Turin Polytechnic, Italy. It is referred as the DIDEM model (DIATI Dispersion and Externalities Model). The DIDEM model was designed to perform an analysis of external health impacts and costs by comparing two or more operating scenarios. DIDEM model was conceived to work with fine spatial resolution and a local geographic scope (cities, metropolis or similar areas). DIDEM model can be used to compare the compatibility of different industrial options, but also various aspects, such as local policy planning or forecasting scenarios.

The main structure and operation of DIDEM model is reported in the following sections. The DIDEM model was tested on a real case study, i.e. the environmental analysis of the district heating system of Turin, a town located in the north-west of Italy.

2. Methodology

The DIATI integrated dispersion and externalities model (DIDEM) calculates the environmental impacts and the external costs associated to the comparative analysis of emission scenarios. In this paper, the term external costs refers to the marginal health damage costs, i.e. those costs generated by the effects on human health resulting from an extra unit of pollutant concentration. Comparative analysis is performed comparing the present situation to an alternative operating energy scenario.

The DIDEM model is based on the impact pathway approach (IPA, Figure 1). The model links the simulation of pollutants dispersion with CALPUFF model to the concentration-exposure-response functions provided by latest WHO recommendations (WHO, 2013a; WHO, 2013b). Monetary values are associated to the incremental incidence of disease calculated. This tool was designed to cover a regional scope, i.e. the EU community. Since it allows a spatial resolution down to 1 km or less, it can be employed at the local scale, e.g. for IPA analysis on large cities.

The DIDEM model was developed with MATLAB® (Mathworks) and tested on a real case study. The study case is represented by an evaluation of the environmental performance of the district heating network of Turin, the fourth most-populated city in Italy.

The methodological concepts at the basis of the model, the model structure and the study case are described in the following.

2.1 Methodological approach

The following general equation conceptualizes the calculation of external costs through the impact pathway approach (modified from van der Kamp and Bachmann, 2015):

$$C_{i,r} = \sum_{r}\sum_{i}[\Delta c_r \times p_r] \times t \times s_{CRi} \times m_i \qquad \text{Equation 1}$$

where $C_{i,r}$ represents the damage costs related to health impact i and to domain cell r, given in $€_{base\ year}$; Δc_r is the concentration change of a given pollutant, referred to domain cell r, given in [$\mu g/m^3$] and p_r is the number of exposed individuals [person]; t is a factor to account for different assumptions on particle toxicity; s_{CRi} is the slope of the impact function of health impact i, given in [(additional cases)/(($\mu g/m^3$) × person × year)], merging information on the risk increase and baseline rate of a given health impact i; and m is the monetary value per case of health impact i, given in [$€_{base\ year}$/case].

The terms Δc_r and s_{CRi} in Equation 1 are the driving variables of the calculation. The delta-concentration is the result of the dispersion modelling and represents the level of exposure of the population to a pollutant (cf. Chapter 2.1.1). The impact function, whose slope is s_{CR}, is defined by a concentration-response function (CRF), usually assumed to be linear with respect to concentration changes (cf. Chapter 2.1.2).

2.1.1 Estimation of delta-concentration

The estimation of pollutants impact on the considered area represents the first step in the impact pathway analysis (Figure 1). The simulation of pollutant dispersion, done with the use of numerical models, provides an estimation of the concentration. Delta-concentration is defined by the algebraic sum of concentrations corresponding to present and alternative scenarios. The dispersion model considered in this study is CALPUFF. CALPUFF is a multi-layer, multi-species, non-steady-state puff dispersion model that simulates the effects of time- and space-varying meteorological conditions on pollution transport, transformation, and removal (US EPA, 2011). The modelling system consists of three main components and a set of pre-processing and post-processing programs. The main components of the modelling system are CALMET (a diagnostic three-dimensional meteorological model), CALPUFF (an air quality dispersion model), and CALPOST (a post- processing package). The model includes algorithms for complex orography, subgrid scale effects (such as terrain impingement), as well as longer range effects, such as pollutant removal due to wet scavenging and dry deposition, chemical transformation, and visibility effects of particulate matter concentrations.

CALPUFF is a model that simulates puffs of material emitted from modelled sources, reproducing dispersion and transformation processes along the way. Temporal and spatial variations in the selected meteorological fields are explicitly incorporated in the resulting distribution of puffs throughout a simulation period. The primary output files from CALPUFF contain either concentrations or deposition fluxes evaluated at selected receptor locations. CALPOST is used to process these files. For more technical details on the CALPUFF model structure, refer the user's guide (US EPA, 2011).

The choice of CALPUFF rather than other dispersion models was given by the need of a costless, well-known and structured instrument, able to run simulations on the largest possible set of modelling scenarios, including complex topographies, variable scale and variable meteorology (Ravina, 2016).

2.1.2 Definition of concentration-response function

In the framework of the European Union's declaration for 2013 as the Year of Air, the WHO Regional Office for Europe coordinated two international projects ("Review of evidence on health aspects of air pollution - REVIHAAP"; WHO 2013b and "Health risks of air pollution in Europe" - HRAPIE; WHO, 2013a) to provide the stakeholders with evidence-based advice on the health aspects of air pollution. New emerging risks to health from air pollution was also documented by these projects. The HRAPIE project report presents the latest available recommendations for the external cost analysis.

Here, the pollutant-outcome pairs recommended for cost analysis are classified into two categories:

- Group A: pollutant-outcome pairs for which enough data are available to enable reliable quantification of effects;
- Group B: pollutant-outcome pairs for which there is more uncertainty about the precision of the data used for quantification of effects.

The pollutants considered are $PM_{2.5}$, O_3 and NO_2. Equal toxicity is assigned to each pollutant, so that the term t of Equation 1 is not accounted. Recommendations for CRFs are given in relative risk (RR). The definition of RR for each pollutant-outcome pair is reported in Table 1. The slope of the CRF (s_{CRi} term in Equation 1) for each pollutant-outcome pair i is calculated as:

$$s_{CRi} = \frac{n_i(RR_i - 1)}{p_{tot,i}} \qquad \text{Equation 2}$$

where n is the average number of occurrences of the health outcome i (cases/year), whose background rates can be found in WHO's mortality and morbidity database, available on-line (WHO HMDB); $p_{tot,i}$ is the background population exposed to health outcome i, also provided on-line by the WHO database (WHO HFA-DB).

The HRAPIE project also reports indications on the additivity of effects of pollutant-outcome pairs. To this end, a limited subset of Group A and Group B (named Group A* and Group B* respectively) is defined, to identify those pairs that contribute to the total effect. The calculation of the range of overall costs is thus recommended to be based on the following principles, here referred as setting 1 and 2 (WHO, 2013a):

- Setting 1 considers a limited set of impacts based on the sum (∑) of Group A*. An uncertainty range is then provided around this estimate. The limits of this uncertainty range are calculated by summing the minimum (or maximum) values of (Group A*; Group A) pollutant-outcome pairs of the same type (e.g. minimum between the long-term exposure to $PM_{2.5}$ of Group A* and the same pair for Group A + minimum between the long-term exposure to NO_x of Group A* and the same pair for Group A + …).

- Setting 2 considers a limited set of impacts based on ∑ Group A* + ∑ Group B*. An uncertainty range is then provided around this estimate. The limits of this uncertainty range are calculated by summing the minimum (or maximum) values of (Group A*; Group A) pollutant-outcome pairs of the same type, added to the minimum (or maximum) values of (Group B*; Group B) pollutant-outcome pairs of the same type.

The calculation of external costs as defined by Setting 1 and Setting 2 was implemented in the DIDEM model.

For more details on the HRAPIE project findings and recommendations, refer to the complete report (WHO, 2013a)

2.2 DIDEM model structure

The DIDEM model performs the comparative analysis of environmental impacts and external costs of energy scenarios, integrating the simulation of pollutant dispersion with CALPUFF to the HRAPIE project recommendations for the calculation of health damage costs. The user is allowed to input customized emission flows, including both point and area sources, as well as customized data of population exposure.

For each scenario, the input to the model is the hourly emission flow of NO_x (as equivalent NO_2), $PM_{2.5}$ and PM_{10}. Ozone formation and evolution is not modelled. The DIDEM model organizes the hourly series in a compatible format to CALPUFF, and executes CALPUFF. Once the CALPUFF simulation is terminated, the DIDEM model extracts and re-formats the output concentration grids and calculates the concentration differences. These latter are passed to the final module calculating the delta-external costs, which represents the core of the model. The DIDEM model provides different outputs (Figure 2):

- Grids of concentration difference of NO_x, $PM_{2.5}$ and PM_{10} over the modelling domain. Grids are provided in ASCII format, in order to be manageable with SURFER® software (Golden Softwares) or GIS tools (e.g. QGIS)
- Table of five maximum and minimum concentration difference, with the related position in the spatial domain and the time of occurrence;
- Grids of distribution of delta external costs over the modelling domain;
- Tables reporting the total variation in external costs associated to the considered scenarios. The results reported herein are differentiated depending on the level of confidence of the input health effect/response pairs considered (group A or group A + Group B, see chapter 2.1.2). An estimation of uncertainty is also reported.

The DIDEM model is composed by the following five integrated modules:

- Module 1 (extract.m): emission source data extraction and analysis;
- Module 2 (pte_bae_gen.m): CALPUFF set-up and execution;
- Module 3 (calpost.m): extraction of CALPUFF output; calculation of average, maximum and minimum concentration difference; generation of delta-concentration grids.
- Module 4 (extern.m): calculation of delta-external costs and related uncertainty range.

The model can be executed entirely by running a control script (didem.m); in alternative, each module can be run separately (Figure 3). Input and output from each module is reported in Figure 2. The modules are described in the following.

2.2.1 Module 1 – Data extraction, analysis and correction (extract.m)

The function/script extract.m collects the data of the emission sources. An analysis and correction of pollutants emission flow is then performed by this module. The script is divided in two sections, one for the present and one for the alternative scenario. For each scenario, the user is first asked to introduce the number of emission sources (ns), the typology (point or area source), the time of start and end of the simulation, the coordinates of the modelling domain (lower-left and upper-right corners) and the number of domain cells (ncell). The following information and data is then required for each source (variables name and unit is reported in brackets):

- Source ID (id);
- Location in UTM ED50 coordinate system (xcoord, ycoord; km). Area sources are defined by 4 couples of coordinates;
- Height and diameter (hei, diam; m). For area sources, the effective radius (effrad; m) is asked instead of the diameter;
- Elevation (elev; meters above sea level);
- Hourly energy production (eprod; MWh);
- Hourly emission temperature (temp; K);
- Hourly exhaust gas speed (vel; m/s). For area sources, the effective rise velocity (effvel; m/s) is asked instead of the exhaust gas speed;
- Hourly NO_x, $PM_{2.5}$ and PM_{10} flow (nox, pm2, pm10; g/s);
- The format of missing value of input data (e.g. -1 or -9999);

The script performs an analysis on the hourly emission flows, indicating the ratio of missing values, the maximum values and the standard deviation of non-zero values. The data are plotted on screen to identify possible values outside the trend. The user is then asked to confirm these data or correct them. If a correction option is selected, the missing or out-of-range values are replaced. Substitution is made by multiplying the thermal energy production by the total emission factor of that source. If a valid datum of thermal energy is missing, emission flow is calculated by linear interpolation between previous and next hourly values. Finally, if no valid data is available for interpolation, the script assigns an emission flow equal to zero.

The output of Module 1 for each scenario is a set of coordinates (2 x ns for point sources and 8 x ns for area sources), 4 x ns variables, and a matrix of 8760 (hours) x ns (sources) x 6 (variables) values. These variables are transferred to Module 2.

2.2.2 Module 2 - CALPUFF set up and execution (pte_bae_gen.m)

Module 2 is divided in two sections, one for the present and one for the alternative scenario. This script/function reads the complete information on emission sources and generates the input source files to input in CALPUFF. If point source type is selected, the file PTEMARB.DAT is generated. Otherwise, if an area source type is selected the file BAEMARB.DAT is generated. These files are composed by a header, time-invariant records and series of time-varying records (one per hour). For more information about the structure of these input files, refer to CALPUFF user's manual (US EPA, 2011).

The input source files are then transferred to CALPUFF model and CALPUFF is executed. The meteorological input files to CALPUFF must be provided by the user. Once the run is terminated, the script transfers CALPUFF output file (CALPUFF.CON) to CALPOST post-processor and executes it. CALPOST model is set to generate 1-hour and 24-hour average concentration grids for each pollutant. In this way, 6 output files are generated for each scenario. Each file contains one grid of ncell size per averaging period. These output files are transferred to Module 3.

2.2.4 Module 3 – Calculation of average delta-concentrations (calpost.m)

Module 3 has the double function of generating delta-concentration grids and the datasets for the calculation of delta-external costs. The input to this script is the time series generated by CALPOST model. The user is first asked to specify the period over the delta-concentrations are calculated, which must be shorter or equal to the period of simulation. The module then overlaps the concentration grids of present and alternative scenario, calculating the difference.

The average concentration difference over the specified period is then calculated. As it is requested by the procedure reported in HRAPIE project, also the daily maximum 1-hour mean concentration for NO_x is calculated. Maximum and minimum concentration difference are also extracted and stored in a separate file, together with their position in the modelling domain and the time of occurrence.

In summary, Module 3 provides the following output in separate text files:

- 1-hr and 24-hr average concentration difference of NO_x, $PM_{2.5}$ and PM_{10} over the selected period (e.g. "nox_avg_tot_1.dat" or "nox_avg_tot_24.dat");
- daily maximum 1-hour mean concentration difference of NO_x over the selected period ("nox_dmm_tot.dat");
- maximum and minimum concentration differences, with related position in the modelling domain and time of occurrence (e.g. "nox_minpos.dat").

These output files can be visualized directly in a map viewer software like SURFER of similar; or they can be transferred to the final module calculating the delta-external costs.

2.2.5 Module 4 - Calculation of delta-external costs (extern.m)

Module 4 represents the core of DIDEM integrated model. This script reads the average concentration difference files provided by Module 3 and calculates the delta-external costs associated to delta-concentrations.

The delta-external costs are calculated for each cell of the modelling domain r and for each pollutant-outcome pair i (Table 1) with Equation 1, as described in Chapter 2.1.

The user is first asked to introduce the country of reference. For each pollutant-outcome pair, the script reads the background rates n_i and the number of exposed individuals $p_{tot,i}$ from WHO mortality and morbidity database. The code is organized to extract the most recent available data. If no data is available for the selected country, an error message is displayed, and the user is asked to change the reference country. The values of relative risk RR_i provided by HRAPIE project recommendations, for each pollutant-outcome pair, are already implemented into the model. In this way, the slope of the CRF for each pollutant-outcome pair can be calculated with Equation 2.

The number of exposed individuals (p_r in Equation 1) must be introduced by the user in form of grid, with the same format of delta-concentration files. For an environmental analysis at the local scale, this variable corresponds to the distribution of population over the modelling domain. It can usually be calculated with the advice of GIS data and software. Monetary values per case of health impact (mi in Equation 1) of EU countries (or Regions) are implemented in the model. These data were taken by the most recent updates issued for the EU Clean Air Package (Holland, 2014b, Table 2). Monetary values are converted to the reference year using an average EU inflation rate of 2.1% (Eurostat).

The range of overall delta-external costs is calculated following the recommendations on level of confidence and additional effects, that is simulating Setting 1 and Setting 2 and their estimation of uncertainties (cf. Chapter 2.1). Module 4 provides therefore two kinds of output:

- a grid of delta-external costs distribution over the modelling domain;
- two tables of overall delta-external costs, one for simulation setting, including mean values and uncertainty range.

2.3 Case study

The DIDEM model was employed to a real case study, represented by a comparative analysis on the district heating network of Turin, a town located in north-western Italy. District heating (DH) is a technology used for supplying a town district or a complete town with the heat generated in large production plants. District heating through combined heat and power (CHP) systems is an increasingly popular solution to meet the thermal energy needs in urban areas (Lund and Van Mathiesen, 2015).

The residential volume currently served by Turin's DH network amounts to about 59,76 million m^3. The length of the network amounts to around 527 km of pipelines and is one of the most extended in Europe (Figure 4). For more information about the actual network structure and operating mode, refer to Jarre et al. (2016). Due to the persistence of critical concentration values of pollutants in the air of Turin, local administrations have for some years been exploring the possibility of obtaining an environmental benefit through the further extension of the DH network. The results of the environmental analysis of this potential extension are reported in a study by Ravina et al. (2017).

In the present case study, the analysis was performed comparing the present situation with an alternative scenario. The present situation is represented by the actual environmental impacts of the entire DH system. The alternative scenario is represented by a total absence of DH network, where centralized autonomous boilers are used for household heating and sanitary hot water production.

NO_x, and PM emissions were studied for a 1-year period. The latest available (related to 2016) power units' emission flow rates were used in this study. The meteorological input datasets collected in 2010 were used, since sufficiently accurate and complete datasets were not available for 2016. However, average meteorological conditions in the period 2010-2016 in the studied area were quite similar, so the introduced approximation is negligible. The emission flows and the meteorological data had an hourly frequency.

Geophysical and meteorological data input in CALPUFF were obtained from the Regional Agency for Environmental Protection of the Piedmont Region (ARPA). Weather and orographic data covered a domain of 100 × 100 km^2 with a horizontal resolution of 1000 m. The same grid represented also the modelling domain. For more information about input datasets and CALPUFF model settings, refer to Ravina et al. (2017).

In the following, the two energy scenarios are described.

2.3.1 Actual situation

The present scenario is represented by Turin's DH system at its actual state of development. The DH network is currently powered by a system of three large cogeneration combined cycle plants fuelled by natural gas. A set of four integration and reserve boilers completes the system. Information on nominal power and geometric configuration of the stacks are reported in Table 3. Total energy production, NO_x emission and total suspended particulate (TSP) emission for the year 2016 were provided by the plants' operator IREN ENERGIA (IREN) and are reported in Table 4. Hourly data of thermal energy transferred to the DH network and hourly emission flow rates of NO_x were also provided by the plant operator. Thermal energy losses of the network amount to 353 GWh (16,3% of the net production). PM emission flow was calculated distributing the yearly total PM amount on an hourly basis, scaling it to the hourly thermal energy production. Since these plants are fuelled by natural gas, total particulate is expected to be composed mainly by fine and ultra-fine components (Chang et al., 2004; D'Anna, 2009). For this reason, $PM_{2.5}$ and PM_{10} emission flows were supposed equal to total PM emission flow. For the combined-cycle cogeneration plants (Torino Nord and Moncalieri units), jointly producing heat and electricity, it was not possible to allocate the amount of NO_x and PM attributable to the only thermal energy transferred to the DH network. For this reason, the total flow of pollutant was used in the simulations. For the simulation of pollutant dispersion, a point source was assigned to each plant. The location of the emission sources is reported in Figure 4.

2.3.2 Alternative scenario

The alternative scenario was developed considering the absence of a DH network. Flow of thermal energy, NO_x and total PM from the same areas currently served by the DH network were calculated. In this scenario, thermal energy for household heating and production of sanitary hot water was assumed to be provided by autonomous centralized boilers (one boiler per building). The average rate of fuels distribution was assumed as: natural gas, 92.7%; diesel oil, 6.4%, heavy fuel oil, 0.8%; LPG, 0.1%.

The annual thermal energy demand of the residential units was calculated with the model proposed by Fracastoro and Serraino (2011). The annual amount was then distributed on an hourly basis scaling it to the reference curve of a benchmark building subject to continuous monitoring of consumption.

NO_x and TSP emission flow rates were calculated multiplying the hourly thermal energy consumption by the corresponding emission factor. NO_x emission factor was set to 120 kg/GWh, as established by Piedmont's Regional Decree n. 46-11968 (Piedmont Region, 2009). Total PM emission factor was set to 4.3 kg/GWh according to EMEP/EEA database (EMEP/EEA, 2016). A comparison between the total amount of thermal energy consumption, NO_x and total PM emission of present and alternative scenario is reported in Table 4 and Table 5.

For the simulation of pollutants dispersion, the studied area was divided into 14 sub-areas based on geometric criteria, to obtain a full coverage of the territory. A barycentric stack was assigned to each sub-area. The location of the barycentric stacks is reported in Figure 4. The height of the emission sources was set to 25 m, according to the average conformation of buildings that is observed in this town (5 to 8 floors). The diameter of the emission sources was set to 0.8 m, according to the standard sizing of centralized residential heating devices' chimneys (Taraschi and Martinetto, 2015). The exhaust gas exit temperature and velocity were set to 363 K and 5.0 m/s respectively.

3. Case study results

The DIDEM model was executed to simulate Turin's DH network case study. The simulation period covered the entire heating season of year 2016, i.e. from January 1st to March 15th and from October 15th to December 31st. The analysis of power plants emission data performed by Module 1 reported no missing or out-of-range values. Module 2 executed CALPUFF for present and alternative scenario. The result provided by running Module 3 is reported in Figures 5 and 6. The map of average 1-hour NO_x concentration difference over the metropolitan area of Turin is reported in Figure 5. This map shows negative concentration differences, meaning that the present situation (large centralized cogeneration plants and DH network) is preferable to the alternative scenario (de-centralized autonomous heating of buildings). The reduction of NO_x concentration ranges from 0.5 to μg/m^3 to 8.5 μg/m^3. These local effects are mainly limited to the urban area and to the hilly areas located in the eastern part of the town. The map of average 1-hour total PM concentration difference is reported in Figure 6. The concentration differences reported in Figure 6 are still negative and range from -0.01 μg/m^3 to -0.3 μg/m^3. Lower values of total PM concentration with respect to NO_x are the result of lower emission flows and lower emission factors (Table 4 and Table 5).

Delta-external costs were calculated running Module 4. The delta-external costs distribution over the entire modelling domain are reported in Figure 7. The area with the highest external costs

reduction corresponds to the urban centre of Turin. A higher reduction of external costs is the result of a higher concentration difference matched to a high population density.
Total delta-external costs for the case study are reported in Table 6. Table 6 reports the results of Setting 1 and Setting 2 and the related maximum and minimum values. If pollutant-outcome pairs with high confidence level on CRF data are considered (Setting 1), total external costs reduction ranges from 3,880,000 €/y to 12,245,000 €/y, with a mean value of 8,550,000 €/y. If pollutant-outcome pairs with both high and medium confidence level on CRF data are considered (Setting 2), total external costs reduction ranges from 32,245,000 €/y to 85,652,000 €/y, with a mean value of 58,815,000 €/y. If the same result is reported in term of delta-external cost per unit of net thermal energy consumption (€/kWh), the obtained value ranges from -0.214 $€_{cent}$/kWh to -4.724 $€_{cent}$/kWh.
The results reported in Figure 7 and Table 6 show that the reduction of environmental impacts (i.e. lower NO_x and PM concentration) brought by the presence Turin's DH network corresponds to a significant reduction of external health costs. Without a DH network, Turin would have been more polluted, and local collective health care costs would have been significantly higher. Figure 8 reports total delta-external costs divided by pollutant and exposure term (short and long term exposure), for Setting 1 and Setting 2 respectively. If Setting 1 is considered, the largest contribution to delta-external costs is given by short-term exposure to NO_2 (81.9%). If Setting 2 is considered, the largest contribution is given by long-term exposure to NO_2 (67%). It is important to note that the importance of PM impact is higher if delta-external costs are analysed instead of delta-concentrations. In fact, even though the reduction of total PM concentration is one order of magnitude smaller than NO_x reduction, the contribution of PM pollution to total delta-external costs is around 12 % – 18%. This is due to the higher values of relative risk associated to the CRFs of PM.

4. Discussion

A comparison of the case study results with other publications provides information on DIDEM model performance. Several studies are reported in bibliography where external costs of energy systems are calculated with the use of modelling tools. Bachmann and Van der Kamp (2014) applied the EcoSenseWeb model to the case of a DeNOx retrofit at a coal-fired power plant hypothetically located at three different sites in Europe. The external costs of the plant without a DeNOx ranged between 2.30 $€_{cent}/kWh_{el}$ and 4.15 $€_{cent}/kWh_{el}$. The installation of a DeNOx provided a reduction of marginal external costs of 33%, 22% and 17% respectively, depending on the location of the plant.
Andersen et al. (2006). compared the performance of EVA and EcoSense models on three combined heat and power (CHP) plants in Denmark: a CHP unit fuelled by coal (60%) and natural gas (40%), a CHP unit fuelled by coal only, and a waste incinerator. The three plants emitted an average of 147 t, 14 t and 6.3 t of primary $PM_{2.5}$ respectively. The EVA model returned a value of external costs per unit of kWh_t (year 2005) of 1.32 $€_{cent}/kWh_t$, 0.24 $€_{cent}/kWh_t$, 4.45 $€_{cent}/kWh_t$ respectively. The same calculation done with Ecosense model resulted in significantly lower values (around 40%).
Saez et al. (1998) analysed the effect that the consideration of external costs may have on biomass energy competitiveness. EcoSense model was applied to a 20 MW power plant located in Southern Spain, fuelled with an herbaceous energy crop. The only contribution of $PM_{2.5}$ was considered to contribute to total health external costs. The results showed a unitary external cost between 0.28 €/kWh and 0.67 €/kWh.
Van der Kamp and Bachmann (2015) calculated external costs on a 600 MW_{el} pulverized coal combustion unit located in Western France. Four methodologies of implementation of the impact

pathway approach were compared: ExternE1998 (ExternE), New Elements for the Assessment of External Costs from Energy Technologies (NewExt2004, European Commission 2004), New Energy Externalities Developments for Sustainability (NEEDS2009) and a new version of EcoSenseWeb updated with the latest WHO recommendations (Year2013). This study provided the following unit external costs: ExternE1998, 5.21 $€_{cent2000}/kWh_{el}$; NewExt2004, 1.77 $€_{cent2000}/kWh_{el}$; NEEDS2009, 2.78 $€_{cent2000}/kWh_{el}$; Year2013, 3.21 $€_{cent2000}/kWh_{el}$.

Comparing the performance of DIDEM model with existing studies, it can be concluded that the result is consistent with the average values commonly found in the literature. On the other hand, these results cannot be generalized, because they depend on the emission profile and location of the source. More information could be obtained by simulating the same case study with another modelling tool.

Beside the considerations on modelling results, some important comments can be obtained by comparing DIDEM model's structure and scope with existing methodologies and tools. Anenberg et al. (2016) recently published a review article that was first developed as a white paper for input to the WHO expert meeting on Health Risk Assessment held in Bonn, Germany, May 12-13, 2014. In this article, 12 multinational air pollution health impact assessment tools were analysed and compared. The paper confirms that the quantification and minimization of uncertainty remains the main challenge in external health costs analysis. The impact pathway approach combines in fact information from different sources such as pollutant exposure, population data, and CRFs. Each of these source carries with it some degree of uncertainty, that has an influence on the result. If the air quality modelling approach is considered, two main kinds of modelling tools can be identified: detailed air quality models or reduced form models. Detailed air quality models account for the complex atmospheric chemistry and transport governing air pollution, and may be implemented for analysis at the local scale. Since it implements CALPUFF's detailed structure, the DIDEM model can be classified in this category. Other examples include the Ecosense model (Preiss and Klotz, 2008; IER, 2004) or the EVA model (Brandt et al., 2013; Andersen et al., 2006). Ecosense uses the WTM-model (Windrose Trajectory Model; Derwent et al., 1988) for estimating pollutant dispersion. The model assumes a constant average wind speed and the trajectories of emission transport are assumed to run along straight lines. EVA implements a non-linear Eulerian air pollution model, that comprises a standard local Gaussian plume model OML (Operational Meteorological Air quality model; Olesen et. al., 1992) and the regional Eulerian model DEHM (Danish Eulerian Hemispheric Model; Christensen, 1997; Frohn et al., 2001). Reduced form tools use broad-scale estimates for air pollution impacts and are increasingly being used at a national and regional scale, as they are less resource intensive and more flexible (Fann et al., 2012). Examples of reduced form models are the Geographic Information System (GIS) based BenMAP tool (Davidson et al., 2007; Sun et al., 2015), the TM5-FASST tool (van Dingenen et al., 2014), the Long-range Energy Alternatives Planning System - Integrated Benefits Calculator (LEAP-IBC) tool (Lazarus et al. 1995), or the Health Impact Assessment (HIA) model (Flachs et al., 2012, Flachs et al., 2013).

Detailed air quality models like the DIDEM model, since are based on advanced simulation of dispersion phenomena (e.g. non-stationary processes, fine spatial resolution and chemical transformation, cf. Paragraph 2.1.1), have the main advantage of reducing the amount of uncertainty associated with the dispersion modelling step.

This is an important contribution, since the uncertainty related to air modelling has been calculated to contribute in a significant amount to the overall error (Bridges et al., 2015; van der Kamp and Bachmann, 2015). Reduced form models may, in some case, not capture the full scope of changes in ambient air pollution, because the treatment of secondary formation, transport, and deposition is simplified (Fann et al., 2012).

Anyway, the use of detailed air quality modelling also presents some disadvantage. The first is that their use is resource-consuming (a complete CALPUFF run of the case study scenarios took around 16 hours). Another disadvantage is that modelled concentrations may not match the method or spatial resolution of the exposure characterization in the epidemiology studies from which concentration-response associations are drawn, which may introduce error into the analysis (Anenberg et al., 2016).

Beside the air modelling approach, another main source of uncertainty in modelling external health impacts and costs is related to the simulation of exposure-response-monetary evaluation steps. The main sources of errors in these steps are: the definition of the CRFs, the estimation of exposure, the extrapolation of baseline mortality and morbidity rates and the definition of monetary values. The DIDEM model is based on latest WHO recommendations on air pollution health impacts, resulted by the REVIHAAP and HRAPIE projects (WHO, 2013a; WHO, 2013b). These advices are based on a review of the latest scientific evidence on the health effects of pollutants. The methodology reported in the HRAPIE project incorporates a sensitivity analysis by including/excluding a limited set of parameters. In addition, an indication of the confidence intervals around the values of relative risk of each pollutant-outcome association is provided. These aspects favour the quantification and reduction of the overall uncertainty.

If the features of usability and flexibility are considered, the DIDEM model is flexible enough to allow users to input their own data sets (emission flows, background mortality and morbidity rates, population data). On the other hand, its usability is limited by two factors: the need of expertise in setting up CALPUFF model pre-processing, and the absence of a graphical user's interface (GUI).

Resuming the conclusion reported by Anenberg et al. (2016), different tools are appropriate for different assessment contexts, and analysis must consider the technical and operational specifications of the tool necessary to meet the needs of the assessment context. The DIDEM model appears to be a suitable tool for cost-benefit comparative analysis at the local scale. It should be tested on different new scenarios and case studies, to achieve more information on its performance and usability. The comparison with other similar modelling tools may contribute to this perspective.

A possible improvement of the DIDEM model could consist in enlarging the scope of analysis. Other factors than the sole emission from power units could be implemented in the model, to allow a wider assessment context. Some examples reported in bibliography include the calculation of external health costs in transport scenarios (Miranda et al., 2016) or refurbishment and other heat saving measures on buildings (Zvingilaite and Jacobsen, 2015).

5. Conclusion

External costs are a direct indicator of air pollution impacts on human health. Their quantification provides clear and detailed information, suitable to be used at all communication levels (companies, administrations, population). Comparative analysis is an efficient method for evaluating different solutions and support policy and strategic decision. Modelling tools have been widely used to implement the estimation of externalities associated to air pollution and they are increasingly integrated into decision processes. This paper presented the DIATI Dispersion and Externalities (DIDEM) model, that was developed at the Department of Engineering for Environment, Land and Infrastructures of Turin Polytechnic, Italy. DIDEM integrates CALPUFF dispersion modelling with latest recommendations on health concentration-response functions issued by the WHO, and latest updates of monetary values elaborated for the EU Clean Air Policy Package.

The DIDEM model was designed with a regional scope (Europe) to perform comparative analysis at the local scale. Compared to other existing modelling tools, DIDEM allows a detailed spatial

resolution (down to 1000 m) and enough flexibility in the definition of the pollution source and background exposure data. An estimation of uncertainty is provided with the estimation of health impacts, to include in the analysis those pollutant-health outcome pairs whose data are currently subject to a medium confidence level. The application of DIDEM model could, therefore, be preferable to the use of a reduced form model in some circumstances (at the town scale, for example). On the other hand, the main drawback is that the use of CALPUFF model and a limited interface, require users with a high level of expertise as well as higher calculation resources.
In summary, the application of DIDEM model is recommended for the analysis of the health effects of local emission scenarios (up to 100-200 km of domain extension), where detailed information about the emission sources (type and location of source, hourly emission flows, detailed emission parameters) and background exposure to health effects is available. Users must be confident with CALPUFF or other similar dispersion models. Conversely, DIDEM model is not recommendable for the analysis at the national or regional scale working with wider spatial resolution and aggregated emission data (e.g. for the development of national or regional policies). Different tools are appropriate for different assessment contexts. The development of high-resolution tools based on detailed air quality modelling, like DIDEM, allow for greater confidence and precision of the results. Nevertheless, to quantify and limit the overall uncertainty of the simulation chain, a great effort is still needed in the definition of more detailed, harmonized and widespread datasets (e.g. local baseline mortality and morbidity rates), exposure-response functions (e.g. local epidemiological studies) and monetary evaluation (e.g. local socio-economic studies).

Conflict of interest

The authors declare that they have no conflict of interest.

Acknowledge

The authors would like to acknowledge IREN ENERGIA S.p.A. company for the data supplied and for their continuous support in the development of this work.

References

Andersen M.S., Frohn L.M., Nielsen J.S., Nielsen M., Jensen J.B., Jensen S.S., Christensen J., Brandt J. (2006), EVA – a non-linear eulerian approach for assessment of health-cost externalities of air pollution. Paper presented at the Biennial Conference of the International Society for Ecological Economics (ISEE), New Delhi, December 2006. Department of Environmental Science, Aarhus University, Denmark;

Anenberg S.C., Belova A., Bramdt J., Fann N., Greco S., Guttikunda S., Heroux M.E., Hurley F., Krzyzanowski M., Medina S., Miller B., Pandey K., Roos J., Van Dingenen R. (2016), Survey of Ambient Air Pollution Health Risk Assessment Tools, Risk Analysis, 36 (9), 1718 – 1736; DOI: 10.1111/risa.12540

Anenberg S.C., Horowitz L.W., Tong D.Q., West J.J. (2010), An estimate of the global burden of anthropogenic ozone and fine particulate matter on premature human mortality using atmospheric modeling. Environmental Health Perspectives, 2010; 118(9):1189–1195; DOI: 10.1289/ehp.0901220

Anenberg S.C., West J.J., Fiore A.M., Jaffe D.A., Prather M.J., Bergmann D., Cuvelier K., Dentener F.J., Duncan B.N., Gauss M., Hess P., Jonson J.E., Lupu A., MacKenzie I.A., Marmer E., Park R.J., Sanderson M.G., Schultz M., Shindell D.T., Szopa S., Vivanco M.G., Wild O., Zeng G. Intercontinental impacts of ozone pollution on human mortality. Environmental Science & Technology, 2009; 43:6482–6487; DOI: 10.1021/es900518z

Amann M. (2013), Policy scenarios for the revision of the Thematic Strategy on Air Pollution. TSAP Report #10. Laxenburg, Austria: International Institute for Applied Systems Analysis;

Bachmann T.M., van der Kamp J. (2014), Environmental cost-benefit analysis and the EU (European Union) Industrial Emissions Directive: exploring the societal efficiency of a DeNOx retrofit at a coal-fired power plant, Energy, 68:125-139. DOI: http://dx.doi.org/10.1016/j.energy.2014.02.051

Blengini G.A., Brizio E., Cibrario M., Genon G. (2011), LCA of bioenergy chains in Piedmont (Italy): a case study to support public decision makers towards sustainability, Biomass Bioenergy, 57, 36-47; DOI: https://doi.org/10.1016/j.resconrec.2011.10.003

Brandt J., Silver J. D., Christensen J. H., Andersen M. S., Bønløkke J. H., Sigsgaard T., Geels C., Gross A., Hansen A.B., Hansen K. M., Hedegaard G. B., Kaas E., Frohn L.M. (2013), Contribution from the ten major emission sectors in Europe and Denmark to the health-cost externalities of air pollution using the EVA model system – an integrated modelling approach, Atmos. Chem. Phys., 13: 7725–7746; DOI:10.5194/acp-13-7725-2013

Bridges A., Felder F.A., McKelvey K., Niyogi I. (2015), Uncertainty in energy planning: Estimating the health impacts of air pollution from fossil fuel electricity generation, Energy Research & Social Science, 6:74–77; DOI: http://dx.doi.org/10.1016/j.erss.2014.12.002

Chambliss S.E., Silva R., West J.J., Zeinali M., Minjares R. (2014), Estimating source-attributable health impacts of ambient fine particulate matter exposure: Global premature mortality from surface transportation emissions in 2005. Environmental Research Letters, 9:104-109; DOI: https://doi.org/10.1088/1748-9326/9/10/104009

Chang M.C.O., Chow J.C., Watson J.G., Hopke P.K., Seung-Muk Y., England G.C. (2004), Measurement of ultrafine particle size distributions from coal-, oil-, and gas-fired stationary combustion sources, Journal of the Air & Waste Management Association, 54:12, 1494-1505, DOI: 10.1080/10473289.2004.10471010

Christensen J.H., (1997), The Danish Eulerian Hemispheric Model – A three-dimensional air pollution model used for the Arctic, Atmospheric Environment, 31:4169-4191.

Cohen A.J., Anderson H.R., Ostro B., Pandey K.D., Krzyzanowski M., Kunzli N., Gutschmidt K., Pope C.A. III, Romieu I., Samet J.M., Smith K.R. (2004), Urban air pollution, pp. 1353–1434 in Ezzati M., Lopez A.D., Rodgers A., Murray C.J.L. (eds). Comparative Quantification of Health Risks: Global and Regional Burden of Disease Due to Selected Major Risk Factors. Geneva: World Health Organization;

Davidson K., Hallberg A., McCubbin D., Hubbell B. (2007), Analysis of $PM_{2.5}$ using the environmental benefits mapping and analysis program (BenMAP), Journal of Toxicology and Environmental Health, Part A, 70:3-4, 332-346; DOI:10.1080/15287390600884982

Derwent R.G., Dollard G.J., Metcalfe S.E. (1988), On the nitrogen budget for the United Kingdom and north-west Europe, Q.J.R. Meteorol. Soc., 114:1127-1152

van Dingenen R., Leitao J., Dentener F. (2014), A multi-metric global source-receptor model for integrated impact assessment of climate and air quality policy scenarios. Geophysical Research Abstracts, Vol. 16, EGU2014-13949, 2014.

D'Anna A. (2009), Combustion-formed nanoparticles- Proceedings of the Combustion Institute 32, 593–613.

EMEP/EEA (2016), Air pollutant emission inventory guidebook. EEA Technical report. ISSN 1725–2237. Technical guidance to prepare national emission inventories.

European Commission (1995), Externalities of Energy - Vol. 2: Methodology - method for estimation of physical impacts and monetary valuation for priority impact pathways. European Commission DG XII “Science, Research and Development”, JOULE, Luxembourg.

European Commission (2004), New Elements for the Assessment of External Costs from Energy Technologies (NewExt) - Final Report to the European Commission, DG Research, Technological Development and Demonstration (RTD); European Commission, Brussels, p 333;

European Commission (2005), ExternE - Externalities of Energy: Methodology 2005 update. Office for Official Publication of the European Communities, Luxembourg.

Eurostat, Harmonized Indices of Consumer Prices (HICP) - main tables. http://ec.europa.eu/eurostat/web/hicp/data/main-tables (accessed September 7, 2017).

Fann N., Lamson A.D., Anenberg S.C., Wesson K., Risley D., Hubbell B.J., (2011), Estimating the national public health burden associated with $PM_{2.5}$ and ozone. Risk Analysis, 32(1):81– 95; DOI: 10.1111/j.1539-6924.2011.01630.x

Fann N., Baker K.R., Fulcher C.M. (2012), Characterizing the $PM_{2.5}$-related health benefits of emission reductions for 17 industrial, area and mobile emission sectors across the U.S., Environ. Int., 49:141–51. DOI: https://doi.org/10.1016/j.envint.2012.08.017

Flachs E. M., Bønløkke J.H., Sigsgaard T. (2012), Description of the HIA line in the CEEH integrated modelling chain, CEEH Scientific Report No. 5, Centre for Energy, Environment and Health (CEEH), 2012.

Flachs E.M., Sørensen J., Bønløkke J.H., Brønnum-Hansen H. (2013), Population dynamics and air pollution: the impact of demographics on health impact assessment of air pollution, Journal of

Environmental and Public Health, Volume 2013, Article ID 760259, 12 p.; DOI: http://dx.doi.org/10.1155/2013/760259

Fracastoro G.V., Serraino M. (2011), A methodology for assessing the energy performance of large scale building stocks and possible applications. Energy and Buildings, 43:844–852; DOI: https://doi.org/10.1016/j.enbuild.2010.12.004

Frohn L.M., Christensen J.H., Brandt J., Hertel O. (2001), Development of a high resolution integrated nested model for studying air pollution in Denmark, Physics and Chemistry of the Earth, 26:10, 769-774.

Gehring U., Pattenden S., Slachtova H., Antovae T., Braun-Fahrlander C., Fabianova E., Fletcher T., Galassi C., Hoek G., Kuzmin S.V., Luttmann- Gibson H., Moshammeree H., Rudnai P., Zlotkowska R., Heinrich J. (2006), Parental education and children's respiratory and allergic symptoms in the Pollution and the Young (PATY) study, Eur Respir J, 27: 95–107; DOI: 10.1183/09031936.06.00017205

Golden Software. Surfer®. http://www.goldensoftware.com/products/surfer (accessed November 3, 2017)

Guttikunda S.K., Jawahar P. (2012), Application of SIM-air modeling tools to assess air quality in Indian cities. Atmospheric Environment, 62:551–561; https://doi.org/10.1016/j.atmosenv.2012.08.074

He K., Lei Y., Pan X., Zhang Y, Zhang Q, Chen D. (2010), Co-benefits from energy policies in China. Energy, 35(11):4265-4272; DOI: https://doi.org/10.1016/j.energy.2008.07.021

Holland M., Hunt A., Hurley F., Navrud S., Watkiss P. (2005), Service contract for carrying out cost-benefit analysis of air quality related issues, in particular in the Clean Air for Europe (CAFE) Programme. Methodology for the cost-benefit analysis for CAFE: Volume 1: Overview of methodology. Web published:AEATechnology Environment, available at: http://europa.eu.int/comm/environment/air/cafe/activities/cba. htm.

Holland, M. (2014a), Cost-benefit analysis of final policy scenarios for the EU Clean Air Package - Version 2, corresponding to IIASA TSAP Report 11, Version 1. UK, EMRC.

Holland M. (2014b), Cost-Benefit Analysis of Final Policy Scenarios for the EU Clean Air Package - Version 2, Corresponding to IIASA TSAP Report 11, Version 2a. EMRC.

Hubbell B.J., Hallberg A., McCubbin D., Post E. (2005), Health-related benefits of attaining the 8-hr ozone standard. Environmental Health Perspective, 113(1):73–82; DOI: 10.1289/ehp.7186

IER (2004), EcoSense 4.0 User's Manual, Institute of Energy Economics and the Rational Use of Energy, University of Stuttgart, p54;

Iren Energia company website. http://www.irenenergia.it/. (accessed September 7, 2017).

Jarre M., Noussan M., Poggio A. (2016), Operational analysis of natural gas combined cycle CHP plants: energy performance and pollutant emissions, Appl. Therm. Eng., 100:304–314; DOI: https://doi.org/10.1016/j.applthermaleng.2016.02.040

van der Kamp J., Bachmann T.M. (2015), Health-related external cost assessment in Europe: methodological developments from ExternE to the 2013 Clean Air Policy Package. Environ. Sci. Technol. 49, 2929–2938; DOI: 10.1021/es5054607

Kampa M., Castanas E. (2008), Human health effects of air pollution, Environmental Pollution 151, 362-367; DOI: https://doi.org/10.1016/j.envpol.2007.06.012

Kheirbeck I., Wheeler K., Walters S., Kass D., Matte T. (2013), $PM_{2.5}$ and ozone health impacts and disparities in New York City: Sensitivity to spatial and temporal resolution. Air Quality Atmosphere and Health, 6(2):473–486;

Kirtman B., Power S.B., Adedoyin A.J., Boer G.J., Bojariu R., Camilloni I., Doblas- Reyes I., Fiore A.M., Kimoto M., Meehl G., Prather M., Sarr A., Schar C., Sutton R., van Oldenborgh G.J., Vecchi G., Wang H.-J. (2013), Near-term climate change: projections and predictability. In: Plattner G.K., Tignor M., Allen S.K., Boschung J.,

Lai C.K., Beasley R., Crane J., Foliaki S., Shah J., Weiland S. (2009). Global variation in the prevalence and severity of asthma symptoms: phase three of the International Study of Asthma and Allergies in Childhood (ISAAC), Thorax, 64(6):476–483. DOI: 10.1136/thx.2008.106609

Lazarus M., Von Hippel D., Hill D., Margolis R. (1995), A guide to environmental analysis for energy planners. companion manual to assist users of LEAP. Stockholm Environment Institute, Boston, MA, USA

Likhvar V.N., Pascal M., Markakis K., Colette A., Hauglaustaine D. (2015), A multi-scale health impact assessment of air pollution over the 21st century. Science of the Total Environment; 514:439–449; DOI: https://doi.org/10.1016/j.scitotenv.2015.02.002

Lim S.S., Vos T., Flaxman A.D., Danaei G., Shibuya K., Adair- Rohani H., A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990–2010: A systematic analysis for the Global Burden of Disease Study 2010. Lancet, 2013; 380(9859):2224–2260; DOI: https://doi.org/10.1016/S0140-6736(12)61766-8

Lund R., Van Mathiesen B. (2015), Large combined heat and power plants in sustainable energy systems. Appl. Energy, 142:389–395; DOI: https://doi.org/10.1016/j.apenergy.2015.01.013

Mathworks Matlab® Software. https://it.mathworks.com/products/matlab.html (accessed September 7, 2017)

McConnell R., Berhane K., Gilliland F., Molitor J., Thomas D., Lurmann F., Avol E., Gauderman W.J., Peters J.M. (2003), Prospective study of air pollution and bronchitic symptoms in children with asthma. American Journal of Respiratory and Critical Care Medicine, 168(7):790–797; DOI: https://doi.org/10.1164/rccm.200304-466OC

Miranda A.I., Ferreira J., Silveira C., Relvas H., Duque L., Roebeling P., Lopes M., Costa S., Monteiro A., Gama C. Sá E., Borregoa C., Teixeira J.P. (2016), A cost-efficiency and health benefit approach to improve urban air quality, Science of the Total Environment, 569–570:342–351; DOI: http://dx.doi.org/10.1016/j.scitotenv.2016.06.102

Nauels A., Xia Y., Bex V., Midgley P., Stocker T.F., Quin D. (Eds.), Climate Change 2013: The Physical Science Basis. Conribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA.

Nawadha A. (2013), Reductions of $PM_{2.5}$ air concentrations and possible effects on premature mortality in Japan. Water, Air, & Soil Pollution, 224:1508;

NEEDS2009 - New Energy Externalities Developments for Sustainability. http://esu-services.ch/data/needs/ (accessed September 7, 2017).

Olesen H.R., Løfstrøm P., Berkowicz R. and Jensen A.B. (1992), An Improved Dispersion Model for Regulatory Use - The OML Model, pp. 29-38 in Dop H. van and Kallos G.: Air Pollution Modelling and Its Applications IX, Plenum Press.

Ostro, B.D., Rothschild, S. (1989), Air pollution and acute respiratory morbidity: an observational study of multiple pollutants. Environmental Research, 50:238–247.

Panepinto D., Brizio E., Genon G. (2014), Atmospheric pollutants and air quality effects: limitation costs and environmental advantages (a cost–benefit approach), Clean Techn Environ Policy, 16:1805–1813; DOI 10.1007/s10098-014-0727-6

Piedmont Region (2009), Decree of the Regional Council of 4 August 2009, no. 46-11968. Update of the Regional Plan for the Rehabilitation and Protection of Air Quality - Draft plan for environmental heating and conditioning and implementing provisions on energy performance in construction pursuant to Article 21, paragraph 1, letters a) b) q) of Regional Law 28 May 2007, no. 13. In Italian.

Preiss P., Klotz, V. (2008), EcoSenseWeb V1.3 User's Manual and description of updated and extended draft tools for the detailed site dependent assessment of external sosts. Institute of Energy Economics and the Rational Use of Energy (IER), University of Stuttgart, Germany, p 63;

QGIS open source software. https://www.qgis.org/it/site/ (accessed November 3, 2017)

Rabl A., Spadaro J.V. (1999), Damages and costs of air pollution: an analysis of uncertainties. Environ. Int. 25, 29–46.

Ravina M. (2016), Development and application of a comprehensive methodology for the analysis of global and local emissions of energy systems. PhD Dissertation. Politecnico di Torino, Italy. DOI: 10.6092/polito/porto/2674649

Ravina M., Panepinto D., Zanetti M.C., Genon G. (2017), Environmental analysis of a potential district heating network powered by a large-scale cogeneration plant. Environ. Sci. Pollut. Res., 24:13424–13436; DOI 10.1007/s11356-017-8863-2

Saez R.M., Linares P., Leal J. (1998), Assessment of the externalities of biomass energy, and a comparison of its full costs with coal. Biomass and Bioenergy, 14:469-478;

Schindler C., Keidel D., Gerbase M.W., Zemp E., Bettschart R., Brandli O., Brutsche M.H., Burdet L., Karrer W., Knopfli B., Pons M., Rapp R., Bayer-Oglesby L., Kunzli N., Schwartz J., Liu L.-J.S., Ackermann-Liebrich U., Rochat T., The SAPALDIA Team (2009). Improvements in PM_{10} exposure and reduced rates of respiratory symptoms in a cohort of Swiss adults (SAPALDIA). Am. J. Respir. Crit. Care Med. 179, 579–587; DOI: https://doi.org/10.1164/rccm.200803-388OC

Sun J., Fu J.S., Huang K., Gao Y. (2015) Estimation of future $PM_{2.5}$- and ozone-related mortality over the continental United States in a changing climate: An application of high-resolution dynamical downscaling technique, Journal of the Air & Waste Management Association, 65:5, 611-623; DOI: 10.1080/10962247.2015.1033068

Taraschi N., Martinetto M. (2015) Le canne fumarie. Grafill. 186 pp. ISBN: 88-8207-947-5. In Italian.

University of Stuttgart. Institute of Energy Economics and the Rational Use of Energy (IER). ExternE - External Costs of Energy. http://www.externe.info/ (accessed September 7, 2017).

U.S. Environmental Protection Agency (US EPA) (2011), CALPUFF modeling system user's manual, version 6

U.S. Environmental Protection Agency (US EPA) (2012), Regulatory Impact Analysis for the Final Revisions to the National Ambient Air Quality Standards for Particulate Matter. EPA- 452/R-12-005. Washington, DC: U.S. Environmental Protection Agency;

Viggiano F., Panepinto D., Genon G. (2014 a) Energy from biomass: a contribution to GHG limitation and sustainability of the local impact aspect, WIT Trans Ecol Environ, 190 (2), 1023-1034; DOI: 10.2495/EQ140962

Viggiano F., Panepinto D., Genon G. (2014 b), The environmental compatibility of biomass plants: a methodological approach, WIT Trans Ecol Environ, 181, 201-212; DO: 10.2495/EID140171

Wesson K, Fann N, Morris M, Fox T, Hubbell B. (2010), A multipollutant risk-based approach to air quality management: Case study for Detroit. Atmospheric Pollution Research, 1:296–304; DOI: https://doi.org/10.5094/APR.2010.037

WHO (2013a), Health Risks of Air Pollution in Europe - HRAPIE Project. Recommendations for concentration−response functions for cost−benefit analysis of particulate matter, ozone and nitrogen dioxide; World Health Organization, Regional Office for Europe, Copenaghen, Denmark; p 54.

WHO (2013b), Review of evidence on health aspects of air pollution − REVIHAAP Project. Technical report; The WHO European Centre for Environment and Health, Bonn, Germany; p 302.

WHO HMDB. European Hospital Morbidity Database. World Health Organization Regional Office for Europe. http://data.euro.who.int/hmdb/ (accessed September 7, 2017).

WHO HFA-DB, European health for all database (HFA-DB). World Health Organization Regional Office for Europe. http://data.euro.who.int/hfadb/ (accessed September 7, 2017).

Zvingilaite E., Jacobsen H.K. (2015), Heat savings and heat generation technologies: Modelling of residential investment behaviour with local health costs, Energy Policy, 77:31–45; DOI: http://dx.doi.org/10.1016/j.enpol.2014.11.032

List of Figures

List of Tables

Table 3. Data on power plants and emission sources presently feeding the DH network in Turin, Italy

Table 4. Energy and pollutants emission balance for the case study considered, present scenario year 2016.

Table 5. Energy and pollutants emission balance for the case study considered, alternative scenario year 2016.

Table 6. Result of delta-external costs calculation for the case study considered.

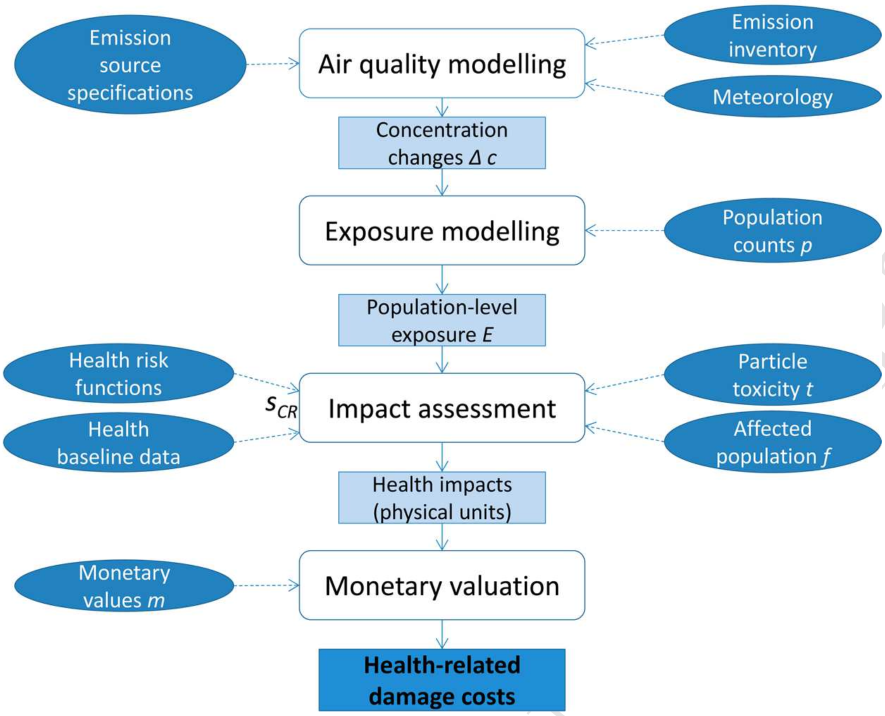


Figure 1. Schematic representation of the impact pathway approach (adapted from Van der Kamp and Bachmann, 2015).

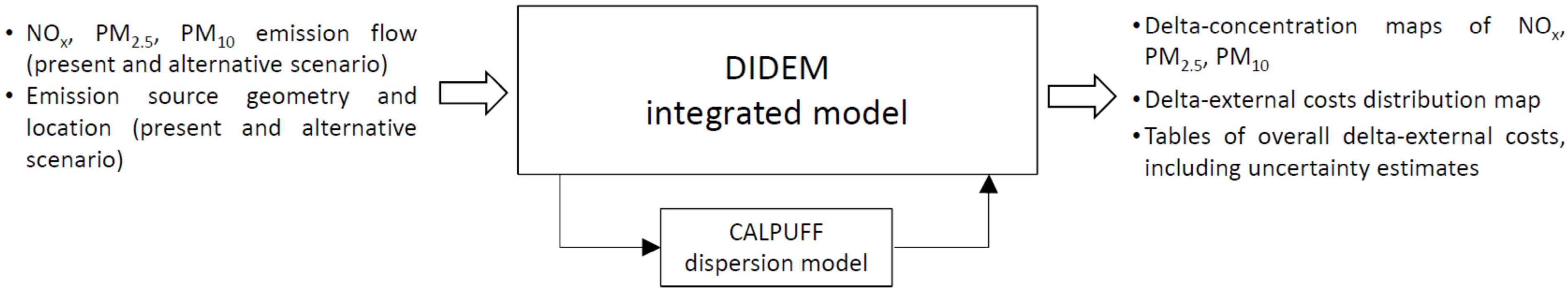


Figure 2. DIDEM model input and output.

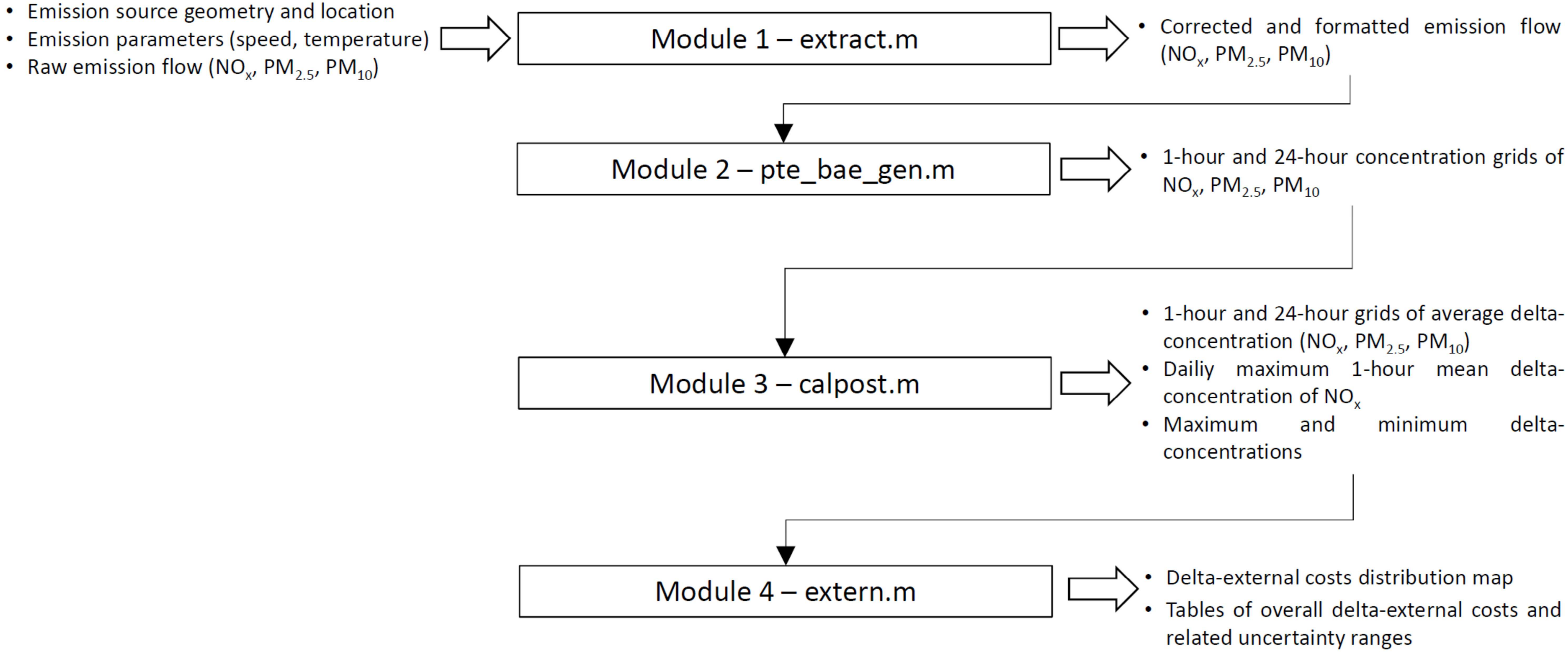


Figure 3. DIDEM model structure. Schematic representation of input and output from each Module.

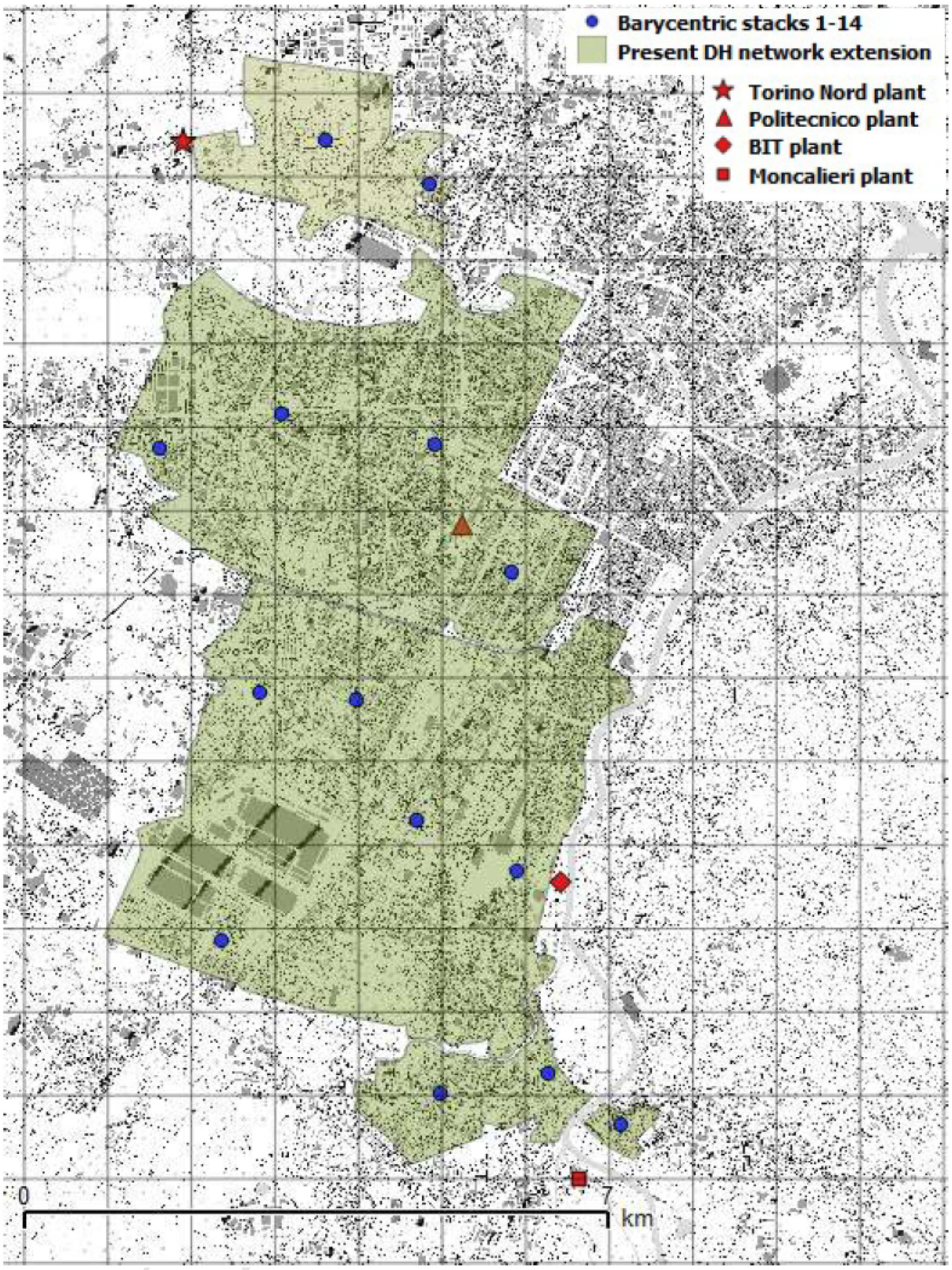


Figure 4. Present extension of Turin's DH network. Location of the plants powering the DH network. Location of the barycentric stacks assigned to the residential areas. The mesh grid represents the cells of the modelling domain.

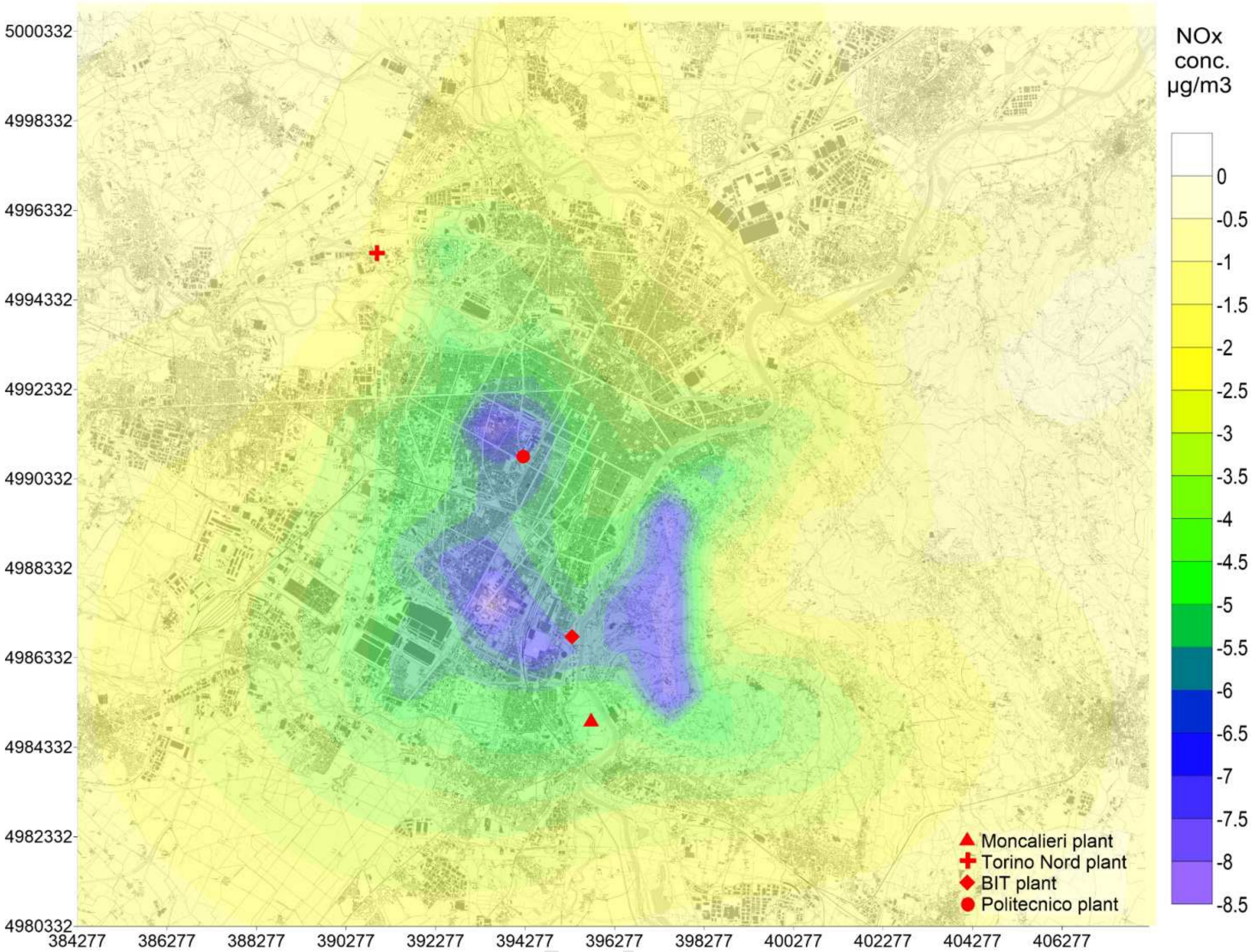


Figure 5. Average 1-hour delta-concentration map of NO_x in the metropolitan area of Turin, resulting from CALPUFF simulation. Average is calculated over the entire heating season (October to March).

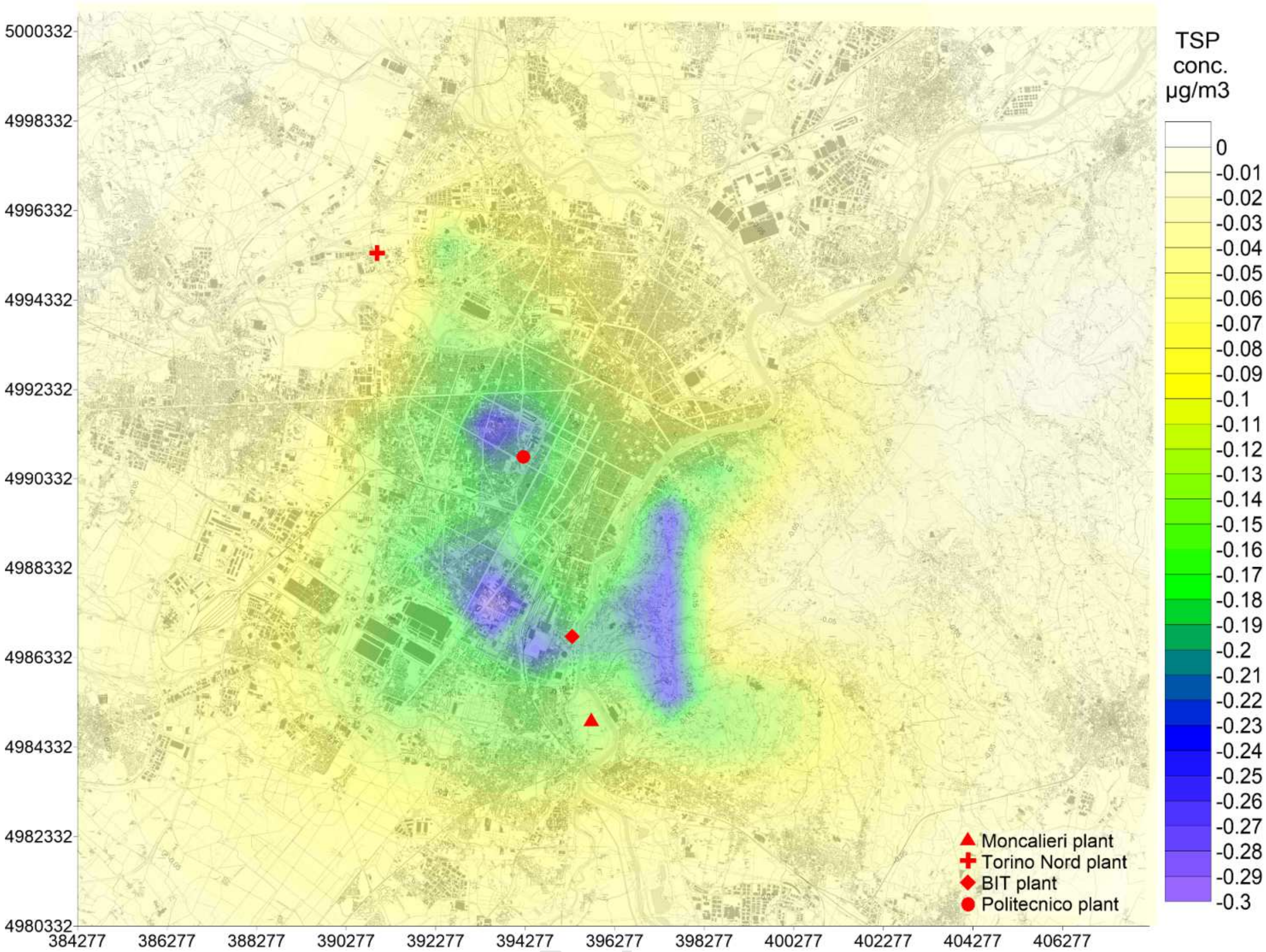


Figure 6. Average 1-hour delta-concentration map of total PM in the metropolitan area of Turin, resulting from CALPUFF simulation. Average is calculated over the entire heating season (October to March).

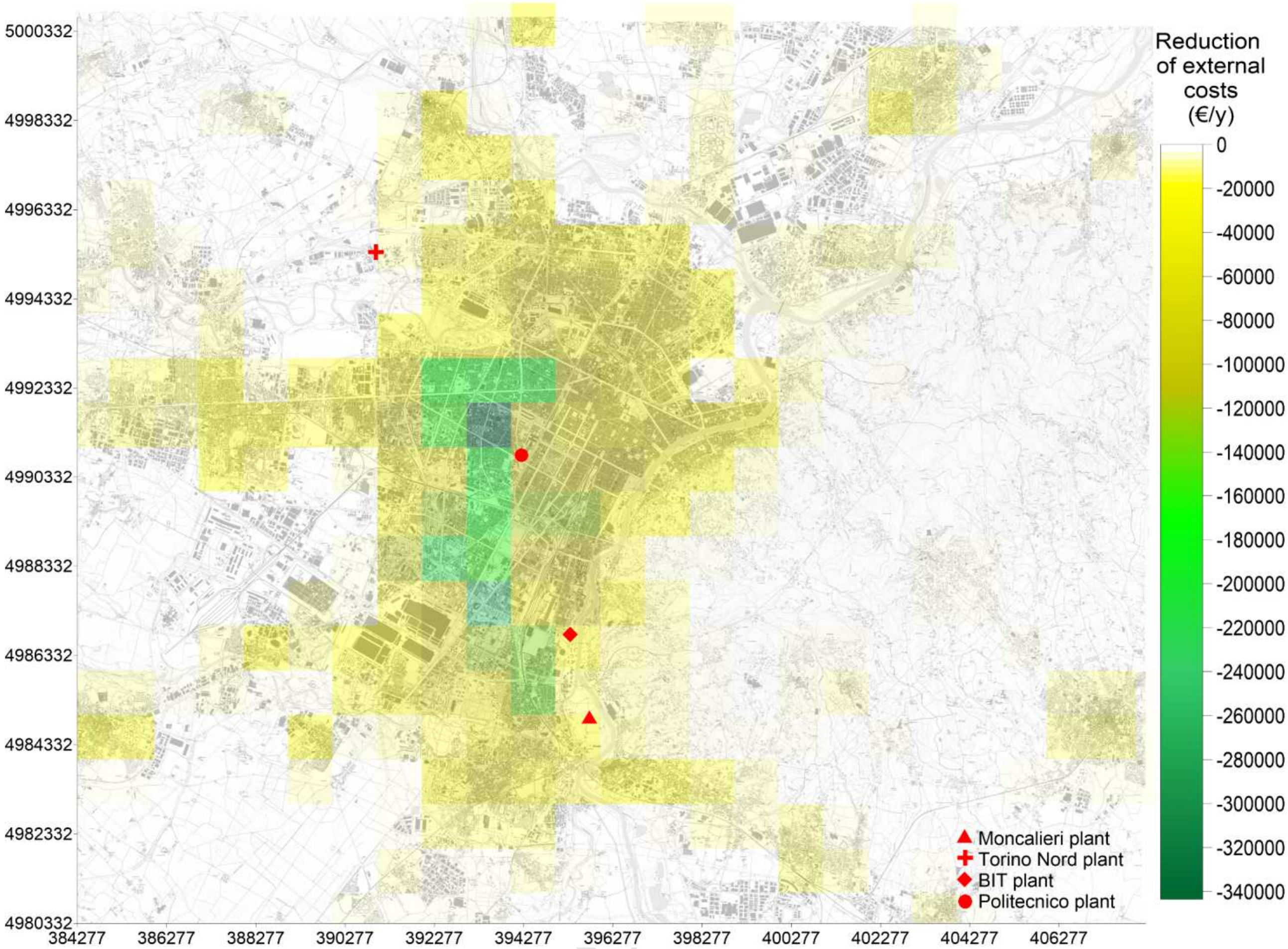


Figure 7. Map of average delta-external costs resulting from the integrated simulation with DIDEM model, referred to Setting 1.

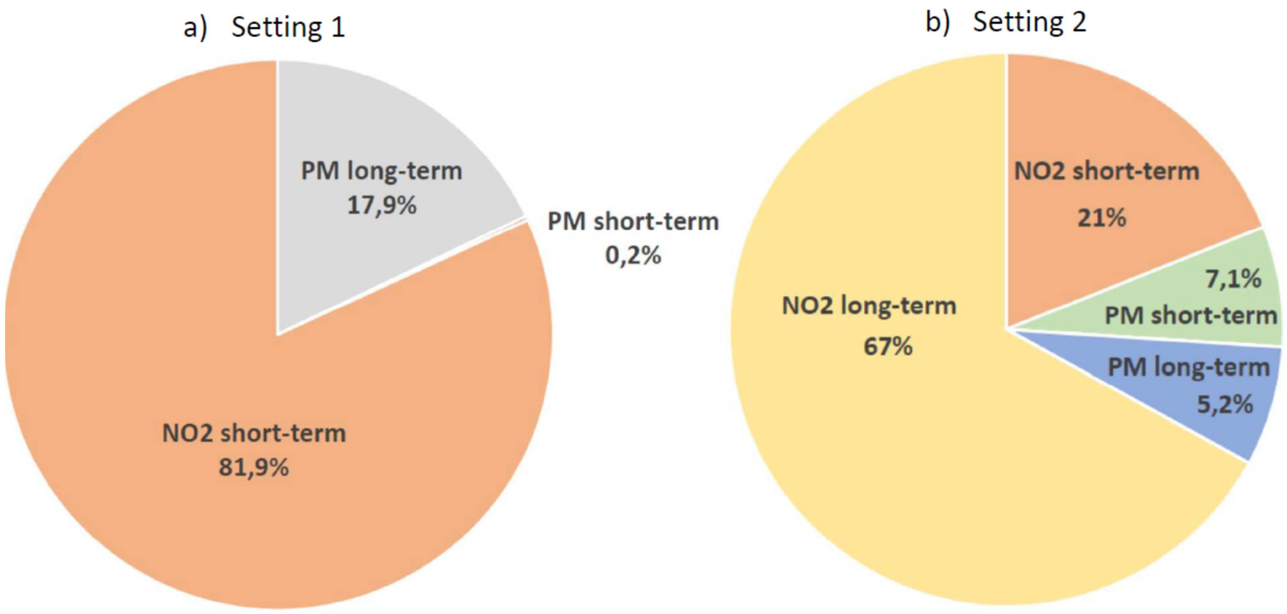


Figure 8. Case study results. Contribution of pollutant (NO_2 and PM) and exposure term (short and long term exposure) to the total delta-external costs, for Setting 1 (a) and Setting 2 (b) respectively.

Table 1. List of the pollutant-outcome pairs implemented in the DIDEM model, with the relative category of confidence level, average relative risk of the CRF and source of background health data (modified from WHO 2013a).

PM, long-term exposure					
Pollutant metric	**Health outcome**	**Group**	**Average RR per 10 µg/m^3**	**Range of concentration**	**Source of background health data**
$PM_{2.5}$, annual mean	Mortality, all- cause (natural), age 30+ years	A*	1.062	All	European mortality database (MDB) (WHO HMDB), rates for deaths from all natural causes (International Classification of Diseases, tenth revision (ICD-10) chapters I–XVIII, codes A–R), latest available data
$PM_{2.5}$, annual mean	Mortality, cerebrovascular disease (includes stroke), ischaemic heart disease, chronic obstructive pulmonary disease (COPD) and trachea, bronchus and lung cancer, age 30+ years	A	1.07	All	European detailed mortality database (WHO HMDB), ICD-10 codes cerebrovascular: I60–I63, I65–I67, I69.0–I69.3; ischaemic heart disease: I20– I25; COPD: J40–J44, J47; trachea, bronchus and lung cancer: C33–C34, D02.1– D02.2, D38.1
PM_{10}, annual mean	Postneonatal (age 1–12 months) infant mortality, all-cause	B*	1.04	All	European Health for All database (WHO HFA-DB) and United Nations projections
PM_{10}, annual mean	Prevalence of bronchitis in children, age 6–12 years	B*	1.08	All	Mean prevalence from the Pollution and the Young (PATY) study: 18.6% (range 6–41%) (Gehring et al, 2006)
PM_{10}, annual mean	Incidence of chronic bronchitis in adults (age 18+ years)	B*	1.117	All	Annual incidence 3.9 per 1000 adults based on the Swiss Study on Air Pollution and Lung Disease in Adults (SAPALDIA; Schindler et al, 2009)
PM, short-term exposure					
$PM_{2.5}$, daily mean	Mortality, all-cause, all ages	A	1.0123	All	MDB (WHO HMDB)
$PM_{2.5}$, daily mean	Hospital admissions, cardiovascular diseases (CVDs) (includes stroke), all ages	A*	1.0091	All	European hospital morbidity database (WHO HMDB), ICD, ninth revision (ICD-9) codes 390-459; ICD-10 codes I00–I99

$PM_{2.5}$, daily mean	Hospital admissions, respiratory diseases, all ages	A*	1.0190	All	European hospital morbidity database (WHO HMDB), ICD-9 codes 460-519; ICD-10 codes J00–J99
$PM_{2.5}$, two-week average, converted to $PM_{2.5}$, annual average	Restricted activity days (RADs), all ages	B*	1.047	All	19 RADs per person per year: baseline rate from the Ostro and Rothschild (1989) study
$PM_{2.5}$, two-week average, converted to $PM_{2.5}$, annual average	Work days lost, working-age population (age 20–65 years)	B*	1.046	All	European Health for All database (WHO, HFA-DB)
PM_{10}, daily mean	Incidence of asthma symptoms in asthmatic children aged 5–19 years	B*	1.028	All	Prevalence of asthma in children based on “severe asthma” in the International Study on Asthma and Allergies in Childhood (ISAAC) (Lai et al., 2009)
NO_2, long-term exposure					
NO_2, annual mean	Mortality, all (natural) causes, age 30+ years	B*	1.055	>20 µg/m^3	MDB (WHO HMDB), rates for deaths from all natural causes (ICD-10 chapters I–XVIII, codes A–R) in each of the 53 WHO Regional Office for Europe countries, latest available data
NO_2, annual mean	Prevalence of bronchitic symptoms in asthmatic children aged 5–14 years	B*	1.021	All	Background rate of asthmatic children, “asthma ever”, in Lai et al. (2009). Prevalence of bronchitic symptoms among asthmatic children 21.1% to 38.7% (McConnell et al., 2003)
NO_2, short-term exposure					
NO_2, daily maximum 1-hour mean	Mortality, all (natural) causes, all ages	A*	1.0027	All	MDB (WHO HMDB), rates for deaths from all natural causes (ICD-10 chapters I–XVIII, codes A–R) in each of the 53 countries of the WHO European Region, latest available data
NO_2, daily maximum 1-hour mean	Hospital admissions, respiratory diseases, all ages	A	1.0015	All	European hospital morbidity database (WHO HMDB), ICD-9 codes 460–519; ICD-10 codes J00–J99
NO_2, 24-hour mean	Hospital admissions, respiratory diseases, all ages	A*	1.0180	All	European hospital morbidity database (WHO HMDB), ICD-9 codes 460–519; ICD-10 codes J00–J99

Table 2. Monetary values implemented in the DIDEM model (from Holland, 2014b).

Health outcome	Monetary value (mean)	Monetary value (min)	Monetary value (max)	Unit
Mortality, age 30+ years	95,350	57,700	133,000	€$_{2005}$/YOLL
Infant mortality, age 1–12 months	2,450,000	1,600,000	3,330,000	€$_{2005}$/case
Bronchitis in children, age 6–18 years	588			€$_{2005}$/case
Chronic bronchitis in adults, age 18+ years	53,600			€$_{2005}$/case
Mortality, all ages	98,200	57,700	138,700	€$_{2005}$/YOLL
Hospital admissions, cardiovascular diseases, all ages	2,200			€$_{2005}$/admission
Hospital admissions, respiratory diseases, all ages	2,200			€$_{2005}$/admission
Restricted activity days (RADs), all ages	92			€$_{2005}$/day
Work days lost, working- age population (age 20–65 years)	130			€$_{2005}$/day
Asthma symptoms in asthmatic children, age 5–19 years	42			€$_{2005}$/case

Table 3. Data on power plants and emission sources presently feeding the DH network in Turin, Italy

Power plant	Emission source name and ID	Nominal power (th,el)	Stack height (m)	Stack diameter (m)	Latitude UTM ED50 (m)	Longitude UTM ED50 (m)
Moncalieri cogeneration combined cycle	1. Combined cycle RPW 2°GT (gas turbine)	395 MW_e 260 MW_t	60	7.5	395652.72	4983228.57
	2. Combined cycle RPW 3°GT (gas turbine)	383 MW_e 260 MW_t	60	7.0	395736.12	4983266.35
	3. Reserve boilers n°1-2-3	47 MW_t x 3	70	1.5	395624.74	4983162.38
Torino Nord cogeneration combined cycle	4. Combined cycle RPW 2°GT (gas turbine)	400 MW_e 220 MW_t	60	6	390950.42	4995655.77
	5. Integration and reserve boilers n°1-2-3	113 MW_t x 3	60	1.8	390975.80	4995571.70
BIT integration and reserve plant	6. Integration and reserve boilers n°1-2-3	85 MW_t x 3	43	1.8	395378.47	4985746.22
Politecnico integration and reserve plant	7. Integration and reserve boilers n°1-2-3	85 MW_t x 3	50	1.8	394275.49	4990844.94

Table 4. Energy and pollutants emission balance for the case study considered, present scenario year 2016.

Variable	**Unit**	**Value**
Fuel consumption for electricity and heat	GWh	9,992
Net electricity production	GWh	5,040
Net heat production for building heating	GWh	1,813
NO_x emission	t	327.7
Total PM emission	t	16.3

Table 5. Energy and pollutants emission balance for the case study considered, alternative scenario year 2016.

Variable	**Unit**	**Value**
Fuel consumption for heat production	GWh	3,705
Net heat production for building heating	GWh	1,813
NO_x emission	t	444.6
Total PM emission	t	16.1

Table 6. Result of delta-external costs calculation for the case study considered.

Confidence level on CRF data (Setting)	Delta external costs MEAN (€/y)		Delta external costs MINIMUM (€/y)		Delta external costs MAXIMUM (€/y)	
	€/y	$€_{cent}$/kWh	€/y	$€_{cent}$/kWh	€/y	$€_{cent}$/kWh
High (Setting 1, Group A)	- 8,550,000	-0.472	- 3,880,000	-0.214	- 12,245,000	-0.675
Medium (Setting 2, Group A+B)	- 58,815,000	-3.244	- 32,245,000	-1.778	- 85,652,000	-4.724

Highlights

- Air pollution represents a continuous hazard to human health
- A new model is presented for comparing external costs of air pollution scenarios
- This tool integrates CALPUFF dispersion model with the latest WHO recommendations
- The model was tested on a real case study and compared to other existing tools
- Its application at the local scale may provide support to decision-makers